# Full-scale experience with the membrane bioreactor-reverse osmosis water reclamation process

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## ABSTRACT

The Gippsland Water Factory (GWF), owned and operated by Gippsland Water in south eastern Australia, is a 35,000 $m^3$/day water reclamation facility which treats 16,000 $m^3$/day of domestic wastewater and 19,000 $m^3$/day of industrial (pulp and paper) wastewater through parallel membrane-bioreactor (MBR)-based treatment trains prior to discharge to the Pacific Ocean via the Regional Outfall Sewer. A portion of the domestic train MBR effluent is further treated through a chloramination and reverse osmosis (RO) system for reclamation, as needed to augment the regional water supply, and is supplied to Australia Paper, the source of the industrial wastewater treated at the GWF. While use of the MBR/RO combination for water reclamation is expected to provide advantages, little full-scale experience exists. Consequently, this paper reports operational and performance results for the first four years of operation for the MBR/RO water reclamation train. Details are provided, not only on process performance, but also on the resolution of equipment and plant performance issues along with ongoing plant optimization. On the basis of these operating results, it is concluded that the combination of MBR and RO is a reliable and robust option for producing high-quality reclaimed water from municipal wastewater.

**Key words** | Gippsland, membrane bioreactor (MBR), reclaimed water, reverse osmosis (RO), water reuse

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## INTRODUCTION

The Gippsland Water Factory (GWF), owned and operated by Gippsland Water (GW) in south eastern Australia, is a 35,000 $m^3$/day water reclamation facility which treats 16,000 $m^3$/day of domestic wastewater and 19,000 $m^3$/day of industrial (pulp and paper) wastewater through parallel membrane-bioreactor (MBR)-based treatment trains prior to discharge to the Pacific Ocean via the Regional Outfall Sewer (ROS). A portion of the domestic train MBR effluent is further treated for reclamation, as needed to augment the regional water supply, and is supplied to Australia Paper, the source of the industrial wastewater treated at the GWF. As illustrated in Figure 1, domestic wastewater treatment consists of headworks (screening and grit removal), primary treatment in an activated primary clarifier, membrane bioreactor (MBR), followed by chloramination and reverse osmosis (RO). Industrial wastewater treatment consists of pre-treatment in covered anaerobic lagoons, followed by a separate MBR. Waste sludges from the domestic train are directed to the industrial anaerobic pre-treatment system. Treated sludge from the industrial anaerobic pre-treatment system and from the industrial MBR is dewatered and composted. RO reject is directed to the ROS, along with industrial MBR effluent and domestic MBR effluent which is not reclaimed. Further details of the GWF are provided elsewhere (Gippsland Water Factory 2013; Daigger *et al.* 2013, 2015).

The combination of conventional activated sludge followed by ultrafiltration and RO is widely accepted to

