The small, the big, and the beautiful: Emerging challenges and opportunities for waste stabilization ponds in Australia

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Abstract
Waste stabilization ponds (WSPs) are used extensively for the treatment of wastewater in Australia, mostly in regional and remote areas. Wastewater treatment plants (WWTPs) using pond technologies are also distributed over the full geographical extent of Australia, encompassing many climatic zones. Predominantly used to service small to medium-sized communities, WSPs are also used to service large metropolitan Australian populations, up to 2.5 million people. When well-maintained, WSPs are a sustainable and resilient treatment option, and treatment is achieved at significantly lower cost when compared with conventional WWTPs. Increasing population, changing regulations, and climate variability are placing increasing pressure on Australian WSP systems. Sludge accumulation over time presents a significant challenge to pond maintenance, along with increasing occurrence of toxic cyanobacterial bloom events. These challenges are only enhanced by the wide geographical distribution and by increasing operational and maintenance costs. Increased demand for recycled water is placing further pressure on Australian WSP systems, as higher value treated water is expected from WSP infrastructure that is often overloaded or under-designed. This increased demand for high-quality treatment presents an opportunity for operators and researchers to develop a better understanding of the coupling between hydraulics and microbial ecology of these systems. With more stringent guidelines for greenhouse gas emissions (GHGs), a better understanding of biophysicochemical processes in WSPs will lead to better estimates of GHG fluxes and variability. This information will become critical for the future planning, maintenance and operation of WSPs, and will result in a better understanding of WSP systems overall.

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Australia, greenhouse gas emissions, pond management, pond operation, waste waterponds, wastewater lagoons, wastewater infrastructure, waste stabilization ponds
1 | INTRODUCTION

It is anticipated that up to two-thirds of the world population could be living under water-stressed conditions by 2025, as demand for safe water will exceed availability in many regions (UNDP, 2006; UN-Water & FAO, 2007). Two of the biggest challenges facing water resource management are the lack of adequate water and wastewater infrastructure in the developing world, and the aging of existing networks in the developed world (Rodriguez, van den Berg, & McMahon, 2012). In addition, in both developed and developing countries, societies are becoming more aware of the need to preserve aquatic ecosystems and restore biodiversity, while satisfying the water needs of the population (Grant et al., 2012). As a result, higher expectations are being placed on existing wastewater infrastructure to deliver treated water, which enables greater societal and ecological benefits for the urban water cycle (Elimelech & Phillip, 2011; Herbing, Waite, Luthy, Drewes, & Sedlak, 2013). However, while water services are essential for socioeconomic development and increased societal productivity, they remain severely underfunded on a global scale, with a large portion of the gap in the investment attributed to delays in building infrastructure and inadequate maintenance (Rodriguez et al., 2012). Therefore, in light of the current economic climate and growing pressures on our wastewater infrastructure, the challenge for the future is to provide the socio-environmental and economic benefits of wastewater treatment in both the developed and developing world. The short-term challenge is to meet these higher expectations for water treatment with infrastructure that has been designed, built, and used in the past century, while the long-term challenge is to provide wastewater treatment across the world by engineering or re-engineering sustainable, appropriate, and affordable infrastructure (Grant et al., 2012; Herbing et al., 2013; Shannon et al., 2008).

This review will focus on some of the key challenges and emerging opportunities facing urban water management in Australia. In particular, we will focus on how to fully integrate waste stabilization ponds (WSPs) within a whole of water cycle approach (e.g., water sensitive cities or nature-based solutions), as well as examining the opportunities for re-engineering WSPs to meet current and future expectations as fully decentralized solutions.

2 | WSPS AND THE AUSTRALIAN CONTEXT

WSPs (also known as lagoons) are the simplest (von Sperling, 2007) and most widely used technology for the treatment of wastewater around the world. These wastewater treatment systems are generally used to service small populations (<5,000) in rural and remote areas. However, where land area is available there are centralized pond-based treatment plants successfully servicing populations of over 1 million people (Mara, 2004; Verbyla, von Sperling, & Maiga, 2017).

Australia has 1,234 wastewater treatment plants (WWTPs), of which 60% (737) primarily use pond technology for treatment, while 77% (943) use ponds as part of the treatment process (Hill, Carter, & Kay, 2012) (Figure 1). These data include one of the largest systems with pond-based treatment in the world, Melbourne’s Western Treatment Plant (Figure 2), which alone provides up to 58% of Melbourne’s wastewater treatment. In Australia, wastewater services currently account for 50% of the cost of the urban water industry (WSAA & IPA, 2015). With the population of Australia projected to double to 48 million by 2061 (ABS, 2013), this will result in the need for a significant increase in wastewater treatment capacity.

