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Decline in Recycled Water Quality

During Short-term Storage in Open Ponds

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Abstract

This paper assesses the changes in chemical and bacterial quality of effluent, produced at urban wastewater treatment plants (WWTPs), during short-term storage in open surface ponds. In this study, water quality was monitored over a five-year period at the inlets and outlets of open storage ponds located at three biological nutrient removal plants. Temperature, rainfall and sewage inflow data was also recorded at each treatment plant. Significant changes occurred in chemical and bacterial quality during storage which challenge the notion that pond storage has, per se, a positive or negligible effect on effluent quality. Changes in faecal coliforms, nutrients, and chemical oxygen demand adversely affected effluent quality and, in this case, were most likely caused through contamination from avian faeces. The increase of one to two orders of magnitude in faecal coliforms were such that they could potentially affect the viability of reuse schemes by limiting the uses of the recycled water under recently adopted Australian water recycling guidelines. Potential improvements to short term recycled water storage management on-site at WWTPs are discussed including the use of enclosed storages to protect the recycled water from contamination, post storage filtration and disinfection, and the monitoring of all water quality parameters, including microbiological ones, at the point of entry into the recycled water distribution system, after storage at the treatment plant, rather than at the end of the treatment process post-disinfection

Keywords

Recycled water quality, effluent, storage ponds.

Article outline

Terms

CFU	colony forming units
COD	chemical oxygen demand
DALY	disability affected life years
DO	dissolved oxygen
EC	electrical conductivity
HACCP	hazard analysis and critical control point
m^3	cubic metre or 1000 litres
Nutrients	nitrogen and phosphorus compounds
Oxidised-N	nitrate-N and nitrite-N

p	probability
SEQ	southeast Queensland
SS	suspended solids
TDS	total dissolved salts
Total-N	total nitrogen
Total-P	total phosphorus
WWTP	wastewater treatment plant

1. Introduction

The climatic trends of declining rainfall and increasing average temperatures, observed in Australia over the last fifty years, are predicted to continue into the future with an estimated 2 - 5% decline in annual rainfall and a 20% increase in drought conditions by 2030 (CSIRO 2007, IPCC 2007). In fact, severe widespread droughts, in some cases the longest on record, have been experienced recently and have produced water shortages throughout most of the country. The sustained stress on conventional water resources, such as rivers, dams and aquifers, experienced during these droughts, has highlighted the urgent need to develop alternative water sources, such as recycling the treated effluent from wastewater treatment plants (WWTPs). Such alternatives are required to mitigate the demand on potable water supplies not only in inland arid areas but also in heavily populated coastal regions of Australia (Radcliffe 2004). The widespread introduction of household water restrictions in Australia, during the recent droughts, and the growing public acceptance for water recycling options for domestic use (Hurlimann and McKay 2007) have promoted the use of WWTP effluent as an alternative source of water.

Despite this recent swing in public acceptance, in principal there is still considerable concern about the quality of treated effluent (Higgins et al. 2002, Po et al. 2003 and Toze 2006), especially for uses involving close human contact or ingestion (Po et al. 2003). One possible solution to ameliorate these concerns is to subject effluent from WWTPs to further treatment such as microfiltration and reverse osmosis. This concept is currently being considered for large scale implementation in Southeast Queensland, Australia (QLD 2007) and elsewhere (NRMMC 2007, WSAA 2006). The environmental down side of this approach is the considerable energy demand and associated greenhouse gas emission that would accompany this solution except, in the rare event, where nuclear power or renewable energy is locally available. In essence, this practice would exacerbate the climate problem that is one of the key drivers for water shortages in the first place. For example, the amounts of energy (kilowatts/kilolitre of product water) required to produce source water for drinking from the desalination of seawater or through the additional treatment of recycled water are 6 or 3 times greater respectively than water obtained through dam catchment (GCW 2005).

Another option with, in the long term, a considerably lower environmental cost is to design new WWTPs for total effluent reuse (TAS 2002, NSW 2004). However, in many regions, total reuse may not be feasible if rainfall variability affects the demand for recycled water and engenders a need for intermittent storage. A third option is to improve, as much as possible, the performance of those existing WWTPs that have a high quality effluent and to focus on identifying and managing those post-treatment elements that might cause deterioration of this effluent quality prior to use.

One of the most common, yet critical, post-treatment steps in many urban WWTPs is the short-term storage of treated effluent in open surface ponds, prior to discharge to the environment or entry into the recycled water distribution system. Such ponds are exposed to, *inter alia*, sunlight, wind-induced mixing and sediment re-suspension, introduction of pathogens through wild animals, especially waterfowl, and deposition of wind-borne external pollutants. Better performing alternatives such as long term or seasonal storage in reservoirs (Azov and Shelef 1991, Fattal et al. 1993, Juanico and Shelef 1994, Liran et al. 1994, NRMMC 2006, VIC 2003, SA 1999) or storage in aquifers (Dillon et al. 2005, QLD 2005, SA 1999) are often not available due to local environmental or space constraints.