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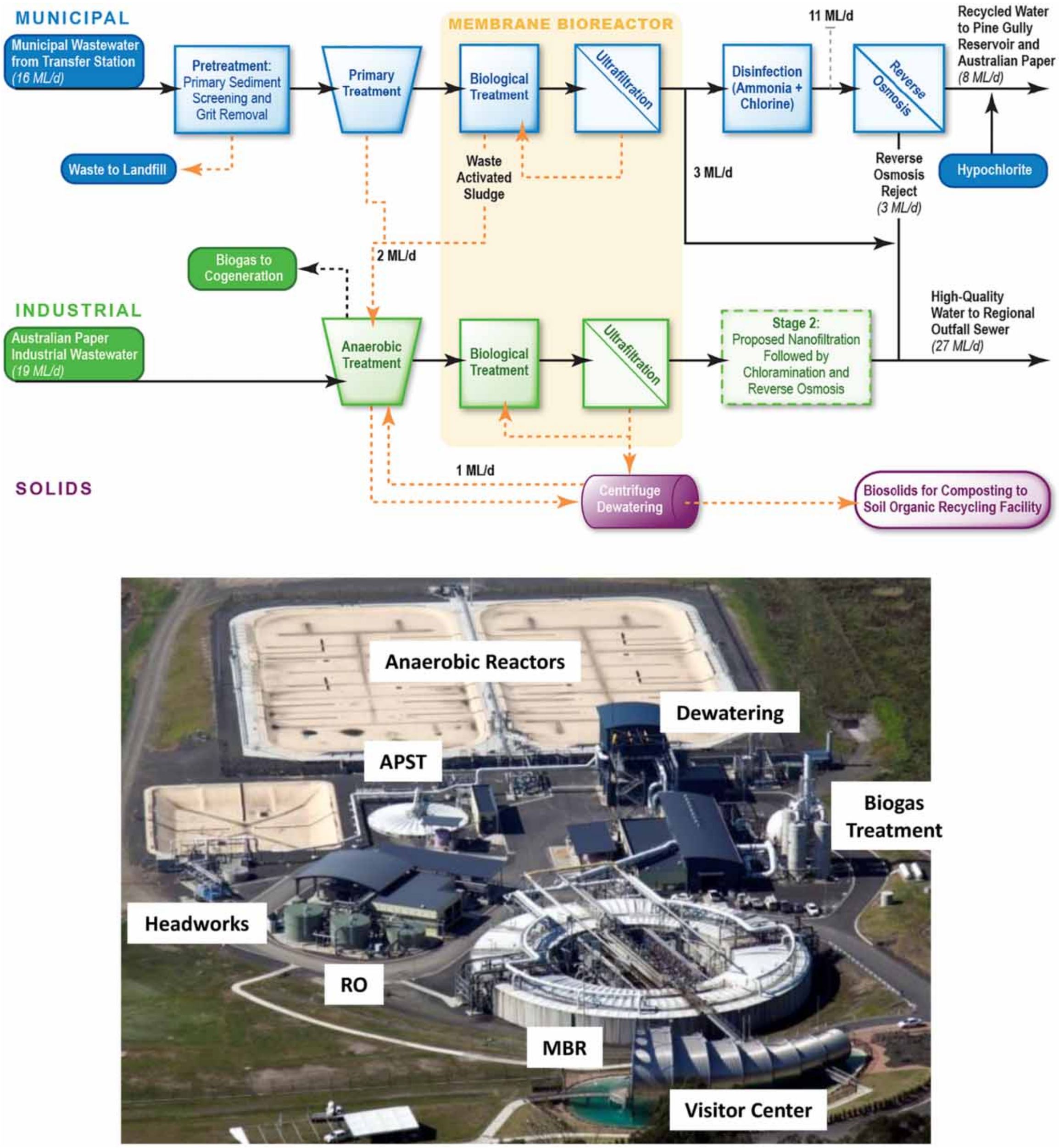


**Figure 1** | Gippsland Water Factory.

reclaim water for reuse from municipal wastewater. It has been further hypothesized that combining activated sludge and ultrafiltration in the MBR process might prove more cost-effective and provide operational and performance advantages when coupled with RO, as compared to the more widely demonstrated activated sludge, ultrafiltration, and RO municipal wastewater reclamation process train (Lozier & Fernandez 2001; Comerton *et al.* 2005; Qin *et al.* 2006; Freeman *et al.* 2011; Moreno *et al.* 2013; Farias *et al.* 2014a, 2014b). More stable biological treatment is expected due to the retention of biomass that occurs in an MBR, due to the relatively long solids retention time (SRT). However, circumstances have not resulted in the construction of many full-scale municipal wastewater reclamation facilities using MBR followed by RO. Consequently, full-scale experience from the GWF can provide valuable insight into the operational and performance characteristics of this water reclamation process train.

The GWF domestic MBR began operation in late 2009, with stable operation since late 2010. The RO system has been operational since early 2012. A detailed evaluation of plant performance was completed in 2012 (Gippsland Water Factory 2012), and a subsequent evaluation of the domestic MBR was completed in 2014 (CH2M HILL 2014). This paper presents the results of those evaluations, along with additional operational and performance results through 2014 so that they may be compared to the operational and performance results from other water reclamation facilities.

