OPTIMISATION OF MEMBRANE BIOREACTOR NUTRIENT REMOVAL PERFORMANCE – SOME PRACTICAL EXAMPLES

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ABSTRACT

Membrane Bioreactors (MBR), are of increased interest in New Zealand, driven largely by tighter effluent consent requirements and greater reuse potential of treated effluent. In Australia, MBR has a more extensive track record and history of application; some recent experiences are presented in this paper.

Experiences and outcomes at Goodna Sewage Treatment Plant (GSTP) and Sarina Water Recycling Facility (SWRF) and provided, with the implementation of:

- Ammonia based aeration control (ABAC) utilising on-line ammonia analysers,
- Ortho-phosphate analyser based dosing control of aluminium chlorohydrate (ACH) and alum dosing, and,
- Enhanced Biological Phosphorous Removal (EBPR) optimisation measures relative to advanced analyser based controls

The Broadspectrum Jacobs JV (Formally Transfield / SKM) delivered the 8,000EP Sarina Water Reclamation Facility (SWRF) in 2015. A 5 Stage Bardenpho configuration incorporating a Membrane Bioreactor (MBR) was selected to meet TN 5, TP 1 and NH3 0.5 criteria.

The 90,000EP Goodna STP was delivered by Thiess and Jacobs (formally SKM) in 2012. This benchmark facility is designed to achieve stringent TN and TP discharge criteria of 3mg/L and 1mg/L respectively. The process configuration integrates an MBR and oxidation ditch within an overall 7 stage BNR and EBPR process.

At both facilities, permeate ammonia and ortho-phosphate concentration is measured by online wet chemistry analysers on a continuous basis and can be used for advanced nutrient removal process control, providing enhanced nutrient removal performance and compliance reliability, and reduced energy and chemical operational costs.

The ABAC is achieved through controlling aeration supply and distribution to the bioreactor relative to measured permeate ammonia concentration and the desired ammonia setpoint. The control philosophy adopts an ammonia controller function which trims the target reactor dissolved oxygen (DO) concentration, and provides protection against analyser failure or incorrect measurement which could result in sub optimal aeration control responses. The resulting control can be optimised in terms of analyser confidence and efficiency gain by the Operator or Engineer. The control has been shown to reduce energy consumption and improve performance and reliability accordingly.

The process design compensates transient EBPR performance associated with catchment and environmental impacts using supplementary chemical phosphorous removal, specifically Alum dosing at GSTP, and ACH dosing at SWRF. An online ortho-phosphate analyser is used to optimise phosphorous removal and EBPR performance, and reduce chemical dosing dependency and costs. Significant reductions in chemical dosing requirements were achieved, as well as a slight reduction in biosolids generation through reduced precipitated solids production.

Control philosophies and improvements in process performance and savings are presented. Lessons learned in controller set up and operational implications and requirements are also provided. These advanced control methodologies may be applied to larger scale facilities to provide substantial cost savings and improved performance reliability. At GSTP, routine sampling shows the plant consistently achieves effluent TP <1.0 mgP/L, ammonia <0.1 mgN/L, and TN <2.5 mgN/L. Control philosophies and improvements in process performance and savings are presented.

KEYWORDS

MBR, Nutrient Removal, EBPR, Advanced Process Control, ABAC

PRESENTER PROFILE

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Damien has specialist experience in wastewater treatment engineering and has lead process design, planning and the application of advanced technologies in Australia, New Zealand, the UK and the Middle East.

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1 INTRODUCTION

MBR emerged at full scale facilities in the early 90s and for the first decade of application saw substantial improvements to the quality and performance of the membrane equipment, but also improvements in its integration into the activated sludge process.

As a means to enter the market the MBR technology was touted to provide reduced footprint and improved effluent quality, ideal for recycled water applications. Whilst this is largely true, the effort to maximise footprint reduction and reduce cost saw the development of inefficient process designs, resulting in the technology being associated with high energy usage, unreliable nutrient removal performance and high mechanical and chemical maintenance requirements. The initial design approaches typically adopted high bioreactor mixed liquor concentrations, in some cases up to 12,000mg/L, limited only by the membrane solids flux allowances. This was an effort to reduce bioreactor size and hence capital cost relative to conventional processes. While this reduced capital costs, it substantially increased energy consumption due to poor aeration efficiency (high alpha at high MLSS) and also high internal recirculation pumping to reduce the difference in MLSS concentration between the bioreactor and MBR tank. Another impact of this design approach was a substantially reduced bioreactor hydraulic retention time (HRT) compared to conventional activated sludge and clarifier systems, from over 24hrs down to 12 hours or less. This resulted in reduced diurnal load buffering, causing susceptibility to nutrient breakthrough, in particular ammonia. It was also found that enhanced biological phosphorous removal (EBPR) was difficult to achieve reliably, compounded by short anaerobic zone HRT and high dissolved oxygen return in the RAS. Further challenges arose in applications of low sludge age, carbonaceous removal only reactors, suffering increased fouling potential due to oil and grease, colloidal and EPS material.

Through the above lessons learned and new generation design refinements it is now accepted that MBR is a very high performance, robust and efficient activated sludge nutrient removal technology. The technology is highly competitive with other conventional technologies and is well suited as a component of recycled water production and can be applied cost effectively from small scale to very large facilities. A practical approach to design to avoid the issues discussed has been to consider the most cost effective lifecycle design basis. This considers the most efficient combination of screening requirements, optimal MLSS for aeration efficiency and resulting reactor volume and HRT, the adoption of MBR air scour requirements as a functional aerobic reactor fraction, and design internal recirculation rates for efficient nitrate return rather than achieving diminishing returns at higher rates. The result of these considerations, in the context of processes able to achieve nutrient removal requirements typical to Australia and New Zealand, are fully integrated MBR systems characterised by moderate sludge ages and MLSS (10-20 days, 5000-6000mg/L), and moderate RAS rates (1.5 – 2x ADWF). This design philosophy was applied at the Cairns Northern (100,000EP) and Southern (90,000EP) MBR facilities in the mid 2000s, highlighting to the industry that MBR was a high performance, robust and cost effective treatment solution.

More recent MBR facility designs adopted further refinements, targeting greater efficiency, higher performance nutrient removal, improved control and operational simplicity and further cost reductions. In 2012 the first comparison of MBR facilities energy consumption with conventional activated sludge facilities was presented for Australian examples (Sharland, 2012). This set the benchmark and softened the reputation of MBR being a high energy treatment process. Since then recent MBR facilities, including Goodna STP and Sarina WFR, are included and shown below in Figure 1.