Extensive research has been documented on the changes in wastewater quality in ponds and lagoons used for wastewater treatment including wastewater stabilisation ponds and maturation ponds (e.g. Maynard et al. 1999, Shilton 2005). Research has also been conducted on the wastewater quality changes during storage after the completion of the treatment process. However, much of this research to date has focussed on storage systems external to the wastewater treatment plants such as deep surface reservoirs (e.g. Azov and Shelef 1991, Fattal et al. 1993, Juanico and Shelef 1994, Liran et al. 1994 and WERF 2003), aquifers (e.g. Dillon et al. 2005) or in surface storage ponds at the point of use, for example at golf courses or crop irrigation schemes (e.g. Bahri et al. 2001, Murakami and Ray 2000). On the other hand, only limited information is available on the changes that may occur in effluent quality, during short term storage in surface ponds at wastewater treatment plants, prior to entry into recycled water distribution systems.

In addition, information provided in Australian national, state and territory guidelines (Table 1), on the management and monitoring of recycled water storages, varies between the different jurisdictions and often does not include information about short term storage. The paucity of research and lack of clarity in the guidelines about the short term storage process may lead to the continuation of less than optimal management systems. If this problem is not rectified, then additional energy may be required to re-process stored recycled water to attain the required quality. This study was undertaken to examine the effects of short-term storage at three WWTP sites to

(i) demonstrate the magnitude and variability of changes in the chemical and bacterial quality of effluent, from biological nutrient removal treatment plants, during short-term storage in open ponds at the treatment plants.

(ii) evaluate the mechanisms likely to be contributing to these water quality changes.

(iii) assess the impact of these changes in quality on effluent reuse options under current water recycling guidelines

(iv) propose improvements in the management of effluent storage at wastewater treatment plants to maximise effluent reuse potential

Table 1

2. Methods

Water quality monitoring data used for this study was collected at three waste treatment plants (WWTPs) over a five-year period from mid 2001 to mid 2006. The WWTPs were all located approximately 70 km south of Brisbane on Australia's eastern seaboard at 27.5° S latitude. The region serviced mainly by these WWTPs had a residential population of 482,500, as of June 2005 (LGP 2006), and experiences an influx of 4.4 million tourists per year.

2.1 Wastewater treatment plants

The wastewater treatment plants studied varied in catchment area, treatment capacity and processes, age and storage pond design and retention times (Figure 1). Land uses in each catchment were largely dominated by residential development and infrastructure including tourism complexes, but also included medical facilities, food and beverage outlets and light industries. The three WWTPs have been gradually upgraded over the past 25 years, to increase capacity and include or improve nutrient removal, and their treatment train components differed due to variations in capacity, age and original design parameters. Initial separate operating licences were recently rolled into one general licence with compliance levels remaining tailored to each plant's treatment capability.

Figure 1

2.2 Sample collection and water quality analysis

Licence conditions stipulated that the WWTPs had to be operated so that total nitrogen (total-N), total phosphorus (total-P), pH, dissolved oxygen (DO), biochemical oxygen demand (BOD) and suspended solids (SS) in the pond outlet samples, and faecal coliforms levels in the pond inlet samples, remained mostly (90 percentile) below individual thresholds set for each WWTP. The water quality data collected by the local water authority and examined during this study also included electrical conductivity (EC), ammonia nitrogen (ammonia-N), oxidised nitrogen (oxidised-N), orthophosphate phosphorus (ortho-P) and chemical oxygen demand (COD).

Water quality data was collected weekly at the storage ponds inlets and outlets over a 5 year period, from July 2001 to June 2006 (WWTPs 1 and 2) and from February 2002 to June 2006 (WWTP 3). The total rainfall and total influent flows for each treatment plant were determined for 1, 3 and 7 day periods prior to the collection of samples for water quality testing.

The tests for COD, SS, pH, DO, EC and chlorine were performed using standard methods for wastewater analysis (Sections 5220D, 2540D, 4500-H^+, 4500-O G, 2510 B and 4500-Cl in APHA 1998). Results for ammonia-N, oxidised-N, ortho-P and total N and P were obtained by flow injection analysis (Sections 4500-NH_3 H, 4500-NO_3^- I and 4500-P G in APHA 1998 and Ebina et al. 1983). Membrane filtration (Section 9222D, APHA 1998) was used to count and confirm faecal coliforms. All samples were collected and tested by an accredited laboratory (National Association of Testing Authorities).

