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Operating boundaries of full-scale advanced water reuse treatment plants: many lessons learned from pilot plant experience

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ABSTRACT

Three Advanced Water Treatment Plants (AWTP) have recently been built in South East Queensland as part of the Western Corridor Recycled Water Project (WCRWP) producing Purified Recycled Water from secondary treated waste water for the purpose of indirect potable reuse. At Luggage Point, a demonstration plant was primarily operated by the design team for design verification. The investigation program was then extended so that the operating team could investigate possible process optimisation, and operation flexibility. Extending the demonstration plant investigation program enabled monitoring of the long term performance of the microfiltration and reverse osmosis membranes, which did not appear to foul even after more than a year of operation. The investigation primarily identified several ways to optimise the process. It highlighted areas of risk for treated water quality, such as total nitrogen. Ample and rapid swings of salinity from 850 to 3,000 mg/l-TDS were predicted to affect the RO process day-to-day operation and monitoring. Most of the setpoints used for monitoring under HACCP were determined during the pilot plant trials.

Key words | microfiltration, operation, reuse, reverse osmosis, wastewater

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INTRODUCTION

Three Advanced Water Treatment Plants (AWTPs) have recently been built in South East Queensland as part of the Western Corridor Recycled Water Project (WCRWP) producing Purified Recycled Water from secondary treated waste water (Walker *et al.* 2007). Each of the AWTPs include a clarification step to remove phosphorus, Microfiltration (MF) and reverse osmosis (RO) membranes, and UV/H_2O_2 Advanced Oxidation Process (AOP) to achieve the desired water quality (Schrotter *et al.* 2007). Each of the AWTP treats effluent from distinct waste water treatment plants (WWTPs), with various concentrations of nutrients (phosphorus, nitrogen) and organic matter. Since the AWTPs process is complex and depends heavily on the raw water quality, with membrane fouling control being the key challenge, demonstration plants were built at two of the three AWTPs to validate the full-scale AWTP design and anticipate membrane fouling issues.

At Luggage Point, the demonstration plant was primarily operated by the Luggage Point Alliance for design verification. It was then handed over to the Scheme Operator (Veolia Water Australia, on behalf of Water-Secure) to further investigate process optimisation, and flexibility of operation.

The paper describes the demonstration plant set-up. It details process by process the operating boundaries and possible optimisation that have been identified through the testing period, as well as other benefits that helped set up the operation of the full-scale plant.

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METHODS

Demonstration plant description

The demonstration plant replicates the full-scale AWTP, and includes:

- Two equalisation basins, to store secondary effluent from the Luggage Point WWTP.
- A ferric chloride coagulation step (nominal dose of 100 mg/l as $FeCl_3$) and associated lamellas settler to remove phosphorus.
- A 15 m^3/h MF skid of 5 full-scale modules (Pall UNA-620 A) operating at the maximum instantaneous flux of 65 l/(h m^2) to remove fine solids prior to the RO.
- A 3-stage, 5.6 m^3/h, 4″ RO skid (TML-10) to remove nitrogen and most of the trace organic contaminants. The skid was operated within a 14.3–18.0 l/(h m^2) flux range.
- A UV/H_2O_2 AOP unit designed to remove contaminants that are not fully rejected by the RO process, with a specific focus on N-Nitrosodimethylamine (NDMA), a disinfection by-product that can form during monochloramine dosing. The process is designed to remove 1.2 log of NDMA, down to below 10 ng/l, with a peroxide dose of 6 mg/L and electrical input (EE/o) of 0.29–0.37 kWh/kgal/order of NDMA removed.
- Preformed monochloramine was dosed in order to avoid biofouling on the RO membranes, targeting a residual of 1.5 mg/l-Cl_2 at the RO feed (maximum 2 mg/l-Cl_2).

The pretreatment primarily aims at reducing the nutrient load carried by the Reverse Osmosis Concentrate (ROC) discharged to the waterways, by lowering the Total Phosphorus (TP) concentration in the RO feed. It also minimises the risk of calcium phosphate scaling and organic fouling on the RO membranes. MF, RO and UV-AOP processes also act as disinfection barriers as per the multi-barrier disinfection strategy.