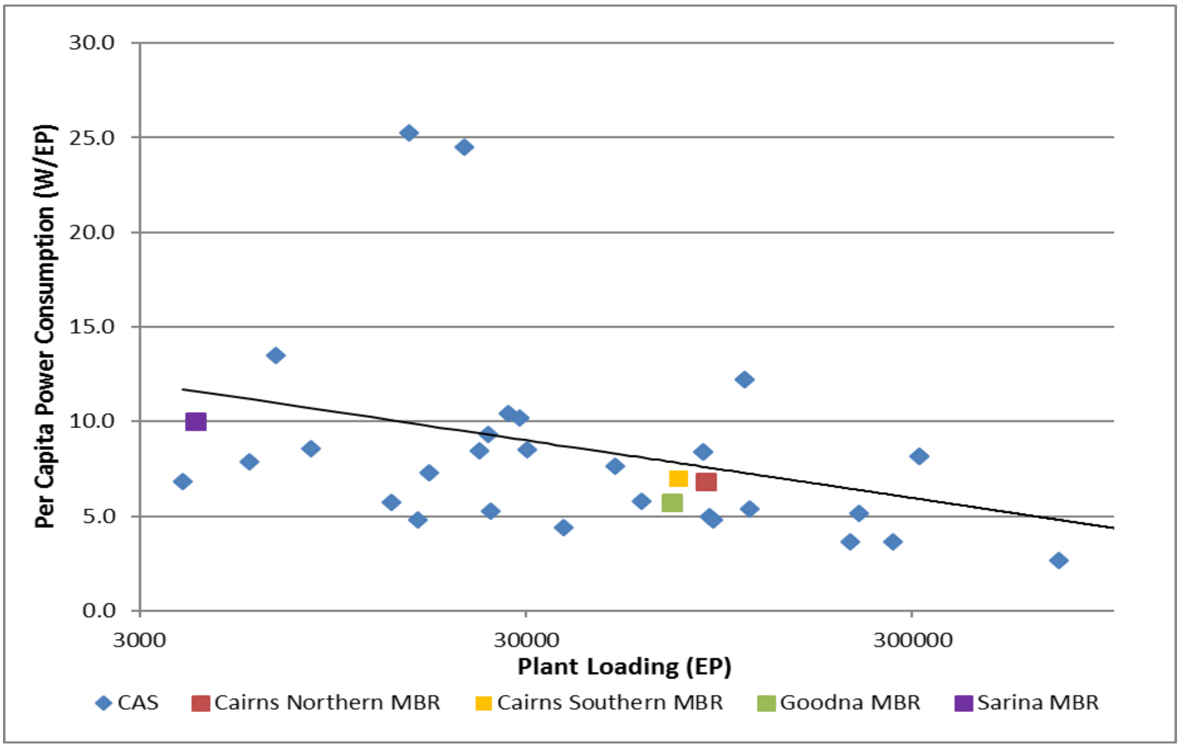

Figure 1. MBR vs Conventional Activated Sludge Power Demand per Equivalent Person Load

We consider the design refinements at the two example facilities, Goodna STP (2012) and Sarina WRF (2015).

The Goodna STP adopts a novel 7 stage BNR MBR configuration to achieve stringent discharge criteria of TN 2.5mg/L and TP 0.8mg/L under relatively poor influent C:N ratios of ≈8:1. The process adopts a fully integrated MBR system with variable reactor depth for diurnal load buffering, and highly advanced aeration control for tight control of SND conditions to maximum endogenous COD utilisation and to minimise aeration demand and supplementary COD and Alum dosing requirements.

Figure 2. Goodna STP MBR, 90,000EP, Brisbane Australia.

The Sarina WRF comprises a 5 stage Bardenpho reactor with fully integrated MBR. The Bioreactor, MBR and an Aerobic Digester are comprised in a single structure to minimise footprint and required construction materials. The facility is required to meet tight effluent quality targets for recycled water provision, and surplus discharges to the sensitive Great Barrier Reef Marine Park.

Figure 3. Sarina WRF MBR, 8,000EP, Sarina, Australia.

Advanced process controls are applied at both of these facilities include:

- Ammonia based aeration control (ABAC) utilising on-line ammonia analysers,
- Ortho-phosphate analyser based dosing control of aluminium chlorohydrate (ACH) and alum dosing, and,
- Enhanced Biological Phosphorous Removal (EBPR) optimisation measures relative to advanced analyser based controls

Operation of both the Goodna STP and Sarina WRF began in July 2012, and January 2015 respectively, and optimisation of the analyser based controls has been undertaken in line with continues improvements strategies. Outcomes of this and also optimisation of wet weather flow management are further presented below.

2 MBR NUTRIENT REMOVAL PERFORMANCE OPTIMISATION

Nutrient removal and operational performance optimisation for the two example MBRs has been aided by the use of advanced process controls, including ABAC and OP analyser based dosing control. Further discussion is provided on phosphorous removal optimisation during commissioning and wet weather events.

2.1 OPTIMISATION OF AMMONIA REMOVAL THROUGH ADVANCED CONTROLS

ABAC is not a new control methodology, however it has had a resurging interest in light of improved analyser reliability, increased energy minimisation drivers, and also perhaps most importantly, its part in the successful control or short cut nitrogen removal processes.

The ABAC functionality was included in the design for Goodna STP and Sarina WRF for the purposes of primarily, nitrogen removal reliability, and secondarily, energy minimisation associated with bioreactor aeration.

ABAC controls aeration supply and distribution to the bioreactor relative to measured bioreactor or permeate ammonia concentration and a desired ammonia setpoint. The control philosophy adopts an ammonia controller function which trims the target bioreactor dissolved oxygen (DO) concentration, and provides protection against analyser failure or incorrect measurement which could result in sub optimal aeration control responses (Figure 4). The resulting control can be optimised in terms of analyser confidence and efficiency gain by the Operator or Engineer. The control has been shown to reduce energy consumption and improve performance and reliability accordingly.