Analyses for nutrients, COD and SS were performed on composite grab samples collected from secondary sedimentation tank outlets, prior to the storage pond inlets, and also on 24 hour composite samples collected at the storage pond outlets. Each faecal coliform value for each storage pond inlet was the median value of 5 grab samples collected, over a 28 hour period, from the outlet of each chlorine contact tank just prior to the storage pond inlets. Faecal coliform concentrations (CFU/100mL) for the pond outlets were determined on single grab samples, collected at the pond outlets, at the end of the same 28 hour period used for pond inlet samples. As this study utilised historical monitoring data, effluent quality was assessed at the sampling points at similar times with no opportunity of studying the same slug of water as it travelled through the storage systems. This problem was mitigated to some extent by the flow balancing effect of the storage ponds and the collection of daily composite samples at the pond outlets.

2.3 Data analysis

Faecal coliform concentrations were transformed to $\log_{10}$ (CFU/100mL + 1) for all descriptive and inferential statistics. Time sequence plots were generated to illustrate differences between the storage pond inlets and outlets and to examine any variations of these differences with time or season. A non-parametric Wilcoxson Signed Ranks test was used to analyse the differences between water quality values in paired samples from these sites. This test negates the need for the underlying distribution to be normal and is unaffected by the potential for sample variance heterogeneity due to the different sampling methodologies. A Monte-Carlo permutation test was used to avoid issues pertaining to dependent observations.

The water quality data was summarised using means and standard errors for each site. To assess quality variability, the number of outlier or extreme outlier values, defined as those being respectively >1.5 or >3 times above the third quartile or below the first quartile, were counted for each variable. Spearman correlation analysis was conducted to examine the relationships between water quality values and either flow, rainfall or temperature. All analyses were performed using SPSS® version 13.0.

3. Results and Discussion

All data examined in this survey included outlier values which may have been caused by a range of factors including changes in influent flow due to rain, treatment plant operational changes, unplanned industrial discharges into the sewer system or due to sample contamination. These outlier values are, however, part of a typical data set and need to be acknowledged and incorporated into effluent management systems, even though they might affect the means and SE values for the various water quality parameters.

3.1 Effluent quality changes during surface storage

Irrespective of the differences in storage pond design, capacity or retention times the values for practically all quality parameters studied during storage, i.e. nutrients, COD, SS and faecal coliforms, were significantly higher at the storage pond outlets than at the inlets (Table 2). The only exceptions were the lower SS at the WWTP 2 outlet and the lack of a significant difference between the inlet and outlet pairs for COD at WWTP 2 and ammonia-N at WWTP 3. The greatest changes during storage occurred in faecal coliform concentrations, as illustrated for WWTP 2 in Figure 2, with increases of one or two orders of magnitude observed across the three WWTPs (Table 2). In terms of quality variation over time, the standard errors of the means were low for the majority of quality parameters at inlet and outlet sites. However, instances of higher variability were noted for ammonia-N and oxidised-N values which reflect the higher percentage of outlier and extreme values reported for these parameters (Table 2).

Table 2

Figure 2

These results indicated that various water quality characteristics deteriorated during short-term storage in open, surface ponds. However, it was the substantial increase in faecal coliform counts during storage that was of particular concern. These findings support those of Murakami and Ray (2000) who observed faecal coliform growth in an open storage reservoir, containing secondary-treated, filtered and chlorinated effluent, and Bahri et al. (2001) who noted a deterioration in the bacterial quality of treated effluent stored in open ponds used for golf course irrigation. These indicator organisms could have increased by continuing to multiply in the pond water column or sediment during storage. Alternatively, the bacteria could have recovered after disinfection as has been reported by Shuval et al. (1973) who observed regrowth of faecal coliforms in chlorinated effluent held in a storage reservoir. However, as birds are a potential source of faecal indicator bacteria (Abbott et al. 2006, Murphy et al. 2005), the faecal coliforms may also have been introduced through contamination by avian faeces. The WWTPs used in this study were situated in areas of natural wildlife habitat and wild birds were often seen on or near the storage ponds, as shown in Figure 3 for WWTP 1, with the quantitative order of birds present being, from highest to lowest, WWTP 1, 2 and 3. Eleven species of wild birds were observed roosting on or near the water, and most likely contributing faecal contamination to the storage ponds, with the most predominate ones being Eurasian Coot (*Fulica atra*) and Pacific Black Duck (*Anas superciliosa*). Consequently, in this case, the most likely cause of the increase in faecal coliforms was contamination by avian faecal material that may have entered the ponds by direct deposition or by being washed off the sloping sides through water level changes during pumping.

This avian faecal contamination may have also caused the small, but statistically significant, increases observed in nutrient levels. Alternatively, the changes in nutrients may have been caused by nutrient fluxes between the water column and the sediments in the storage ponds (WERF 2003). The specific factors causing the consistent increases in levels of both chemical and bacterial water quality parameters during surface storage, observed at all three WWTPs, were not identified in this survey. However, with the continuing introduction of improved wastewater treatment processes worldwide, the quality of the recycled water entering storage systems will continue to improve and, consequently, the effect of any contamination during storage will become more significant. Further research is required, to identify the causes of the undesirable deterioration in recycled water quality during open storage at WWTPs, so that appropriate mitigating management options can be developed.

