Factors affecting the performance and risks to human health of on-site wastewater treatment systems

K. J. Levett, J. L. Vanderzalm, D. W. Page and P. J. Dillon

ABSTRACT

Aerobic wastewater treatment systems (aerobic systems) are the preferred choice in a region overlying a karstic aquifer used for drinking water supplies, as they are thought to provide better protection to groundwater and human health than standard septic systems. However, aerobic systems in operation do not always perform to design standard; while this is often blamed on lack of maintenance, few studies have investigated the link directly. This study investigates the performance of domestic on-site wastewater treatment systems in South Australia, and compares effluent quality to maintenance records. Effluent from 29 septic tanks and 31 aerobic systems was analysed for nutrients, physico-chemical parameters and microbiological indicators. Aerobic systems generally provided greater treatment than septic tanks, yet most aerobic systems did not meet regulatory guidelines with high levels of indicator bacteria in 71% of samples. The effect of system size, number of household occupants and maintenance on aerobic system treatment performance was analysed: chlorine levels were positively correlated with time of last service, and nutrient concentrations were positively correlated with the number of occupants. A microbial risk assessment revealed the observed irrigation practices to be high risk; and sufficient residence time in the aquifer cannot be guaranteed for protection of groundwater used for drinking. Additional preventive measures such as irrigation management or post treatment of drinking water supply (such as UV disinfection) are required to meet public health targets.

Key words | aerobic wastewater treatment system, groundwater protection, Mount Gambier, septic tank, treatment performance

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INTRODUCTION

There are currently several thousand on-site wastewater treatment systems ('on-site systems') in peri-urban and rural areas in the Mount Gambier region in the south-east of South Australia, typical of domestic effluent treatment outside the bounds of reticulated sewerage schemes in rural Australia. However on-site systems and the subsequent localised discharge of treated effluent can lead to public health and environmental concerns through direct contact with effluent and contamination of groundwater resources. The region provides a case study where on-site systems are used and groundwater from the underlying unconfined karstic Gambier Limestone aquifer is used for household water supply. The karstic nature of the aquifer means there is potential for rapid transport of effluent derived contaminants (Harden *et al.* 2008) such as pathogens, nitrate and organic compounds within the groundwater, which increases the area that can be impacted and limits the potential for attenuation in the subsurface. Historically, there has been groundwater contamination from agriculture and dairy pastures (Dillon 1988) and industrial effluents (such as from cheese factories and timber treatment plants) in the Mount Gambier region

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(Emmett & Telfer 1994). Local authorities are keen to determine if on-site systemsare contributing to localised groundwater contamination, in particular nitrate concentrations (Lamontagne 2002).

The majority of the approximately 3,000 on-site systems in the region are septic systems, in use since the 1940s, consisting of a two-chambered septic tank providing primary treatment, and a sub-surface effluent dispersal field, where the soil provides further treatment. Soils in the Mount Gambier region are highly heterogeneous in type and depth, with some areas having less than 300 mm of soil cover over limestone. Common soil types range from clays with low permeability to rapidly draining loamy sands known as Chernic Tenosols (McKenzie *et al.* 2004). Previous studies of septic tank performance in Australia have reported poor or inadequate effluent treatment (Patterson 1999; Sarac *et al.* 2001; Charles *et al.* 2005), and the potential for groundwater contamination by septic tank effluent is a widespread concern.

In light of the potential for contamination of the karstic aquifer in the Mount Gambier region, the current model of best practice requires all new systems in the higher density peri-urban areas to be aerobic wastewater treatment systems ('aerobic systems'). Aerobic systems are package wastewater treatment plants with separate chambers for primary (anaerobic) treatment, aeration, clarification and chlorine disinfection (Figure 1), and the secondary-treated effluent is usually dispersed by surface irrigation using sprayers or drippers. The aerobic treatment stage is either: a suspended growth system, where air blowers aerate the