With the projected increase in flow due to population growth, and increasing water scarcity, comes increased expectations to provide a high level of removal of not only organic compounds, but also the removal of other constituents of concern such as metals, hydrocarbons, pesticides, and pharmaceuticals (e.g., Grant et al., 2012; Margot, Rossi, Barry, & Holliger, 2015; Martin, Santos, Aparicio, & Alonso, 2015; Zhang, Randelovic, Page, McCarthy, & Deletic, 2014). Furthermore, there is ever increasing interest in the recovery of resources, particularly nutrients and energy, during the wastewater treatment process (Brands, 2014), and the increase in societal awareness and a diversification of end uses has driven improvements in treated wastewater discharge quality, both to the environment and for reuse schemes.

More recently, municipal WWTPs have been recognized as substantial greenhouse gas (GHG) emitters, as a result of their high and regular supply of organic matter and nutrients (Daelman, van Voorthuizen, van Dongen, Volcke, & van Loosdrecht, 2012). Recent research in Western Australia has shown that WSPs are particularly large methane (CH$_4$) emitters (Glaz et al., 2016), with a significant contribution from ebullition (Bartosiewicz et al., in preparation); these results are consistent with those recorded in other WWTPs (Detweiler et al., 2014). Nitrous oxide (N$_2$O) emissions may also be particularly high in WSPs given the abundance of nutrients combined with oxygen-limited microhabitats (Kampschreur, Temmink, Kleerebezem, Jetten, & van Loosdrecht, 2009).

With increasingly stringent regulatory guidelines surrounding wastewater treatment operations, discharge, and reuse, a significant improvement in quality and treatment outcomes is required. This is in addition to the significant increase in treatment capacity required to service the growing population. It is certain that a significant capital investment is required to meet future
wastewater treatment demand in Australia and worldwide. However, improved performance of pond treatment technology through the re-engineering of their hydrodynamics, and a deeper understanding of their chemical and biological functioning, will lead to significant savings in capital and operational costs, in both Australia and around the world. In light of the growing pressures on our wastewater infrastructure, including reducing their GHG emissions, it is vital to apply a more integrated approach to understand the drivers in WSP performance in order to meet future demand.

3 | CHALLENGES FACING WSP TECHNOLOGY IN AUSTRALIA

3.1 | Sludge accumulation and pond hydraulics

Perhaps the single most challenging issue facing the water sector in Australia stems from many years of sludge accumulation in WSP assets, in some cases largely unmanaged. This has led to an urgent need to manage large volumes of biosolids under the increasingly strict environmental regulations and license operation conditions imposed upon water utilities and other wastewater operators. The hydraulic inefficiency of WSPs is a problem that increases in severity over time, as long-term hydraulic performance of ponds is increasingly compromised as sludge accumulates, which results in reduced effective treatment volume and changes in bottom bathymetry (Nelson, Cisneros, Tchobanoglous, & Darby, 2004; Olukanni & Ducoste, 2011; Peña, Mara, & Sanchez, 2000; Persson, 2000; Persson, Somes, & Wong, 1999; Persson & Wittgren, 2003; Sah, Rousseau, & Hooijmans, 2012). In turn, the build-up of sludge in these systems contributes to the complexity of pond hydrodynamics (Faleschini, Esteves, & Valero, 2012); for example, pond features such as channels can result in short-circuiting of flow and reduced mean hydraulic residence time (Figure 3).

Despite the interactions between pond hydraulics and sludge accumulation, and their combined effects on hydraulic and treatment performance, the build-up of sludge over time and its management is rarely considered in pond design (Nelson et al., 2004). Furthermore, traditional techniques for the vital measurement of sludge are of low spatial resolution and labor intensive. With increasing interest in the modeling of WSP hydrodynamics, the low-resolution sludge bathymetry data collected using traditional techniques has been a limiting factor for the accuracy and reliability of hydrodynamic models of WSPs (Passos, Dias, & von Sperling, 2016). Studies and reviews have suggested that higher resolution data will significantly
FIGURE 2  Melbourne Water's Western treatment plant (a), situated in Werribee, Victoria, was established in 1897 and occupies a site of more than 10,000 ha (b). This is one of the largest wastewater treatment plants using waste stabilization pond treatment in the world, servicing up to 58% of Melbourne's 5 million residents and producing up to 40 billion liters of recycled water each year. The ponds and wetlands on the site are considered of international significance, with more than 280 bird species recorded on the site, and are protected under the Ramsar convention. 