During the study period, the mean total chlorine values at the pond inlets were 1.0, 1.8 and 2.6 mg/L for STPs 1, 2 and 3 respectively and less than the chlorine detection limit of 0.2 mg/L at the pond outlets. The mean faecal coliform $\log_{10}$ values at the pond outlets were 2.6, 1.7 and 2.2 for STPs 1, 2 and 3 respectively (Table 2). Thus, the STP with the highest faecal coliform levels at the pond outlet, STP 1, had the lowest total chlorine values at the pond inlet. These findings support those of Shuval et al. 1973 who found that regrowth of coliforms in chlorinated effluent held in a storage reservoir appeared inversely correlated to the residual chlorine in the storage reservoir. After the study period from which the data was obtained, the total chlorine at the pond inlet for STP 1 was increased to 3 mg/L and the retention time reduced to < 24 hours. These operational changes were maintained for 4 months during which time the mean faecal coliform $\log_{10}$ value at the pond outlets was reduced from 2.6 to 1.8 thereby demonstrating that these changes to pond management were effective at reducing faecal coliform levels during storage.

3.2 Effluent quality changes with flow, rainfall and temperature.

In this study, WWTPs 1, 2 and 3 processed average sewage inflows of 71 500 (56 800 – 197 400), 33 500 (25 600 – 86 300) and 26 500 (19 700 – 69 200) m^3/d with peak sewage inflows of 3960, 5040, and 4320 m^3/h respectively. Only one third (32%) of the correlations, between sewage inflow and water quality values at the pond inlet and outlet sites, were significant ($p < 0.01$) (Table 3). As the WWTPs were designed to produce effluent of a specified quality at up to three times the average dry weather flow, it was not unexpected to find that sewage inflow had a minimal correlation with effluent quality. The annual rainfall was 800, 1500, 1200, 1600 and 1500 mm, during the 5 years of this investigation, with less than 16% of the correlations of rainfall with water quality data being significant ($p < 0.01$) (Table 3). However, despite the low number of significant correlations between outlier or extreme values and water quality, 41% of faecal coliform outliers and 35% of chemical water quality outliers occurred after higher than average rainfall or flow events. During this study, the mean water temperature prior to the pond inlet was 22.6 ^{o}C (17 - 28 ^{o}C) and 60% of pond inlet and outlet water quality values were significantly ($p < 0.01$) correlated with the pond inlet water temperatures (Table 3).

The majority (64%) of the correlations of water quality, with flow, rainfall or temperature, were not significant ($p < 0.01$). Those that were statistically significant displayed varying trends across the three WWTPs and had low correlation coefficients, ranging from -0.17 to -0.55 for sewage inflow, 0.14 to -0.32 for rainfall and –0.16 to –0.48 for temperature (Table 3). The only instances where all three WWTPs showed the same significant trend were a negative correlation between pond influent temperature and pond inlet suspended solids, pond outlet ammonia or oxidised-N and a positive correlation between pond influent temperature and faecal coliforms (Table 3).

Table 3

3.3 Risk assessment and water recycling guidance

In Australia, effluent reuse schemes can be introduced and maintained without any specific licence under Federal or State legislation. Instead, governments have opted for introducing the recently promulgated national guidelines (NRMMC 2006) along with State water recycling guidelines (e.g. QLD 2005) as the only widely applicable quality control instruments. Both Federal and State guidelines place a strong emphasis on risk management through the estimation of human health risks, expressed as 'disability adjusted life years' (DALY) in the national guidelines (examples for thermotolerant coliforms or *E. coli* are provided in Table 4), and through the implementation of environmental management and audit systems supplemented with 'water quality objectives' for designated uses of recycled water.

All current Australian recycled water guidelines, except two (VIC 2005, NSW 1993), mention the storage of recycled water (Table 1). However, it is not always clear whether the storage takes place at the WWTP or at the reuse site. All refer to either long term or winter storage, with two exceptions (NSW 2004, NRMMC 2007), and four guidelines refer to aquifer storage (NRMMC 2006, QLD 2005 and SA 1999). However, the guidance varies on the health or environmental risks due to the storage of recycled water and the verification monitoring required for quality assurance (Table 1). Some guidelines (NRMMC 2006, VIC 2005) mention the health risk of recycled water contamination, due to birds, yet still recommend that the microbiological monitoring point for recycled water quality be upstream of any storage.

A quantitative microbial risk assessment of the recycled water, from the WWTPs used in this study, identified that even though the increased health risk to users would be small it could potentially exceed the 1 in one million DALY recommended in the national guidelines (Deere at al. 2007). Ensuring that the permissible uses of the recycled water were allocated according to the quality of the water leaving, rather than entering, the storage ponds would mitigate this risk. Consequently the monitoring point for recycled water quality should be downstream, not upstream, of any recycled water storage ponds located at the WWTPs.

