Comparison of the treatment performance of a high rate algal pond and a facultative waste stabilisation pond operating in rural South Australia

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ABSTRACT

South Australian community wastewater management schemes (CWMS) treat wastewater using waste stabilisation ponds before disposal or reuse. This study compared the performance of a facultative pond, 6,300 m^2, 27.5 d theoretical hydraulic retention time (THRT), with a high rate algal pond (HRAP) operated at depths of 0.32, 0.43 and 0.55 m with THRT equivalent to 4.5, 6.4 and 9.1 d respectively. Both ponds received influents of identical quality, differing only in quantity, and were operated in similar climatic conditions. The depth of HRAP operation had only a minor influence on treatment performance. The study showed that the quality of the treated effluent from the HRAP was equivalent to that of the facultative pond, 5-day biochemical oxygen demand removal >89%, NH_4-N removal 59.09–74.45%. Significantly, *Escherichia coli* log_{10} reduction values by the HRAP, 1.74–2.10, were equivalent to those of the facultative pond. Consequently, HRAPs could replace facultative ponds within CWMS while maintaining treated effluent quality. The benefit would be halving the surface area requirement from 4.2 m^2 capita^{-1} for the facultative pond to between 2.0 and 2.3 m^2 capita^{-1}, depth dependent, for an HRAP, with significant attendant reductions in the capital costs for construction.

Key words | faecal indicator organisms, high rate algal ponds, log_{10} reduction values, waste stabilisation pond, wastewater treatment

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INTRODUCTION

Community wastewater management schemes (CWMS), formerly known as septic tank effluent disposal schemes, are adopted in rural South Australia when environmental and public health concerns arise, associated with on-site disposal of treated effluents from residential septic tanks (Palmer *et al.* 2001). Septic tank effluents are reticulated to central treatment facilities that frequently include waste stabilisation ponds (WSPs). Current design guidelines (LGA SA not dated) require a five-cell WSP system, operated in series, comprising a facultative pond, 36 d theoretical hydraulic retention time (THRT), and four maturation ponds, combined 30 d THRT, all with a recommended operational depth of 1.2 m. To assist estimates of dry weather flow, the guidelines assume 3.5 persons per household and a daily flow of 140 L capita^{-1} d^{-1}, which equates to a total WSP surface area equivalent to 7.7 m^2 capita^{-1}. CWMS with WSPs, therefore, occupy relatively large surface areas.

WSPs and high rate algal ponds (HRAPs) depend upon the same treatment mechanisms for their efficacy. Algal growth and photosynthesis assimilates inorganic nitrogen and phosphorus and provides oxygen to heterotrophic bacteria for growth and the mineralisation of organic carbon, yielding CO_2 for photosynthesis (Young *et al.* 2017). WSPs are large open ponds, prone to thermal, pH and dissolved oxygen vertical stratification leading to physically heterogeneous reaction environments throughout their depth (Sweeney *et al.* 2005). These conditions result in spatial variations in treatment performance (Sweeney *et al.* 2007). Mixing is effected only by inflowing wastewater and wind (Sweeney *et al.* 2003). Wind speed and direction influence treatment performance and potentially the outcomes of performance monitoring (Sweeney

et al. 2007). In contrast, HRAPs are shallow, 0.2–0.5 m, intentionally mixed, most commonly by a slowly rotating paddlewheel, and consequently do not experience vertical stratification. Disinfecting UVB and UVA irradiances are rapidly attenuated with depth in turbid wastewaters (Bolton *et al.* 2010). Intentional mixing increases exposure of the wastewater to these disinfecting irradiances at and near the surface of an HRAP, with the potential to increase pathogen inactivation and log_{10} reduction value – the difference (log_{10}) between the concentration of the organism (log_{10} 100 mL^{-1}) in inlet wastewater and that of the treated effluent (Fallowfield *et al.* 1996).

