On the Hydrodynamics and Treatment Efficiency of Waste Stabilisation Ponds: From a Literature Review to a Strategic Evaluation Framework

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Abstract:

Waste stabilisation ponds (WSP) are designed to treat wastewater through natural microbiological, photosynthetic, biochemical, physico-chemical and hydrodynamic processes. They are used throughout the world for wastewater treatment due to their minimal technical requirements, low cost and minimal energy consumption. It is well recognised that WSP hydrodynamics plays a crucial role influencing WSP treatment efficiency. In this study, published WSP literature is reviewed with a focus on the importance of environmental forces, pond configurations and pond loadings on WSP hydrodynamics and pond treatment efficiency. The findings are used to propose future WSP design and modelling requirements. It has been found that the interrelated effects of multiple factors such as pond length-to-width ratio, inlet/outlet configuration, temperature, solar radiation and wind on WSP treatment performance are not investigated sufficiently at present. It is suggested that a system based on numerical pond modelling and field measuring analyses be formulated to address the interacting influences of these factors on WSPs. Consequently, field studies on full-scale WSPs are required to obtain a complete dataset for validation purposes. In this regard, a combination of three-dimensional pond water temperature survey and tracer concentration mapping is suggested. Details of specific modelling components, such as sludge accumulation, turbulence mechanisms and the assumption of constant influent conditions, require further attention. As a result of this review process, a strategic evaluation framework together with the required dataset for the modelling and field work activities are proposed. This paves the way for subsequent studies on WSP hydrodynamics and treatment efficiency, thus benefitting pond design and operation processes.

Key words:

Waste stabilisation ponds; Hydrodynamic modelling; Treatment efficiency; Environmental factors; Strategic evaluation framework

Contents:

1. INTRODUCTION	3
2. REVIEW SCOPE AND METHOD.....	7
3. WSP HYDRODYNAMIC STUDIES	8
3.1 COMPUTATIONAL HYDRODYNAMIC MODEL	9
3.2 HYDRODYNAMIC AND WATER QUALITY MODEL INTEGRATION	12
4. HYDRODYNAMIC CHARACTERISTICS OF WSPS.....	15
4.1. POND GEOMETRIC CONFIGURATIONS	15
4.1.1 Pond depth	15
4.1.2 Length-to-width ratio	17
4.1.3 Inlet and outlet settings	18
4.1.4 Baffles	20
4.1.5 Sludge accumulation	22
4.2. ENVIRONMENTAL FACTORS	23
4.2.1 Wind effects	23
4.2.2 Thermal effects	25
4.2.3 Solar radiation	27
4.2.4 Climate conditions	28
4.3 ENGINEERING INTERVENTIONS	30
5. DISCUSSIONS AND FUTURE RESEARCH RECOMMENDATIONS	32
6. A STRATEGIC MODELLING FRAMEWORK.....	34
REFERENCES	44

1. Introduction

Waste stabilisation ponds (WSPs) are shallow constructed basins for wastewater treatment. They use natural microbiological, photosynthetic, biochemical, physico-chemical and hydrodynamic processes to generate a reduction of organic matter and pathogenic organisms in wastewater, accompanied by other processes such as nutrient and heavy metal removal (Watters et al., 1973). Intentional use of ponds started in the early 1900's, more often by accident than design (Wood, 1997). A pond was found to have formed after a prepared gravel seepage area became clogged thus detaining 0.9 m deep sewage at Santa Rosa in California in 1924 (Caldwell, 1946). Observations of the performance of the pond showed a substantial reduction of total biochemical oxygen demand (BOD) throughout the pond. Due to favourable outcomes, authorities and engineers started to investigate the utilisation of WSPs for treatment of wastewater before it flowed into natural environment.

According to Mara and Pearson (1987), there are three principal types of WSPs; namely anaerobic ponds, facultative ponds and maturation ponds, which are often used in sequence for wastewater treatment systems (see Figure 1). In some cases, raw wastewater goes through prior treatment such as screening and grit removal, before flowing into the pond system. Anaerobic ponds have a typical depth of 2-5 m and are designed to undertake bulk removal of organic loading. With a relatively short retention time of only a few days, they can reduce the organic loading by 40%-70% (Shilton, 2005). Facultative ponds, which often receive water from the anaerobic pond, are normally shallower than anaerobic ponds, with a typical depth of between 1 and 2 m. These operate in aerobic conditions in the upper layers, and anaerobic conditions close to the pond bottom. A maturation pond receiving effluent from a facultative pond or an equivalent treatment process (such as a mechanical treatment system) is regularly used at the final stage of a wastewater treatment plant. It is anticipated that most organic matter has already been removed, and therefore maturation ponds serve mainly to remove pathogenic organisms including bacteria, viruses, protozoan cysts and helminth eggs. Generally the size and number of maturation ponds are determined by the required effluent quality, and they are normally shallower compared with anaerobic and facultative ponds. A list of key characteristics of the three typical pond types is shown in Table 1.

Pond systems are widely used in many countries. There are more than 2,500 WSPs in France, about 3,000 in Germany, 100 in New Zealand and more than 8,000 in the United States

(Mara, 2009; United States. Environmental Protection Agency. Office of Research Development, 2011). As of 2012, there are about 1,200 to 1,300 engineered wastewater treatment plants in operation in Australia, of which about 600 are pond systems (Kay et al., 2012; Kelly, 2013), and at least 400 of these treatment plants have at least one pond in their treatment processes (e.g., as polishing ponds to further remove nutrients and/or pathogens). It is estimated that pond systems serve at least 600,000 Australians residing in rural and/or remote regions (an average of 1,000 people per pond system), or, the service population could be as high as seven million if including all treatment plants that have ponds (on average 18,000 people per treatment plants national wide). Pond systems have been playing and will continue to play an important role in wastewater treatment in Australia. Typically, the geographical distribution of ponds is closely governed by the population density, as shown in Figure 2, and most ponds are located in tropical or subtropical temperate regions. It is widely accepted that correctly designed pond systems are highly robust, easy to maintain and can operate effectively throughout the year in these regions (Pearson, 2003; Mara, 2004; Shilton, 2005; Von Sperling, 2007).

Studies have been undertaken to evaluate WSP treatment performance, and identified hydrodynamics as a crucial factor when predicting WSP efficiency (Ouedraogo et al., 2016; Verbyla and Mihelcic, 2015). Watters et al. (1973) stated that ‘the hydrodynamic flow characteristics will have an effect on the dispersion and the retention time of the wastewater, and consequently on the removal efficiency of organic and pathogenic organisms’. Wood et al. (1995), through the review of the pond systems operated in Australia, concluded that many systems are found to operate below optimal level due to hydrodynamic problems including short-circuiting, alternating stratification and de-stratification in hot Australian climates, and dead zones of stagnant fluid. Short-circuiting is the passage of wastewater through a WSP in a short period of time before receiving adequate treatment, resulting in reduced treatment efficiency of WSPs. While short-circuiting is most likely to occur due to inappropriate layout of inlets and outlets, it may also be driven by wind or thermal stratification. Stagnation zones refer to the pond volume, such as at pond corners, that is bypassed by the main flow within the pond. A portion of wastewater stays there for an extended period of time, with a less than desirable rate of mixing occurring. This essentially reduces the effective volume of the pond, and consequently its treatment efficiency. Stratification occurs within ponds on a seasonal or daily basis (Gu et al., 1996), due to the

comparatively warmer temperature in summer and during daylight hours than that of winter and at night. Stratification simply means a noticeable temperature gradient develops within the water body, resulting in a density variation in the pond. Warm and light water sits within top layers, while cold and dense water stays at the bottom. De-stratification is due either to the wind effect or to the cooling of the upper water layers through the water surface (Badrot-Nico et al., 2009). From the hydrodynamic point of view, stratification will encourage wastewater to short-circuit either through the warm top layer or the cold bottom layer, depending on the influent temperature, without sufficient mixing. Further, temperature stratification leads to stratification of DO, pH and other water quality parameters, which breaks the mixing balance in a WSP and adversely affects WSP treatment efficiency. According to Sweeney et al. (2005) and Badrot-Nico et al. (2009), stratification and de-stratification occur alternately in WSPs under the influence of solar radiation and wind, which affects the hydrodynamic properties of WSPs. The Department of Environment and Planning in the state of Tasmania, Australia, surveyed 39 wastewater treatment systems and reported that 74% of the pond systems failed to achieve the effluent requirements, largely due to hydrodynamic problems (Tasmania. Department of Environment Planning, 1992).

Griffith University, Australia, engaged 4 other universities and 10 industry partners to commission a multidisciplinary research project entitled “*Validation of treatment ponds/lagoons in order to enhance safe and economical water recycling*” (Stratton et al., 2015). The project encompassed a wide range of research areas in terms of microbiology, hydrodynamics, chemical and eco-toxicology and health risk assessment. Research methods employed included a national data inventory (Kelly, 2013), a literature survey, numerical and stochastic modelling, field sampling and experiments and laboratory analyses. Through more than 3 years of dedicated work, the team made substantial strides in acquiring a wider appreciation of wastewater treatment pond technology. The outcomes of the project included a commissioned report (Stratton et al., 2015), a series of publications in areas of pathogen removal mechanism (Sheludchenko et al., 2016) and modelling (Dahl et al., 2017), hydrodynamic performance analysis (Li et al., 2013; Li et al., 2015) and health risk assessment and modelling (Beaudequin et al., 2016, 2017; Beaudequin et al., 2015a, b; Xie et al., 2016, 2017). Expertise gained through this project is to inform policy-makers, developers and managers in the water sector and the entire community of tools to design, operate and maintain maturation ponds, ultimately to optimise the use of recycled water and improve

water safety and security in remote and regional areas with significant public health, societal and environmental impacts and benefits.