Table 4

Results from this study highlight the need for providing more details in the guidelines and licences about effluent storage and illustrates the lack of integration, generally for historical reasons, between the two regulations (Table 4). Conditions for discharge of effluent from secondary treatment plants to land or water in Queensland require faecal coliform levels to be generally (90 percentile) lower than < 150 CFU/100mL with a maximum of 600 CFU/100mL. Guideline quality parameters for recycled water, however, are set at logarithmic intervals for *E. coli* or thermotolerant coliforms, determined immediately after disinfection. In this study, using WWTPs with short-term storage in open lagoons, the high level of compliance (generally above 95%) with discharge or reuse quality objectives at the pond inlets is reduced across the three WWTPs to between 13% to 60% at the pond outlets (Table 4). These findings strongly support the guidelines' recommendation to validate log removal assumptions for individual components of the treatment processes, notably in the storage systems.

Recent national guidelines (NRMMC 2006) recommend that post disinfection verification monitoring for health risks occurs only upstream of any open lagoons, and require only end user controls in the distribution system. Governments with strong interests in widespread and rapid uptake of effluent reuse programs, as part of their response to increasing demand on water supplies, should consider integration of monitoring requirements for treatment plant operation licences with effluent reuse management systems. Such integration should include and optimise routine monitoring at delivery end-points as additional critical control points for more effective quality control.

4. Conclusions

This study was undertaken using water quality data collected over a five year period to examine the effects of short-term storage at three WWTP sites. The main conclusions derived from this investigation were that

- significant changes occurred in the chemical and bacterial quality of water, reclaimed from sewage at biological nutrient removal plants, during subsequent short-term storage in open ponds at the treatment plants.
- the most likely cause of the water quality changes during storage, in this instance, was contamination from avian faeces but further research is required to establish causality.
- faecal coliforms, nutrients and COD increased during surface storage with the magnitude of the increase in faecal coliforms being such that it could limit the guideline uses of the recycled water. The high level of compliance (generally above 95%) with discharge or reuse quality objectives at the pond inlets was reduced across the three WWTPs to 13% - 60% at the pond outlets.
- management of effluent storage at wastewater treatment plants could be enhanced by introducing technical measures to protect the recycled water from

contamination, such as the use of enclosed storages, further treatment after storage, such as filtration and disinfection; and by monitoring all water quality parameters, including microbiological ones, at the point of entry into the recycled water distribution system, after storage at the treatment plant, rather than at the end of the treatment process post-disinfection.

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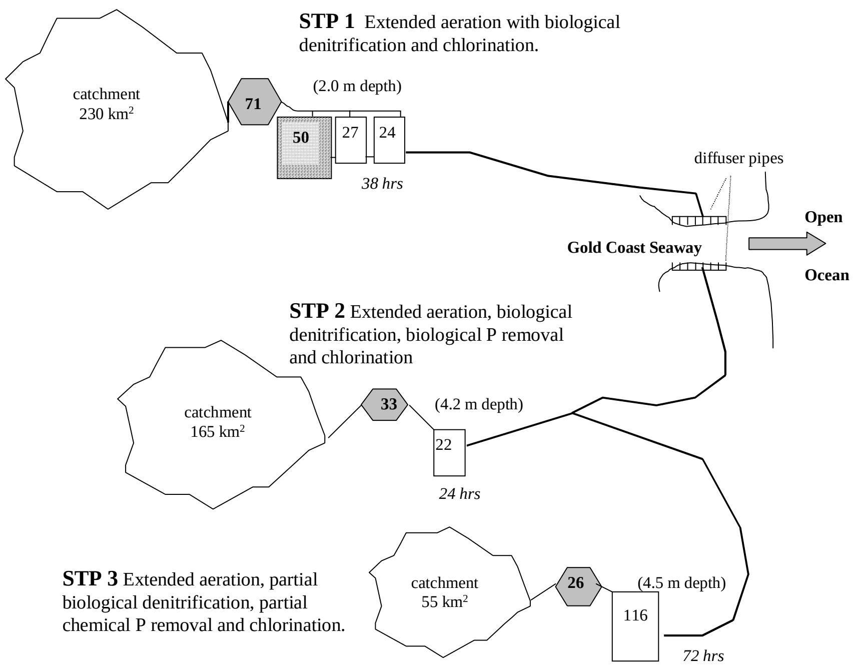
Figure 1. Wastewater catchments, treatment plants (WWTP 1, 2 and 3) and their recycled water distribution systems on the Gold Coast, Queensland, Australia.