Pilot trial objectives

The AWTP design had already been verified at its nominal conditions (see Table 1 for raw water quality) in a previous 8-month trial. The trials were extended for 6 months and focused on investigating operation-related topics, such as assessing process performance over a longer term and a wider range of setpoints, to determine an operating window for each process operating boundaries, and identify ways for future process optimisation.

Table 1 | Luggage Point AWTP raw water quality

Parameter	Unit	Quality Average	Minimum	Maximum
Temperature	Degrees C	24	17	32
Conductivity	μS/cm	2,810	1,460	4,160
Orthophosphate	mg/l-P	7.5	2.0	11
Total nitrogen	mg/l-N	3.9	1.1	7.5
Ammonia	mg/l-N	0.22	<0.02	1.5
TOC	mg/l-C	10	7.0	14

RESULTS AND DISCUSSION

Pretreatment – clarifier: reduction of the ferric chloride dose

Impact on the membrane performance

The pretreatment is designed to remove Total Phosphorus (TP) to a median target of 4 mg/l-P at the ROC discharge. Since nearly all the phosphorus is rejected by the RO membranes, it is concentrated by a factor close to 6.7 through the RO process (85% recovery ratio), which means that the pretreatment should be operated to maintain a median TP concentration of 0.6 mg/l-P at the RO feed. In order to achieve such a low target in the RO feed, a very high dose (100 mg/l) of ferric chloride is required. Throughout the trials, the TP concentration in the RO feed was relaxed to a median of 1.0 mg/l-P, by reducing the ferric chloride dose. The MF feed and RO feed Total Organic Carbon (TOC) concentration then rose from 2 to 6 mg/l-C. However no significant fouling, either scaling or organic, occurred during the 6-month trial period.

Environmental impact

The AWTP does not capture all the WWTP effluent. Therefore two streams of TP are discharged to the Brisbane River: the WWTP excess effluent (circa 25,000 m^3/day) that contains 7.2 mg/l-P on average, and the AWTP ROC stream (circa 12,400 m^3/day). If the AWTP runs as per the design assumption with 4 mg/l-P in the ROC, the AWTP captures 75% of the total TP load released by the WWTP effluent. If the ferric chloride dose is reduced to achieve a target of 7 mg/l at the AWTP ROC, then the TP load conveyed by the ROC nearly doubles. Nevertheless the AWTP still captures 70% of the total TP load. Therefore, decreasing the ferric chloride dose is not as detrimental to the overall scheme TP removal as expected. Indeed the bulk of the TP load not removed is actually conveyed by the excess WWTP effluent that the AWTP cannot treat.

Increasing the ROC TP concentration from 4 mg/l-P to 7 mg/l-P enabled to cut the ferric chloride dose by 30–40% from 100 mg/l to 60–70 mg/l. Cutting down the ferric chloride usage would not only provide significant savings on chemicals cost, but also improve the environmental footprint of the plant: less clarifier sludge and subsequent solid waste is generated and hauled off-site, less greenhouse gases would be generated from interstate deliveries of ferric chloride, and finally the quality of living of the local community is improved with reduced traffic in the AWTP area.

Ferric chloride quality

Ferric chloride from various suppliers was used, depending on availability. A particular supply source applied during several weeks in May contained more manganese impurities than others. Indeed, during that time, the manganese concentration reached 0.2 mg/l at the RO feed (Figure 1), while the raw water concentration remained stable. Simultaneously, the MF fouling rate increased: the chemical cleanings (EFMs) had to be repeated twice more frequently to control the transmembrane pressure (TMP) below 80 kPa (Figure 1).

Pretreatment – monochloramine dosing

Monochloramine is a disinfectant primarily used to prevent biogrowth on the RO membranes. It is dosed upstream the MF step, so that it can also benefit from its biocide effect. At Luggage Point, monochloramine is preformed, by mixing aqueous ammonia and sodium hypochlorite. The two chemicals are mixed at a ratio of 4:1 as Cl_2:N by weight in RO permeate carrier water, before being dosed to the process. A monochloramine residual of 1.0 to 1.5 mg/l -Cl_2 at the RO feed is targeted.