## MATERIALS AND METHODS

### Plant description

Table 1 summarizes the major facilities that comprise the GWF domestic treatment train. While the design average capacity of the facility is 16,000 $m^3$/day, served by four membrane cells, the peak wet weather capacity is approximately 40,000 $m^3$/day. Treatment of the peak wet weather flow can be accommodated in the MBR by use of the eight industrial membrane cells for domestic treatment duty during peak wet weather periods (membranes only, not the industrial bioreactor), effectively increasing the available membrane area by a factor of three (i.e., from 4 cells to 12 cells). Facilities are available to store industrial wastewater during such events, allowing the use of the industrial membranes for peak wet weather service. Twelve Memcor Memjet submerged hollow-fiber ultrafiltration membrane racks were initially installed in each of the 12 membrane cells. However, for a variety of operational and commercial reasons the 12 Memjet racks in each of the four dedicated domestic modules were replaced with 15 Mempulse racks.

The Memcor Mempulse racking system is a newer format for the Evoqua (formerly Siemens) submerged UF membrane modules in which agitation air rises through the submerged fiber bundles in sporadic large bubbles or pulses. This agitation method produces a more beneficial boundary layer clearing effect at the membrane surfaces than the older Memjet system, in which a continuous stream of air was injected into the bottom of the membrane bundles. A key additional feature of the Mempulse agitation

**Table 1** | GWF domestic train major treatment units

| Unit process | Number | Size/Capacity | Description |
|---|---|---|---|
| Domestic headworks | 1 | 40,000 $m^3$/d | Two 5 mm screens followed by one vortex grit chamber; screening, washing and compaction, and grit classification and dewatering |
| Activated primary sedimentation tank | 1 | 21 m diameter, 4 m SWD | Circular unit designed to operate in either conventional or activated modes |
| Balance tank | 1 | 5,000 $m^3$ | Lined earthen lagoon with membrane cover and liner, pumped mixing |
| Domestic pre-filters | 3 | 20,000 $m^3$/d each | 1 mm opening automatic, self-cleaning units |
| Domestic biological nutrient removal bioreactors | 2 | 3,068 $m^3$ each | Three-stage units consisting of initial mixed zone receiving ML recirculation from downstream aerated zone, main aeration zone receiving recirculation from membranes, and final mixed zone |
| Domestic membranes | 4 | 64 $m^3$ each tank | Memcor Mempulse units each containing 15 racks per tank with 7,220 $m^2$ of membrane area for each tank |
| Industrial membranes (used for peak wet weather domestic treatment | 8 | 64 $m^3$ each tank | Memcor Memjet units each containing 12 racks per tank with 7,220 $m^2$ of membrane area for each tank |
| RO | 2 Two-stage trains | 7,085 $m^3$/d each train | Nominal 200 mm diameter elements with 7 elements per vessel. 26 vessels per train first stage; 13 vessels per train second stage. 75% average recovery, 85% max |

format is that is uses less agitation air than the Memjet system, and thus is less costly to operate.

These changes were completed by early 2011. The Memjet agitation format remained in the eight industrial membrane cells, although extra membrane racks were added to some cells and progressive conversion of all cells to the Mempulse format is underway.

The RO facility is sized to produce 8,000 $m^3$/day of product water on a yearly average basis, based on 75% recovery of the domestic filtrate feed water. Based on prior experiences of the design team, an availability of 93.6% was assumed, making the required daily production capacity 8,550 $m^3$/day. A balance tank for raw domestic wastewater is provided to capture diurnal peak flows during dry weather conditions so that the RO plant can continue operating during daily lower flow periods.