Key

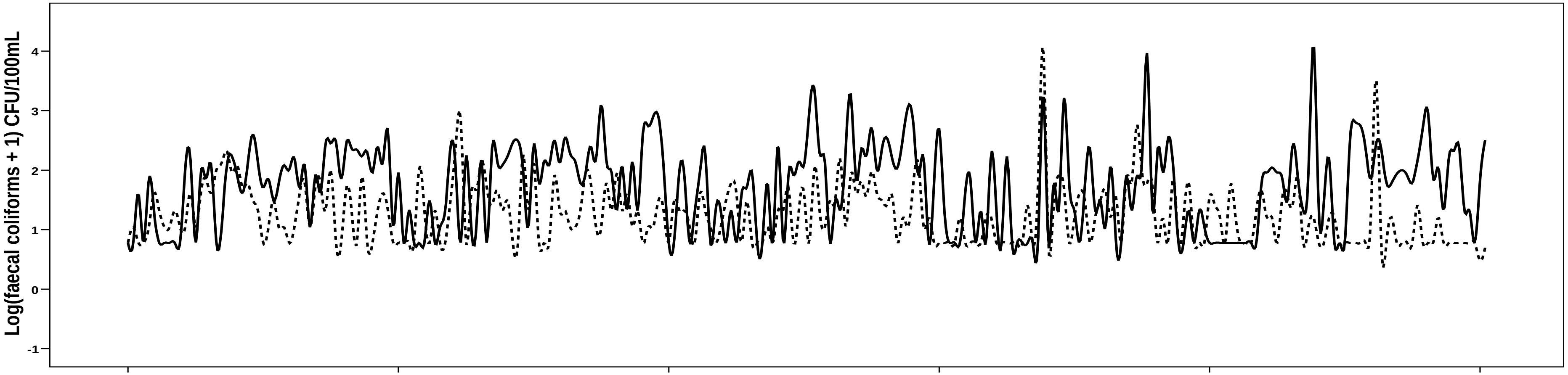
hexagons	WWTPs with average daily flow rates (1000 m^3/day) shown in bold font
rectangles	storage ponds with storage capacity shown in 1000 m^3
shaded rectangle	wet weather overflow storage pond
thick black lines	recycled water distribution trunk mains
italicised values	retention times in storage ponds (hours)

Figure 2. Faecal coliform counts observed at WWTP 2 pond inlet and outlet sites over a five year period.

a) Faecal coliform counts ($\log_{10}$ (x + 1) CFU/100mL) at pond inlet (---) and pond outlet (–).

b) Difference (pond outlet – pond inlet) faecal coliform counts ($\log_{10}$ (x+1) CFU/100mL).

(a)



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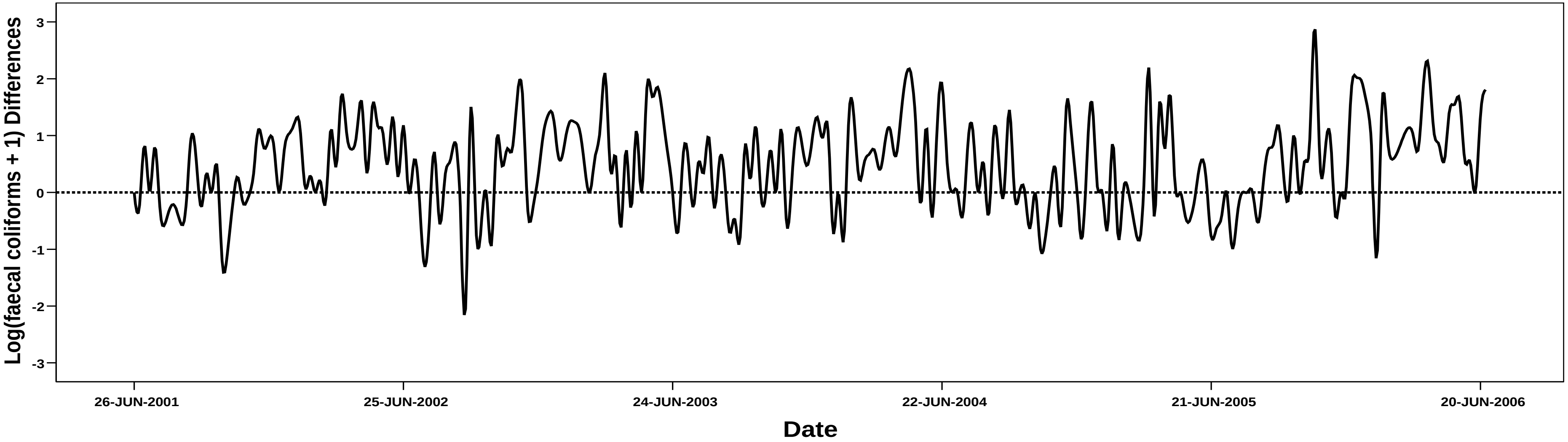

Figure 3 Wild birds observed on or near the storage ponds at WWTP 1.

Refer black and white photo as separate file

Table 1. Current guidance on recycled water storage.