Fallowfield & Garrett (1985) using data from Azov & Shelef (1982) and Arthur (1983), primarily 5-day biochemical oxygen demand (BOD$_5$) reduction, predicted significantly reduced retention times and area requirements if HRAPs were employed to treat domestic wastewaters rather than WSPs. Real world comparisons were congruent with these predictions. Picot *et al.* (1992) compared two HRAP systems with a standard three-cell WSP at Meze in the South of France. They concluded that HRAPs are comparable to WSPs regarding wastewater treatment performance but require a fifth of the surface area. In another study, El Hamouri *et al.* (2003) compared the wastewater treatment performance of an HRAP and a three-cell WSP in Ouarzazate, Morocco. They showed that the adoption of the HRAP in place of a series of three facultative ponds reduces the net land area requirement by at least 40%.

The reduced depth and surface area of HRAPs compared to WSPs results in a reduction in earthworks and consequently construction costs (Young *et al.* 2017). Additionally, the reduced surface area of HRAPs also results in reduced evaporative losses. Young *et al.* (2017) estimated that compared to a five-cell facultative-maturation WSP system an HRAP treating the same volume of wastewater, 100 m^{-3} d^{-1}, would reduce evaporative losses from 30% to 12.3–15.3%. This increase in treated wastewater for reuse is especially significant for communities in water-scarce regions like those in rural South Australia (Cox *et al.* 2016). Over the past decade, South Australia has experienced a decline in surface water flows and groundwater levels compared to long-term means, with this expected to worsen due to climate change (Cox *et al.* 2016).

This study is, to the authors' knowledge, the first to compare the wastewater treatment performance of a facultative WSP and an HRAP both receiving treated septic tank effluents in Australia. The objective of the research was to determine if an HRAP could replace the facultative pond in a five-cell WSP CWMS.

METHODS

The community wastewater management systems

Lyndoch WSP

In the 2011 census, the population of Lyndoch (34.6000° S, 138.8833° E) was recorded as 1,909. The daily inflow from on-site septic tanks to the three-cell WSP system was 165 m^3 d^{-1}, which was delivered in 5-minute pumping events every 15 minutes throughout the day. The Lyndoch WSP comprises three ponds with gravity flow between each pond. The facultative pond (WSP, 180 m × 35 m) is a 6,300 m^2 pond with a design depth of 1.2 m (Figure 1). However, the pond had not been desludged since construction in 1979. A bathymetric survey of the WSPs in 2010 determined a mean facultative pond depth of 0.68 m. The effective volume was 4,533 m^3 resulting in a THRT of 27.5 d.

Kingston on Murray HRAP

The HRAP (Figure 2) was built in 2008 at Kingston on Murray (KoM; E 140 20′, S 34 14′) for a population of approximately 300 permanent residents. The HRAP consisted of two channels (base dimensions 30 m × 5 m) and was operated at depths of 0.32, 0.43 and 0.55 m. The central baffle dividing the channels was a floating curtain constructed from the same high density polyethylene material as used to line the HRAP. The 3:1 wall batter increased the effective surface area from 192 m^2 (0.32 m) to 208 m^2 (0.43 m) and 226 m^2 (0.55 m). An eight-bladed, stainless

Figure 1 | Facultative waste stabilisation pond at Lyndoch, SA, wastewater treatment plant.

Figure 2 | High rate algal pond at the Kingston on Murray, SA, wastewater treatment plant.

steel paddlewheel powered by a 750 W electric motor directly coupled to a 1:100 reduction gearbox provided mixing, with a mean surface water velocity of $0.2 \, \text{m s}^{-1}$. The HRAP received $12 \, \text{m}^3 \, \text{d}^{-1}$ of wastewater pre-treated in on-site septic tanks (THRT 24 h) delivered in six daily pumping operations. A consequence of the constant daily inflow was that the THRT of the HRAP increased with increasing operational depth to 4.5, 6.4 and 9.1 d. Following a change in operational depth, a minimum of three retention times elapsed, to enable equilibration before sampling was conducted over a minimum of three retention times. The median temperature of the wastewater over the sampling period was $17.6 \, °\text{C}$. Individual depths were operated and evaluated over periods greater and less than the median temperature. The data from both periods for each depth were aggregated and presented in the comparison.