Experiences gained from conducting an extensive amount of modelling work with respect to WSP hydrodynamics and on the integration of WSP hydrodynamics and water quality urged the authors to critically review the current state-of-the-art of WSP modelling. Studies have been carried out on several aspects of WSP hydrodynamics, including measurements, numerical models, and individual and interrelated effects of hydrodynamic factors (Alvarado et al., 2011; Ferrara and Harleman, 1981; Pearson et al., 1995; Sah et al., 2011; Shilton, 2001; Shilton and Harrison, 2003b; Sweeney, 2004; Vega et al., 2003; Watters et al., 1973). All of these have substantiated the importance of hydrodynamics and boosted the present knowledge of WSPs. Sah et al. (2012) conducted a literature survey in respect of the modelling activities of WSPs, HRAPs (high-rate algal ponds) and AFLs (aerated facultative lagoons). This covered a total of 39 peer-reviewed papers and tabulated: (1) key features of each model; (2) details on water quality modelling, ie whether aerobic/anoxic carbon removal, anaerobic carbon removal, nitrogen, phosphorus and *E. coli* removal have been included; (3) whether a thermal balance was included; (4) the dimension characteristics of each model (zero, one-, two- or three-dimensional); (5) the nature of the model in respect of steady-state versus dynamic; (6) modelling software used; (7) the inclusion of a parametric sensitivity analysis, and (8) the validation status of each model. This review resulted in a categorisation of WSP modelling into three groups: (1) hydrodynamic modelling focusing on flow patterns; (2) water quality models focusing only on water quality, and (3) models incorporating both hydrodynamics and water quality. It concluded that, to date, only one semi-dynamic model in three dimensions encompassing both hydrodynamic and biochemical processes has been developed, and this requires validation. The review therefore proposed the need for development of a three-dimensional dynamic model that includes hydrodynamic and details of biochemical interactions. It is also essential that the model be fully validated and calibrated against field data from full-scale WSPs for universal application.

However, it was not the focus of Sah et al. (2012)'s review to elaborate the current-state-of-art of WSP hydrodynamics. There was no explicit discussion on how models handle environmental factors, or what aspects of pond configurations have been addressed by

researchers so far. No discussions were presented in terms of how environmental factors, such as wind, affect pond performance, or how certain pond design contributes positively or negatively to pond treatment efficiency. Information in these regards, scattered in published material, requires consolidation and critical synthesis to clarify the current framework of WSP hydrodynamics.

In addition, several review articles about aspects of pond design principles based on pathogen inactivation models (Ho et al., 2017), and die-off mechanisms of bacterial indicators (Ansa et al., 2015; Bolton et al., 2010; Dias et al., 2017; Verbyla and Mihelcic, 2015) suggested that an update on the efficiency of WSP treatment from the hydrodynamic perspective was needed. It is the primary aim of this present review to update, refine and extend Sah et al. (2012)'s review, and to contribute to the holistic review process on WSP studies. This review makes a valuable contribution in two ways. It details the various factors pivotal to the treatment mechanisms of WSPs. It also proposes a strategic evaluation framework, supported by a comprehensive dataset, that integrates both computer modelling and field work activities. The framework is expected to inform future research directions for those studying WSP treatment performance.

2. Review scope and method

This literature review formed part of a larger research project on WSPs described in Stratton et al. (2015), in which the WSP numerical modelling was an integral component. The review process was guided by the systematic quantitative literature review method documented by Pickering et al. (2015). The ultimate goal of the literature review was to capture the current state-of-the-art in WSP modelling, while identifying challenges and opportunities that are instrumental to the advancement of WSP technology. Specifically, this has been addressed by answering the following two questions: (1) what is the scope of the current WSP modelling study? For example, is the study restricted to a particular combination of hydrodynamic factors such as wind, baffles, and/or sludge or is the hydrodynamic modelling integrated with the microbiological component (fate of pathogens/indicator organisms)? (2) what is the context of the current WSP modelling study? For example, is the WSP considered a black box and are the characteristics of a WSP fully investigated in three dimensions? To focus the search of the literature, the keywords used included: 'waste stabilisation (stabilization) pond', 'maturation pond', 'facultative pond', 'wastewater treatment pond' in combination with

‘modelling’, ‘tracer’, ‘hydrodynamic/hydraulic efficiency’, ‘stratification’, ‘geometry’, ‘baffle’, ‘sludge’, ‘wind’, ‘meteorological’, ‘treatment efficiency’, ‘depth’, ‘inlet/outlet’, ‘pathogen’, ‘removal’, ‘inactivation’, ‘ecology’. The search terms excluded ‘wastewater treatment plant’, even though the modelling techniques could be interchangeable between WSPs and the wastewater treatment plants. This is to restrict the review to the ‘natural processes’ which are distinctive to WSPs.

The majority of the material was obtained via online databases including: Web of Science, Science Direct, Scopus, ProQuest and Google Scholar to ensure the breadth of literature examined included refereed publications and the grey literature. This was supplemented by a small percentage of documents that were obtained from hardcopy sources. Ultimately, the selected articles consisted of a wide range of material types including journal articles, conference papers, national and international guidelines, corporate reports and research theses (PhD, Master’s and Honour’s degrees), resulting in a total of 152 documents. The outcomes of the review process are illustrated in the upcoming sections.

3. WSP hydrodynamic studies

A significant amount of work has been undertaken to study WSP hydrodynamics. This work can be classified into the two categories of physical and computational models according to the methodology adopted. Physical model studies dominate the early stage of hydrodynamic studies, prior to the 1990’s before computational resources were able to meet the requirements of numerical calculations. Physical studies primarily used tracers either in the field or in laboratories. Tracer-based studies reported in literature have been limited to those collecting tracer concentration data at the outlet only, which is then used to quantitatively derive hydraulic measures of the ponds (Alvarado et al., 2012a; Alvarado et al., 2011; Broughton and Shilton, 2012; Short et al., 2010). Such information can only reflect general WSP hydrodynamics. The authors’ work (Stratton et al., 2015) has found that tracer studies can certainly be used more fully to capture internal WSP hydrodynamics. A tracer concentration distribution pattern can be mapped in detail throughout the whole pond to identify the phenomena of short-circuiting and stagnant zone(s). The tracer concentration profile data can also be used for model calibration and validation.

Besides tracer studies, drogue tracking technologies have also been used to understand the flow pattern of WSPs (Barter, 2003; Shilton and Kerr, 1999). A typical study conducted on a dairy shed WSP system in Australia revealed a short-circuiting route along the pond

perimeter, whereby the influent could have reached the outlet within 45 minutes (Fyfe et al., 2007). The same study showed that a number of drogues did not travel, but rather oscillated in the immediate vicinity of the inlet. This implied the formation of small eddies, which trapped and sometimes pulled the drogues back towards the edges of the inlet. Drogue tracking technique provide a useful insight into the velocity field and the incidence of short-circuiting and dead zones within WSPs, but it is limited by the horizontal two-dimensional nature of the drogue movement, and the interference of stochastic wind can lead to erroneous interpretation of the results.

3.1 Computational hydrodynamic model

The study of WSP hydrodynamics has witnessed rapid progress since the early 1990s, when computational modelling was elevated through enhanced numerical schemes and computer power (Badrot-Nico et al., 2009; Fares, 1993; Fares and Lloyd, 1995; Sah et al., 2012; Sah et al., 2011; Sweeney et al., 2005; Vega et al., 2003; Wood, 1997; Wood et al., 1995). The fundamentals underpinning WSP hydrodynamic modelling are the conservation principles in terms of mass, momentum and energy. Studies have been carried out in both two and three dimensions, as shown in Table 2 and Table 3, respectively.

The two dimensional models solve a depth-integrated version of the conservation equations (Benelmouffok and Yu, 1989; Fares et al., 1996; Fares and Lloyd, 1995; Persson, 2000; Vega et al., 2003). They apply to situations where the horizontal length scale of the flow field is much greater than the vertical length scale; the vertical velocity component of the flow is rather small and the vertical pressure gradient nearly hydrostatic. The velocity field of a horizontal level is considered constant throughout the depth of the flow field. Outcomes obtained from two dimensional modelling were used to confirm poor pond performance and identify possible reasons (Fares et al., 1996; Fares and Lloyd, 1995), propose favourable pond design suggestions (Persson, 2000; Vega et al., 2003; Wood et al., 1995) and investigate pond hydrodynamic mechanisms (Abbas et al., 2006). However, some of the studies were not validated (Abbas et al., 2006; Persson, 2000; Wood et al., 1995). In addition, important hydrodynamic aspects such as wind-induced mixing or temperature stratification cannot be represented in two-dimensional models (Persson, 2000; Vega et al., 2003; Wood et al., 1995; Wood et al., 1997).

Two-dimensional models are adequate when exploring basic WSP hydrodynamics, providing ponds have uniform topography, thermal stratification is not prominent, and inflow velocity can be assumed uniform throughout pond depth (Vega et al., 2003). However, this required a significant amount of effort on calibration and verification processes. Calibration parameters in this study included: inflow rate; water level difference; bed roughness coefficient; wind speed and the friction coefficient, and the dispersion number. Persson (2000) stated that “it was possible to simulate the flow conditions in ponds using two-dimensional models, provided that the flow did not contain larger three-dimensional effects like stratified flow or complex topography.” However, these aforementioned situations rarely exist in practice, making two-dimensional models incompetent in representing WSP behaviour. The work in Wood (1997) suggested “two-dimensional CFD models cannot be used *a priori* to give an adequate description of the hydrodynamic patterns in WSP”. Badrot-Nico et al. (2010) said “two-dimensional models were soon shown to be ill-adapted to the modelling of WSPs which, despite they are shallow water bodies, are subject to influential three-dimensional mechanisms”. Therefore, three-dimensional models are essential for complete and accurate evaluation of WSP performance.

Three-dimensional models strive to include various aspects of pond features to advance pond hydrodynamic studies. This includes incorporating three dimensional effects of inflow depth and velocity (Wood, 1997), effects of thermal stratification structure of pond water (Salter et al., 2000; Sweeney et al., 2005), comprehensive meteorological conditions (Badrot-Nico et al., 2009), sludge effects (Alvarado et al., 2012a; Alvarado et al., 2012b; Coggins et al., 2017; Ouedraogo et al., 2016) and improving pond hydrodynamic performance by retrofitting pond structures (Olukanni and Ducoste, 2011; Salter et al., 2000; Shilton, 2000).

As far as the modelling features are concerned, most studies (Alvarado et al., 2012a; Alvarado et al., 2012b; Salter et al., 2000; Shilton, 2000; Wood, 1997) employed the standard $k - \varepsilon$ model to describe the turbulence mechanisms associated with WSP hydrodynamics. The $k - \varepsilon$ model uses two model equations to describe the transport of k and ε (Launder and Spalding, 1974). Here, k denotes the turbulent kinetic energy and ε the rate of dissipation of the turbulent kinetic energy per unit mass. The modelling results of these studies (Alvarado et al., 2012a; Alvarado et al., 2012b; Salter et al., 2000; Shilton, 2000; Wood, 1997), however,

were not validated adequately. Only the three-dimensional modelling results of Wood (1997) fitted reasonably well with the experimental studies documented by Mangelsso and Watters (1972). Persson (2000) selected the Smagorinsky's turbulence model when performing a two-dimensional hydrodynamic analysis of the performance of 13 hypothetical ponds. The main focus of the study was not on the modelling, rather to derive the influence of various pond layouts on pond hydraulic performance. Hence, the applicability of Smagorinsky's model in WSP hydrodynamic modelling was not testified.