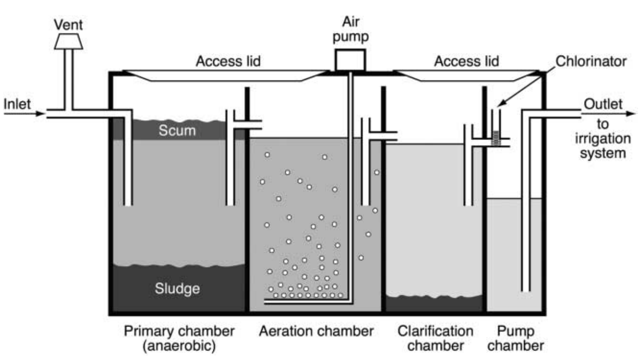

Figure 1 | Cross-section of a typical aerobic wastewater treatment system, showing separate chambers for primary (anaerobic) treatment, aeration and clarification, and chlorine tablets in the chlorinator prior to the pump chamber.

primary treated effluent and promote the growth of aerobic bacteria suspended in the liquid; or an attached growth system, where bacteria form a biofilm on media that the effluent is trickled over. State government legislation requires that all aerobic systems are capable of treating effluent to guideline values and are serviced quarterly by a service agent accredited by the system manufacturer (South Australian Health Commission 1998) but at the time of writing, there was no requirement to verify the performance of the system after installation.

Aerobic systems are thought to provide better protection to groundwater and human health than standard septic systems, due to their treatment of effluent to a secondary level with disinfection before discharge to a designated irrigation area, and increased level of management through mandatory quarterly servicing (NSW DLG 1998). Nevertheless, internationally, studies of aerobic system effluent quality show poor compliance with relevant quality guidelines (Khalife & Dharmappa 1996; Charles *et al.* 2005; Nunn & Ross 2006; Roeder & Brookman 2006; Moelants *et al.* 2008). Lack of maintenance is often cited for the failure of aerobic systems operating in households to conform to guideline criteria (Khalife & Dharmappa 1996; Nunn & Ross 2006), yet to date very few studies have linked known maintenance regimes to effluent quality. An exception is Moelants *et al.* (2008), who compared effluent quality of aerobic systems with and without maintenance contracts in Belgium.

Furthermore, the design regulations for effluent irrigation areas are intended to provide an additional barrier between people and effluent. Complete disinfection of effluent may not always be achieved, as chlorine tablets may not be present, and viruses and protozoa can be resistant to chlorine (NRMMC–EPHC–AHMC 2006). Hence, a multi-barrier approach is needed to protect public health (Nunn & Ross 2006). That is, effluent irrigation areas need to be separate from recreation or utility areas, and of sufficient size to absorb the effluent without waterlogging occurring, and without excessive leaching of contaminants to groundwater in proximity to drinking water wells. Other authors have noted a poor standard of irrigation areas in their surveys (Khalife & Dharmappa 1996; Arnold & Gallasch 2001; Nunn & Ross 2006), but have not quantified the human health risk resulting from the configuration

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of the irrigation area and the operational performance of the systems.

To provide a scientific basis for improving on-site wastewater treatment system management it is important to understand how aerobic systems are performing and the subsequent impact on human health. Thus, the objectives of this paper are to:

1. Determine the performance of operational aerobic systems in the study region, in relation to both effluent guideline values and the performance of conventional septic tank systems;
2. Analyse the effect of maintenance regime, system size, and number of occupants on aerobic system effluent quality;
3. Assess the quality of groundwater for indicators of contamination by on-site systems
4. Quantitatively assess the potential risk to human health from pathogens from irrigation with aerobic system effluent;
5. Quantitatively assess the risk to human health from pathogens in groundwater contaminated by aerobic system effluent; and
6. Identify additional preventive measures required to achieve adequate health protection with respect to maintenance and irrigation standards.

METHODS

The city of Mount Gambier is in the southeast of South Australia (Figure 2). The region has a temperate climate with dry summers and cool wet winters, with an average annual rainfall of 707 mm falling predominantly between June–Aug. The mean maximum summer temperature is 25.2°C (in January) and the mean minimum winter temperature is 5.2°C (in July).