Source: Images courtesy of Melbourne Water
3.2 | Improvements in sludge measurement and pond modeling

Traditionally, sludge heights have been measured using low-resolution and labor-intensive methods, such as a “sludge judge” (Figure 4a). Despite the low-resolution of the data collected in time-costly traditional sludge surveys, the information is vital for planning pond maintenance, which can be expensive and complex. In addition, with the increasing interest in computer modeling of WSPs, it has become apparent that validation of pond hydrodynamics in models is difficult with traditional low-resolution bathymetry data (e.g., Alvarado et al., 2013; Olukanni & Ducoste, 2011; Passos et al., 2016).
In order to overcome the shortcomings presented by low-resolution data, along with increasing occupational health and safety requirements, a remotely operated vehicle (ROV) was designed and fitted with a sonar device with built-in GPS and data logging ability (Figure 4b). The collected measurements are highly comparable with those collected with a sludge judge, and the sonar-equipped ROV is capable of collecting significantly more data points (Figure 4c,d) on pond bathymetry (Coggins, Ghisalberti, & Ghadouani, 2017). The ROV has been implemented as the preferred WSP sludge profiling method at four major Australian state water utilities, and has been used on >400 WSPs across Australia.

In addition to addressing safety concerns surrounding sludge data collection, the data collected with the ROV can be input into computational fluid dynamics (CFDs) models of WSPs. A validated two-dimensional model has been used for the assessment of the impact of sludge accumulation and distribution in WSPs (Coggins et al., 2017), as well as for the design and assessment of baffles to improve pond hydraulics (Coggins, Sounness, Zheng, Ghisalberti, & Ghadouani, 2018). By improving the accuracy of WSP models, researchers and pond managers will be better placed to assess current hydraulic performance, design new ponds, design retrofits of current assets, and plan future upgrades.

### 3.3 Pond ecology and cyanobacterial blooms

WSP ecology, encompassing the microbial communities, plays a major role in treatment, as algae and bacteria are fundamental in both the empirical design and operation of these systems (Daims, Taylor, & Wagner, 2006; Ishii et al., 2013; Mara, 2004; Pearson, 2003; Rey et al., 2018; Speth, in ‘t Zandt, Guerrero-Cruz, Dutilh, & Jetten, 2016; Van Loosdrecht & Brdjanovic, 2014). Optimizing the ecology in wastewater treatment ponds is often difficult; however, there is growing interest in the opportunities that a deeper understanding of microbial processes could contribute to effective and resilient treatment performance (Curris & Sloan, 2006; Ferguson, Coulon, & Villa, 2018; Harris et al., 2012; McMahon, Martin, & Hugenholtz, 2007; Nielsen, 2017; Raes & Bork, 2008).

Cyanobacteria have been recorded in WSPs throughout the world (Barrington, Reichwaldt, & Ghadouani, 2013; Furtado et al., 2009; Huisman et al., 2018; Kotut, Ballot, Wiegand, & Krienitz, 2010; Martins, Peixe, & Vasconcelos, 2010; Martins, Peixe, & Vasconcelos, 2011; Oudra et al., 2002; Ourdou et al., 2000; Vasconcelos & Pereira, 2001; Zamyadi et al., 2019), and their toxins impact upon WSP ecology through physical, chemical, and biological mechanisms (Martins et al., 2011). Cyanobacteria have a competitive advantage over other phytoplankton due to their ability to regulate their buoyancy, forming dense blooms and surface scums (Figure 5d), resulting in shading of organisms below (Brookes & Ganf, 2001; Casanova, Burch, Brock, & Bond, 1999; Huisman et al., 2018; Paeur, 1988; Scheffer, Rinaldi, Gragnani, Mur, & van Nes, 1997). The growth of other autotrophic organisms required for wastewater treatment is inhibited by this shading effect. This limits the beneficial removal of coliform bacteria and viruses, and the photodegradation of micropollutants, through reduced exposure to ultraviolet radiation. Cyanobacterial blooms may also change the biological oxygen demand (BOD), through inhibition of natural treatment or cell decay. The impact of blooms on the pond oxygen budget can have significant ecological consequences, by decreasing dissolved oxygen concentration, which will effect operations and treatment efficiency (i.e., less oxygen to process BOD). In addition to the loading of sludge and suspended solids in WSPs, cyanobacteria can be deleterious to the microbial balance of these systems. These changes in pond ecology caused by cyanobacteria have the potential to drive a shift towards less beneficial microbial communities with respect to wastewater treatment, and potentially, non-compliance of the discharged effluent to the environment. This situation may be exacerbated by climate-change induced cyanobacteria dynamics (Reichwaldt & Ghadouani, 2012).