Each bioreactor consists of three passes and is configured with three zones to provide biological nitrogen and phosphorus removal (Daigger *et al.* 2013, 2015). Including the aerated volume in the submerged membrane cells, it is configured as a four-stage Bardenpho facility consisting of initial mixed zone, main aerated zone, second anoxic zone, and final aerated zone in the aerated submerged membrane cells. The initial mixed zone is 28% of the bioreactor volume, the main aerated zone 48%, and the second anoxic zone 24%. The aerated cells in the membrane tanks add a further 4% volume to the system. Recycle from the submerged membranes is directed to the main aerobic zone rather than the initial mixed zone because of the elevated dissolved oxygen (DO) concentrations it contains. Mixed liquor (ML) recirculation from the main aerobic to the initial mixed zone at a rate of four times the design average flow is also provided. Process modeling during design indicated that biological phosphorus removal would occur, even though a dedicated anaerobic zone was not provided. Ferric chloride feed capability was also provided as a back-up, although it has not been used as sufficient phosphorus removal has been achieved as predicted. This performance is described further below.

## Analytical procedures

Much of the data presented were obtained through routine operation of the full-scale GWF using standard sampling and certified analytical procedures. Details of these procedures have been documented elsewhere (GWF 2013; Daigger *et al.* 2013), and interested parties are referred to these documents for further details.

## RESULTS

The domestic treatment train, except for the RO facility (referred to here as the domestic train), was fully operational with the revised submerged ultrafiltration membrane racks by late 2010. In contrast, the RO facility did not become fully functional until early 2012. The domestic train performed well (as described below), and only modest efforts were made to optimize its performance through 2012, including the period included in the overall detailed plant evaluation. Further efforts were made to improve the performance of the domestic MBR in 2014, as described below. The performance of the RO facility was characterized during much of 2012. It was run periodically during 2013 and 2014 as it was not needed as a water supply by GW during this time period due to relaxation of the previous drought conditions. The performance of the domestic train and the RO facility are summarized below.

### Domestic train performance

Domestic train influent flows and constituent loadings for the intensive evaluation period of December 2010 through October 2012 are compared in Table 2 with the design values and

**Table 2** | Comparison of domestic train loadings with design values for December 2010 through October 2012

| | Values, December 2010 through October 2012 | | | | |
|---|---|---|---|---|---|
| **Item** | **Average** | **Standard deviation** | **Number data points** | **Design average** | **Ratio actual to design** |
| Flow ($m^3$/day) | 14,600 | 4,580 | 629 | 15,200 | 0.96 |
| $BOD_5$ (kg/day) | 3,583 | 1,980 | 63 | 3,574 | 1.06 |
| COD (kg/day) | 8,057 | 2,720 | 238 | 7,062 | 1.14 |
| TSS (kg/day) | 3,973 | 1,832 | 206 | 3,509 | 1.13 |
| VSS (kg/day) | 3,194 | 1,406 | 197 | – | – |
| TN (kg/day) | 588 | 178 | 350 | 609 | 0.92 |
| TP (kg/day) | 133 | 65 | 238 | 130 | 1.02 |

$BOD_5$: biochemical oxygen demand; COD: chemical oxygen demand; TSS: total suspended solids; VSS: volatile suspended solids; TN: total nitrogen; TP: total phosphorus.

demonstrate that the domestic train was essentially loaded to design average values through this period. The average influent flow was marginally lower than the design value, while constituent loadings exceeded the design values modestly for most parameters. Thus, this period is appropriate for assessing the capability of the plant under full design load. Table 3 summarizes domestic MBR influent (primary effluent) flows and constituent loadings for the same period, compared to the design values, further confirming that the domestic train MBR was loaded to its design values. Flows and constituent loadings were similar in 2013 and 2014, indicating again that the domestic train MBR was consistently loaded to its design values.