Jurisdiction	**National**	**National**	**Western Australia**	**Queens-land**	**New South Wales**	**Victoria**	**Tasmania**	**South Australia**	**Australian Capital Territory**
Reference	NRMMC 2007[a]	NRMMC 2006[b]	WA 2006	QLD 2005	NSW 2004	VIC 2003	TAS 2002	SA 1999	ACT 1999
Recycled Water Storage	•	•	•	•	•	•	•	•	•
Storage at WWTP	•	•	–	•	–	•	–	–	–
Storage at point of use external to WWTP	•[c]	•	•	•	–	•	•	–	–
Long-term storage	–	•	•	•	–	•	•	•	•
Winter storage	–	•	–	–	–	•	•	•	–
Aquifer storage	•	•	–	•	–	–	–	•	–
Health risk due to storage	•	•	–	•	–	•	•		•
Environmental risk due to storage	•	•	•	•	•	•	•	•	•
Wild birds and storage	•	•	–	•	•	•	–	–	–
Birds as risk	•	•	–	•	–	•	–	–	–
Algal growth during storage	•	•	•	•	•	•	•	•	•
Short circuiting in storage ponds	•	•	–	–	–	•	–	•	–
Microbiology monitoring point upstream of storage	–	•	–	–	–	–	–	–	–

Victoria dual pipe (VIC 2005) and New South Wales urban (NSW 1993) guidelines are not included in Table 1 as they refer mainly to recycled water distribution systems.

• topic mentioned in guideline document.

– topic not mentioned in guideline document.

a = recycled water used for augmentation of drinking water supplies

b = recycled water used for purposes other than augmentation of drinking water supplies

c = In this context, the point of use is the drinking water supply being augmented.

Table 2. Variability of recycled water quality and significance of differences between paired samples collected from pond inlets and pond outlets at each WWTP.

Quality Parameter	WWTP	Pond Inlet		Pond Outlet		Inlet & Outlet		Pond Inlet			Pond Outlet		
		Mean	SE	Mean	SE	n	Sig[a]	O	E	O+E%n	O	E	O+E%n
Ammonia-N	1	0.42	0.054	0.63	0.045	252	***	13	17	11.9	18	8	10.3
mg/L	2	0.66	0.060	0.89	0.059	256	***	3	4	2.7	13	5	7.0
	3	2.57	0.115	2.43	0.096	224	0.054[ns]	7	0	3.1	2	0	0.9
Oxidised-N	1	0.89	0.051	1.13	0.043	252	***	14	5	7.5	13	6	7.5
mg/L	2	1.38	0.052	1.83	0.043	256	***	13	3	6.3	9	0	3.5
	3	5.22	0.188	7.39	0.186	224	***	7	0	3.1	3	0	1.3
Ortho-P	1	3.65	0.052	3.77	0.041	252	***	1	0	0.4	2	0	0.8
mg/L	2	1.33	0.040	1.58	0.043	256	***	1	1	0.8	6	3	3.5
	3	2.75	0.044	2.87	0.033	223	***	1	0	0.4	0	0	0
Total-N	1	2.27	0.080	2.81	0.065	253	***	6	6	4.7	4	5	3.6
mg/L	2	2.98	0.075	3.74	0.070	256	***	6	3	3.5	6	1	2.7
	3	6.87	0.223	8.21	0.206	38	***	1	0	2.6	4	0	10.5
Total-P	1	3.89	0.054	4.03	0.044	256	***	1	0	0.4	1	0	0.4
mg/L	2	1.48	0.040	1.76	0.046	257	***	3	1	1.6	8	4	4.7
	3	2.86	0.118	3.04	0.085	38	**	0	0	0	2	0	5.3
COD	1	38.4	0.803	39.9	0.667	257	*	10	5	5.8	1	0	0.4
mg/L	2	39.3	0.673	38.2	0.660	257	0.083[ns]	14	7	8.2	10	4	5.4
	3	37.1	0.675	40.1	0.714	225	***	4	3	3.1	5	1	2.7
Suspended	1	4.33	0.141	6.05	0.239	257	***	4	1	1.9	4	1	1.9
solids	2	4.60	0.183	3.53	0.150	256	***	6	4	3.9	15	10	9.8
mg/L	3	3.71	0.136	4.42	0.158	224	***	3	0	1.3	1	0	0.4
Log_{10} Faecal	1	0.894	0.039	2.648	0.041	260	***	4	1	1.9	0	0	0
coliforms	2	1.259	0.032	1.716	0.044	256	***	2	0	0.8	1	0	0.4
CFU/100mL	3	1.044	0.027	2.200	0.044	226	***	6	0	2.7	1	0	0.4

a = significance of difference between paired samples using a randomised Wilcoxon Signed Ranks test, with *** $p < 0.001$, **$p < 0.01$, *$p < 0.05$ and ns = not significant,
n = number of paired samples and SE = standard error.
Number of Outlier (O) and Extreme outlier (E) values.