Furthermore, the potential for release of effluent or recycled (reclaimed) water containing both cyanobacterial biomass, as suspended solids, and cyanotoxins, represents a significant risk to both humans and the environment. Releasing water that contains a high concentration of cyanobacterial biomass might adversely affect natural ecosystems, while contact with cyanobacteria cells can also lead to short-lived, irritative symptoms caused by unknown cyanobacterial substances (Ghadouani & Coggins, 2011; Huisman et al., 2018; Reichwaldt & Ghadouani, 2012; Reichwaldt, Stone, Barrington, Sinang, & Ghadouani, 2016; WHO, 2003). Most importantly, releasing water that contains cyanotoxins can pose a severe hazard to the environment and human health. As such, the World Health Organization has set out a series of guideline values associated with the incremental severity and probability of health effects (WHO, 2003). Depending on the reuse of the effluent from WWTPs, there is a varying potential for contact with the environment, animals, and humans. Cyanotoxins have an extensive toxicological profile, including hepatotoxins, dermatoxins, cytotoxins, neurotoxins, and lipopolysaccharides. These toxins can induce both acute and chronic effects, and may pose a risk to both humans and ecological systems (Babica, Hilscherova, Bartova, Blaha, & Marsalek, 2007; Carmichael, 2001; Christoffersen, 1996; Dawson, 1998; de Figueiredo, Azeiteiro, Esteves, Goncalves, & Pereira, 2004; Funari & Testai, 2008; Landsberg, 2002; Reichwaldt et al., 2016; Wiegand & Pflugmacher, 2005).

The risk of discharge of cyanobacterial cells, and especially cyanotoxins, has been assessed in a large number of WSPs in Western Australia (Figure 6). In general, the systems could be classified into four categories of increasing severity when both...
FIGURE 5  Examples of waste stabilization pond systems from regional Western Australia (a, b), showing normal operating conditions (c) and one experiencing a spectacular outbreak of cyanobacterial blooms in warmer months, potentially leading to significant shading of the water column (d).

FIGURE 6  Cyanobacterial and cyanotoxins occurrence and risk assessment in waste stabilization ponds in Western Australia. Reuse water from waste stabilization ponds (WSPs) was classified into four groups with respect to maximum cyanobacterial biomass: From low (I; green), medium (II; blue-green), high (III; orange) to very high (IV; red). Red crosses indicate maximum microcystin (MC) concentrations found in the reuse samples with +++ being >20 μg MC L⁻¹, ++ being 4–20 μg MC L⁻¹, and + being >0–4 μg MC L⁻¹. No microcystins were found in sites not marked by red crosses. Please note that cyanobacterial biomass is on a logarithmic scale. WSPs in this case study were divided into three categories requiring different monitoring frequencies, with a requirement for very regular monitoring in the red category as established by a recently developed risk assessment framework (Barrington, Ghadouani, Sinang, & Ivey, 2014; Reichwaldt et al., 2016).
cyanobacterial biomass and their toxins were considered. In particular, the reuse schemes where there was the potential of human exposure to toxins were identified and assessed based upon a risk-based approach developed for WSPs (Reichwaldt et al., 2016). The occurrence of high levels of cyanobacterial biomass was not positively correlated with microcystins, and only a small number of sites showed a prevalence of toxins after the water was discharged from the WSP (Figure 6). A higher frequency of monitoring as well as regular maintenance of those systems is recommended to ensure the cyanobacterial blooms are adequately monitored and managed.