The MBR has generally been operated at a total SRT, based on the inventory in the bioreactor, of 15 to 16 days, and the mixed liquor suspended solids concentration was generally in the range of 5,000 to 6,000 mg/L (varying with influent loading conditions of course). It is also worth noting that the influent temperature varies over the year from a low in winter of 15 °C to 16 °C to a high in late summer of 22 °C to almost 23 °C. The aerobic SRT was generally 7 to 8 days. Table 4 summarizes average effluent quality for the intensive evaluation period, which indicates excellent performance. Effluent total and soluble chemical oxygen demand (COD) values are essentially the same, as expected. Effective nitrification along with removal of total nitrogen (TN) and total phosphorus (TP) was achieved. Domestic MBR effluent nutrient concentrations were variable, however, as illustrated in Figures 2 and 3 where effluent TN, ammonia, and TP results are presented for the entire operating period (2010 through 2014). Effluent TN concentrations were generally around 5 mg/L or below for most of the data period, but with occasional elevated values. Increased effluent TN was generally a result of increased effluent ammonia. Effluent ammonia and TN concentrations became more stable and declined, beginning the second half of 2013 as a result of ongoing process optimization efforts during this time period. These efforts were focused primarily on improved DO control in the MBR bioreactor. Effluent TP was variable throughout the entire period, except for two periods of more stable performance in late 2013 and early 2014 (Figure 3). Analysis of operating data during 2013 and early 2014 confirmed that improved effluent TN, and the period of improved effluent TP, were a result of improved DO control (CH2M HILL 2014). This work, and principal finding, led to a program of improvements targeting DO control. Actions, to date, have addressed balance tank level management to reduce influent stoppages (when the balance tank reserve was exhausted), optimized positioning of the oxidation-reduction potential (ORP) probe in anoxic zones, moderate reduction in internal recirculation to reduce DO return to the anoxic zone, adjustment of DO set points and aeration control loop tuning. However, although some improvement in MBR effluent quality has been reported so far, improvement work continues, and the desired results are yet to be fully demonstrated. The impact of these variations of MBR nutrient removal on RO performance is addressed below.

Capillary suction time (CST) data for the MBR ML are summarized in Figure 4 and demonstrate that good filterability was achieved except for periods in mid-2011 and mid-2013. This deterioration is hypothesized to have been caused by inadvertent overflows of ML from the companion industrial MBR systems into the domestic system. The filtration characteristics of the industrial MBR are consistently poorer than those of the domestic MBR (Daigger et al. 2015). Sludge filterability was not a constraint on

**Table 3** | Comparison of MBR loadings with design values for December 2010 through October 2012

| Item | Design | Actual | Ratio actual to design |
|---|---|---|---|
| Flow ($m^3$/day) | 14,300 | 13,500 | 0.94 |
| $BOD_5$ (kg/d) | 2,964 | 3,133 | 1.05 |
| COD (kg/d) | 5,517 | 5,700 | 1.03 |
| TSS (kg/d) | 1,673 | 1,728 | 1.03 |
| VSS (kg/d) | 1,157 | 1,357 | 1.19 |
| TN (kg/d) | 567 | 480 | 0.85 |
| TP (kg/d) | 120 | 111 | 0.92 |

**Table 4** | Domestic MBR effluent quality, December 2010 through October 2012

| Item | MBR influent | MBR effluent | Removal (%) |
|---|---|---|---|
| COD (mg/L) | 422 | 35.4 | 92 |
| sCOD (mg/L) | 255 | 35.4 | 86 |
| TN (mg-N/L) | 35.6 | 3.6 | 87 |
| $NH_4$-N (mg-N/L) | 26.6 | 1.4 | 95 |
| TP (mg-P/L) | 8.2 | 2.8 | 66 |