Climate data

Both sites were provided with a weather station, Environdata WeatherMaster 2000™ (Warwick, Queensland, Australia), which continuously logged photosynthetically active radiation (400–700 nm), total UV irradiation and air temperature over the study period May (winter) 2010 to April (Autumn) 2011.

In situ pond measurements

The mid-pond *in situ* wastewater temperature (T-TEC A™, Temperature Technology, Adelaide), dissolved oxygen

(DO; Danfoss Oxy1100 partnered with Danfoss EMCO transmitter-controller) and pH (Hach pH probe and GLI Pro transmitter-controller) were continuously monitored (0.2 m below the surface) at all three WSPs at Lyndoch and the data logged (T-TEC A™, Temperature Technology, Adelaide) every 30 minutes. Identical equipment was used at the KoM Murray HRAP, to measure and log mid-stream and mid-depth parameters similarly.

Wastewater sample collection

Wastewater samples (1 L) were manually collected, following pumping events, from the inlets to the Lyndoch WSP 1 and the KoM HRAP. At Lyndoch, wastewater samples (1 L) were collected manually from the outlet weir points for WSP 1, refrigerated, transported to the laboratory and analysed within 24 h of collection. At the HRAP samples were collected into the same sample bottle at 01:00 and 13:00, each 400 mL, providing a daily 800 mL composite sample, using a refrigerated auto-sampler (ISCO Avalanche). The samples were held at $1 \, °\text{C}$ in the sampler until retrieval. They were then transported and stored ($1 \, °\text{C}$) until analysis within 24 h of retrieval.

Wastewater analysis

The methods described in *Standard Methods for the Examination of Water and Wastewater* (Greenberg *et al.* 1992) were used to analyse influent and treated effluent wastewater samples for turbidity (NTU), suspended solids (SS) and chlorophyll *a*. Filtered water (GFC Whatman, exclusion size $1.2 \, \mu\text{m}$) was used for the analysis of BOD_5, and the nutrients $NH_4\text{-N}$ and combined $NO_2\text{-N}$ and $NO_3\text{-N}$ (expressed as $NO_x\text{-N}$) and $PO_4\text{-P}$. *Escherichia coli* per 100 mL was enumerated using the Colilert® chromogenic MPN system (IDDEX Ltd) as described by Young *et al.* (2016).

Log_{10} reduction value calculations

The log_{10} reduction values (LRVs) of the indicator organisms for both ponds were equal to the difference between the log_{10} concentration of the organisms entering each pond and the log_{10} concentration of the organisms leaving each pond.

Statistical analysis

Statistical analysis and graphical presentations were prepared using Microsoft Excel and IBM SPSS Statistics, version 23 (Armonk, NY, USA).

The combined data from the operation of the HRAP at all depths were compared with all data from the WSP. Additionally, for *E. coli* concentrations and LRVs the values collected for each HRAP depth were separately compared to the values collected from the facultative WSP during each depth. Data sets were tested for normality using the Shapiro–Wilk test for normality (Supplementary Material, available with the online version of this paper). When found to be normally distributed, data were analysed using independent-samples t-test for equality of means; if found to violate normality, data were compared using the independent-samples Mann–Whitney U-test. Significance was tested to the 0.05 level for all statistical comparisons.

RESULTS AND DISCUSSION

Climate at the two study sites

The comparison between Lyndoch WSP and the KoM HRAP was conducted under similar climatic conditions

(Figure 3), suggesting that any climatic impact on the relative performance of the WSP and the HRAP was negligible.