Monochloramine is a weak oxidant that can potentially alter the RO membrane performance by modifying its surface properties. The residual concentration was increased from 1.5 to 3–4 mg/l-Cl_2 during several weeks. The salt rejection did not visibly deteriorate. Two RO modules were autopsied, and the Fujiwara test response was negative for both, confirming the membrane chemistry was not severely altered. Therefore if important biofouling develops in the future, more monochloramine could be dosed to control it, without damaging the RO membranes. However, the higher the monochloramine residual, the more ammonia must be added to process, and the more ammonia is discharged via the ROC. In such a configuration, the ammonia

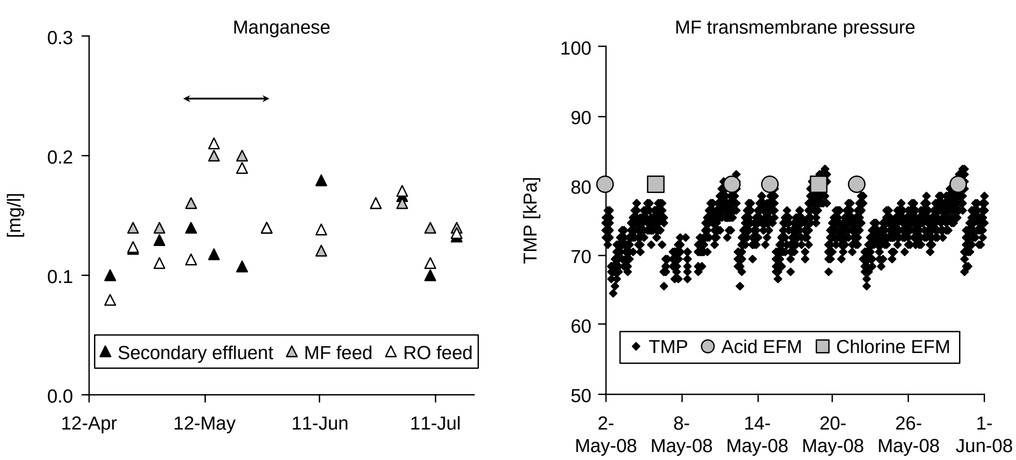

Figure 1 | Manganese residual in MF and RO feed waters (left) versus MF TMP (right).

concentration in the ROC could eventually exceed the maximum allowed in the environmental licence.

Very little NDMA (<6 ng/l at the RO feed) was formed throughout process. This can be explained by a number of positive factors, such as the addition of preformed monochloramine, the short contact time throughout the pilot plant, and the location of the dosing point, after the pretreatment, where some of the precursors may have already been removed (Farré 2009). RO permeate samples were all below the reporting limit (5 ng/l), well under the maximum concentration that the UV/AOP process is sized to treat (180 ng/l), hence a very significant operating margin for this process.

Microfiltration fouling and cleaning regimes

The microfiltration cleaning regime consisted of frequent mild cleans (Enhanced Flux Maintenance (EFM)) and less frequent, but longer and stronger Clean In Place (CIP), when the membrane performance cannot be routinely recovered with EFMs. EFMs occured every 3 days per the design, alternating a chlorine clean (500 ppm-Cl_2, 35°C) and an acid clean (0.25% citric acid, 0.5% sulfuric acid, 30°C) depending on the day. With this cleaning regime, performances remained stable throughout the trials, except during one event of ferric chloride overdose. The subsequent increase in TMP was easily recovered with two successive acid EFMs. CIP was never performed over the trialing period, since the membranes did not significantly foul. This suggested that EFMs could be either less concentrated or less frequent, to save chemical costs, generate less chemical waste, as well as reducing the time MF racks are offline during the clean. One acid EFM was performed at the ambient temperature of 19°C during the winter period. It was as efficient as a warm acid EFM. As a consequence, potential power costs could be saved and the offline time could be further reduced, thanks to shorter cleaning sequences, where the heating step is skipped.