Both the management of nuisance cyanobacterial blooms, as well as integration of more microbial ecology, into engineering wastewater treatment systems is reliant, in part, on rapid, culture-independent tools (McMahon et al., 2007). Rapid, culture-independent tools, such as flow cytometry (FCM), have become increasingly common for the study of aquatic microbial communities in drinking water systems (e.g., Berney et al., 2008; Prest, Weissbrodt, Hammes, van Loosdrecht, & Vrouwenvelder, 2016; Van Nevel et al., 2017). However, their use for the study of WSP wastewater has been lacking. FCM has tremendous potential to significantly improve our understanding of WSP microbiology composition and evolution, and as such needs to be assessed for its efficacy in the characterization of WSP communities. The development of this technique for the assessment of ponds would not only improve our knowledge of WSP microbiology, but could also be developed into a more rapid and reliable diagnostic tool to provide vital information to pond managers and help respond to cyanobacterial incidents, as well as general troubleshooting in WSPs (Box 1).

### BOX 1 Rapid characterization techniques for wastewater

WSP microbial communities are relatively unexplored despite their critical role in wastewater treatment. Microbial communities can evolve and respond to their environment rapidly, making the understanding of WSP microbiology a challenge. Traditional microbial measurement techniques, such as heterotrophic plate counts, are only able to detect a small fraction of aquatic bacteria in the environment and in drinking water networks (e.g., Hammes et al., 2008; Staley & Konopka, 1985).

In recent years, FCM has helped to improve our ability to rapidly characterize microbial communities. In particular, this technique has been in the assessment of drinking water quality (e.g., Berney et al., 2008; Van Nevel et al., 2017), and is a recognized guideline method for drinking water analysis in Switzerland. However, FCM is under-represented in the study of wastewater microbiology, having only been used in the study of activated sludge processes (i.e., bacteria only) (e.g., Foladori, Bruni, Tamburini, & Ziglio, 2010). As WSP environments are rich in both bacteria and phytoplankton communities, the rapid characterization of their community is complicated. However, FCM can be used to detect both auto-fluorescent species (algae) and, with the help of staining, non-fluorescent species (bacteria). The development of rapid characterization techniques, such as FCM, for WSPs could act as a diagnostic tool to aid the management of WSP assets.

4 | CARBON NEUTRAL WASTEWATER TREATMENT AND IMPLICATIONS FOR WSPS

#### 4.1 How WSPs contribute to GHG emissions

WSPs are essentially open environmental systems displaying ecosystem functions similar to lakes, wetlands, and natural ponds (Figure 5a–c), thus potentially playing a key role in GHG emission and the global carbon cycle. The primary role of WSPs is the processing of carbon and nutrients resulting in release of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). While only a handful of studies explore direct measurement of GHG emission from WSPs (Glaz et al., 2016; Hernandez-Paniagua et al., 2014; Silva, Lasso, Lubberding, Pena, & Gijzen, 2015; Silva, Ruiz, Pena, Lubberding, & Gijzen, 2012), it is expected that these systems may be responsible for a large portion of GHG emissions, as a consequence of their shallow nature, high carbon loads, and mixing regime (Holgerson & Raymond, 2016).

There are four main pathways whereby GHGs can be released from the water column: diffusive flux, ebullition flux, storage flux (a subset of diffusive flux), and plant mediated transport (Figure 7). The latter is less relevant to WSP, whereas the diffusive and ebullition pathways are dominant; water to air gas exchange is dominated by the diffusive and ebullition pathways. The internal interplay between the biogeochemical and hydrodynamic processes is responsible for determining the
relative significance of each of the GHG production processes; however, the fluxes are controlled by both internal and external drivers, such as meteorological processes and wind forcing. It is important to note that the relative contribution of each of the processes, and consequently the composition of biogenic gases, can vary significantly between systems and spatially within the same system. A recent study has shown contrasting GHG fluxes when systems from Western Australia were compared with ones in Quebec, Canada (Glaz et al., 2016). Such differences are the result of biogeochemical conditions, operational processes, as well as climate conditions. Local considerations such as the composition of wastewater, loading, as well as the design of the WSP, could also result in differences within the same climate zone.