Composition of the inlet wastewaters

This comparison between the performance of the HRAP and the facultative WSP was made on almost identical wastewaters since independent-samples Mann–Whitney U-test showed there were no statistically significant differences in the concentrations of BOD_5 ($p = 0.395$), PO_4-P ($p = 0.055$), SS ($p = 0.055$) and *E. coli* ($p = 0.068$) in the inlet wastewaters entering the HRAP or facultative WSP (Table 1). As expected in treated septic tank effluent the concentration of oxidised nitrogen was low for both inlets and, while the difference in concentrations was statistically significant ($p < 0.001$) according to an independent-samples Mann–Whitney U-test comparison, practically the difference was negligible. The HRAP inlet NH_4-N was, however, slightly higher than that going into the facultative WSP; the difference in means was statistically significant ($p < 0.001$) according to independent-samples Mann–Whitney
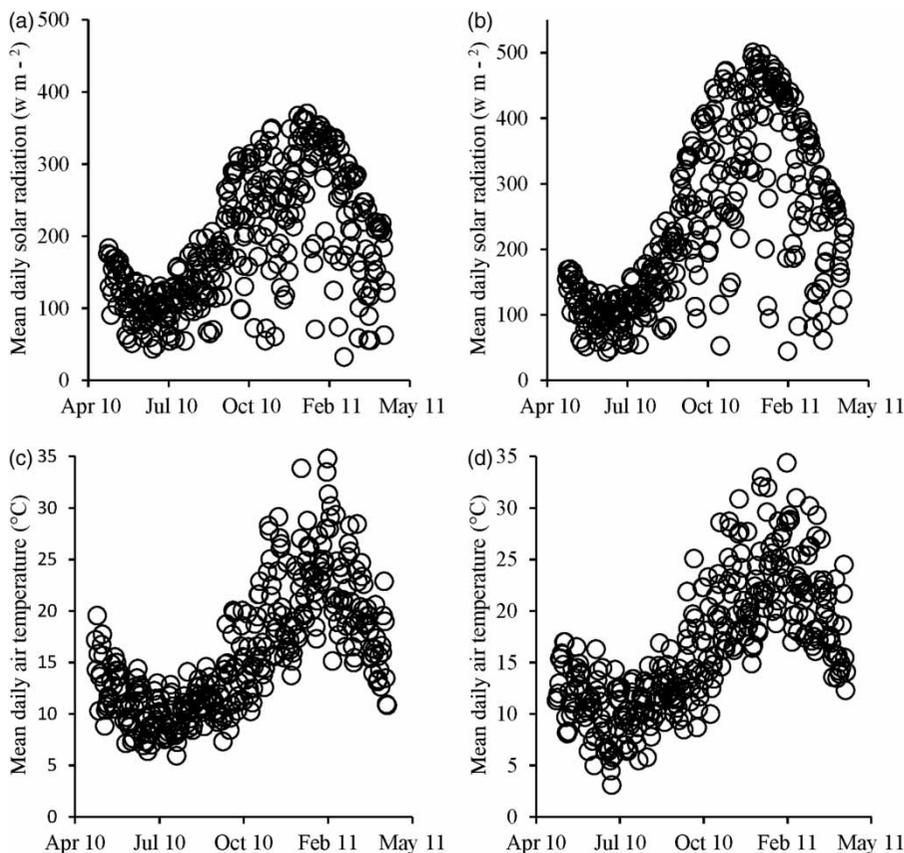

Figure 3 | Daily mean solar radiation (W m^{-2}) at Lyndoch (a) and Moorook (b), 5 km from the HRAP at Kingston on Murray and daily mean air temperature (°C), recorded on site at the Lyndoch WSP (c) and the HRAP at Kingston on Murray (d).

Table 1 | The composition of the inlet wastewater (mean ± standard deviation) from on-site septic tanks to the Kingston on Murray HRAP at and the Lyndoch facultative WSP between 1 May 2010 and 28 March 2017, where n = number of samples analysed

	WSP	HRAP
n	36	>121
BOD_5 (mg L^{-1})	216.86 ± 36.43	203.99 ± 39.60
BOD_5 areal loading rate (kg ha^{-1} d^{-1})	52.80 ± 10.51	135.28 ± 43.11
Suspended solids (mg L^{-1})	102.75 ± 15.82	107.29 ± 27.41
E. coli ($\log_{10}$ 100 mL^{-1})	6.29 ± 0.16	6.38 ± 0.33
NH_4-N (mg L^{-1})	76.27 ± 10.77	90.06 ± 11.92
NO_x-N (mg L^{-1})	0.03 ± 0.06	0.40 ± 0.47
PO_4-P (mg L^{-1})	12.44 ± 3.41	13.79 ± 4.16