Reverse osmosis

Antiscalant choice for TP load reduction

The antiscalant primarily selected for the pilot plant trials was a phosphonate-based formula, with a dose of 5 mg/l, which was twice more than the dose recommended by the supplier, in order to mitigate any risk of phosphate scaling. In this configuration, TP testing demonstrated that the antiscalant was contributing to half of the TP load in the ROC. This considerably narrowed the operating window for phosphorus control at the pretreatment. Indeed, the pretreatment had then to achieve a 0.3 mg/l-P target at the RO feed, prior to antiscalant addition, instead of the 0.6 mg/l-P concentration projected. A phosphorus-free antiscalant was selected in order to restore operation flexibility at the pretreatment. The antiscalant was applied at a dose of 2.5 mg/l, per the supplier recommendation, with no detrimental impact on RO scaling, hence also reducing the load of chemicals discharged to the waterways via the ROC.

Calcium phosphate scaling

Towards the end of the trials, the ferric dose was further decreased, to achieve a phosphorus residual of 2.5 mg/l-P in the RO feed. The pH was further raised from 7.0 to 7.5 by dosing sodium hydroxide at the MF feed. These operating conditions triggered rapid fouling of the RO third stage, which permeability dropped by 50% over 4 weeks only (Figure 2).

An autopsy of the tail module was then performed. SEM-EDS analysis of distinctive deposits suggested that the fouling phenomenon was a mix of calcium phosphate and calcium carbonate scales. Scaling calculations using a calcium phosphate Stability Index (Kubo *et al.* 1979) demonstrated that the RO could be operated with a phosphorus residual up to 1.5 mg/l-P provided that the pH was maintained below 6.8 (Table 2). Unfortunately, this cannot be achieved at the AWTP since no acid dosing system is provided upstream the RO process. Therefore, the phosphorus residual at the RO feed must be limited to 1 mg/l-P for now. This induced scaling event seem to indicate that the scaling calculations were more conservative than the reality, probably thanks to the good performance of the antiscalant, which has not been investigated in detail in this work.

RO flux setpoint

The full-scale plant includes three duty and one standby RO trains of 23.3 Ml/d (23,300 m^3/day), each contributing

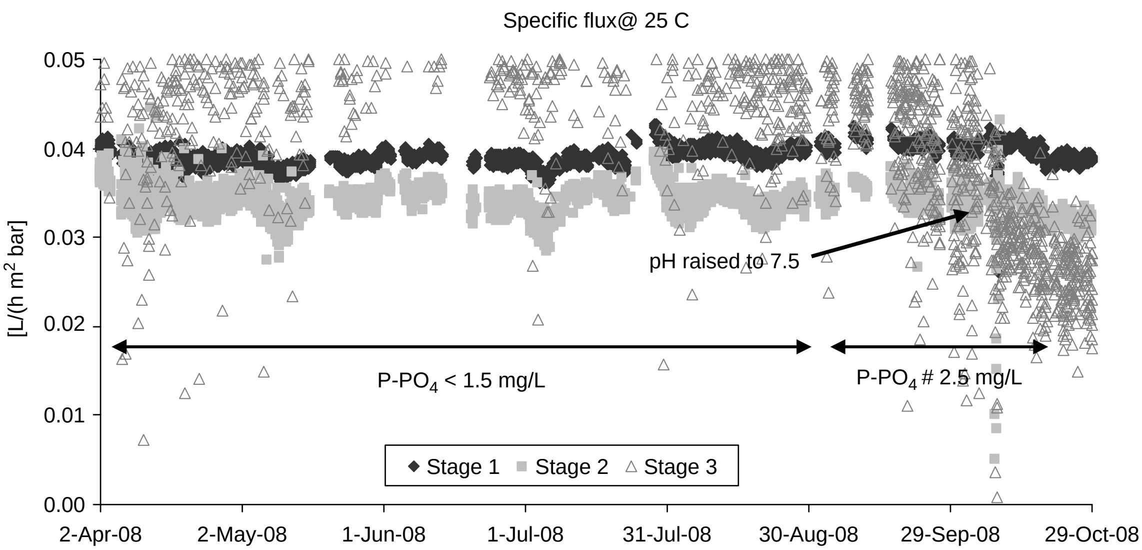

Figure 2 | RO specific flux during a scaling event.

to a third of the AWTP flow capacity. Each train can be operated within a 14.3–18.0 l/(h m^2) flux range, so that RO trains can slow down and avoid frequent starts and stops if the treated water demand is not an exact multiple of 23.3 Ml/d. However, RO rejection properties are usually poorer at lower flux. Therefore, there is a risk that the plant would not meet the total nitrogen specification for the treated water, when operating at low flux. This was confirmed during the low flux trial period, where the TN concentration was at the highest in the RO permeate (see Figure 3). This could become a serious limitation in the future, given that the nitrogen rejection is expected to decline further over the years, with increasing membrane age.