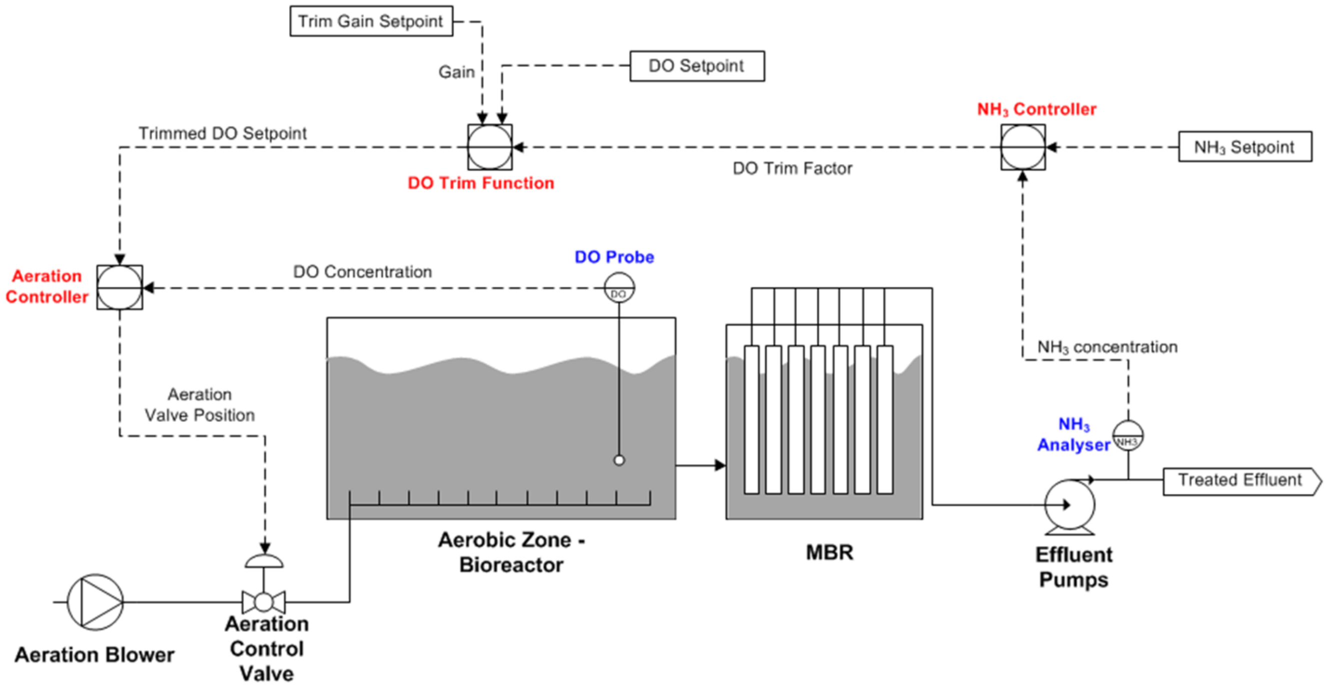

Figure 4. Ammonia Based Aeration Control (ABAC) Schematic

The result of applying ABAC at Goodna STP is represented by the processes robust nutrient removal performance under SND process conditions since commissioning and also its benchmark energy consumption as referred previously. Figure 5 shows the historic effluent total nitrogen and ammonia concentrations and associated aeration energy consumption under ABAC operation.

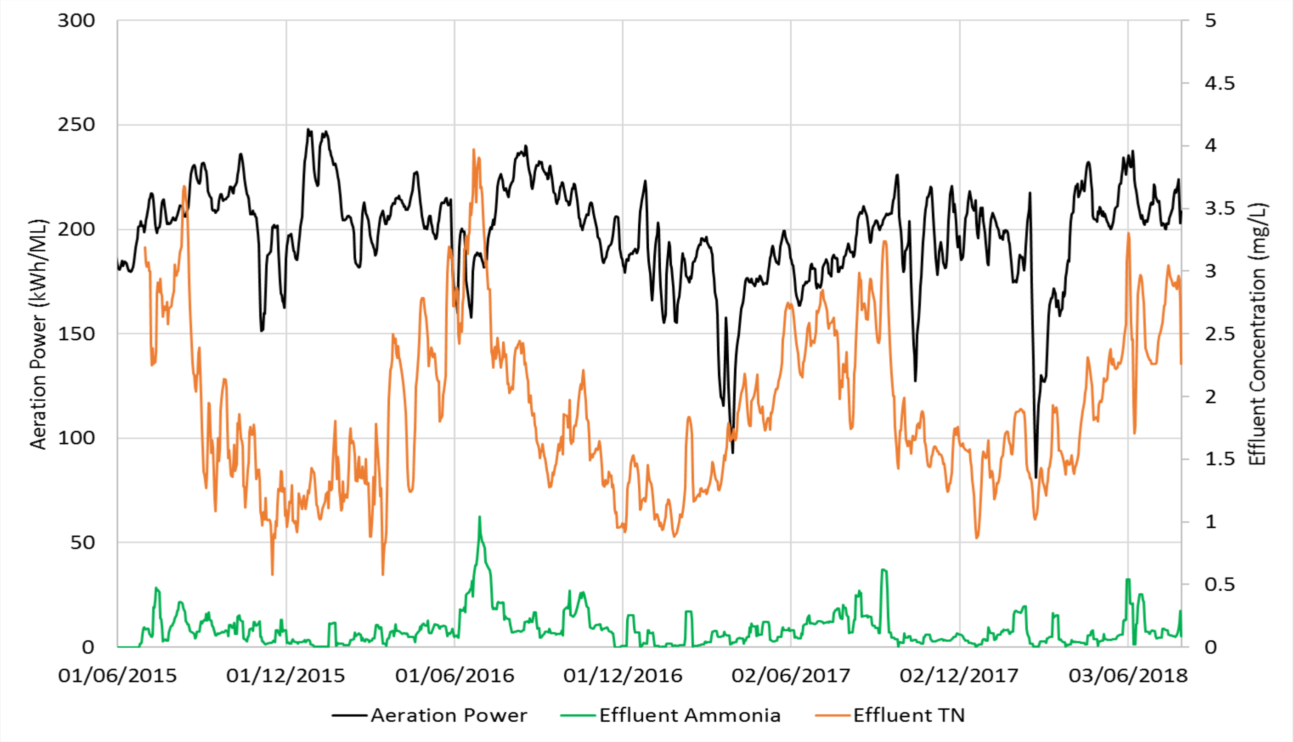

Figure 5. Goodna STP Historical Effluent Nitrogen Performance under ABAC Operation.

The historical performance shows ease of compliance with the Licence conditions for effluent total nitrogen of 3.0mg/L annual median and ammonia of 1.0mg/L annual median. Further, some minor improvement in aeration energy efficiency can be observed from 2017 as a result of control setting refinements.

At Sarina WRF the application of ABAC in years since commissioning was hampered by ammonia analyser failure. Rectification of the analyser failure in late 2017, and re-initiation of ABAC resulted in a measurable improvement in energy efficiency. Table 6 shows the average annual power consumption per day for each year, 2014 to 2017 under DO aeration control only, and then 2018 under ABAC control.

Year	Aeration Control	Power (kWh/d)	Load (EP)	Efficiency (W/EP)
2014	DO	1253	3900	13.4
2015	DO	1278	3900	13.7
2016	DO	1259	4000	13.1
2017	DO	1230	4100	12.5
2018	ABAC	1012	4200	10.0

Table 6. Sarina WRF Annual Average Daily Power Consumption under DO Control and ABAC.

Earlier efforts to implement ABAC at Sarina, although hampered by ammonia analyser reliability, measured an improved effluent total nitrogen concentration. Figure 7 shows a modest 11% improvement in effluent total nitrogen upon implementing ABAC 'trim' control, improving process performance robustness and Licence compliance.