Turbulence affects the transport of water particles, water temperature and density in ponds. The validation of a turbulence model is an important aspect in the validation process of WSP hydrodynamic modelling. One approach to this is through examining the thermal structure in the pond by collecting pond water temperature data, especially to capture prominent stratification profiles. Comparing the modelled temperature distribution pattern with the measured stratification pattern offers suggestive information about the selection of turbulence model as well as its associated parameters. Another strategy for validating the turbulence model is related to the tracer study. It is suggested that the tracer concentration be mapped spatially within the pond to compare with the modelled tracer profiles. This requires looking into the flow regime within the pond in more detail and utilises more of the turbulence information. The above two procedures will ensure an adequate validation process of WSP hydrodynamics, especially the turbulence model. This, however, is yet to be documented in literature.

Apart from specifying turbulence models, another important feature in WSP hydrodynamic modelling is the assignment of boundary conditions. Previously reported modelling activities have specified boundary conditions in terms of pond inflow and outflow conditions (Badrot-Nico et al., 2009; Persson, 2000; Salter et al., 2000), pond side wall and bottom conditions (Abbas et al., 2006; Wood et al., 1997), free surface conditions (Salter et al., 2000; Wood et al., 1997) and environmental forcing (Badrot-Nico et al., 2009; Sweeney et al., 2005). Normally, pond inlets have been specified as velocity inlets, introducing mass and momentum into the flow system, and outlets assigned as mass flux boundaries (Salter et al., 2000). The influent conditions have been assumed to be constant, with fixed velocity, temperature (Badrot-Nico et al., 2009) and flow rate (Abbas et al., 2006; Persson, 2000). This

assumption of constancy is one of the shortcomings associated with current WSP hydrodynamic modelling. In the real situation, the influent velocity, temperature and flow rate vary with time. A sensitivity analysis on how the variations in these parameters affect WSP hydrodynamics should be conducted before constant values can be confidently applied in models. However, this aspect has not been reported to date.

In addition, pond side walls and bottoms are usually assigned with no-slip boundary conditions (Wood et al., 1997). That is, wastewater has been assumed to have zero velocity relative to the solid pond boundaries. Abbas et al. (2006), in a two-dimensional study, incorporated the Manning's roughness n -value to represent the boundary frictional effect when formulating the hydrodynamic governing equations of the wastewater flow. In circumstances when wind effects were not considered, a frictionless boundary condition with zero shear stress has been applied on pond surface (Salter et al., 2000; Wood et al., 1997). However, it is now generally accepted that wind forces play an important role in WSP hydrodynamics, along with other meteorological factors. One of the most comprehensive inclusions of meteorological conditions in WSP hydrodynamic modelling can be identified as the work conducted by Badrot-Nico et al. (2009), in which the authors included wind speed and direction, solar radiation, air temperature and relative humidity. So far, none of WSP hydrodynamic studies reviewed have included rainfall in the modelling, which may have substantial influence on WSP performance during wet seasons.

Assumptions associated with WSP hydrodynamic modelling have also been noticed in respect of wastewater properties. There have been a few studies (Alvarado et al., 2012a; Alvarado et al., 2012b; Wood, 1997; Wood et al., 1995; Wood et al., 1997) that have explicitly assumed the fluid in ponds to be incompressible and Newtonian with a fluid density of roughly 1000 kg/m^3 and dynamic viscosity of 0.001 kg/(m s) , which corresponds to the properties of normal water at 20°C (Graebel, 2001). Due to significant amounts of suspended solids being present in wastewater, the actual fluid properties in ponds could not possibly meet these assumptions. Unfortunately, this has been neglected by the WSP hydrodynamic studies to date. This assumption can only be applied confidently once the difference between real and assumed pond water properties has been proven sufficiently insignificant.

3.2 Hydrodynamic and water quality model integration

Studies utilising CFD models offer a clearer understanding of WSP hydrodynamic mechanisms than when they were treated as a ‘black box’. The inherent flexibility and versatility of numerical modelling provides effective and efficient investigations of pond performance over physical modelling or analytical formulations. The variation in pond configurations, such as length-to-width ratio, inlet/outlet positioning and baffling can be accounted for more easily through CFD modelling than in field or laboratory studies. An appealing feature of CFD models is that they allow the reaction processes of microorganisms and chemicals to be incorporated in its solution domain, which provides a straightforward evaluation of pond treatment efficiency. This invariably requires substantial and accurate knowledge on the reaction dynamics of microorganisms and chemicals, and a suitable and sufficient dataset for model validation.

In his doctoral thesis, Shilton (2001) briefly documented the integration of a reaction model and a hydrodynamic model. The author took the assumption that the decay of coliforms in a WSP can be represented by using the first order kinetics. That is, the rate of decay is equal to a reaction rate constant multiplied by the concentration of the coliforms remaining in the pond. The predictive equation of the constant reaction rate proposed by Marais, G.V. (1974) was employed to determine the decay rate constant for faecal coliform die-off. Subsequently, Shilton and Harrison (2003b) applied Shilton (2001)’s integrated model to a practical design process. The integrated model developed in these two studies simply demonstrated the potential of predicting WSP treatment efficiency by integrating CFD and pathogen die-off models. The authors stated “this is the first time such an approach, that directly integrates hydraulic and reaction modelling for a waste stabilisation pond has been published, and because of this further studies are obviously recommended”. Subsequently, Shilton and Mara (2005) reported the usage of integrated CFD models to investigate the optimised design option of a secondary facultative pond. The authors employed first-order decay kinetics in the integrated model, and pointed out that extensive field tests were required to validate the modelling results.

Banda et al. (2006b) quantified the improved performance of a twin-baffled WSP in terms of *E. coli* removal using an integrated model. They looked at both isothermal and thermally

stratified conditions. The former assumed uniform water temperature throughout the pond, whereas the latter constructed a temperature profile: 8°C, 10°C, 12°C, 14°C, 16°C and 17°C at 0.25 m, 0.5 m, 0.75 m, 1.00 m, 1.25 m and 1.5 m above the pond bottom, respectively. Validation of the model was conducted on a pilot-scale pond. Under isothermal conditions during winter, the model predicted a 2.16-log *E. coli* removal, with the observed value of the pilot-scale pond being 2.76-log. When thermal stratification developed in summer, a 2.25-log removal of *E. coli* was measured and the model predicted a 2.58-log removal. These results justified a satisfactory level of accuracy of the prediction of the *E. coli* removal in a baffled pond using the integrated model. Similarly to previously mentioned models that integrated hydrodynamics and water qualities, the authors also employed first order kinetics to evaluate *E. coli* decay.

Models integrating hydrodynamics and water quality aspects have invariably been subjected to the simplification of first order kinetics for BOD and *E. coli* removal. There are a few studies addressing nutrient removal with integrated hydrodynamic and water quality modelling. Sah et al. (2011) conducted modelling of a secondary facultative pond by means of a three-dimensional hydrodynamic model coupled with an ASM-type (Activated sludge model: a generalised framework of mathematical models developed by the International Water Association that can be used to model activated sludge for nitrogen removal) biochemical model. The ASM was used to describe COD and nutrient removal as a function of bacterial growth, and *E. coli* was modelled as first order decay. The effects of environmental conditions as well as engineering interventions on pond treatment performance were assessed. Conclusions were: the addition of baffles or wind or the combination of wind and baffles did not lead to any prominent improvement in the removal of total COD or filtered COD, but a fair increase in *E. coli* removal was seen under these three scenarios. The authors made it clear these conclusions were based solely on simulation results, the validity and credibility of which were unattended due to the lack of an empirical dataset. This study posed an urgent need for a complete validation process for WSP modelling.

A systematic review of the current state-of-the-art of WSP numerical modeling was conducted by Sah et al. (2012). This review covered various models addressing both water quality and hydrodynamics, and revealed the state of the art of modelling has advanced

dramatically. However, due to the complex nature of hydrodynamic, microbiological and biochemical processes involved in WSPs, models have been configured individually and have focused only on selective factors. Sah et al. (2012) concluded there is a need to develop a comprehensive model incorporating the hydrodynamic, microbiological and biochemical aspects of WSPs, as well as a detailed dataset of full-scale WSPs for calibration and validation purposes. The ultimate objective of WSP modelling activities is to apply the developed model reliably and efficiently for the evaluation of pond performance, and subsequently for optimising pond design. Significantly, this needs to be undertaken using modern three-dimensional modelling approaches, as they offer the possibility of accurately describing hydrodynamic, microbiological and biochemical processes, subject to model calibration and validation, and permit various scenario testing.

4. Hydrodynamic characteristics of WSPs

As can be seen from the previous section, a substantial volume of work has been undertaken into the hydrodynamics of WSPs. The following section reviews dominant factors that appear to control pond hydrodynamics. They are grouped into two main categories: pond geometric configuration and external environmental factors.

4.1. Pond geometric configurations

4.1.1 Pond depth

The influences of pond depth on WSP treatment efficiency result mainly from the depth-dependent solar energy attenuation, by which the bacterial die-off is directly affected. It is generally accepted that bacterial die-off is faster in shallow ponds than in deep ponds (Moawad, 1968; Toms et al., 1975). Sarikaya and Saatci (1987) showed the significant effect of pond depth on bacterial removal and formulated a depth-averaged die-off rate constant in vertically-mixed ponds:

$$k = k_d + \frac{k_s S_0}{KH} (1 - e^{-KH}) \quad (1)$$

where k is the depth-averaged die-off rate constant; k_d denotes the die-off rate constant in dark; k_s symbols the rate constant for the light mortality term; K is the light attenuation coefficient; S_0 represents daily solar radiation; and H stands for the pond depth. This equation

was verified for a relatively limited range of pond depth (0.6 m and 0.86 m). Sarikaya et al. (1987) further checked the validity of Eq. (1) for a wider range of pond depths by studying batch-type ponds with depths of 0.3 m, 0.7 m and 1.0 m, and pilot-scale ponds with depths of 0.5 m, 1.0 m and 1.5 m. Eq. (1) was then modified to:

$$k = 1.156 + 5.244 \times 10^{-3} \frac{S_o}{KH} (1 - e^{-KH}) \quad (2)$$

The die-off constant k is directly proportional to the daily solar radiation S_o and inversely proportional to the pond depth H . However, this does not necessarily suggest all ponds should be shallow. This requires integrated analyses of pond hydraulic retention time and the die-off dynamics. Sarikaya and Saatci (1988) stated that a shallow pond may result in an excessive footprint and accordingly a huge cost considering the required pond volume for a desired level of bacterial removal. They formulated optimised pond depths on the basis of minimum cost for the same bacterial removal efficiency. While the series of studies conducted by Sarikaya and his co-workers thoroughly evaluated the influence of pond depth on bacterial die-off, the applicability of the derived equations (1) and (2) and the optimisation depth were confined to only limited cases. They acknowledged that small errors in the estimation of key parameters, k_d and k_s for example, would result in significant changes in the calculated pond depth.