Aerobic systems and septic tanks were randomly selected from council records across the Mount Gambier region. Household interviews and site inspections were undertaken to obtain information on system type, capacity and age, number of occupants in the household, maintenance history and the condition of irrigation areas or dispersal trenches, and any obvious problems such as waterlogging or pooling of effluent (Table 1). Full details including the survey questionnaire can be found in

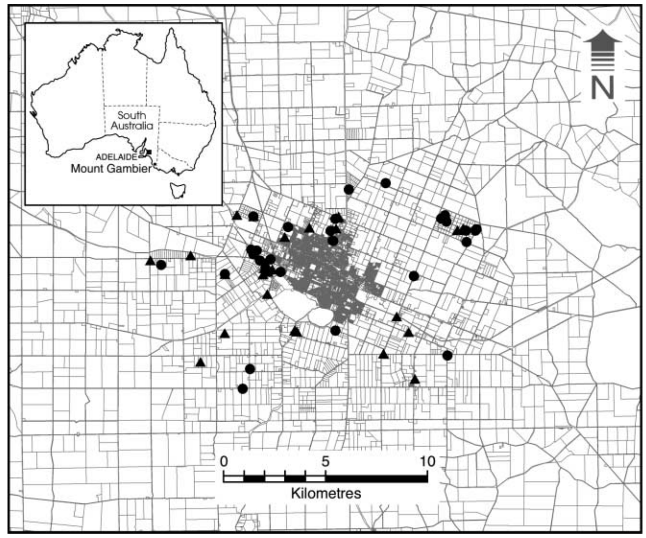

Figure 2 | Map showing the location of Mount Gambier in the southeast of South Australia, and the study area in and around the city of Mount Gambier. Aerobic system sampling sites are marked with triangles, and septic systems are marked with circles.

Levett *et al.* (2009). Aerobic system service history was verified from council and service agent records.

Samples of effluent from 31 aerobic systems and 29 septic tanks were taken between 14 January and 27 February 2008. All aerobic system samples were collected from the first chamber following chlorination; in most systems this was also the pump-out chamber. Septic tank samples were taken from the second chamber or from a point between the tank outlet and the dispersal trenches if this could be accessed. Groundwater samples were taken from 31 household bores (on all properties where an on-site system was sampled that also had a bore which could be accessed for sampling). Ten bores were on properties with an aerobic system, and 21 were on properties with a septic system. Samples were taken from a garden tap when parameters measured *in situ* (i.e. pH, conductivity, temperature) were stable. For microbiological samples all taps were disinfected with ethanol prior to sampling.

Physico-chemical parameters (temperature, pH, electrical conductivity, dissolved oxygen and redox potential) were analysed *in situ* using a TPS 90-FLMV field analyser. Chlorine residuals were analysed *in situ* with a Hach DR/890 portable colourimeter. Sample preservation and storage were undertaken according to the *Standard Methods for the Examination of Water and Wastewater* (1992). Samples were

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Table 1 | Basic system and household information for the on-site systems sampled

	Septic systems (n = 29)	Aerobic systems (n = 31)
Number of occupants	1 to 5 people in household (median = 2.5)	2 to 8 people in household (median = 4)
Year installed and capacity	17 installed from 1968 to 1986–most 1,620 L (some built *in situ* may be larger)	Installed 1997–2007 (median = 2006) 25 had 3,000 L primary chambers
	12 installed from 1989 to 2006–all 3,000 L	6 had 4,250 L primary chambers
Maintenance	22 desludged within 4 years	All but one system is professionally serviced
	4 not desludged for 5 or more years	Median time since last service = 95 days, maximum time = 156 days
	3 unsure (but probably more than 5 years)	

analysed for major ions and metals, microbiological indicators (*E. coli*, thermotolerant coliforms and Enterococci) (within 24 hours) and nutrients by the Australian Water Quality Centre, SA, and the Environmental Health Department of Flinders University, SA (Levett *et al.* 2009).

Data analyses were performed using SigmaPlot 11 (Systat Software Inc 2008). Data were checked for normality and non-parametric analyses used where appropriate. Unpaired t-tests or the Mann-Whitney Rank Sum test were used to determine if the difference between groups was significant. The non-parametric Spearman rank order correlation was used to measure the strength of association between variables (significance $\alpha = 0.05$ for all analyses).