U-test comparison. The mean BOD_5 areal loading rate for the HRAP was also 2.5 times higher, 135 kg BOD_5 kg ha^{-1} d^{-1}, than the Lyndoch facultative WSP, 54 kg BOD_5 kg ha^{-1} d^{-1}; the difference was statistically significant ($p < 0.001$) reported by independent-samples Mann–Whitney U-test comparison. This is consistent with, or higher than, other reported HRAP loading rates. El Hamouri *et al.* (1995) reported organic loading rates of 86 and 97 kg BOD_5 kg ha^{-1} d^{-1}, respectively, in the hot and the cold season in Morocco.

Temperature, pH and DO regimes of the WSP and the HRAP

These parameters were measured 0.2 m below the water surface in the facultative WSP so do not account for potential variations throughout the pond depth (Sweeney *et al.* 2005). The values shown (mean ± one standard deviation) for the HRAP are metrics produced by analysing values for all operational pond depths. The daily mean temperatures of the WSP was in the range 9.73–31.94 °C with a mean of 18.83 ± 6.07 °C. The HRAP recorded slightly lower temperatures with a minimum of 7.94 °C, a maximum of 29.00 °C and a mean of 17.95 ± 5.40 °C. The wastewater temperatures within the WSP and the HRAP at all depths were remarkably similar and an independent-samples Mann–Whitney U-test found these values not to be significantly different ($p = 0.072$). The wastewater mean DO concentration was lower in the HRAP than the facultative WSP, 6.43 ± 3.31 mg DO L^{-1} compared with 7.34 ± 5.00 mg DO L^{-1}, although the difference was not statistically significant ($p = 0.454$) according to an independent-samples Mann–Whitney U-test comparison. The mean pH and range were lower in the HRAP (7.40–8.73; mean of 7.84 ± 0.21) than the facultative WSP (8.07–10.56; mean of

8.76 ± 0.51) and an independent-samples Mann–Whitney U-test showed this difference was significant ($p < 0.001$). The ranges of pH and DO values recorded for the HRAP are lower than normally reported for these systems. In general, the pH was not as high as reported by some other authors in HRAPs (Azov & Shelef 1982, 1987; Picot *et al.* 1993; El Hamouri *et al.* 1995; El Hamouri *et al.* 2003). It was, however, consistent with the peak range found by other authors (Fallowfield & Garrett 1985; Craggs *et al.* 2003).

Wastewater treatment

The composition of the respective wastewaters following treatment in the HRAP operated at three depths and in the facultative WSP at Lyndoch are shown in Table 2. There were subtle differences identified in the performance of the HRAP associated with operational depth and moderated by ambient temperature, which are beyond the scope of this paper. The data from an HRAP operated at a specific pond depth collected over periods above and below the median temperature were aggregated. This facilitated comparison of HRAP performance data with the mean performance data for the facultative WSP over the duration of the study, which ranged from winter to early autumn.

It can be inferred (Table 2) that irrespective of the depth of operation the percentage of BOD_5 removed by the HRAP, from effluents of virtually identical composition, was almost identical to the facultative WSP, with an independent-samples Mann–Whitney U-test indicating that statistically there was no significant difference between the systems ($p = 0.948$). Most notably, the HRAP at all depths achieved this similar level of removal with a significantly shorter THRT compared to the facultative WSP operating at a THRT of 27.5 d. There was, however, poor phosphorus removal by both the HRAP at all depths of

Table 2 | The composition of the treated wastewater effluent (mean ± standard deviation) from the Kingston on Murray HRAP operated at three depths and the Lyndoch facultative WSP between 1 May 2010 and 28 March 2017, where n = number of samples analysed