Pond depth imposes different effects on pond performance criteria. This was demonstrated by Pearson et al. (2005), who studied experimental pond systems located in the Federal University of Campina Grande, Brazil. Four identical primary facultative ponds were operating at depths of 1.25 m and 2.30 m. It was reported that the total BOD removal was unaffected by pond depth, while faecal coliforms and NH_3 removal in the 1.25 m deep pond were more efficient. The deeper pond produced a higher concentration of H_2S , and thus was subjected to higher risk of odour release than the shallow pond. Another set of experiments was conducted on a series of ponds consisting of an anaerobic, a secondary facultative and three maturation ponds. This experiment was designed to operate the pond system in three modes: deep mode, shallow mode and innovative mode. All ponds had a depth of 2.20 m in the deep mode. When operating in the shallow mode, the anaerobic pond was 1.25 m deep and the depth of the facultative and all maturation ponds was 1.0 m. In the innovative (the shallowest) mode, the depth of the three maturation ponds varied between 0.3 m to 0.9 m, with an average of 0.6 m. Similar to the single facultative pond case discussed above,

shallower pond systems presented more efficient faecal coliform and nutrient removal. However, deeper pond systems indeed saved a significant amount of land area, by roughly 35% compared with shallow ones. The conclusions from this study were subject to the designated experimental forces; for example, an annual mean water temperature of 25°C was enforced and no wind or light conditions were specified. In addition, the conclusion about BOD removal being unaffected by the pond depth is informative as pond geometry does not influence particulate BOD such as algae, but only soluble BOD. Therefore, the implications they offered for WSP physical design could be considered limited.

4.1.2 Length-to-width ratio

Pond length-to-width ratio (L/W) has been shown to have greater influence on hydraulic performance of WSPs, than either pond depth or inlet/outlet settings. This was established in the early 1970's when Mangelsso and Watters (1972) and Watters et al. (1973) conducted numerous tracer tests on wastewater treatment lagoons at Logan, Utah. The lagoons had an L/W ranging between 1.6 and 2.3, and the average hydraulic efficiency λ was 0.58. They also conducted measurements on a model lagoon in a laboratory with $L/W = 2$. For the unbaffled model, λ varied in between 0.52 and 0.64. When baffles were used to alter L/W , λ was increased to 0.72 for $L/W = 5.26$, and to 0.93 for $L/W = 13$. Studies conducted by Marske and Boyle (1973) on ponds with a wide range of L/W also confirmed a direct relationship between L/W and λ . Thackston et al. (1987) reported the research conducted at dredged material containment areas (DMCAs) for the United States Army Corps of Engineers. Most of the DMCA sites were rectangular, with an L/W varying between 0.7 and 4.1. They performed a regression analysis based on DMCA data corresponding to a hydraulic efficiency ranging between 25% and 100%:

$$\lambda = 0.9 \left(1 - \exp \left(-0.3 \frac{L}{W} \right) \right) \quad (3)$$

Considering the limited range of L/W , Thackston et al. (1987) used data from Mangelsso and Watters (1972), Watters et al. (1973) and Marske and Boyle (1973) (see Figure 3), and modified Eq. (3) to become:

$$\lambda = 0.84 \left(1 - \exp \left(-0.59 \frac{L}{W} \right) \right) \quad (4)$$

Eq. (4) and Figure 3 show that the larger the L/W , the higher the hydraulic efficiency, but only to a certain level. Mara and Pearson (1987) interpreted this information quantitatively while formulating the WSP design manual for Mediterranean Europe. Generally, anaerobic

and primary facultative ponds are rectangular, with an L/W of less than 3 to avoid sludge accumulation and organic overloading near the inlet. Secondary facultative and maturation ponds, if permitted, are preferred to have a large L/W up to 10 or even 20 to approach the plug-flow residence pattern. Forero (1993) reported the work conducted by PAHO (Pan American Health Organization) Environmental Health Program for designing WSPs in tropical areas. Their design suggested using primary anaerobic ponds followed by elongated facultative ponds with an L/W ratio of at least 15:1 to minimise pond area and volume.

Evidence to support the claims that increasing L/W of ponds offers performance benefits appears to be inconsistent. Pearson et al. (1995) demonstrated that increasing L/W from 1:1 to 6:1 in a large experimental pond complex in Northeast Brazil did not significantly improve the reduction in BOD or microbiological parameters such as faecal coliforms. To examine the validity of this finding, Persson et al. (1999) and Persson (2000) utilised the flexibility of numerical modelling to study 13 hypothetical ponds, four of which were used to look at the relationship between L/W and λ , as plotted in Figure 3. They also reviewed published data and tabulated hydrodynamic parameters: the short-circuiting indicator S and the effective volume e for several L/W . The short-circuiting indicator S is defined as t_{16} divided by the theoretical retention time t_n :

$$S = \frac{t_{16}}{t_n} \quad (5)$$

where t_{16} represents the time for the passage of the 16th percentile tracer through the outlet. A smaller value of S corresponds to severer short-circuiting in the pond than a larger one. The effective volume ratio e is calculated by:

$$e = \frac{t_m}{t_n} \quad (6)$$

and measures the amount of pond volume occupied by the main water flow. They found the short-circuiting effect decreases (the value of S is increasing) and the effective volume increases with an increasing L/W .

4.1.3 Inlet and outlet settings

The importance of inlet and outlet configurations to WSP hydrodynamic and treatment efficiency has become valued gradually. In early days, inlets and outlets were believed to

impose fewer effects on WSP hydraulic efficiency compared with pond L/W (Mangelso and Watters, 1972; Watters et al., 1973). Contrary opinions were also presented that the position and layout of inlets and outlets may have greater beneficial impacts on pond treatment efficiency than the pond shape (Pearson et al., 1995).

Several studies have suggested that the inlet position and its relation to the outlet were one important factor (Persson, 2000; Shilton, 2001; Shilton and Harrison, 2003a). By performing a computer-simulated tracer study, Persson (2000) found that ponds with the inlet and outlet positioned diagonally at pond corners showed similar hydraulic performance to those with inlet and outlet opposite to each other along the pond longitudinal centre axis. However, when inlet and outlet were configured close to each other, short-circuiting occurred. It is therefore suggested that the inlet and outlet be placed as far apart as possible to create a long flow path, ensure maximum use of the pond volume, avoid short-circuiting and eventually maximise the hydraulic retention time. This conclusion was also reinforced by Agunwamba (2006).

Shilton (2001; 2005) conjectured the primary influence of inlets on pond performance over the outlets and devised laboratory-scale and CFD models, along with field tests to testify their hypothesis. They examined three outlet positions respectively located in the middle and near either corner of the wall opposite the inlet. An image analysis tracking the flow paths of drogues showed little variation in the flow pattern under the three situations. They suggested the outlet be considered as a secondary parameter inferior to the inlet. Consequently, they examined four inlet scenarios: a small horizontal inlet; a large horizontal inlet; a diffused inlet; and a vertical inlet. The results from the small horizontal inlet showed a series of peaks on the tracer time-concentration curve, each corresponding to a volume of tracer exiting the pond after circulating around the pond. The vertical inlet diminished the horizontal momentum and significantly lengthened actual retention time. However, they suspected that since the horizontal momentum is minimised, other factors such as wind effects may dominate the overall flow pattern, thereby creating short-circuiting problems. Vertical inlets may also cause sludge accumulation in the vicinity of the inlet.

It is noted that none of the abovementioned investigations described the effect of vertical

location of inlet and outlet structures. Normal experience is: for anaerobic and primary facultative ponds, wastewater is discharged below water surface to minimise short-circuiting and reduce scum. For secondary facultative ponds, discharge at mid-depth level is recommended (Mara and Pearson, 1986). Agunwamba (2006) conducted a study using a 1:20 scale model of a conceptualised prototype WSP. They noted that a case with the inlet located at the bottom of the pond and the outlet at the surface presented the lowest degree of short-circuiting. The study also showed locating inlets and outlets at the same level led to the highest degree of short circuiting, subject to prevailing experimental conditions. More specifically, the influent has the same density as the pond wastewater. Additionally, factors such as stratification may complicate the effect of inlets and outlets on WSP treatment efficiency, which unfortunately was not considered in their study.

4.1.4 Baffles

The significant improvement of WSP treatment efficiency through the installation of baffles indicates that it would be counterproductive not to baffle facultative and maturation ponds (Banda et al., 2006a; Mara, 2009). Shilton and Mara (2005) also stressed that “there is certainly large potential for significant cost optimisation to be achieved by the intelligent incorporation of baffles in facultative and maturation ponds in tropical countries”. However, the length and the orientation of baffles within a WSP require careful consideration. Watters et al. (1973) pioneered the study of baffling effects on WSP behaviour. They performed three series of tests. The first examined optimal baffle length and spacing within a pond, with baffle lengths of 50%, 70% and 90% of the pond width and spacing ratios of 1/3, 1/5 1/7 and 1/9 of the pond length. It was found that with baffle length being half of the pond width, maximum hydraulic efficiency can be achieved by using six baffles (a spacing ratio of 1/7) in the pond. More than six baffles (a spacing ratio $< 1/7$) will cause wastewater to short-circuit through the centre of the pond, therefore decreasing pond hydraulic efficiency. This phenomenon was circumvented when increasing the length of the baffles, which forced the flow towards the pond walls. However, extending baffle length to 90% across the pond width created a very narrow flow path accompanied by increased flow velocity. This consequently reduced wastewater retention time in the pond, and accordingly its hydraulic efficiency. Therefore, it was concluded that a spacing of 1/7 of pond length with a length of 70% of pond width is the favoured baffling configuration (see Figure 4). Experiments were also designed

to compare the effect of vertical baffling as opposed to horizontal baffling, and longitudinal baffling versus transverse baffling (see Figure 5). The horizontal baffling scheme appeared more efficient than the vertical scheme for a comparable number of baffles, and both longitudinal and transverse baffling gave essentially the same results. These conclusions were solely based on pond hydraulic performance.