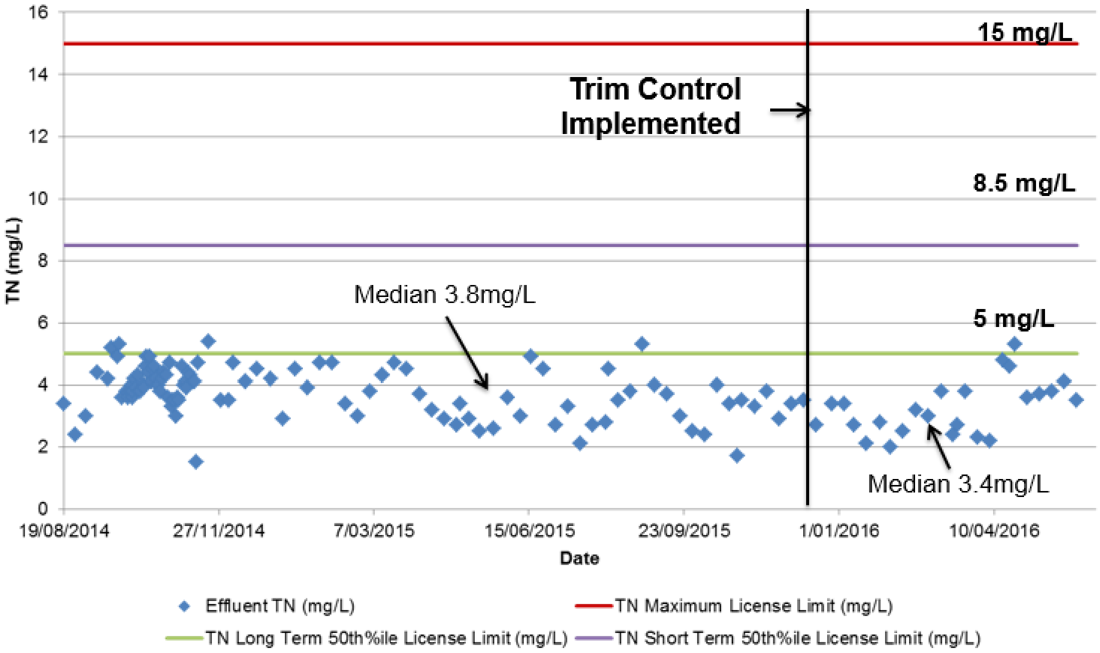

Figure 7. Improved Effluent Total Nitrogen under ABAC 'Trim' Control.

These examples demonstrate the substantial value of applying ABAC at high performance facilities, and in particular MBR installations, to reduce energy consumption and increase performance reliability.

2.2 OPTIMISATION OF PHOSPHOROUS REMOVAL THROUGH ADVANCED CONTROLS

Enhanced biological phosphorous removal (EBPR) has historically been challenging to achieve in MBR systems due to low reactor zone HRTs and also high return DO potential in the RAS stream. Design refinements have largely improved EBPR performance and reliability, however when targeting low effluent TP criteria, supplementary chemical phosphorous removal is also necessary.

Under supplementary chemical phosphorous removal, a metal salt such as Alum is dosed to meet the shortfall in phosphorous removal between EBPR capacity and the target effluent phosphorous. The shortfall is however variable, and significantly impacted by influent and environmental conditions, such as wet weather.

Operation of the facility relies on Operator skill and experience to determine the required chemical supplementation dose rate to prevent chemical wastage, but also to prevent out competing of the EBPR process, which can lead to a full chemical phosphorous removal process condition. Experience shows that inevitably the process tends to move between efficient EBPR condition and a full chemical phosphorous removal condition, resulting in high chemical costs and variable effluent phosphorous performance.

The application of advanced controls such as OP analyser based chemical dosing control greatly improves EBPR efficiency and reliability and reduced chemicals consumption. This control greatly aids the Operator, removing the 'crystal ball' approach to dosing rate selection. A simple schematic shows the advanced dosing control in Figure 8.

Both short term and long term success of the advanced control can be easily demonstrated. At Sarina in 2018, the advanced control settings were optimised after demonstrated confidence was achieved in the reliability of the OP Analyser. The impact of the control was assessed by trialing operation before and after adoption of the advanced control.

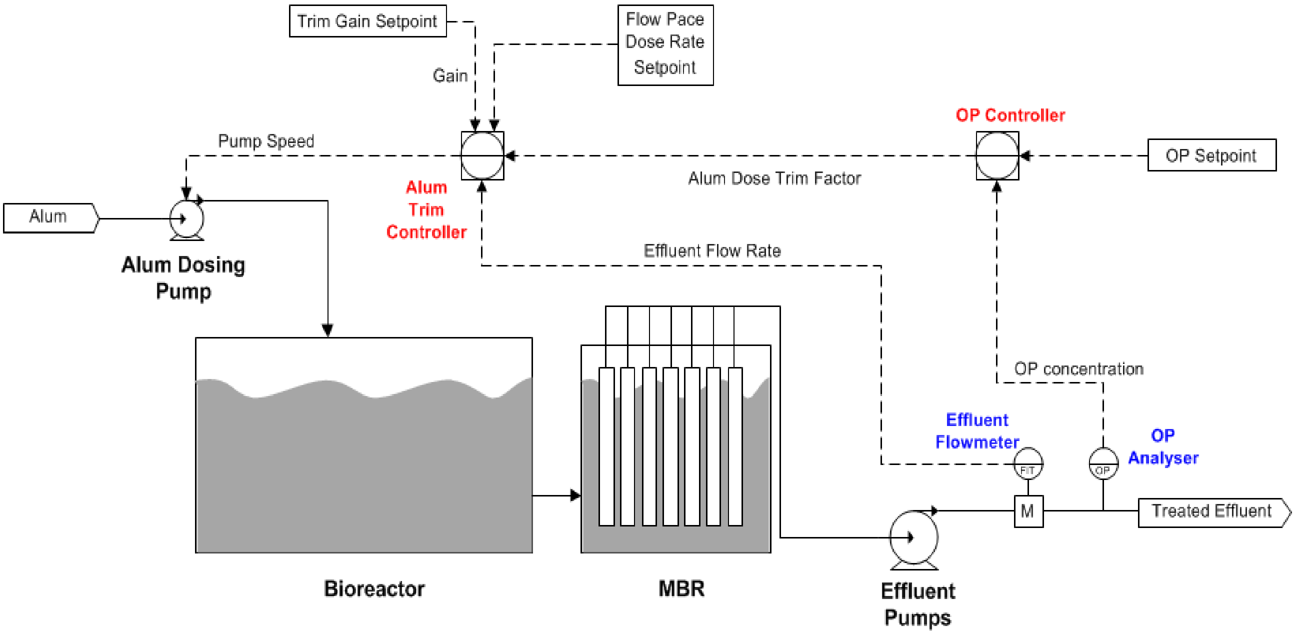

Figure 8. OP Analyser Based ACH/Alum Dosing Control Schematic

Average effluent phosphorous values increased from 0.28 mg/L to 0.45 mg/L, based on a selected setpoint OP of 0.5mg/L to safely achieve the effluent Licence criteria of 1.0mg/L. This demonstrates improved control to meet the Licence requirement more efficiently without overshooting. As an outcome of the improved control, ACH dosing rates were reduced from 59.3L/d to 34.6L/d, and regarded as a highly successful outcome. Figure 9 shows the effluent OP trend and ACH dosing rates during the trial period.