The traditional approach to identifying tolerable risk has been to define maximum levels of infection or disease. However, this approach fails to consider the varying severity of outcomes associated with different hazards. This shortcoming can be overcome by measuring severity in terms of disability adjusted life years (DALYs). The basic principle of the DALY is to weight each health impact in terms of severity within the range of zero for good health to one for death. The weighting is then multiplied by the duration of the effect and the number of people affected. In the case of death, duration is regarded as the years lost in relation to normal life expectancy. DALYs have been used extensively by agencies such as the World Health Organisation (WHO) to assess disease burdens (WHO 2008) and is the approach adopted in this study. Microbial health-based targets for the reduction in concentrations of three reference pathogens, *Campylobacter*, *Cryptosporidium* and rotavirus, from untreated source water required to achieve compliance with the upper limit of 10^{-6} DALYs per person per year was undertaken using the methodology described in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006). Published data for pathogen numbers (95th percentile) in primary treated wastewater were used along with mean indicative log removals by secondary treatment and chlorination (Table 2; NRMMC–EPHC–AHMC 2006) in calculating the residual human health risk. The deterministic data on pathogen decay rates were taken from Toze *et al.* (2010). *Salmonella enterica* was used as a surrogate for *Campylobacter* as the decay of *Salmonella* and *Campylobacter* in groundwater have been shown to be similar (Toze *et al.* 2010).

In assessing the risk to human health, each of the three index pathogens was assessed for two exposure scenarios–the first being routine ingestion from spray or drip irrigation with aerobic system effluent, and the second being drinking groundwater contaminated by aerobic system effluent. Exposure levels and frequencies were taken from NRMMC–EPHC–AHMC (2006); with the exception of exposure to irrigated effluent, which as a conservative estimate was assumed to occur in the warmest six months of the year (180 days).

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Table 2 | Parameters used in the calculation of microbial health-based targets for the reduction in concentrations of reference pathogens

Parameter	*Campylobacter*	*Cryptosporidium*	Rotavirus	Source
Source concentration (orgs/L)	7,000	2,000	8,000	AGWR*
Drinking groundwater:				
Exposure (L)	2	2	2	AGWR
Frequency (days)	365	365	365	AGWR
Routine ingestion during irrigation:				
Exposure (L)	0.0001	0.0001	0.0001	AGWR
Frequency (days)	180	180	180	Estimated
Mean log reductions through:				
Secondary treatment	2	0.75	1.25	AGWR
Chlorination	4	0.25	2	AGWR
UV disinfection	2– > 4	>3	>1	AGWR
No access during irrigation	2	2	2	AGWR
Drip irrigation	4	4	4	AGWR
Subsurface irrigation	5–6	5–6	5–6	AGWR
T_{90} in limestone aquifer (days)	1†	39	29	Toze *et al.* (2010)

*Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).
†T_{90} for *S. enterica* used as a surrogate for *Campylobacter* Spp.

RESULTS AND DISCUSSION

Effluent quality

Aerobic system and septic tank effluent quality were assessed by comparing the study results to relevant state guidelines (Table 3) which are based on the Australian and New Zealand Standards for on-site domestic wastewater management (AS/NZS1547:2000). Aerobic system performance is compared against South Australian approval guidelines (South Australian Health Commission 1998), but also the New South Wales expected quality guidelines (NSW DLG 1998) as this is the most comprehensive set of state guidelines for on-site systems in Australia. There are no guidelines for septic tank effluent quality in South Australia, so septic tank effluent quality is compared against NSW expected quality guidelines (NSW DLG 1998).

Only one aerobic system (3%) was compliant with all effluent quality approval guidelines, and this system had been in operation for less than three months at the time of sampling. All but one aerobic system (97%) exceeded the total suspended solids (TSS) guideline, and the biological oxygen demand (BOD_5) guideline was exceeded by 37% of systems. Dissolved oxygen (DO) levels did not reach the expected 2 mg/L in 23% of systems, indicating that many systems were not operating aerobically. This correlates with the effluent nitrogen composition being dominated by organic nitrogen rather than nitrate in the majority of systems. DO levels were inversely correlated with total organic carbon (TOC), total Kjeldahl nitrogen (TKN), total phosphorous (TP), BOD_5 and indicator bacteria levels; indicating that systems that operated more aerobically produced better quality effluent. Nutrient levels varied widely with maximum of 136 mg/L for total nitrogen (TN), though only 19% of aerobic systems did not meet the expected quality guideline for TN, while 58% of aerobic systems did not comply with the expected quality guideline for TP.