Selection of RO CIP recipes

RO CIPs were performed every 4 months as a precaution, even though the RO membranes did not appear to foul. The CIP sequence consisted of a caustic step (NaOH, pH 11, 35°C) followed by an acid step (hydrochloric acid, pH 2, 35°C). EDTA and citric acid could be used in limited amount as metal chelating agents. CIP waste is diverted to the head of the WWTP feeding the AWTP. Since EDTA is not removed by the WWTP process, it was expected to be recycled to the head of the AWTP upon discharge. EDTA can upset pretreatment performance, and lead to non- compliance issue for the treated water (maximum of 250 μg/l). Challenge tests were organised by spiking the raw water with 3 mg/l of EDTA. The EDTA concentration in the RO permeate was below the detection limit (50 μg/l), therefore complying to the treated water quality guidelines. However, further research pointed out that one should be prudent before resorting to EDTA for CIPs. Indeed, EDTA has been reported as a possible inhibitor of nitrifying bacteria (Hu *et al.* 2003), therefore potentially disrupting for the WWTP process nitrogen removal process, and further penalising the AWTP with a degraded source water quality of high nitrogen content.

Table 2 | Calcium phosphate scaling predictions, depending on phosphate and pH conditions

PO_4 RO feed (mg/l-P)	0.6	1.0			1.5	
pH RO feed	7.0	6.5	6.8	7.0	6.5	6.8
pH_c for $Ca_3(PO_4)_2$ saturation	7.49	7.14	7.14	7.14	6.90	6.90
pH_c +0.5 (antiscalant)	7.99	7.64	7.64	7.64	7.40	7.40
Projected ROC pH	7.7	7.3	7.6	7.7	7.3	7.6
$Ca_3(PO_4)_2$ scaling risk?	N	N	N	Y	N	Y

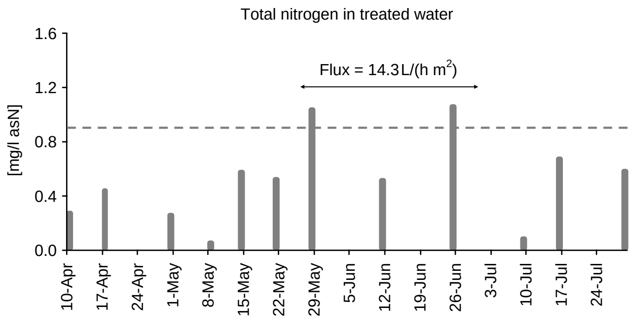

Figure 3 | Total nitrogen concentration in RO permeate, at 18.0 L/(h m^2), and 14.3 L/(h m^2).

Salinity variations

The Luggage Point WWTP is built in a wetland type, low-lying area close to the sea. Sea and rain water intrusion into the sewage pipes to the WWTP induces wide variation of salinity from 850 to 3,000 mg/l Total Dissolved Solids, and subsequent variations of operating pressure and RO permeate salinity. The actual permeate conductivity does not provide any help in RO monitoring given the scatter of the trend (Figure 4). The operation of the RO at various flux also induced changes of pressure and flow, which makes performance troubleshooting more complex. Even though not perfect given the wide range of operating conditions encountered, normalised RO performance are so essential at Luggage Point, that the normalised parameters are all calculated real time in the SCADA system, and accessible to the operators via trends.

Process long-term performances

Microfiltration

Over a year of operation, only one broken fibre was detected, amongst the 5 × 500 ones contained in the five modules, which is considerably low.

Reverse osmosis

The RO showed no sign of rapid/irreversible fouling provided a CIP was performed every 4 months of operation, and that pH and phosphorus were adequately controlled in the RO feed. The above convinced the operating team of the robustness of the AWTP process design.