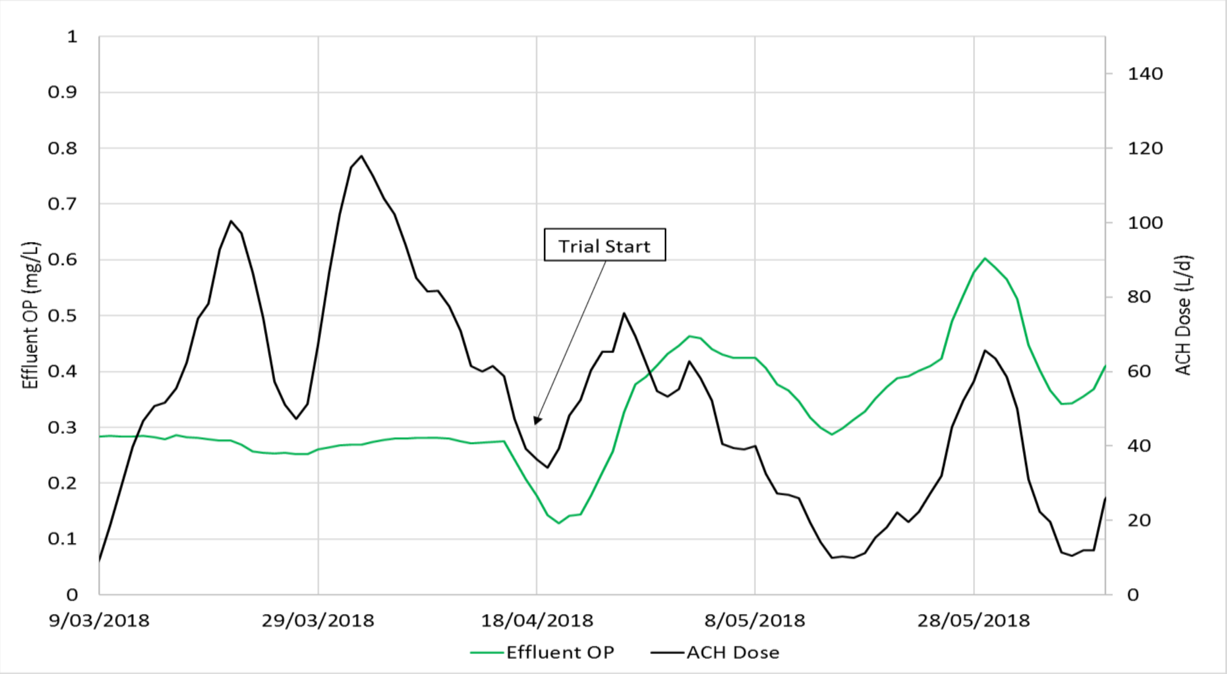

Figure 9. Sarina Advanced Controls Trial: Effluent OP vs ACH Dosing

Longer term success of the implementation of the OP Analyser based dosing control is also demonstrated at the Goodna facility. Over the years since commissioning, the control settings have been fine-tuned as greater confidence in the analyser and control response is achieved.

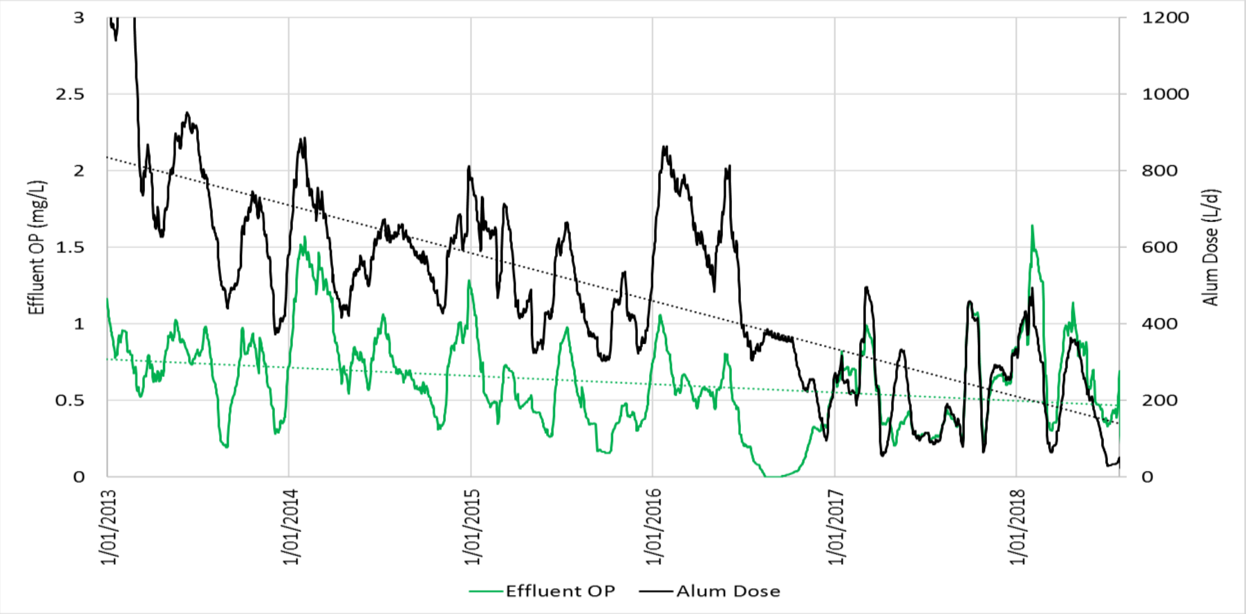

Figure 10. Goodna STP OP Analyser Based Control Performance Since Commissioning: Effluent OP vs Alum dose.

Figure 10 shows the reliability of the advanced control of EBPR and supplementary Alum dosing to meet the Licence TP 1.0mg/L requirement. It also shows the gradual reduction of Alum dosing, whilst not impacting the effluent OP result. The outcome both provides significant alum chemical cost savings, and also increased performance reliability.