Over half of the aerobic systems did not have chlorine tablets present at the time of sampling, and 74% of all systems failed the minimum free chlorine level of 0.5 mg/L. There was a negative correlation between free chlorine levels and thermotolerant coliforms ($P = 0.02$). The relationship between pathogen indicators and chlorine residuals was similar to that found by Nunn & Ross (2006), who reported that a relatively small decrease in chlorine residual corresponded to a large increase in *E. coli* numbers.

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Table 3 | Assessment of on-site wastewater treatment system performance

	Aerobic systems (n = 31)					Septic tanks (n = 29)				
	Guideline	n (%) not complying	Range	Median	Mean	Guideline	n (%) not complying	Range	Median	Mean
DO (mg/L)	>2*	7 (23%)	0.2–6.3	3.6	3.4					
TSS (mg/L)	<30†	30 (97%)	19–176	92	98	<50*	27 (93%)	19–1740	164	254
BOD_5 (mg/L)	<20†	11 (37%)	0–172	12	30	<150*	6 (21%)	54–265	98	119
TOC (mg/L)			8.6–213	39.7	64.5			48.7–689	176	203
TN (mg/L)	25–50*	6 (19%)	4.6–136	34.7	39.6	50–60*	27 (93%)	52.0–456	102	126
TP (mg/L)	10–15*	18 (58%)	1.2–31.8	15.9	16.3	10–15*	11 (38%)	3.3–59.3	17.4	19.3
Thermotolerant coliforms (cfu/100 mL)	<10†	22 (71%)	$<1-1.8\times10^6$	4.1×10^3	1.7×10^5	10^5-10^7*		$1.3\times10^4 - >2.4\times10^7$‡		
Free Cl_2 (mg/L)	>0.5†	23 (74%)	0–9.2	0.06	0.6					
Chlorine tablets		Present	13 (43%)							
		Absent	17 (57%)							

**Expected quality* from NSW DLG (1998).
†Approval guideline from SA Health Commission (1998).
‡Due to method of reporting of thermotolerant coliform numbers, summary statistics cannot be calculated for septic tanks.

Comparing median effluent quality values for BOD_5, TSS, TOC, TN and TP from aerobic system and septic tank effluent reveals that aerobic systems generally treat effluent to a higher standard than do septic tanks (Figure 3). The largest difference in treatment performance is for BOD_5, where the median value for aerobic systems is only 12% of that for septic tanks. Nevertheless, most aerobic systems in this study did not comply with effluent quality guidelines, and a few aerobic systems produced effluent that was of a poorer quality for individual parameters than the median values for septic tanks. There was little difference in TP between aerobic system and septic effluent, (8% based on the median quality) but this is to be expected as most on-site systems are not designed to remove phosphorous, aside from a small reduction (~15%) due to bacterial assimilation, precipitation and adsorption (Tchobanoglous *et al.* 2003).

Effect on aerobic system treatment performance

The effect of maintenance on aerobic system effluent quality was examined through considering the time since the last service (ranging from 0 to 156 days, with a median of 95 days). The only parameter to show a correlation with time since last service was total chlorine, which decreased as time since last service increased as expected ($P = 0.017$; Figure 4).

Of the 13 aerobic systems that had been serviced within three months, 12 had chlorine tablets present, and the median free chlorine residual was 0.56 mg/L, compared to a median of 0.06 mg/L for systems that had not been serviced within three months. These values are consistent with those from Charles *et al.* (2005), who reported the free chlorine residuals for 119 systems that had all been serviced within

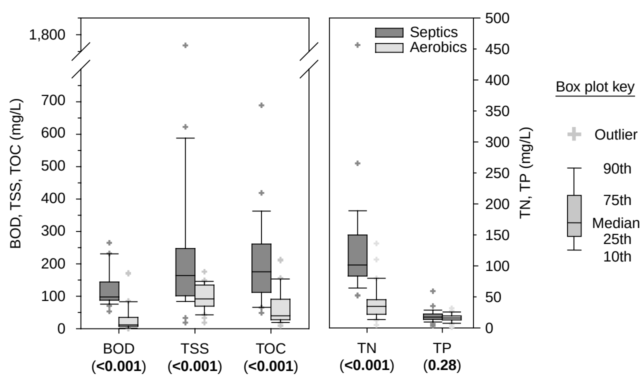

Figure 3 | Comparison of aerobic system and septic tank effluent quality showing 10th, 25th, 50th (median), 75th and 90th percentiles (numbers in brackets indicate P-value, values in bold indicates statistically significant result).