Furthermore, the amount and composition of biogenic gases emitted from WSPs to the atmosphere can show significant spatial and temporal variability making it challenging to assess their overall contribution to GHG emissions. The sources of the variability are controlled by the overall composition and strength of wastewater, as well as environmental biotic and abiotic variables, given that WSPs are open environmental systems. WSPs can then be compared with shallow aquatic systems, where the CO₂ fluxes greatly depend on the ratio of primary production to respiration (Kortelainen et al., 2006). In highly productive WSP environments, CO₂ may be absorbed from the atmosphere through daily photosynthetic uptake (Park, Craggs, & Shilton, 2011). A high level of CH₄ production is expected given the high organic carbon loads present in ponds, elevated decomposition rates, and anaerobic conditions dominating the water sediment interface. N₂O is produced through nitrification when oxygen levels are low (Mengis, Gachter, & Wehrli, 1997), or by denitrification under anoxic conditions (Codispoti & Christensen, 1985; Kampschreur et al., 2009). Emissions may be higher in WSPs in locations where nutrient rich parts of the water column combine with oxygen-limited micro-habitats. The response of CH₄ and N₂O fluxes to environmental conditions has received a lot of attention recently, but information on GHG emission dynamics, and their relative importance in WSPs is limited (Glaz et al., 2016; Hernandez-Paniagua et al., 2014; Silva et al., 2015). Considering the growing concern about global climate change and anthropogenic GHG emissions, a better estimation of the contribution of municipal WSPs to the global GHG budget is needed. Furthermore, similar to small lakes (Downing et al., 2006) or natural ponds (Holgerson & Raymond, 2016), the global contribution and significance of WSPs is still unaccounted for.

4.2 | Biosolids management

With the increased production of sewage sludge, effective biosolids management processes need to be identified and implemented to allow for future sustainable sewage sludge management (Baily, 2009; Gopalakrishnan, Grubb, & Bakshi, 2017; Majumder, Livesley, Gregory, & Arndt, 2015; Wang, Shammas, & Hung, 2007). Results of a national survey conducted in 2010 found that 1.2-1.5 million tonnes of wet biosolids are produced in Australia annually (Pollution Solutions & Designs Pty Ltd, 2012); with population growth, this amount will certainly increase. Across Australia, various sludge management
practices and end-use schemes are in place, including but not limited to: agriculture (land application as fertilizer), composting, landfill, ocean discharge, and stockpiling (Appels, Baeyens, Degreve, & Dewil, 2008; Pollution Solutions & Designs Pty Ltd, 2012). Common historical biosolid disposal methods, such as landfill, are seen as unsustainable today, with a need to transition to more sustainable methods as demand on wastewater treatment facilities increases (Appels et al., 2008). Biosolids are also a significant contributor to the total GHG emission linked with the wastewater treatment process (Alvarez-Gaitan, Short, Lundie, & Stuetz, 2016; Brown, Beecher, & Carpenter, 2010). Identification of the processes that biosolids undergo in their lifecycle from treatment to end-use provides an insight into their overall contribution to GHG emissions (Delre, Monster, & Scheutz, 2017; Gopalakrishnan et al., 2017; Horan, Rouch, & Hutton, 2011). Further research on sludge production and management pathways could help in the design of new approaches to reducing GHG emissions from WWTPs (Horan et al., 2011).

5 | OPERATION AND PERFORMANCE ASSESSMENT

5.1 | A more integrated approach for WSP operations

As WSPs are the most widely used wastewater treatment infrastructure worldwide (Mara, 2013; Peña Varón & Mara, 2004), it is paramount that we advance our knowledge of these systems in order to improve treatment performance, delay costly upgrades, and to transition them to more sustainable water systems. This is an ideal opportunity for applying a combination of science and engineering innovation for the benefit of achieving a sustainable water system. In light of the increasing pressure on our water networks due to population growth, it is essential to invest in new infrastructure to meet future demand. However, ensuring that current infrastructure is performing at its full potential is of foremost importance. In the case of WSPs, it is important that the main controls of these systems — including hydraulics, microbial ecology and sludge accumulation (Figure 8) — are fully integrated with design and planning frameworks to ensure optimal performance in constantly evolving operating conditions.

A better understanding of the interplay between hydraulics, ecology, and sludge dynamics in WSPs would not only enhance our knowledge of how these systems work, but could also inform efforts to modify or re-engineer systems to meet specific requirements. For a range of systems with varying levels of sludge, it was shown that hydraulic performance of WSPs is not only influenced by sludge accumulation, but that the spatial distribution also plays a critical role in reducing the treatment performance (Coggins et al., 2017). This information is of vital importance to inform sludge management operations, as this knowledge will allow pond managers to prioritize ponds based on their hydraulic behavior, as well as sludge inventory.