2.3 PHOSPHOROUS REMOVAL DESIGN FOR WET WEATHER RESILIENCE

At Goodna STP, immediately after commissioning in November 2012, the process suffered reduced biological phosphorous removal performance after moderate and significant wet weather events (Figure 11). Prior to the wet weather conditions, effluent phosphorous concentrations were well below 1mgP/L and only minor supplementary alum dosing was required. In response it was necessary to increase the supplementary alum dosing to lower effluent phosphorous concentrations below the License maxima of 3mgP/L and long term median of 1 mgP/L.

The onset of wet weather in early November and upon a significant wet weather event on the 18th November 2012 saw a significant increase in effluent orthophosphate (OP). It was observed that the reduced EBPR performance occurred ≈1 day after the 'first flush' and persisted for another 3 to 4 days. This observation is similar to those by Okada et al. (1992), who reported that prolonged disturbances may lead to recovery times of over 4 weeks.

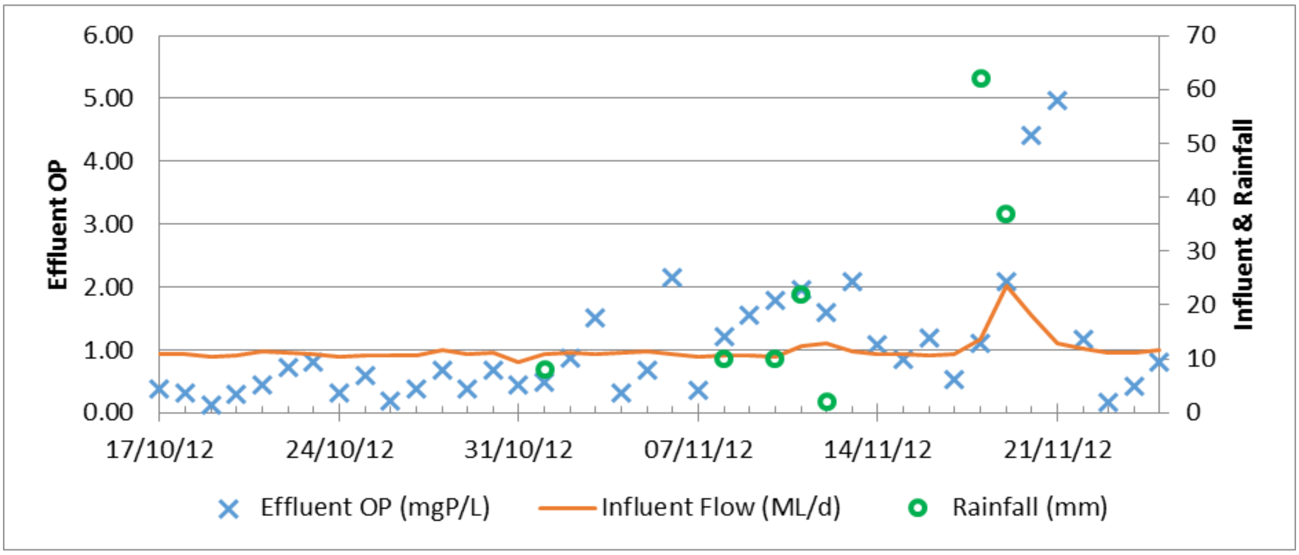

Figure 11. Effluent OP Exceedance During Wet Weather Events

Analysis of reactor conditions during and after the event identified the follow possible reasons for the reduced phosphorous removal:

- High 'slug' nutrient loading at the start of the wet weather event,
- High dissolved oxygen and/or nitrate RAS concentration, impacting anaerobic zone function,
- Reduced Anaerobic Zone hydraulic retention time, impacting VFA extent,

- Reduced volatile fatty acid (VFA) concentrations during and after the wet weather event, reducing substrate availability for PAOs and EBPR,
- Reduced sewage temperature and high dissolved oxygen concentration, reducing reaction rate and inhibiting anaerobic reactions
- Insufficient alum dosing control response to meet the short fall in EBPR

In response to these potential causes, efforts were initiated to recover EBPR performance as quickly as possible. The sludge age was reduced from 16 to 13 days to increase the removal of phosphorous from the system. A portion of sewage feed to the RAS Deaeration zone for RAS denitrification was directed to Anaerobic Zone 1 to maximise RAS Deaeration and minimise DO carry over. RAS nitrate was also further reduced to between 0.1 and 0.5 mg/L by reducing the Oxidation Ditch DO setpoints at the compensation of slightly higher effluent ammonia.

Upon implementation of these changes, EBPR performance recovered well and the reactor was reconfigured to normal, as shown in Figure 12 by OP release and uptake across the Bioreactor profile.

The actions taken and recovery of EBPR demonstrate the value in providing for a flexible anaerobic zone arrangement which can allow for adjustment to RAS Deaeration extent and location of sewage feed to optmise EBPR.

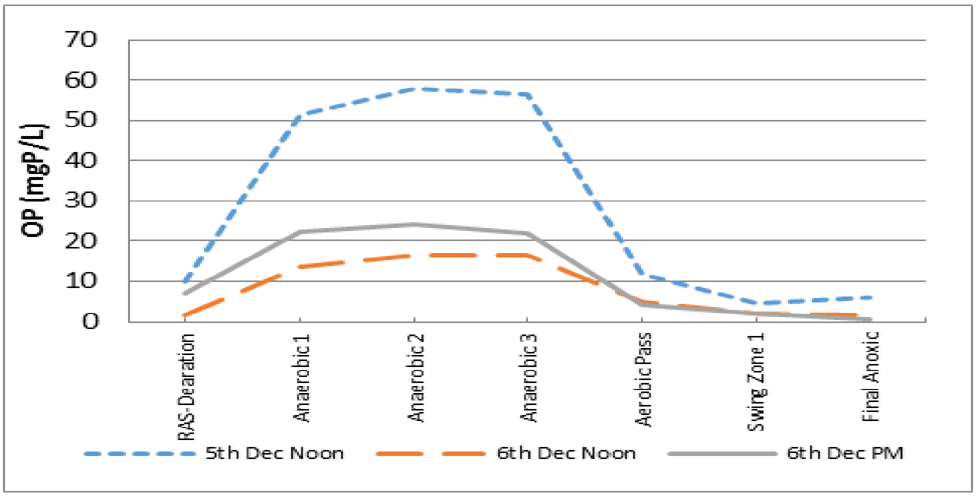

Figure 12. EBPR Recovery after Wet Weather Event

However, it is noted that EPBR will not always be viable, subject to the environmental conditions in the catchment, and additional design allowances are necessary for robust effluent phosphorous compliance. These conditions include sewage characteristics, temperature, VFA concentration and sewage dissolved oxygen. As these parameters cannot be manipulated, it is prudent to understand variations during wet weather flows and how this may impact EBPR and the necessity for chemical phosphorous removal supplementation strategies.