Watters et al. (1973) looked into the effects of baffles on WSP performance only from the hydrodynamic point of view, not accounting for the influence of other factors. On the other hand, Pedahzur et al. (1993) investigated the effects of baffles on a WSP by examining both hydrodynamic flow pattern and water quality measures. They compared the microbiological (faecal coliform and enterococci) and physico-chemical (temperature, DO, BOD, pH) qualities of the pond's influent and effluent, and found that installing four baffles failed to improve the pond's treatment efficiency. While the field tracer study indicated the baffles succeeded in channelling the flow, the appearance of peak outflow at the outlet occurred 15-20 hours after tracer injection in a pond with a 5-day theoretical retention time. Temperature, DO and pH profiles indicated a strong thermal stratification, with the difference in temperature between the top and bottom of the pond being 10 °C. This caused the relatively cold influent to sink to the pond bottom and move rapidly along a confined flow path to the outlet. This study highlighted that the baffling effect was quite trivial in the presence of thermal stratification, thus emphasising the importance of the interrelated effects of other factors when evaluating the baffling effects on WSP treatment efficiency.

Shilton and Harrison (2003a) studied more than thirty different baffle arrangements when formulating the 'Development of guidelines for improved hydraulic design of waste stabilisation ponds'. Some of the examples are tabulated in Table 4.

With horizontally-directed inlets, Shilton and Harrison (2003a)'s studies showed the coliform concentration at the outlet of the pond with stub baffles was of the same order as those in other baffled ponds. By examining the velocity profiles of the four cases, it was found that once inflow momentum had been redirected and dissipated after interacting with the initial part of the baffle, the rest of the baffle's length contributed little. This obviously represented a significant cost-saving in respect of construction. However, the authors stated the effectiveness of stub baffles requires testings on other pond configurations. In terms of the

number of baffles, a single baffle model did not perform as effectively as two-baffled ponds. Four baffles did provide additional improvement, but further increase in the number of baffles was considered unnecessary, as it was noted to offer only minor improvement to the removal efficiency of coliform. It has to be made clear that the authors excluded the inference of other factors such as wind when performed the analysis.

Several studies have looked into the combined effect of baffles and other factors. Abbas et al. (2006) reported that ponds with a length-to-width ratio of 4:1 with two or four baffles are the most effective measures for improving pond hydrodynamic and BOD removal efficiency. De Oliveira et al. (2011) investigated compound effects of baffles and vertical inlets and outlets setting at different water depth on WSP performance. The authors concluded that longitudinal baffling of a primary facultative pond in combination of the vertical inlet and outlet didn't significantly improve pond performance. The significance of these studies was limited, as they only accounted for restricted situations. The interpretation of their findings can be misleading when applied to other scenarios.

4.1.5 Sludge accumulation

One specific factor that tends to be overlooked by current WSP hydrodynamic modellers is, the sludge effect. This is in contrast to basic pond structural configurations, such as L/W , inlet/outlet and baffle layouts, and environmental factors, such as wind, solar and air temperature, that are recognised as having significant effects on pond hydraulic performance. The settling of influent suspended solids from water columns as well as the algae and bacteria grown in ponds results in a layer of sediment material known as sludge (Nelson et al., 2004). The accumulation of sludge at the bottom of ponds over time decreases a pond's effective volume, causes potential short circuiting and reduces retention times (Nelson et al., 2004). Wastewater spends less time in the treatment system and most likely exits the pond with lower than expected quality. In addition, sludge accumulation changes pond bottom topology, and affect wastewater flow patterns in ponds (Peña et al., 2000). It has been noted that the characteristics of sludge vary spatially in ponds and the accumulation processes differ in each pond (Abis and Mara, 2005; Alvarado et al., 2012a; Nelson et al., 2004; Peña et al., 2000; Vega et al., 2003). Studies from Abis and Mara (2005), Peña et al. (2000) and Nelson et al. (2004) suggested maximum sludge accumulation occurred in the vicinity of single inlets and

some of pond corners, but the reasons for such behaviour were not explained in these studies (Alvarado et al., 2012a). Vega et al. (2003) looked at three different pond configurations with different levels of sludge volume evenly distributed throughout the pond: high (50%), medium to low (20%) and a desludged pond (0%). The authors examined the velocity field and found a high sludge accumulation caused a jet current from the inlet to the outlet. A medium to low and zero sludge volume yielded a more even velocity field. The magnitude of the wastewater flow velocity increased as the percentage of the sludge volume decreases. The simulated RTD results showed a decreasing ratio of mean RTD to theoretical RTD from 0.74 to 0.64 when the percentage of sludge volume varied from 0 to 50%. The study concluded that a sludge accumulation of 50% can be detrimental to pond hydrodynamics and process performance. Alvarado et al. (2012a) studied the sludge accumulation pattern and rate in a large facultative pond (13 ha) over a period of 10 years. Alvarado et al. (2012a) further confirmed the strong influence of single inlets to the deposition pattern in the pond reported in previous studies. In addition, a slight increase in the accumulation rate over the period of operation was noted, which was attributed to the decrease in treatment effectiveness due to volume reduction. It is therefore essential that the sludge accumulation in ponds be considered in modelling activities to control unfavourable deduction in pond effective volume.

4.2. Environmental factors

4.2.1 Wind effects

A general belief has prevailed that wind has positive effects on pond performance due to wind-induced aeration and mixing (Ukpong, 2013b). However, as the investigation of pond hydraulic performance progresses, there is a growing belief that wind may encourage short-circuiting, and have a negative influence (Brissaud et al., 2000; Brissaud et al., 2003; Lloyd et al., 2003). These two statements, though contradictory, have both been proven correct as a result of the variation of wind speed and direction. Aldana et al. (2005) studied two of the three equal sized maturation ponds severing the village of Lidsey in southern England. The low hydraulic efficiency of both an unbaffled pond and a three-channelled pond were found to be due to the prevailing wind.

The circulation patterns within a WSP in the presence of wind force need to be understood in order to gain accurate data on the wind effects on WSPs. Some researchers favour the three-

dimensional circulation pattern consisting of a surface flow and a reverse bottom current. After conducting an experimental drogue tracking, Shilton (2001) found the flow was circulating mainly in the horizontal direction. It turns out the flow pattern of a WSP is not solely dependent on either the wind force or inlet momentum; but rather whichever is stronger. Following Shilton (2001), a proposed calculation of the power introduced to a WSP by an inlet (P_{inlet}) is written as:

$$P_{inlet} = \frac{811Q^3}{D^4} \quad (7)$$

and the power by wind (P_{wind}) is:

$$P_{wind} = 0.03k\rho_a v_{wind}^3 A_{pond} \quad (8)$$

where Q is the inflow rate; D represents the inlet pipe diameter; k denotes the empirical constant, and is related to the level at which the wind speed is measured; ρ_a stands for the density of air; v_{wind} symbolises wind speed; and A_{pond} signifies the surface area of the pond over which wind force is exerted. In cases when wind dominates (ie $P_{wind} > P_{inlet}$), vertical circulation prevails. On the other hand, if inlet power drives the flow regime ($P_{wind} < P_{inlet}$), the flow predominantly swirls in the horizontal plane towards the outlet. These estimates of the power input, as shown in Eqs. (7) and (8), are really rough. For example, in Eq. (8), the wind direction is not incorporated, and there is no clear specification as to the level at which wind speed should be measured. Additionally, Eqs. (7) and (8) ignore mechanisms such as internal energy transfer and energy dissipation, and apply only to submerged horizontal inlets.

Banda et al. (2006b) investigated the treatment efficiency of a facultative pond in terms of *E. coli* removal under wind effects. Wind was applied as shear stresses across the pond surface. Isothermal conditions were assumed to exclude any short-circuiting possibly caused by thermal stratification. Effluent *E. coli* count was calculated with a range of wind speeds from 3 to 6 m/s blowing in four directions. When the wind comes from the same direction as the wastewater flow at a speed of 6 m/s, *E. coli* removal efficiency was reduced by 13% compared with the case with no wind. However, an opposite direction of the wind will entail an 81% increase in the treatment efficiency. When the wind direction is normal to the water flow, the effluent *E. coli* count was not significantly different from the no-wind situation.

Different conclusions were drawn by Badrot-Nico et al. (2010) when investigating the effects

of wind in combination with baffles on the treatment efficiency of WSPs. Instead of the generally-used two-dimensional or three-dimensional steady state isothermal models (Wood et al., 1995; Banda et al., 2006b), they used non-steady non-isothermal models and took into consideration meteorological factors such as solar radiation and relative humidity. Four pond layouts with 12 evenly-distributed wind directions (with an angle increment of 30°) and three wind speeds: 2 m/s, 4 m/s and 6 m/s were studied. The conclusion was that an orientation of the pond such that the dominant wind is orthogonal to the inlet/outlet direction should always be preferred.

4.2.2 Thermal effects

Thermal stratification is another crucial phenomenon that affects WSP performance (Ukpong, 2013a; Ukpong et al., 2006a, b). Although normally only 1-2 m deep, measurements show that WSPs stratify and destratify intermittently due to temperature variations (Gu and Stefan, 1995). Stratification develops when surface layers of a pond concentrate a large amount of solar energy compared with lower layers. The pond is then thermally divided into three zones: a relatively low density epilimnetic zone above a mid-density thermocline zone; then a higher density hypolimnetic zone below the thermocline. The difference in temperature and density can prohibit vertical mixing within the pond, which can cause short-circuiting by deactivating a significant fraction of the pond volume from the inflow field. Consequently, this is adverse to WSP treatment efficiency, as the pond retention time will be reduced. Torres et al. (2000; 1999; 1997) found out that the real hydraulic retention time varied from 70% to 20% of the theoretical retention time as a consequence of stratification, with a great drop being encountered during the warmer summer period.

Additionally, stratification affects the mixing and transport pattern of dissolved oxygen, nutrient and other water quality parameters among different water layers, and ultimately affects the treatment efficiency of WSPs. Llorens et al. (1992) studied the influence of temperature on the behaviour of a deep WSP receiving domestic wastewater, which was measured 85 m in length, 40 m in width, and maximum 8 m in depth. The field measurement started in October 1986 and lasted until December 1987. It covered a thermal homogeneous winter season (October 1986-February 1987) with a minimum temperature around 7-9 °C in January, and a remarkable stratification summer season (July-September 1987) with a

maximum temperature at upper layers around 24-26 °C, and a minimum temperature at bottom layers being 12-13 °C. Measurements of the concentration of such parameters as dissolved oxygen, pH, BOD, nitrates and nitrites were conducted throughout the testing period. Represented by an indicator (the ammonia nitrogen), removal efficiencies of 99.6% and 38.8% for the upper and lower layers were observed during the stratification months. This study highlighted the significance of involving temperature effects in the evaluation of WSP treatment performance.