HACCP setpoints for full-scale validation

The operation set-up plan included the early implementation of the HACCP risk management system. Operating experience from the demonstration plant enabled the selection of realistic Critical Control Points monitoring parameters and setpoints, prior to commissioning of the full-scale plant (Table 3). This gave the opportunity to include the response procedures in the full-scale plant control system functionality. Having the responses procedures as automated actions undertaken by the control system give a great degree of robustness to the HACCP system.

The demonstration MF unit included an automated pressure decay test system identical to the full-scale plant

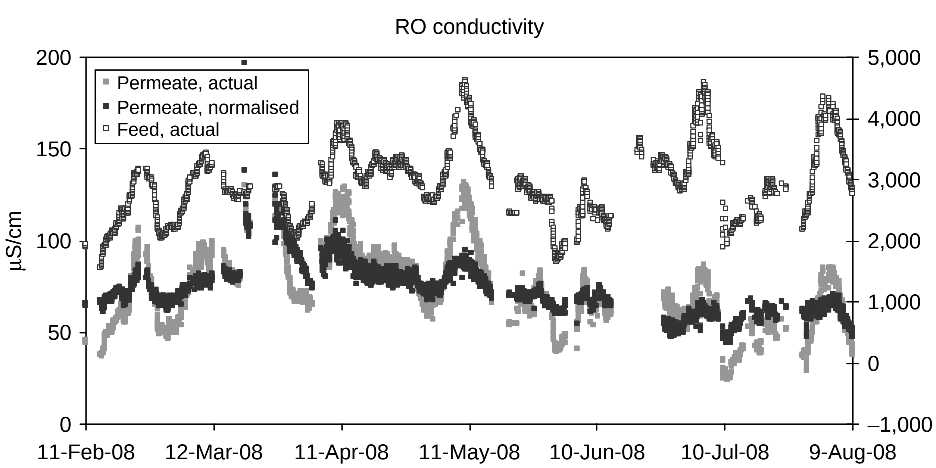

Figure 4 | Conductivity trends over the trial period: RO feed, RO permeate (actual, and normalised).

Table 3 | CCP alert and critical limit setpoints derived from experienced at the pilot plant

Parameter	Raw water ammonia concentration	MF pressure Decay Test	RO conductivity log removal
Alert limit	>1 mg/l-N for >4 h	> 10 kPa/5 min	≤1.2
Critical limit	>2 mg/l-N for >4 h	> 13 kPa/5 min	≤1.0

system. Hence, it was possible to demonstrate that the MF could achieve the 4 log removal projected for the full-scale plant. It also provided some guidance for the HACCP triggers and response procedures, in order to manage MF integrity with the particular Pall system.

The RO was primarily credited with 1 log removal for virus, and conductivity was used as a surrogate to verify it. Given the dramatic and rapid fluctuations of salinity in Luggage Point source water, a specific parameter has been developed to monitor the RO performance and integrity. The conductivity log removal achieved by the RO was selected as the main parameter, in order to take the variations of feed conductivity into account. It is calculated in real time by the SCADA system.

Operators process training

Most of the demonstration plant processes had to be manually adjusted by the operators. Doing so, the operators developed the process understanding required to operate the full-scale plant, prior to its commissioning, and more generally familiarised themselves with all operations aspects, from chemical hazards to records management, according to Veolia Water Australia Integrated Business Management System (IBMS).

CONCLUSIONS

The demonstration plant helped identifying the operating window of the full-scale AWTP.

The pretreatment operating boundaries were partly process-driven, seeking the limitation of fouling risks onto the membranes process. Indeed, the ferric chloride dose adjustment takes into account phosphate scaling and organic fouling potential. Similarly, monochloramine dose selection is a balance between the limitation of biogrowth on the RO membranes, and the possible detrimental alterations of the membrane chemistry and rejection properties if the dose is too high.

The trials highlighted that a significant number of boundaries were set by environmental constraints. This includes the introduction of ammonia in the process to generate monochloramine, as well as the selection of CIP chemicals and antiscalant. The ferric chloride dose range was also mostly driven by the phosphorus load discharge requirements to the waterways, though the environmental footprint of the AWTP itself was identified as another levier.

Finally, the scope of the trials was larger than expected, with significant contributions in non-process related area, such as HACCP, possible costs reduction, global environmental footprint and training of the operators, prior to stepping into the commissioning of the full-scale AWTP.

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