	HRAP			WSP
Depth (m)	0.32	0.43	0.55	0.68
Surface area (m^2)	192	208	226	6,300
THRT (d)	4.5	6.4	9.1	27.5
n	58	35	31	36
BOD$_5$ (mg L^{-1})	13.34 ± 8.48	16.09 ± 9.44	21.79 ± 13.45	28.76 ± 33.40
NH$_4$-N (mg L^{-1})	25.88 ± 17.79	22.95 ± 12.29	36.92 ± 19.36	39.30 ± 16.24
NO$_2$-N (mg L^{-1})	5.29 ± 8.19	1.96 ± 1.73	2.21 ± 2.49	0.14 ± 0.24
NO$_3$-N (mg L^{-1})	7.66 ± 4.29	15.39 ± 4.54	6.96 ± 6.71	0.17 ± 0.26
PO$_4$-P (mg L^{-1})	11.50 ± 2.77	12.41 ± 2.04	15.19 ± 5.54	9.17 ± 2.93
Chlorophyll a (mg L^{-1})	3.86 ± 3.54	3.81 ± 4.32	0.90 ± 0.75	2.56 ± 2.73
Log$_{10}$ E. coli 100 mL^{-1}	4.62 ± 0.38	4.19 ± 0.75	4.52 ± 0.51	4.07 ± 0.60

operation and the facultative WSP (Tables 2 and 3). Even though the removal of phosphorus from both ponds was poor, the facultative WSP did outperform the HRAP at all depths and this difference was found to be statistically significant from the WSP ($p = 0.010$) as reported by independent-samples Mann–Whitney U-test.

The concentration of NH$_4$-N in the treated effluent increased with increasing depth of HRAP operation. The concentration in the treated effluent from the 0.55 m deep HRAP was equivalent to that of the 0.68 m deep facultative WSP (Table 2). At all depths the HRAP outperformed the facultative WSP in NH$_4$-N removal with this difference found to be statistically significant ($p < 0.001$) according to an independent-samples Mann–Whitney U-test comparison. This increased removal is particularly impressive given the shorter hydraulic retention time of the HRAP compared to the facultative WSP (Table 3).

The greatest difference in the nitrogen speciation of the systems was that the HRAP demonstrated high rates of nitrification compared with the facultative WSP (Table 2). The

mean inorganic, oxidised nitrogen (NO$_x$) concentration, calculated for the facultative WSP as the sum of NO$_2$-N and NO$_3$-N concentrations, was 0.31 mg NO$_x$ L^{-1}. The equivalent oxidised nitrogen concentrations in the HRAP, operated at 0.32, 0.43 and 0.55 m were considerably higher at 12.95, 17.35 and 9.17 mg NO$_x$ L^{-1} respectively, indicating increased nitrification of ammonium in the HRAP. An independent-samples Mann–Whitney U-test showed this difference in NO$_2$-N and NO$_3$-N between the ponds was statistically significant, $p < 0.001$ and $p < 0.001$ respectively. Oxidation of inorganic nitrogen within the treatment system has environmental benefits since it decreases subsequent oxygen demand associated with nitrification of ammonium by the biota in natural aquatic systems receiving the effluent. Furthermore, although not an inorganic nitrogen removal mechanism *per se*, conversion of ammonium to nitrate may facilitate subsequent effluent treatment via denitrification (Craggs 2005; Pearson 2005).

The difference in the E. coli count between the inlet and treated effluent wastewater is used as one indicator

Table 3 | Percentage removal from the respective inlet wastewater of chemical constituents and mean log$_{10}$ removal value for E. coli following treatment in the Kingston on Murray HRAP operated at three depths and the Lyndoch facultative WSP between 1 May 2010 and 28 March 2017