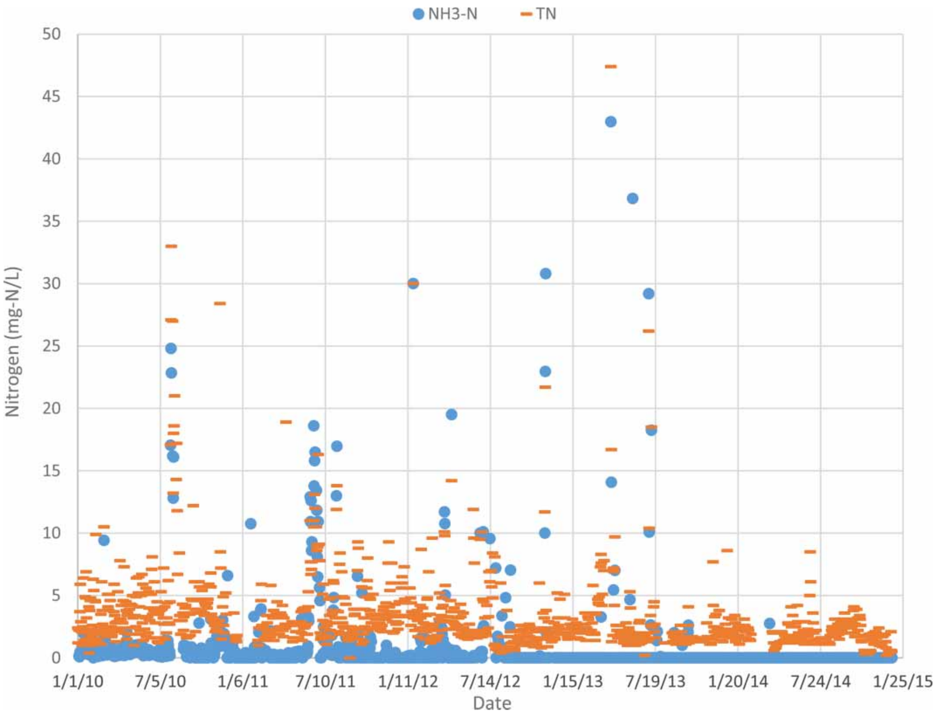


**Figure 2** | Domestic MBR effluent TN and ammonia concentration for 2010 through 2014.

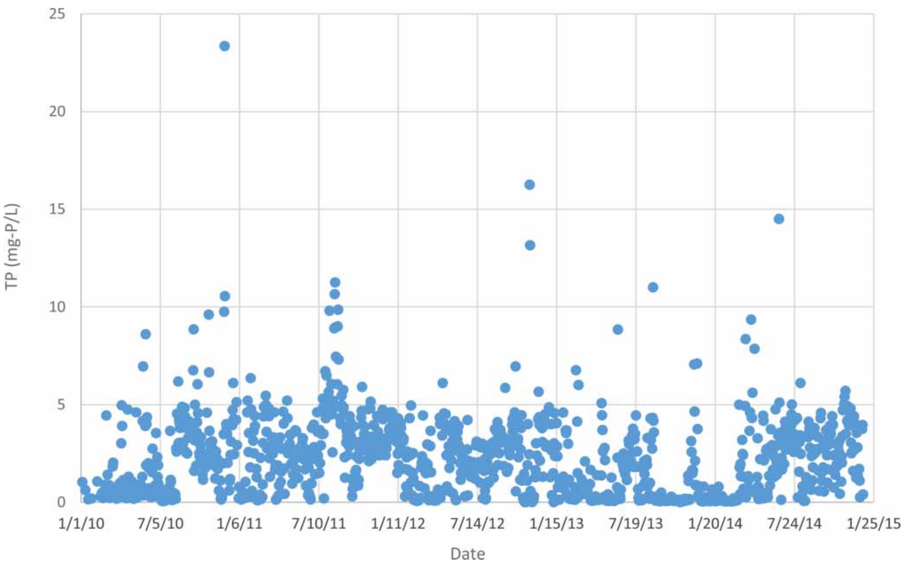


**Figure 3** | Domestic MBR effluent TP for 2010 through 2014.

domestic MBR operation, except for the periods of elevated CST.

The design average membrane flux, based on the 15 racks installed in the four dedicated 'domestic' membrane cells, is 21.1 L/m$^2$-hr, while the actual flux during the detailed evaluation period was 19.9 L/m$^2$-hr, with a typical peak flux of 29.2 L/m$^2$-hr. Figure 5 summarizes domestic membrane flux over the entire period (2010 through 2014)