Longer term analysis of sewage VFA (acetate) was considered. Acetate is an important VFA substrate for PAOs and well performing EBPR. Influent phosphorous was observed to be relatively constant, with expected dilution during high wet weather flows. Influent acetate however was observed to reduce significantly by comparison (Figure 13).

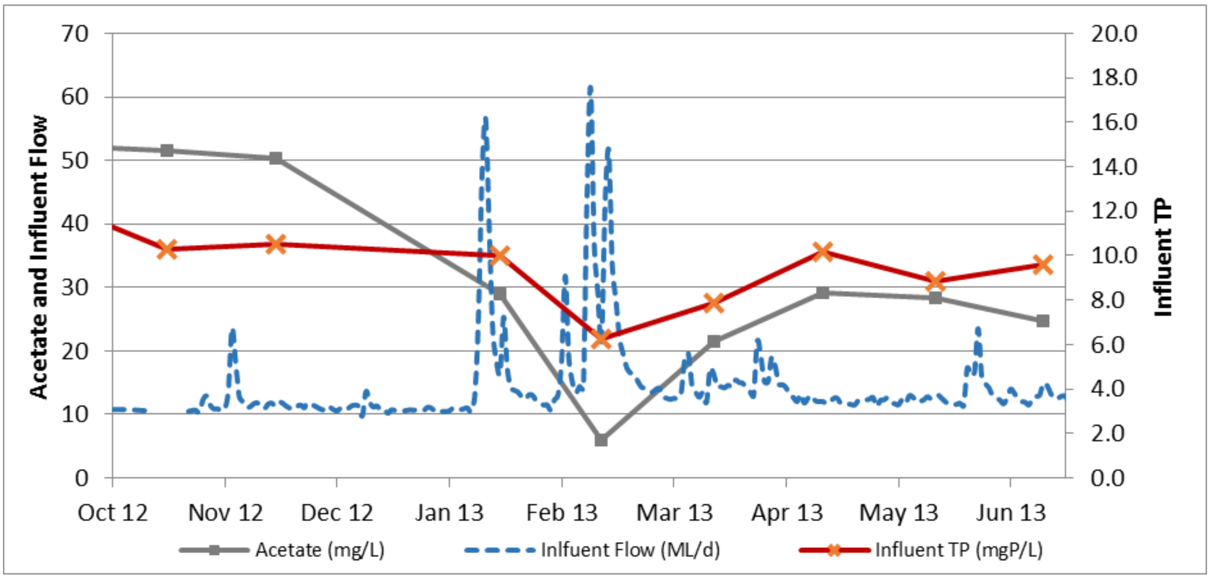

Figure 13. Variation in Influent TP and VFA as Acetate During Wet Weather Conditions

EBPR requires 7–9 mg of VFA to remove 1 mg of phosphorous (Barnard, 1993), or a ratio of acetate:OP of 7-9. The sewage acetate:OP ratio was plotted with rainfall and influent flow (Figure 14).

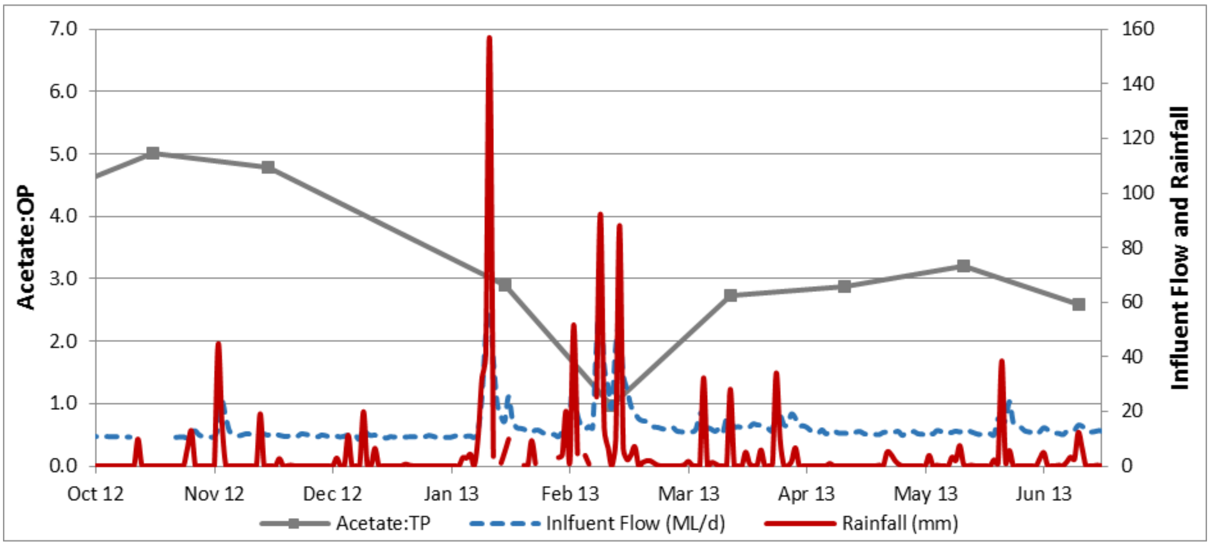

Figure 14. Wet Weather and Seasonal Impacts to Sewage Acetate:TP Ratio

The analysis indicated that the acetate:OP ratio was below 5 overall, and significantly reduced during wet weather when compared to dry weather conditions. The trend also showed that the ratio lowered with decreasing wastewater temperatures during the cooler months. This observation provides reasoning behind reduced EBPR performance, where less sewage VFA is present due to reduced fermentation in the sewer caused by reduced hydraulic residence time during wet weather and also lower wastewater temperatures. Furthermore sustained decreased EBPR performance after wet weather events may be due to ‘flushing’ of fermenting organisms responsible for VFA production.

This observation is consistent with those by Brdjanovic et al., (1998) who noted that the biological phosphorous removal process is sensitive to disturbances, such as dilution of the wastewater, e.g. in times of heavy rainfall.