Thermal effects on a WSP's mixing behaviour have also been investigated on a diurnal timescale (Gu and Stefan, 1995). Temperature difference at the surface layer of a pond from 6:00 am to 6:00 pm reached up to 8°C. This study was half completed by only identifying three types of stratification behaviour through measurements and simulations: continuously well-mixed during days and nights; stratification during days and destratification at nights; and continuously stratified during days and nights. The effect of stratification on WSP treatment efficiency was not explicitly evaluated in terms of nutrient or bacteria removal. Kellner and Pires (2002) presented a mathematical model to forecast the temperature profile of WSPs. The model assumed stratified ponds as a superposition of several water layers with the same thickness except the surface layer, and heat flowed through horizontal interfaces between each layer by advection and diffusion. The comparison of the predicted temperature profile along pond depth with the experimental data reported by Silva (1982) revealed a discrepancy ranging between -5% to 15%, with the largest relative difference being observed close to the pond surface. This was due to the complex effects of wind on the temperature profile, which couldn't be included in the model. In a three-dimensional modelling of the thermal changes in a WSP, Sweeney et al. (2005) also emphasised that even wind with very low speeds can alter or break the stratification, which again weren't adequately incorporated in the model.

Understanding the effects of stratification on WSP treatment efficiency requires knowledge of other factors. Stratification encourages algae growth at surface layers due to high light intensity, and therefore contributes to nutrient recycling. Further, it helps in the settlement of suspended solids (SS) and in confining the sludge to the bottom of the pond due to minimised stirring or mixing. On the other hand, as explained above, stratification does cause hydraulic

short-circuiting, which is unfavourable to WSP treatment. However, Abis and Mara (2003) and Abis and Mara (2006) suggested that positioning the inlet closer to the pond bottom than the surface can achieve very high removals of BOD and SS, despite long periods of thermal stratification. However, the question of whether stratification should be encouraged or destroyed remains problematic. This requires further studies incorporating both hydrodynamics and chemical reaction kinetics, subject to key external factors such as wind and inlet/outlet positions. Biological kinetics, which is significantly affected by stratification, also needs to be considered.

4.2.3 Solar radiation

Solar-mediated disinfection caused by the sunlight is the most instrumental factor in WSP disinfection due to ultraviolet (UV - wavelength: 10 nm to 400 nm) and photosynthetically active radiation (PAR - wavelength: 400 nm to 700 nm) components (Davis-Colley et al., 2000; Dias et al., 2017). However, debates prevail about the actual disinfection mechanisms and associated factors after the recognition of the inadequacy of applying the Marais equation (1974) in pond design (Bolton et al., 2010; Curtis et al., 1992a, b; Davies-Colley et al., 1999; Kadir and Nelson, 2014; Liu et al., 2015; Maïga et al., 2009a; Maïga et al., 2009b; Nelson et al., 2009; Ouali et al., 2014; Ouali et al., 2015; Sinton et al., 2002). The inconsistency in the arguments is largely attributed to the thought that several factors contribute interactively to the inactivation mechanism of different pathogens. In addition, each study represents unique conditions which promote the discrepancies in the conclusions. The studies cited that deal with this are presented in Table 5. Appreciably, there is still a need for in-situ light intensity measurement in ponds and studies on the correlation between solar radiation and the pathogen inactivation, as proposed by Dias et al. (2017).

Since solar radiation constitutes the primary source of pathogen organism inactivation, it is essential to incorporate this process into WSP modelling activities. Solar radiation dominates the pond water evaporation and thermal structure (i.e., stratification and de-stratification patterns), and it is the energy source for algae metabolism and photosynthesis, hence affecting the pond pH, DO and turbidity, all of which are influencing factors to pond pathogen die-off (Curtis et al., 1992b; Pearson et al., 1987; Sweeney et al., 2007).

The magnitude of the solar energy reaching the surface of the pond water is measured by

solar irradiance. It is governed by the latitude and the longitude of the geographical location, the season/time of the year, atmospheric relative humidity and the clearness/cloudiness of the sky. Subsequently, the penetration of the light (UVA, UVB and PAR) in pond water is calculated following the Beer-Lambert's law (Curtis et al., 1994):

$$Id_z = Id_0 \cdot e^{-K \cdot d}$$

where:

Id_z – downward irradiance at depth z ;

Id_0 – downward irradiance at the pond surface;

K – attenuation coefficient for downward irradiance;

d – depth from pond surface to the reference level.

It has been suggested that impact of turbidity shall be explicitly included in the above equation (Dias and von Sperling, 2017) in the following formats:

$$Id_z = Id_0 \cdot e^{-K' \cdot T \cdot d}, \text{ or } Id_z = Id_0 \cdot e^{-K' \cdot \log_{10}(T) \cdot d}$$

with K' and K'' being the attenuation coefficients for downward irradiance considering turbidity (T) and considering $\log_{10}$ of turbidity, respectively. These equations were regressed from the measurement conducted by Dias and von Sperling (2017), which showed that the light attenuation factor has the same tendency with respect to time as the turbidity. Suggestions were also made to take caution when applying these equations to other ponds considering the equations were derived from a set of turbidity data showing no expressive variation in a shallow pond (44 cm deep).

4.2.4 Climate conditions

It is a general cognition that WSPs perform optimally under advantageous ranges of ambient air temperature and solar radiation. In fact, regions with distinct seasons (cold winters and warm summers) and extreme climate conditions, such as the continental climate zones, equally appreciate WSPs in wastewater treatment (Heaven and Banks, 2005; Heinke et al., 1991; Price et al., 1995; Ragush et al., 2015; Rockne and Brezonik, 2006; Tilsworth and Smith, 1984; Whalley et al., 2012; Whalley et al., 2007). There have been studies reporting on the performance of WSPs in cold climate regions since 1940s (Banks et al., 2003; Heaven

et al., 2003; Heaven et al., 2011; Liu et al., 2015; Oleszkiewicz and Sparling, 1987; Prince et al., 1995; Zhang et al., 2013). WSPs in these regions experience an average annual air temperature as low as -12°C, with extremes of -59 °C in cold winters to 38 °C in hot summers (Tilsworth and Smith, 1984). The formation of ice and snow covers over winters renders WSPs different functional and operational mechanisms than their ice-free counterparts in (sub-) tropical regions. More specifically, these differences can be illustrated by the following aspects:

climate features:	<p>temperature extremes from -45 °C to 40 °C, with an average annual temperature of 2.5 °C (Oleszkiewicz and Sparling, 1987);</p> <p>mean annual precipitation 100-5080 mm; mean annual snowfall 510 – 5720 mm (Tilsworth and Smith, 1984);</p> <p>ice cover can last 5-6 months from October to March with a thickness of 0.8 m to 1.2 m; substantial changes in daylight hours from 16 hours in summer to 8 hours in winter (Price et al., 1995);</p>
basic pond type composition:	<p>anaerobic – facultative – maturation/storage (Price et al., 1995; Prince et al., 1995);</p> <p>a robust system (for North America) consists of 4 anaerobic, 1 facultative and 1 maturation ponds with a 12-month discharge (Heaven and Banks, 2005);</p>
discharge mode:	<p>intermittent; once a year in late summer or early fall prior to freeze-up (Banks et al., 2003; Price et al., 1995; Ragush et al., 2015) or twice a year, late spring and fall (Heinke et al., 1991);</p>
pond layout:	<p>baffling - installation of baffles is recommended but can be difficult to implement due to ice cover (Heaven and Banks, 2005);</p> <p>volume – accommodate the change in pond volume during ice formation (Heaven and Banks, 2005);</p>
seasonal features of the functional mechanisms:	<p>anaerobic ponds (3 – 3.5 m deep) for sedimentation and storage of raw wastewater solids, with a detention time of 3-10 days (Banks et al., 2003); function in an anaerobic condition due to high organic loading; year-round continuous flow through anaerobic ponds to facultative ponds;</p> <p>facultative ponds (1 - 1.5 m deep) for treatment, with a detention time of months; ponds present anaerobic and aerobic conditions simultaneously;</p> <p>maturation ponds (2.5 m deep) primarily for storage of treated water between discharges, supplemented by natural disinfection in ice-free periods, with a detention time up to a year;</p> <p>Figure 6 shows a cycle of the seasonal variation of key parameters: BOD, DO, temperature and algae, in the ponds, and labels distinctive functional features at critical stages and periods of the treatment process.</p>

WSPs in cold climates concentrate in regions with a geological latitude greater than 50° N (Ragush et al., 2015; Whalley et al., 2012), such as the USA, Canada, northern Europe and the former Soviet Union (Heaven et al., 2003). So far, studies and discussions reported from

literature mainly focus on field monitoring to collate data and experience to modify existing design guidelines of warm climates. No published work is identified to apply the method of hydrodynamic/transport and water quality modelling to investigate WSPs in cold climates. This is due to the fact that the formation of the ice cover challenges the modelling process in many pivotal mechanisms relevant to the treatment process, such as light penetration and wind-induced mixing. More importantly, the ice evolution introduces disruptions to the fundamental governing equations of the mass, momentum and thermal dynamics in the pond fluid, which can't be represented by generic computational fluid modelling.

4.2.5 Rainfall

Rainfall affects WSP treatment performance by diluting wastewater (Ashworth and Skinner, 2011) and interrupting suspended solids and the mass, momentum and energy balance in WSP hydrodynamics (Shilton, 2005). It also imposes additional requirements on WSP structural design (Mitchell Laginestra and van-Oorschot, n.d.). A set of rainfall data was explicitly shown in Fares and Lloyd (1995)'s work, but no direct elaborations on how rainfall affected pond treatment performance were given. A number of engineering reports and design guidelines have considered the rainfall's effects in various aspects (Dowson et al., 1996; Government of Western Australia, 2009; Kayombo et al., 2004).

Rainfall in tropical climate with cyclone seasons can reach as high as 500 mm/day (Ashworth and Skinner, 2011), very likely to affect the hydraulic design of inlet works and lead to the washout of pond organic matters and embankment overtopping failure (Ashworth and Skinner, 2011; Government of Western Australia, 2009). Suggestions made by Ashworth and Skinner (2011) are to use regional site topology contours and Australian Rainfall and Runoff data to position site drainage to divert surface run off. Pond hydraulic structures must be designed on the level of peak flows to ensure controlled storm flows and reduce the threat to pond embankments. Storm bypasses can be installed as a result of the extreme rainfall, runoff and infiltration if pond biomass is not to be washed out to the receiving water body. U.S. Environmental Protection Agency (2011) suggested the pond size (area and volume) should be able to compensate extreme conditions from direct rainfall and any catchment run-off, where a balance of evaporation and rainfall needs to be considered.