	HRAP			WSP
Depth (m)	0.32 m	0.43 m	0.55 m	0.68 m
THRT (d)	4.5	6.4	9.1	27.5
BOD$_5$	93.03 ± 4.89	92.48 ± 4.32	89.19 ± 5.53	87.7 ± 14.73
NH$_4$-N	69.70 ± 19.68	74.45 ± 14.87	61.1 ± 23.8	48.75 ± 18.67
PO$_4$-P	6.14 ± 7.83	15.53 ± 9.02	9.31 ± 10.58	20.95 ± 20.89
E. coli log$_{10}$ removal	1.74 ± 0.28	2.10 ± 0.68	2.00 ± 0.46	2.22 ± 0.68

of the disinfection performance and reported as LRV. Table 2 shows that septic tank effluent treated in the HRAP over all depths returned mean *E. coli* concentrations of the same order of magnitude as those of the facultative WSP. Despite the small difference in absolute values, an independent-samples Mann–Whitney U-test reported this difference as being significantly different ($p = 0.001$). Further investigation compared the *E. coli* concentrations in the HRAP effluents from ponds operated at the three depths with contemporaneous WSP effluent concentrations. The *E. coli* concentration in the medium depth (0.43 m) HRAP was found not to be significantly different according to an independent-samples t-test for equality of means ($p = 0.002$) from that of the WSP operated concurrently. The *E. coli* concentrations of the shallow (0.32 m) and deep (0.55 m) HRAP were, however, shown to be significantly different from the WSP concentrations according to an independent-samples Mann–Whitney U-test ($p = 0.001$) and an independent-samples t-test for equality of means ($p = 0.002$).

The LRVs achieved by each system were also found to be within the same order of magnitude but differed significantly when comparing the aggregated HRAP data with that from the WSP (Mann–Whitney U-test comparison, $p = 0.001$). Comparing the LRVs for individual depths with those achieved by the WSP over the same period showed that this statistically significant difference was only apparent for the shallow (0.32 m) HRAP as reported by an independent-samples Mann–Whitney U-test ($p = 0.004$). The mean *E. coli* LRVs of the HRAPs operated at 0.43 m and 0.55 m did not differ significantly from those of the WSP according to an independent-samples Mann–Whitney U-test ($p = 0853$) and an independent-samples t-test for equality of means ($p = 0.002$). The LRVs achieved by the HRAP at all depths fall within the range reported by other studies (Young *et al.* 2017).

Furthermore, the 5th percentile *E. coli* LRVs were remarkably similar: 1.34 for the Lyndoch facultative WSP and 1.36 for the HRAPs, determined by combing LRV data from all HRAP operational depths. These values were obtained following exposure to UV irradiances that differed significantly ($p < 0.001$); the daily mean UV irradiation (W m^{-2}) was 5.73 ± 3.74 at Lyndoch and slightly less at KoM, 3.95 ± 1.86. Significantly, while the 5th percentile values were similar for both pond systems the LRV was achieved at much shorter THRTs within the HRAP, between 4.5 and 9.1 d, compared with 27.5 d for the Lyndoch facultative WSP.

Treated effluents from CWMS are discharged for beneficial reuse, typically for irrigation of non-food crops, commonly woodlots, or amenity spaces. These disposal pathways must be consistent with the *Australian National Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)* (NRMMC 2006) to minimise potential exposure of the population to pathogenic microorganisms. These guidelines set the water quality objective for non-food crop irrigation as an *E. coli* median concentration of $<10^4$ 100 mL^{-1} in the final effluent. This guideline would not normally be applied to effluent from a facultative WSP since there is a requirement that it be followed by four maturation ponds operating in series. This guideline was marginally exceeded by the facultative WSP operating at a THRT of 27.5 d and the HRAP operating between 4.5 and 9.1 d. The interpretation of the relative influence of HRAP depth and retention time on disinfection is confounded by the fact that at constant daily influent flow increasing HRAP operation depth also increases retention time. Furthermore, the study design attempted to account for seasonal variation by operating the single HRAP twice at each depth, above and below the annual median air temperature, over three hydraulic retention times. Notwithstanding, the indicative performance and potential benefit associated with the adoption of HRAPs for CWMS was such that subsequently an independent, winter validation of the HRAP was conducted (Fallowfield *et al.* 2018) consistent with that required by the *Australian National Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)* (NRMMC 2006). This clearly showed that HRAPs operated at a depth of 0.3 m at a THRT of 10 d achieved a mean LRV of 3.30 producing a mean concentration of 2.89 *E. coli* 100 mL^{-1} in the final treated effluent (Fallowfield *et al.* 2018). A design guideline for the incorporation of HRAPs into CWMS was subsequently promulgated.