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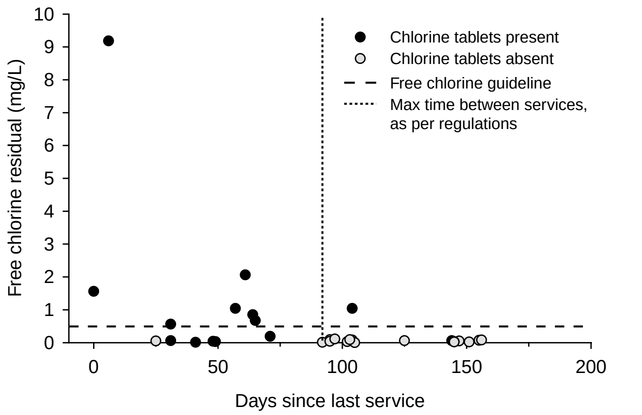

Figure 4 | The relationship between the free chlorine residual and time since last service.

three months, with the average being 0.5 mg/L, and the median 0.2 mg/L.

Aerobic system effluent nutrient concentrations were correlated with the number of occupants in the household (a surrogate for hydraulic loading). TOC ($P = 0.005$), TKN ($P < 0.001$) and TP ($P = 0.01$) tended to increase as the number of occupants increased, and nitrate (an indicator of the aerobic status of the system) tended to decrease with an increase in occupants ($P = 0.017$). TP was inversely correlated with system size, with lower TP levels found in the larger tanks ($P = 0.002$). TSS was positively correlated with system age, with lower TSS levels found in newer aerobic systems ($P = 0.02$).

Other studies of aerobic system effluent quality have also found poor treatment performance; assumed to be due to a lack of maintenance (Khalife & Dharmappa 1996; Nunn & Ross 2006). Moelants *et al.* (2008) reported a link between maintenance and effluent quality; five systems with maintenance contracts produced better quality effluent than 18 systems without maintenance contracts, by comparing chemical oxygen demand, biological oxygen demand and suspended solids levels. However, many of the professionally maintained aerobic systems in this study failed effluent quality guidelines. Time since last service did not appear to affect BOD_5 and TSS, nor nutrient levels, which were correlated with the number of occupants. These factors may be influenced more by influent quality, hydraulic loading and system design than maintenance. Alternatively, the current standard of maintenance performed by service agents in the region may not be adequate to keep the systems performing optimally. The training provided by the manufacturers to the service agents is an additional unknown. A proposed government accreditation of service agents (as per the SA Department of Health's draft Onsite Wastewater Systems Code (2007)) will help to ensure a higher standard of maintenance in the future.

Groundwater quality

Groundwater quality from household supply bores was generally acceptable for drinking, with only three bores showing low level detections of indicator bacteria (Table 4). Nitrate levels were highly variable and within the range of concentrations found throughout the Gambier Limestone aquifer; most likely due to historical contamination in some areas. However only three bores exceeded the nitrate drinking water guideline for infants under three months, and no bores exceeded the guideline for adults. The three bores that

Table 4 | Quality of groundwater sampled from household bores

	n	Range	Median	Mean	SD	ADWG*	*n* (%) not complying
Thermotolerant coliforms (cfu/100 mL)	29	<1–18.5	<1	1.2	3.5	Should not be detected	2 (7%)
E. coli (cfu/100 mL)	29	<1–18.5	<1	1.2	3.5	Should not be detected	2 (7%)
Enterococci (cfu/100 mL)	26	<1–4	<1	<1	0.71	No guideline	1 (4%)†
TN (mg-N/L)	31	0.03–17	4.2	5.7	4.6	No guideline	–
NO_3 (mg-N/L)	31	<0.025–17	4.1	5.2	4.7	<11.3 mg-N/L (infants)	3 (10%)
						<22.6 mg-N/L (adults)	0 (0%)

*Australian Drinking Water Guidelines, NHMRC-NRMMC (2004).
†Number of detections.

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exceeded the nitrate guideline for infants were not the same three bores that had detections of indicator bacteria.