4.3 Engineering interventions

While conventional retrofitting strategies for improving WSP treatment efficiency focus on

pond structural factors, such as the L/W and baffling, Agunwamba and his co-workers (Agunwamba, 2008; Agunwamba et al., 2009; Ogarekpe et al., 2016; Utsev and Agunwamba, 2012a; Utsev et al., 2013) investigated an alternative potential of optimising WSP performance from the viewpoint of solar-mediated disinfection mechanism, and proposed the concept of solar enhanced WSPs (SEWSPs). A SEWSP is an upgraded conventional WSP fitted with solar reflectors to concentrate more incident sunlight radiation. A SEWSP is usually characterised by higher pond water temperature (Agunwamba et al., 2009), increased removal efficiency of BOD, COD, total suspended solids, *E.coli* and total coliform compared with a conventional WSP (Agunwamba et al., 2009; Ogarekpe and Agunwamba, 2016; Utsev and Agunwamba, 2012a, b). The proposal of SEWSPs is intended to circumvent the extensive land requirement, accompanied by an advantage of further cost reduction of a conventional WSP.

A series of systematic studies have been carried out and investigated various aspects of SEWSP performance in terms of the pond depth, L/W , positioning of the solar reflector effects. These studies were conducted via monitoring conceptualised 1: 20 scaled model ponds in the University of Nigeria. The outcomes corroborated the statement on the advantages of SEWSPs in that the shallowest ponds with the minimum width achieved the best treatment efficiency. The treatment performance can further be enhanced by positioning the solar reflector at the outlet of the pond and/or ponds being constructed with hydraulic jumps (steps) (Agunwamba et al., 2013; Ogarekpe and Agunwamba, 2016; Ogarekpe et al., 2016; Ogarekpe, 2017). It is fair to argue that these derivations subject to rather simplified experimental conditions and disregarded other factors due to the limitations of the scaled model. The implications are very insightful in terms of promoting significant improvement in WSP treatment efficiency, generalising its application in both rural and urban areas with reduced land and cost requirements.

Owing to the beneficial facts of oxygen in WSP treatment processes and pond ecology, it is appealing to apply mechanical aerators in ponds for improved oxygenation capacity and degree of mixing. Aerators prevent the formation of adverse hydrodynamic phenomena, such as short-circuiting, stratification, and sludge (Ashworth and Skinner, 2011). They introduce an elevated level of DO in ponds to promote biological processes, minimise odorous

problems and achieve reduced BOD concentrations (Dowson et al., 1996). Normally, aerated ponds are relatively deeper than other facultative or maturation ponds, measured roughly at 3 m (Mitchell Laginestra and van-Oorschot, n.d.). This is to correspond to the installation of the aeration equipment. Aerated ponds require specific knowledge and skills for installation and maintenance, such as the installation depth, the influence zone of each aerator and the oxygenation efficiency. They also introduces substantial energy consumption at the price of the economical nature of WSPs (von Sperling, 2007). Aerators dominate pond hydrodynamics (Shilton and Harrison, 2003a) and ultimately affect treatment efficiency. Ponds with aerators are not recommended at the final polishing stage of a WSP system due to high level of suspended solids (United States Environmental Protection Agency, 2002).

In addition, by bringing nutrients from bottom sludge to pond surface, aerators and any forms of mechanical mixers encourage algae metabolism and photosynthesis processes (Ashworth and Skinner, 2011), hence positively contribute to healthy pond ecology. Due to this reason, Mara (2009) suggested aerated rock filters to polish facultative pond effluents in preference to maturation ponds.

5. Discussions and future research recommendations

This literature survey has reviewed the current status of hydrodynamic modelling of WSPs, with the ultimate goal of formulating the framework of future research to enhance the overall treatment efficiency of WSPs. It is noted that numerous studies have been carried out into various aspects of WSP hydrodynamics.

For the physical problem, it is clear that the hydrodynamics of WSPs is subject to multiple factors with sophisticated interrelationships. Key factors are identified as environmental (wind, temperature and solar radiation) and structural (pond geometric configuration, length-to-width ratio, inlet/outlet positioning and baffling). As reviewed in each section, individual factors are case sensitive and scenario-dependent. They may contribute positively to WSP hydrodynamic behaviour in some circumstances, while creating adverse effects when the situation varies. That is to say, the effect of each parameter on WSP hydrodynamics cannot

be evaluated in solitude. The understanding of how individual elements affect WSP hydrodynamics can only offer preliminary information. It is the interrelated effects from multiple factors under certain practical scenarios that govern pond hydrodynamic performance. Consequently, mutual and interactive effects amongst those identified factors must be acknowledged.

None of the studies published to date provide constructive information on integrated effects, as they each address only certain aspect. Therefore, a comprehensive knowledge- and experience-based system encompassing all interrelated factors is required to inform optimal WSP design. It is suggested that local meteorological and environmental information be acquired and studied before a comprehensive design process can be conducted. Dominant factors need to be identified to guide the attention of design engineers, who then will propose corresponding effective design schema.

Despite experience from the significant existing volume of work, the formulation of the proposed system entails a substantial number of additional studies. Numerical modelling is suggested as the primary research methodology due to the built-in flexibility and high efficiency. What is missing is the lack of a full dataset for validation purposes. Thus field or physical model studies are encouraged to fulfil this purpose, so that the three-dimensional investigation of WSP hydrodynamics can move towards a more advanced level. Datasets including three-dimensional temperature distribution patterns as well as the three-dimensional tracer concentration patterns within ponds are suggested for the validation processes. There are also some specific aspects in the modelling activities that require further attention. These have been identified in this review as the assumptions in terms of constant influent conditions and pond water properties. Sensitivity analysis on these factors should be performed before the assumptions can be confidently employed.

Finally, once the hydrodynamic system has been established, an integration of the system into the overall evaluation of the treatment efficiency of WSPs, such as the water quality and risk analysis modelling, should be performed. This will accomplish the ultimate goal of WSP performance assessment.

6. A strategic modelling framework

To serve the above purpose of conducting a complete and systematic WSP study, the authors combined the outcomes of this literature assessment and the extensive knowledge and experience acquired over the duration of the project (Stratton et al., 2015), and proposed a strategic modelling framework (Figure 7) to guide future investigation on WSP treatment efficiency. The framework encompasses the acquisition of a substantial amount of field data to support model calibration and validation in terms of pond hydrodynamics as well as the water quality components. The output for hydrodynamic and water quality parameters from the validated model are then used to assess WSP's treatment efficiency. Ultimately, the water quality data are used as input data for quantitative microbial health risk assessment. Parametric analysis is to be carried out to derive optimal WSP design and operation schemes to inform regulators and operators in the water sector to make decisions.

Accompanying the strategic framework,

Figure 7 suggests a comprehensive dataset required for the modelling and validation activities. The data are categorised into two predominant groups for modelling input and validation purposes, respectively. The nature of the data is time dependent and three-dimensional, and encompasses pond geographical, geometrical and operational features; meteorological data; pond water physio-chemical data such as pH, dissolved oxygen, temperature; pond water microbiological data, i.e., the concentration of pathogen indicators; and tracer data for hydrodynamic studies. A catalogue of the parameters is presented in

Figure 7 **Error! Reference source not found..** Sources of obtaining the required data are also suggested. The strategic modelling framework and the associated dataset are generic and transferrable. They pave a direct and clear pathway for future research in studying WSP treatment efficiency.

Funding:

This work was supported by the Queensland Government Science Fund Support (QSFS); the Department of Science Information Technology and Innovation; and the Australian Water Recycling Centre of Excellence (AWRCoE).

Table 1. Comparisons of characteristics of typical pond types (Sweeney, 2004)

Pond type	Organic loading	Function	Depth (m)
Anaerobic	>100 g BOD ₅ /m ³ day	BOD and Suspended Solids (SS) removal	2-5
Facultative	100-400 kg BOD ₅ /ha day	BOD and nutrient removal, some disinfection	1-2
Maturation	<17 kg BOD ₅ /ha day	Disinfection and some nutrient removal	1-1.5

Table 2. Computational modelling of WSP hydrodynamics – two dimensional

References	Modelling technique	Model features and focus	Benchmark case	Conclusions and implications	Limitations of the study
Benelmouffok and Yu (1989)	2D; Alternating direction implicit finite difference method	verifying conservation principles of the model	(1) transport across a vertical profile in the middle of a pond (surface area = 6758 m ² ; 2.3 m deep; in/out flowrates = 1 m ³ /s); (2) mass conservation of a pond (142.1 × 64.96 × 2 m); (3) inflow rate = 0.3 m ³ /s at two inlets and an outflow rate = 0.6 m ³ /s	pollutant concentration was compared with measured data with a reasonably acceptable agreement; model free from numerical instabilities and obeying laws of conservation.	no discussions on flow pattern, short circuiting or retention times;
Fares et al. (1996); Fares and Lloyd (1995)	2D; Implicit finite difference scheme	uniform wind shear stress; constant density; inflow and outflow simulated by point sources and sinks;	surface wind effects on residence time of two facultative (160 × 60 × 1.75 m) and two maturation lagoons (107 × 57 × 1.5 m); daily inflow > 2,000 m ³ ;	residence time dropped from 7.5 and 2.5 days to 6 and 2 hours when wind speed increased from 0.5 m/s to 2.6 m/s for the facultative and maturation ponds, respectively.	no thermal stratification effects were considered
Wood et al. (1995)	2D; FIDAP, finite element based CFD package	stead-state flow; incompressible and Newtonian with density = 1000 kg/m ³ and dynamic viscosity = 0.001 kg/(m s).	a rectangular pond (100 × 50 m) with an inlet of 0.3 m width; pond with a baffle placed 20 m away from the inlet with a length of 10 m; pond with a baffle positioned 35 m away from the outlet and with a length of 35 m; and pond with a surface aerator.	The pond with the outlet baffle performs superior to the first two ponds, due to the prevention of short-circuiting. The pond with an aerator showed a large circular flow of high velocity around the aerator, and relatively low flow in pond corners.	effects of pond depth, temperature or wind were not considered, inlet and outlet were assumed over the entire depth; laminar flow; isothermal conditions; model not validated
Persson	2D;	small vertical	13 hypothetical ponds with	larger L/W led to plug-flow,	not verified on existing