It is widely recognised that HRAPs treating wastewater have the potential to yield large quantities of biosolids which comprise algae, bacteria, zooplankton and detritus and are potentially a source of biomass energy, e.g. via anaerobic digestion (Pearson 2005; Christenson & Sims 2011). Chlorophyll *a* is frequently used as a surrogate measure of algae biomass. Chlorophyll *a* concentrations were high in effluents treated in the 0.32 and 0.43 m deep HRAP and decreased when the operation depth was increased to 0.55 m, which had a mean chlorophyll *a* content lower than that of the facultative WSP at Lyndoch. It is interesting to note that the *E. coli* LRV measured for the 0.55 m deep pond was similar to that for other depths.

This may be as a consequence of its lower chlorophyll *a* content increasing light penetration and compensating for any adverse effect of its greater depth (Curtis *et al.* 1994).

The results of this research clearly demonstrate that an HRAP could replace the facultative WSP in a community wastewater management scheme while maintaining effluent quality. It is likely that the performance of the HRAP is related to its shallow depth (compared to a WSP) and improved hydrodynamics, a consequence of intentional mixing via incorporation of a low energy paddlewheel. Mechanical mixing has been perceived as a disadvantage of HRAP technology for application in rural and remote communities since it requires electrical energy and connection to the power grid. Recently, 5.3 kW h^{-1} of solar voltaic cells coupled with battery storage has been installed at the KoM HRAP demonstrating operation independent of the electricity grid (Figure 4).

Application of HRAP technology to replace only the facultative WSP would halve the pond surface area required to treat domestic wastewater to an equivalent quality. Using KoM data presented here the per capita area requirement would reduce from 4.2 m^2 for a facultative WSP to 2.0 m^2 (0.32 m, 4.5 d); 2.1 m^2 (0.43 m, 6.4 d) and 2.3 m^2 (0.55 m, 9.1 d) for the HRAP. These reductions are consistent with those predicted by Fallowfield & Garrett (1985) and those observed by Picot *et al.* (1992) and El Hamouri *et al.* (2003). A consequence of the reduced area requirements is significant savings in the capital costs for construction. They also enable application of a low energy, low greenhouse gas emission pond technology in locations where the land area was insufficient for larger

facultative WSPs (Shilton *et al.* 2008). The finding that depth of HRAP operation had little overall influence on treatment performance offers more flexible HRAP operation. Townships that experience marked seasonal fluctuations in population, e.g. vacation destinations, could increase the depth of HRAP operation during that period without decreasing treated effluent quality or incurring increased capital costs to manage such.

CONCLUSIONS

- The wastewater treatment performance of the HRAP operated at all depths and THRT equalled or exceeded that of the facultative WSP in regards to BOD$_5$ and NH$_4$-N.
- Although little PO$_4$-P was removed by either the WSP or the HRAP, the former outperformed the latter at all depths.
- The facultative WSP and the HRAP achieved remarkably similar *E. coli* log$_{10}$ reduction values and both produced effluent of similar quality with regard to *E. coli* concentration.
- The depth of operation had little effect on the treatment performance of the HRAP.
- Replacing the facultative pond with an HRAP in CWMS would reduce the surface area requirement by 50% with concomitant savings in the capital cost of construction.
- The reduced THRT required for effective treatment by the HRAP reduces evaporative losses compared with the facultative WSP operated at an extended THRT comparatively. Consequently, approximately twice as much effluent is available for beneficial reuse following HRAP treatment.

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Figure 4 │ The 5.3 kW h^{-1} solar voltaic cells installed at the Kingston on Murray, SA, wastewater treatment plant.

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