Table 3. Correlation of water quality data with sewage influent flow, rainfall or temperature.

Quality Parameter	WWTP	Pond Inlet			Pond Outlet		
		Flow [a]	Rain [a]	Temp [b]	Flow [a]	Rain [a]	Temp [b]
Ammonia-N mg/L	1	ns	ns	ns	ns	ns	-0.30**
	2	-0.33**	-0.19**	-0.30**	-0.22**	ns	-0.37**
	3	-0.26**	-0.24**	-0.26**	ns	ns	-0.28**
Oxidised-N mg/L	1	ns	ns	-0.20**	ns	ns	-0.44**
	2	ns	ns	-0.25**	ns	ns	-0.36**
	3	-0.26**	ns	ns	-0.36**	ns	-0.23**
Ortho-P mg/L	1	ns	ns	ns	-0.42**	ns	ns
	2	-0.32**	-0.32**	ns	-0.54**	ns	-0.18**
	3	-0.19**	ns	ns	ns	ns	0.25**
Total-N mg/L	1	ns	ns	-0.27**	ns	ns	-0.48**
	2	ns	ns	-0.37**	-0.17**	ns	-0.47**
	3	ns	ns	ns	-0.36**	-0.19**	0.35**
Total-P mg/L	1	ns	ns	ns	-0.42**	ns	ns
	2	ns	-0.32**	ns	-0.55**	ns	-0.16**
	3	ns	ns	ns	ns	ns	0.23**
COD mg/L	1	ns	ns	ns	ns	ns	ns
	2	ns	ns	ns	ns	ns	ns
	3	ns	ns	ns	-0.18**	ns	ns
Suspended solids mg/L	1	ns	ns	-0.19**	ns	ns	ns
	2	ns	0.17**	-0.18**	ns	ns	0.17**
	3	ns	ns	-0.21**	ns	ns	-0.26**
Electrical Conductivity mS/cm	1	-	-	-	-0.42**	ns	ns
	2	-	-	-	ns	ns	ns
	3	-	-	-	-0.21**	ns	ns
Dissolved Oxygen mg/L	1	-	-	-	-0.27**	-0.21**	-0.25**
	2	-	-	-	ns	ns	0.39**
	3	-	-	-	ns	ns	0.24**
pH	1	-	-	-	ns	ns	0.27**
	2	-	-	-	ns	ns	0.28**
	3	-	-	-	ns	ns	ns
Log_{10} Faecal coliforms CFU/100mL	1	ns	ns	0.23**	ns	ns	0.21**
	2	-0.20**	ns	0.20**	ns	0.18**	0.34**
	3	ns	0.14**	ns	ns	ns	0.32**

a = sewage influent flow (m^3) or rainfall (mm) over the 7 days prior to water quality testing

b = temperature (^oC) of pond influent prior to chlorination at WWTP 2 on morning of water quality testing

Spearman correlation, ** = p <0.01 and ns = not significant.

Table 4. Compliance with water quality objectives for designated uses of recycled water (NRMMC 2006) and with WWTP operating licences.

Guideline compliance				Licence compliance			
	WWTP	Pond inlet	Pond outlet[1]		WWTP	Pond inlet	Pond outlet[1]
E. coli or thermotolerant coliforms (see below)				Faecal coliforms (requirement for discharge to land or water)			
	1	95.4%	13.4%	Median	1	97.7%	15.7%
< 100 CFU/100mL	2	93.5%	60.4%	< 150 CFU/100mL	2	96.9%	72.5%
	3	95.6%	33.2%	(90th percentile)	3	97.8%	42.9%
	1	98.9%	69.0%	Maximum	1	98.5%	48.3%
< 1 000 CFU/100mL	2	99.2%	97.3%	< 600 CFU/100mL	2	98.9%	95.3%
	3	100.0%	89.4%		3	99.6%	81.0%
	1	100.0%	100.0%				
< 10 000 CFU/100mL	2	99.6%	99.6%				
	3	100.0%	100.0%				
TDS (only 1 level)				TDS not included in licence conditions			
TDS < 1150 mg/l or	1	n.c.	94.6%				
Electrical conductivity	2	n.c.	99.6%				
< 1.77mS/cm	3	n.c.	99.6%				

n.c. = not collected, 1 = not required for current guidelines or discharge licence compliance

Water quality objective (*E. coli* or thermotolerant coliforms) and designated uses of recycled water:
< 1 CFU/100mL: dual reticulation for indoor or outdoor use, municipal use with unrestricted access, commercial food crops consumed raw or unprocessed;
< 100 CFU/100mL: municipal use with restricted access and application, commercial food crops with harvesting and irrigation restrictions;
< 1 000 CFU/100mL: municipal use with enhanced restrictions on access and application, landscape irrigation with irrigation and access controls, commercial food crops processed before consumption or with no ground contact;
< 10 000 CFU/100mL: irrigation of non-food crops with restricted access and irrigation controls.