**FIGURE 8** A schematic showing the key biogeochemical process responsible for the treatment process in waste stabilization ponds (WSPs), but also supporting ecosystem function. The strong relationship between hydraulic and biological/chemical process is considered key in the performance of WSPs.
To date, the investigation of the effect of sludge accumulation on hydrodynamic performance in WSPs using hydrodynamic modeling has been very limited, and the study of sludge distribution even more so (Coggins et al., 2017; Ouedraogo et al., 2016). The knowledge generated about the effect of sludge accumulation and distribution on pond hydraulic performance provides the motivation to find a solution to improve hydraulic control in WSPs. Previous laboratory, pilot scale, and hydrodynamic modeling exercises have shown that baffles could be used to improve pond hydraulics (e.g., Abbas, Nasr, & Seif, 2006; Farjood, Melville, Shamseledin, Adams, & Khan, 2015; Passos, Ferreira, & von Sperling, 2019; Rey et al., 2018). Until recently, however, there have been no published studies to demonstrate and validate these findings at the fully operational pond-scale. In Western Australia, a full-scale hydrodynamic reconfiguration of a pond was trialed, using an approach that combined high-resolution pond bathymetry and 2D hydrodynamic modeling (Coggins et al., 2018). Through this approach, the optimal site-specific solution was determined and constructed. This was then assessed with field tracer testing to validate the findings. The full-scale reconfiguration of the pond resulted in a measured increase in pond mean residence time of at least 20%; this increase occurred despite in situ sludge infill (for more detail: Coggins et al., 2018). The full-scale trial not only validated the hydrodynamic modeling, but also, for the first time, demonstrated the success of hydraulic reconfiguration to improve pond hydraulics at the full-scale. This study demonstrates very clearly that a better understanding of hydraulics and sludge accumulation in WSPs can improve performance and management. Additional Australian studies have also shown the importance of the link between pond physical characteristics and pond microbial community performance in maturation ponds, with a particular focus on sunlight disinfection (Dahl, Woodfield, Lemckert, Stratton, & Roiko, 2017; Sheludchenko, Padovan, Katouli, & Stratton, 2016). Furthermore, a recent study from the United States has shown that redesigning WSPs to target certain treatment aspects, such as light penetration and nitrate removal, can be very successful (Silverman, Sedlak, & Nelson, 2019).

Considering WSPs are the most widely used technology worldwide, there is still plenty of incentive to find ways to improve treatment outcomes to achieve the goal of sustainable water systems that are able to meet current and future demand, and systems which have higher potential for high-level water reuse and resource recovery. Looking to the future, there is still potential to further develop and integrate technology platforms, such as using sonar to determine the water content (or “density”) of sludge, to better inform sludge removal operations, including the assessment of whether or not desludging is the best management option to maintain good water quality. Using high-resolution bathymetry, we may be able to construct better coupled models of WSPs (both hydrodynamics and biology), which may then be used to assess the impact of sludge accumulation and hydraulics on the overall treatment performance in ponds. With regard to hydraulic reconfiguration, the use of baffles that support attached growth need to be assessed in order to determine the effect that they have on the microbial communities in pond and upon treatment performance more generally.

In light of the growing pressures on wastewater infrastructure, it is vital to apply a more integrated approach to understand the drivers in WSP performance in order to meet future demand. Improving the resolution of sludge measurement will facilitate a reduction in the cost of sludge management, and lead to the development of more reliable and accurate models of pond hydraulics. Furthermore, our ability to diagnose problems in WSP systems is becoming increasingly important, as more pressure is placed upon systems to meet increasing demand. Overall, a more integrated approach is required to understand how WSPs currently perform, and to inform design criteria (Figure 9) for new pond systems and the upgrading of existing assets. To this end, the development of rapid, high-resolution tools for studying WSPs will be important, and will highlight processes and interactions that are often overlooked due to their complexity, or the inherent difficulty in quantifying them.

5.2 | Connecting the dots by adopting a whole-of-water-cycle approach for regional water security

WSPs are widely distributed throughout the Australian continent and its diverse climatic zones, with more than 900 sites (Figure 1) offering opportunities to provide recycled water for a range of applications. The key challenge is to ensure better integration of all the components of the water cycle, including WSPs, in water security strategies with more reliance on recycling. Many regional towns and remote areas in Australia are under increasing water stress and require more localized solutions and the identification of reliable water sources to meet the needs of the growing human population, animals, as well as environmental flows. Integrated water planning is required in order to identify long-term solutions at all spatial scales, as are analyses of options against multiple criteria including social, economic and environmental. Integrating strategies for producing recycled water, energy and nutrients from WSPs will ensure an accelerated transition towards a circular economy in regional Australia. This is especially important in the current context where significant investment in water infrastructure will be required in regional Australia to offset a historically high maintenance gap (GHD, 2015). The situation will only to be
5.3 | An integrated “omics” approach could unlock the mysteries of WSPs and help performance