(2000)	MIKE 21 by Danish Hydraulic Institute (DHI)	velocity; hydrostatic pressure; homogeneous density; Smagorinsky's turbulence; dispersion coefficient = 0.0005 m ² /s in the x direction; flow = 40 l/s	different layouts in terms of pond length-to-width ratio (L/W), pond shape, inlet and outlet locations; baffle arrangement, and with an island or a sub-surface berm	with reduced short-circuiting and stagnant volume; sub-surface berms or islands improved pond hydraulic performance.	ponds; no wind or thermal effects were considered.
Vega et al. (2003)	2D; MIKE 21 (DHI)	small vertical velocities negligible vertical accelerations; hydrostatic pressure	anaerobic pond (52 × 26 × 4 m) and 12 ponds with different sludge volumes, dimensions, inlet/outlet and baffle layouts	50% sludge accumulation was detrimental; baffles along the longitudinal axis increased retention time. Baffling and better inlet-outlet positioning are suggested interventions	outcomes sensitive to inflow rate, dispersion number and roughness coefficient; wind speed and friction have moderate influence; no discussions on thermal effects
Abbas et al. (2006)	2D; finite element based Surface-water modelling system	steady-state; isotropic eddy viscosities, diffusion coefficients, Manning's n -values and dispersion coefficients.	12 ponds with different baffling and geometries; constant rectangular surface area, water depth = 1.5 m; flowrate = 0.18 m ³ /s; retention time = 31 days; water temperature = 15°C.	increase in L/W causes a slight increase in flow velocity, effluent DO concentration and a bulk increase in BOD removal; a minimum of two baffles was recommended with further improvement by using four. $L/W = 4:1$ with two and four cross baffles at $1/3 L$ and $1/5 L$, respectively, is the most effective.	no model verification
Olukanni and	2D, finite element	diagonal inlet and outlet; water	cost optimisation analysis of laboratory-scaled anaerobic	results suggested that the previously reported 70%	physics occurring in field were not

Ducoste (2011)	based COMSOL Multiphysics	temperature = 24 °C; 2 mm galvanised metal gauge plates to vary pond area, depth and baffle layout	(0.95 × 0.32 × 0.065 m), facultative (2.1 × 0.70 × 0.045 m), and maturation pond (2.47 × 0.83 × 0.04 m); inflow rate = 0.12 m ³ /day; varying velocity	pond width baffles in considered such as literature is not consistently wind shear, solar radiation, relative humidity and air temperature the best design.
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Table 3. Computational modelling of WSP hydrodynamics – three dimensional

References	Modelling technique	Model features and focus	Benchmark case	Conclusions and implications	Limitations of the study
Wood (1997); Wood et al. (1997)	2D and 3D; FIDAP, finite element based CFD package	stead-state; $k-\varepsilon$ turbulence model; incompressible and Newtonian with density = 1000 kg/m^3 and dynamic viscosity = 0.001 kg/(m s) ; side and bottom walls of the pond assigned zero velocity; zero shear stress, waves or water level variation on the pond's free surface	a rectangular pond ($12.2 \times 6.1 \text{ m}$); eight inlet-outlet setups with both the inlet and the outlet having a width of 610 mm ; tracer's molecular diffusivity = $1 \times 10^{-9} \text{ m}^2\text{s}^{-1}$, injected for an interval of 100s with an inlet concentration 1 kg/m^3	inlet geometry has the biggest impact on flow patterns; 2D CFD models cannot adequately describe WSP hydrodynamics; 3D results fitted reasonably well to the experimental analysis (Mangelso and Watters, 1972)	factors such as temperature-induced stratification, solid deposition or wind effects were neglected
Shilton (2000)	3D; PHOENICS CFD package	steady-state; $k-\varepsilon$ turbulence model; presented the velocity field as well as hydraulic retention time analysis from the transport module; first-order treatment kinetics.	The second pond ($120 \times 60 \text{ m}$) of a two-facultative pond system serving a population of 2,600; retrofitted by installing a baffle half way down the length of the pond and extended 40 m across the width	confirmed the potential of CFD for pond design; the treatment efficiency for BOD and coliforms significantly improved due to baffle retrofitting	this study did not account for temperature or wind effects
Salter et al. (2000)	3D	two models: (1) steady flow; constant temperature; a velocity inlet and a mass flux outlet; frictionless fixed wall free surface; (2) time dependent model including	a facultative pond	retrofitting baffles created a plug-flow condition, reduced the degree of short-circuiting and improved the treatment performance;	no wind effects were considered

		thermal conditions; $k-\epsilon$ turbulence model		the thermal effect during daytime increased short-circuiting	
Sweeney et al. (2005)	3D, FLUENT, a commercial CFD software package.	boundary conditions included diurnal solar radiation, air temperature, inlet temperature, and mean daily wind speed	a 1.4 m deep, 112 ha pond	low wind speed (1.5 m/s) breaks down stratification, demonstrating the importance of including wind when modelling heat transfer in WSPs	the model negated incorporating wind shear stress in the CFD model.
Badrot-Nico et al. (2009)	3D	fixed-velocity and fixed-temperature at inlet; wind speed and direction, solar radiation, air temperature and relative humidity were enforced as model forcing; first-order kinetic decay = $0.6 d^{-1}$	a polishing pond in France; surface area = 1.7 ha, and depth = 0.9 m.	stratification appears when wind speed < 3 m/s, and on sunny days with wind speed < 5 m/s; a continuous stirred-tank reactor flow pattern for wind speed > 6 m/s, and a dispersed flow with smaller wind speeds.	modelling results agreed well with the measured data in terms of temperature stratification, but no comparison between simulated bacterial log removal and field data was made.
Alvarado et al. (2012a); Alvarado et al. (2012b)	3D, FLUENT	incompressible and Newtonian; density = 998.2 kg/m^3 ; dynamic viscosity = $1.003 \times 10^{-3} \text{ kg/m/s}$; inlet velocity = 0.94 m/s ; unsteady flow; $k-\epsilon$ turbulence model; varying geometries for different sludge accumulation	(1) a facultative pond (volume = $260,000 \text{ m}^3$; depth = 1.8 m); (2) a maturation pond (area = 7 ha ; depth = 1.7 m); submerged inlet pipe of 0.9 m diameter; 10 m length overflow outlet	velocity profile did not change despite the sludge accumulation, all exhibiting a circular flow pattern; considerable sludge deposit found near the inlet region; sludge accumulation changed the topology and flow pattern of the ponds	The effects of wind and temperature gradient were neglected in both ponds

Table 4. Comparison of the removal efficiency of coliform for ponds with different baffle arrangements with an influent coliform concentration of 1×10^8 f.c./100 ml

Baffle arrangement	No baffles	Traditional baffles	Modified long baffles	Stub baffles

Outlet coliform concentration (f.c./100 ml)	6200×10^3	6.0×10^3	11×10^3	4.4×10^3

Table 5. Sunlight-mediated inactivation mechanisms for pathogenic organisms in WSPs

Inactivation mechanisms	Acting light component	Target	Interaction with Oxygen	Repair ability	Influencing factors	Extend	Representative pathogen organisms	Primary ponds
Direct photo-biological damage	UVB wavelength (290 – 320 nm)	Damage DNA	Oxygen-independent	Can possibly correct much damage	The inactivation mechanism has little relevance to pH and DO (Bolton et al., 2010); however, turbidity affecting the penetration/attenuation of UVB (Dias and von Sperling, 2017).	Limited, occurring in the first 2.5 cm – 8 cm (Bolton et al., 2011; Kohn and Nelson, 2007; V.-Balogh et al., 2009) in ponds due to rapid UVB attenuation.	Enterococci; Virus (F+DNG phage; porcine rotavirus; MS2 coliphage)	Maturation ponds
Indirect-photo-oxidation damage (endogenous)	UVB UVA and PAR participation is debatable (Kadir and Nelson, 2014)	Damage DNA and poetically DAN repair mechanisms	React with oxygen under aerobic conditions	Still possible	Interrelated influence from pH and DO contributing to the disinfection by UVA in the absence of UVB (Bolton et al., 2010), and turbidity (Dias and von Sperling, 2017)	Up to 8 cm – 15 cm deep in ponds (Bolton et al., 2011; Dias and von Sperling, 2017; Kohn and Nelson, 2007)	Dominant mechanism for E.coli; no effect on virus;	Maturation ponds
Indirect photo-oxidation damage (exogenous)	UV range (290 – 400 nm) and much of the PAR range (400 – 700 nm), with	Damage to the external structures of microorganisms such as the bacterial cell	React with oxygen under aerobic conditions	No	Interrelated influence from pH and DO: elevated pH and DO enhance the inactivation process (Davis-Colley et al., 2000) and turbidity	Up to 43 cm deep in a facultative pond (Bolton et al., 2011; Dias and von Sperling, 2017)	Virus (MS2 coliphage); Enterococci (primary) (Davies-Colley et al., 1999);	Maturation ponds

UVA membranes.
leading the
disinfection
mechanism

(Dias and von
Sperling, 2017)

Little
disinfection
effect on
E.coli (Kadir
and Nelson,
2014;
Nguyen et
al., 2015) but
debatable
with high pH
values
(Davies-
Colley et al.,
1999)

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Figure 1. A typical wastewater stabilisation pond system (von Sperling, 2007)

(a)

(b)

Figure 2. Geographical distribution similarity between pond locations and population density, Australia: (a) WSP locations, labelled as ‘●’ (Kelly, 2013) and (b) population density (Australian Bureau of Statistics, 2017)

Figure 3. Hydraulic efficiency λ versus L/W

Figure 4. Plan view of a WSP with the optimised baffle setting

Figure 5. Baffling effect tests: (a) vertical baffling and (b) longitudinal baffling

Figure 6. Seasonal features of the functional mechanisms of a facultative/maturation pond in a cold climate and a qualitative description of the yearly variation of key parameters (the curves, the solid line for BOD and the dash dotted line for temperature, DO and algae, show the variation in the key parameters, the magnitudes of which are measured by the distance from the curve to the circle along the radial direction)

Figure 7. A strategic modelling framework for evaluating WSP treatment efficiency

Accepted Manuscript

On the hydrodynamics and treatment efficiency of waste stabilisation ponds: From a literature review to a strategic evaluation framework

Miao Li, Hong Zhang, Charles Lemckert, Anne Roiko, Helen Stratton

PII: S0959-6526(18)30227-0

DOI: [10.1016/j.jclepro.2018.01.199](https://doi.org/10.1016/j.jclepro.2018.01.199)

Reference: JCLP 11879

To appear in: *Journal of Cleaner Production*

Received Date: 20 September 2017

Revised Date: 23 January 2018

Accepted Date: 24 January 2018

Please cite this article as: Li M, Zhang H, Lemckert C, Roiko A, Stratton H, On the hydrodynamics and treatment efficiency of waste stabilisation ponds: From a literature review to a strategic evaluation framework, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.01.199.

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