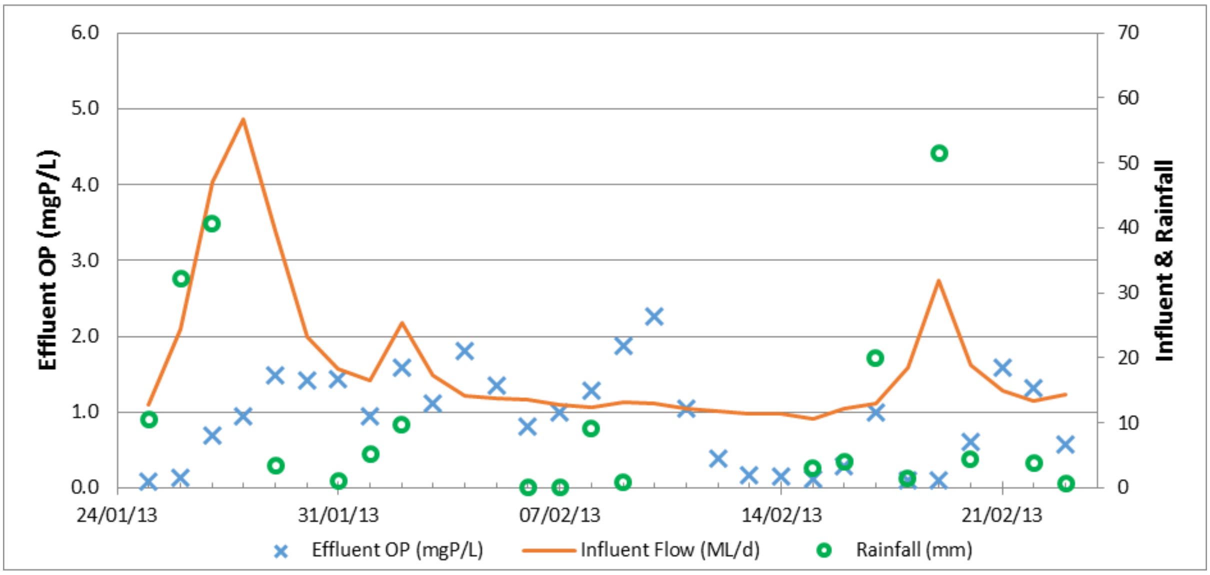

Figure 15. Optimised Alum Dosing for Improved Wet Weather Effluent Phosphorous

Subsequently, to meet effluent phosphorous concentration targets, supplementary alum dosing for chemical phosphorous removal was optimised for wet weather conditions and immediately after. Flow paced alum dosing control was optimised with trim dosing proportional to the measured effluent OP concentration, as measured by an online analyser. TP concentrations were substantially reduced in January and February during wet weather events, with concentrations below the License maxima of 3mgP/L (Figure 15).

2.4 MBR TRAIN PHOSPHOROUS RELEASE ELIMINATION

Ongoing process investigation identified significant effluent OP concentration spikes during commissioning. The spikes were 10 fold the average effluent OP concentration and identified to be the cause of increased daily composite effluent phosphorous concentration results (Figure 16). This posed a threat to meeting the license criteria of 1mgP/L, hence rectification was necessary.

Review of the MBR system operation revealed the occurrence of secondary phosphorous release in standby MBR trains. The spikes were shown to correspond with initiation of trains that had been in standby mode for extended durations, even when aerated periodically. As the standby train was brought online, permeate produced contained very high soluble phosphorous concentrations.

To eliminate these soluble phosphorous spikes, control adjustments to MBR train standby operation was implemented, including increasing the train flushing frequency and simultaneous aeration of trains in duplicate. Also a longer MBR train initiation flush was allowed. These changes reduced the residence time and doubled the aeration cycle frequency of standby trains, successfully eliminating the occurrence of standby phosphorous solublisation events.

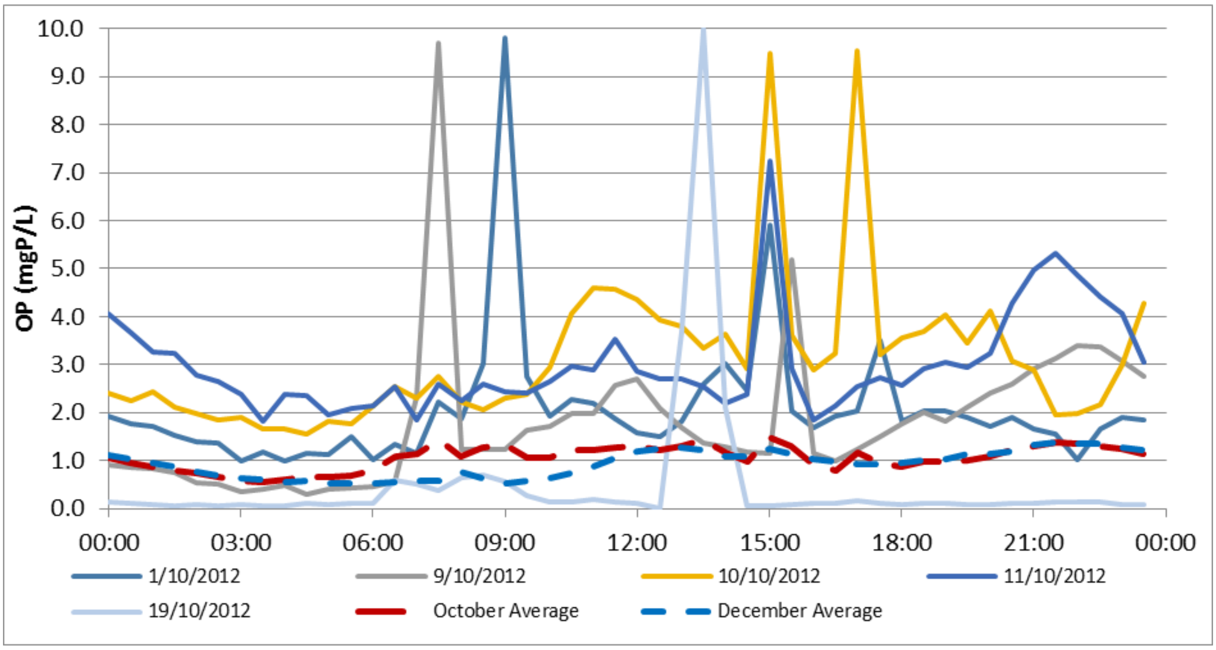

Figure 16. Diurnal Effluent OP Trends Showing MBR OP Solublisation Spikes (October) and Rectification (November).

3 CONCLUSIONS

Examples of optimisation of MBR nutrient removal performance have been provided based on Goodna STP and Sarina WRF facilities.

The use of advanced controls including ABAC and OP analyser based dosing controls are shown to provide energy and chemical cost reductions respectively and also improved total nitrogen and total phosphorous compliance reliability. The success of the implementation of these advanced controls indicates substantial value can be achieved by utilities and operators when configured correctly and optimally, and also when continually optimised over time.

Further examples of process optimisation has been provided for phosphorous removal performance in MBR systems under wet weather conditions and also phosphorous solublisation events in standby MBR trains.

In summary, the control and design strategies presented represent important and practical design refinements that have resulted in MBRs acquiring a reputation in the region for achieving benchmark nutrient removal performance and highly reliable operation whilst maximising energy and chemical operating cost efficiency.

It is anticipated that these lessons learned and design refinements for MBRs can be adopted and further refined in new facilities throughout the ANZ region for the betterment of the community and the environment.

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