WSPs are known to harbor thriving microbial communities responsible for the treatment processes, but also having applied, and at times unexpected, biotechnological significance beyond wastewater treatment processes (Daims et al., 2006). The recent genetic sequencing of some microbes has the potential to provide fundamental insight into antibiotic resistance processes, as well as lead to biotechnological application in synthetic microbial ecology (Ben Said & Or, 2017; Daims et al., 2006). However, their dynamics remain largely unknown due to the lack of understanding of their in situ ability to respond to environmental and operational conditions. The rapidly growing area of omics offers a great opportunity for integrated analyses, involving metatranscriptomics, metaproteomics and metabolomics, to be used in WSPs to help unravel key aspects of community structure, function and dynamics (Narayanasamy, Muller, Sheik, & Wilmes, 2015). Most importantly, these approaches could help in the understanding of key physiological responses of microbial communities to environmental and operational conditions, as well as in the diagnosis and subsequent troubleshooting of ponds.

The ability to characterize the whole-of-community and system response under specific conditions will provide unprecedented advantages leading to optimal operational outcomes (Rodriguez, Garcia-Encina, Stams, Maphosa, & Sousa, 2015). Specific performance indicators for treatment efficiency can also be developed using metabolites leading to a near real-time understanding of the microbial activity, with implications for operations, as well as the discharge obligations (Reichwaldt, Ho, Zhou, & Ghadouani, 2017). The increasing availability of genomes from mostly non-pond wastewater microbes is making a significant contribution to the understanding of genomic variability (Rodriguez et al., 2015), thus further omic explorations, especially from pond systems from a range of Australian climatic conditions, could only provide more insight. Further application of these powerful tools and their integration into the operational manuals of WSP operation will lead to greater performance and discharge quality. Omic approaches may also be applied as pollution monitoring tools to help understand the impact of discharge from wastewater of a range of emerging constituents of concern, such as pharmaceuticals, personal care products, and household and industrial chemicals (Skelton et al., 2014).
6 | CONCLUSIONS

Waste stabilizations ponds will continue to be the most widely used wastewater treatment technology into the future; this is especially relevant considering the significant number of WSP assets in operation around the world. Population growth is putting increasing pressure on wastewater infrastructure, and WSPs are still a simple, cost-effective way to provide wastewater treatment in both the developed and developing world. WSP technology also provides the opportunity and flexibility for non-expensive upgrades (such as baffles), which can increase their treatment capacity, prolong their lifespan, and delay costly upgrades to more conventional, energy-intensive processes.

Pond technology is an integral part of Australia’s wastewater infrastructure. In the medium to long-term future, it is imperative to enhance the performance of pond infrastructure in Australia, and worldwide, by the inclusion of interventions targeted at improving pond characteristics, such as hydrodynamics and biogeochemical processing. Without moving towards more energy intensive (conventional) treatment processes, or large capital investment, it is conceivable that WSP technology could meet future treatment demand through optimization and targeted upstream and/or downstream enhancement. There is great potential for the coupling of WSPs with solid organic waste digestion facilities for energy production. This will not only meet aspirations of the food-energy-water nexus, and sustainable development goals, but will also contribute to a circular economy.

The optimization of WSP technology will also be beneficial for odor management and in reducing GHG emissions. This will be beneficial for the utilization of land for development previously set aside as buffer zones; this is particularly important for relieving housing pressure in areas of high population growth. A better integration of low-footprint decentralized systems, including WSPs, wetlands, and other hybrid wastewater treatment technologies, could be the ideal option for new urban developments (infill or rural-urban fringe) were centralized infrastructure is at or near capacity, or too far away.

In Australia, WSP technology is here to stay, and will play a key role in the delivery of treated wastewater for the rest of this century and beyond. The future of WSPs in Australia will heavily depend upon a comprehensive understanding of all the processes involved in treatment. This will require a full integration of traditional design criteria, load, sludge, hydraulics, ecology, and climate, into new system modeling and design criteria. The inclusion of new technologies for real-time monitoring, as well as comprehensive GHG measurement, will lead to not only better treatment outcomes, but also more cost-effective maintenance of these important treatment assets. Better performance assessment tools are needed to help assess treatment efficiency and water quality, to reduce environmental risks, such as cyanobacterial blooms, to provide significant savings in operation and capital investment, and to delay costly upgrades.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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