Concentrations of other inorganic chemicals that may be used as indicators of wastewater contamination in groundwater, such as boron, phosphorus, potassium and chloride (Wolf *et al.* 2006), were generally low and also within the range found throughout the aquifer. In this region the groundwater is subject to numerous pollution sources including agriculture and historical contamination from cheese factories and timber processing plants (Emmett & Telfer 1994) which can mask the impact of on-site system contamination; this contrasts with the study of Harden *et al.* (2008) in a karstic aquifer within the Manatee Springs State Park where on-site systems were the sole pollution source. Hence, while low level faecal contamination was detected in $\sim$10% bores, the source of contamination being on-site systems can be neither confirmed nor excluded.

No significant difference in groundwater quality was found between properties with septic tanks and those with aerobic systems, and the distance between the on-site system and the bore (ranging from 2 m to $>$100 m, with a median of 50 m) was not found to have a significant effect. The bores sampled were generally deep (all but one were deeper than 25 m, with a median of 47 m, and a maximum depth of 84 m), and properly constructed (i.e. drilled and cased), and this may help to protect the bore water from surface sources of pollution. The depth to water table ranged from 3 m to 70 m, with a median of 24 m.

Human health risk from aerobic system effluent

Risks to human health from aerobic systems can occur through exposure to effluent during surface irrigation, and are likely to increase as a result of poor quality effluent and inadequate irrigation areas.

The areas designated for irrigation with aerobic system effluent generally did not comply with guideline standards, leading to a high chance of householders coming into contact with effluent. Only 26% of irrigation areas were equal to or larger than the required 200 m^2. Access to the irrigation area was easy on 43% of properties due to the area being lawn or only sparsely planted with trees or shrubs; of these easy to access irrigation systems, only one was fully fixed as required under the regulations, with the others having movable sprinklers, or no spray heads or drippers connected (effluent irrigated via 40 mm polypipe). These findings are consistent with the low standard of irrigation areas reported by other authors (Khalife & Dharmappa 1996; Arnold & Gallasch 2001; Nunn & Ross 2006).

Alexander *et al.* (2010) reported that many of the same householders from this study were unaware that secondary treated effluent is considered unfit for direct human contact. Poor compliance with irrigation regulations is contributed to by irrigation systems being installed by householders themselves, and insufficient checks on irrigation areas after installation. It is recommended that irrigation areas be fully set-up before councils issue the approval to operate permit.

The low level of compliance with thermotolerant coliform guidelines (29%) indicates that surface irrigation of aerobic system effluent potentially represents a public health risk. A well set-up irrigation area provides an exposure barrier between residents and wastewater pathogens (Nunn & Ross 2006), but the many inadequate aerobic system irrigation areas observed provide little or no barrier. The calculation of pathogen health-based targets reveals the level of treatment required to adequately protect public health based on the 95th percentile numbers in primary treated wastewater for the three reference pathogens nominated in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006). When spray irrigating with effluent from a correctly operating aerobic system (assumes secondary treatment and effective chlorine disinfection of effluent), *Campylobacter* treatment levels ($\log_{10}$ removal) are acceptable, however an additional 2.3 $\log_{10}$ and 1.6 $\log_{10}$ treatment for *Cryptosporidium* and rotavirus, respectively, are required to achieve the guideline of 10^{-6} DALYs (NHMRC–NRMMC 2004). This could be achieved through the barriers of preventing access during irrigation (2.0 $\log_{10}$), drip irrigation (4.0 $\log_{10}$) or subsurface irrigation (6.0 $\log_{10}$). These barriers are considered additive; controlling access and a drip irrigated area gives a total exposure reduction of 6.0 $\log_{10}$. If chlorination was not effective, additional $\log_{10}$ reductions of 2.6 for *Cryptosporidium*, 1.5 for *Campylobacter* and 3.6 for rotavirus would be required, which again could be achieved with an appropriate irrigation area.

The low quality of aerobic system effluent revealed (Table 3) and the karstic nature of the underlying aquifer leads to the potential for groundwater contamination.

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Thus there may be a risk to human health when groundwater is used for drinking water supply. To further investigate this link a human health risk assessment was conducted to determine the minimum residence time in the aquifer required following aerobic system treatment to provide sufficient pathogen attenuation to meet the guideline value of 10^{-6} DALYs under the increased exposure volume and frequency associated with drinking groundwater.

This risk assessment shows that additional aquifer treatment ($\log_{10}$) required to achieve an acceptable health risk are 2.1 $\log_{10}$ for *Campylobacter*, 7.0 $\log_{10}$ for *Cryptosporidium* and 6.2 $\log_{10}$ for rotavirus. Using decay rates (T_{90}) from Toze *et al.* (2010) as determined for an unconfined carbonate aquifer of 1 day for *Campylobacter*, 39 days for *Cryptosporidium* and 29 days for rotavirus, the required residence time in the aquifer to reach 10^{-6} DALYs for each of the reference pathogens is 2.1 days, 273 days and 180 days, respectively. While these calculations do not consider treatment in the unsaturated zone, filtration or adsorption is inappropriate in karst terrain due to potential for direct discharge into the aquifer through karst conduits (Doerfliger *et al.* 1999).

A set-back distance between an on-site system and a bore of 50 m is mandated in South Australia, but this is inappropriate in a karstic aquifer where set-back distances cannot be relied upon to ensure adequate residence times. More sophisticated protection zones defined based on travel time through the saturated zone are required for adequate pathogen attenuation, however these need an understanding of flow velocities and directions (Schmoll *et al.* 2006), impractical to achieve for every household. For householders who rely on bore water sourced from a karstic aquifer, the additional protection of a UV treatment system (providing an additional removals of $>3.0 \log_{10}$ for *Cryptosporidium* and $>1 \log_{10}$ for rotavirus) on their water supply is a cost-effective method of ensuring human health protection.

The QMRA results suggest that either additional treatment measures or longer residence times are required for *Cryptosporidium* and rotavirus to meet the guideline values. However, the risk assessment is conservative for several reasons. Firstly, members of the household (or local community) would need to be infected for these pathogens to be present in the system in the first place. The risk assessment assumes groundwater consumption of 2 L per day, which is possible but unlikely when additional water supply sources such as rain water or reticulated supply (peri-urban areas) are available. Also, assuming all domestic wastewater treated by an on-site system contributes to groundwater recharge, this amounts to around 25% of total recharge beneath a typical 5,000 m^2 allotment in the region. Thus, the concentration of pathogens is diluted in the groundwater. The T_{90} values for pathogen degradation in a carbonate aquifer given in Toze *et al.* (2010) do not account for attenuation via filtration in the aquifer matrix which could be significant, but again cannot be relied upon in a karstic aquifer. Finally, the decay of microbial pathogens in groundwater is influenced by aquifer characteristics such as temperature, electrical conductivity, dissolved oxygen and organic carbon concentrations (Toze *et al.* 2010), so differences in decay rates will be expected in different aquifers.

CONCLUSIONS

In order to provide a scientific basis for improving on-site system management effluent from aerobic systems and septic tanks was sampled to determine system operational performance, the effect of maintenance regime, system size and number of occupants on aerobic system effluent quality was analysed. Aerobic systems generally treated effluent to a higher standard than septic tanks but most aerobic systems did not comply with all effluent quality standards. Groundwater quality did not conclusively demonstrate contamination by on-site systems due to multiple sources of contamination by various land uses in the area.

A key finding of this study was the significant positive effect that quarterly maintenance by a service agent had on the chlorine residual, with a corresponding decrease in the level of indicator bacteria. However, most systems inspected had a history of inadequate servicing, leading to non-compliance with microbial guidelines. Combined with the inadequate irrigation areas, irrigation of inadequately treated effluent currently poses an unacceptable public health risk. Additional treatment of up to 3.6 $\log_{10}$ (for viruses) are required; this treatment can be achieved by using drip irrigation (4 $\log_{10}$). The risk assessment also indicated that additional measures such as UV treatment should be implemented where sufficient residence time

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in the aquifer cannot be guaranteed for protection of groundwater used as drinking water supply.

Recommendations for improved management of aerobic systems by councils in the region were: 1) inform householders about the importance of regular system maintenance and the health consequences of contact with secondary-treated effluent; 2) recommend the use of drip irrigation; and 3) approval to operate systems is not given until the irrigation area is completely set-up. The first steps towards engaging the community to improve on-site system management have already been taken, with focus groups conducted to determine community attitudes towards on-site systems and changes in management (Alexander *et al.* 2010). Local councils have also developed new information flyers to inform residents about their on-site systems, and are working towards completing their databases of on-site systems installed.

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