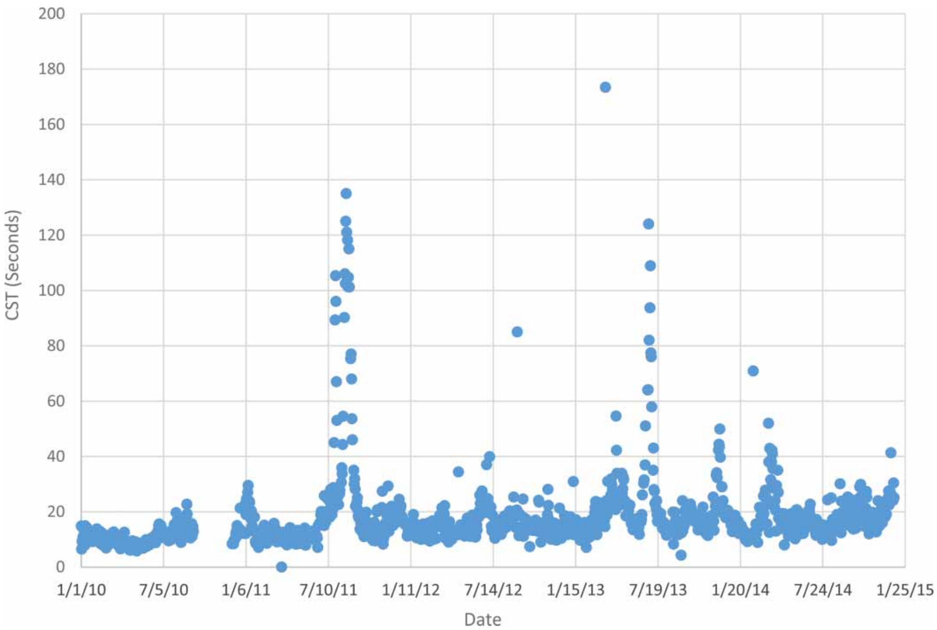


**Figure 4** | Domestic MBR CST for 2010 through 2014.

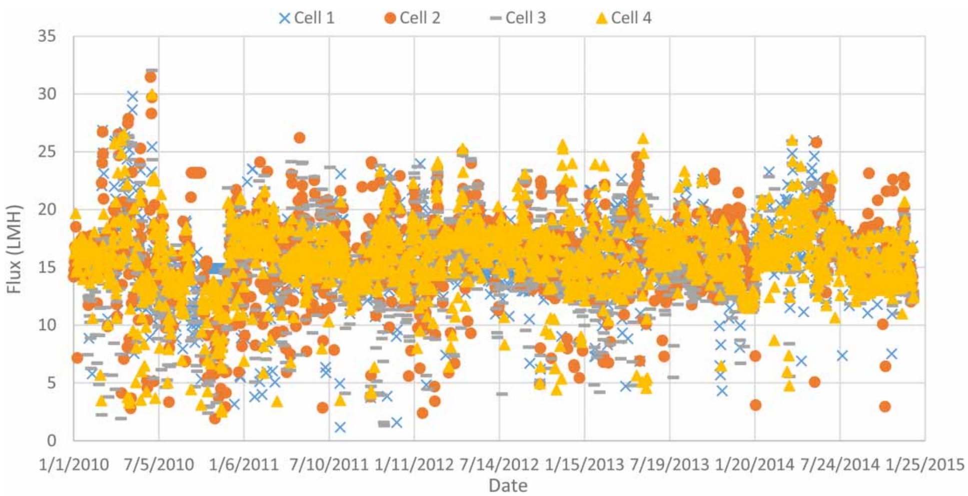


**Figure 5** | Time course of domestic flux.

for each of the four membrane cells. Membrane cleaning averaged once per month, with the majority being short cleanings (referred to as maintenance cleans) with chlorine. Full chlorine clean-in-place (CIP), using higher hypochlorite concentrations and longer contact times, averaged about once every four months, with citric acid-based CIPs occurring only about once every two years. During the detailed evaluation period the domestic membranes were in productive operation 82 to 88% of the time, in stand-by 4 to 8% of the time, with a downtime of 9 to 12% of the time. This cleaning regime resulted in maintenance of sufficient permeability, as illustrated by the data presented in Figure 6.

Effluent turbidity data for each of the four membrane cells are summarized in Figure 7, showing a trend of consistent improvement over the entire operating period (2010

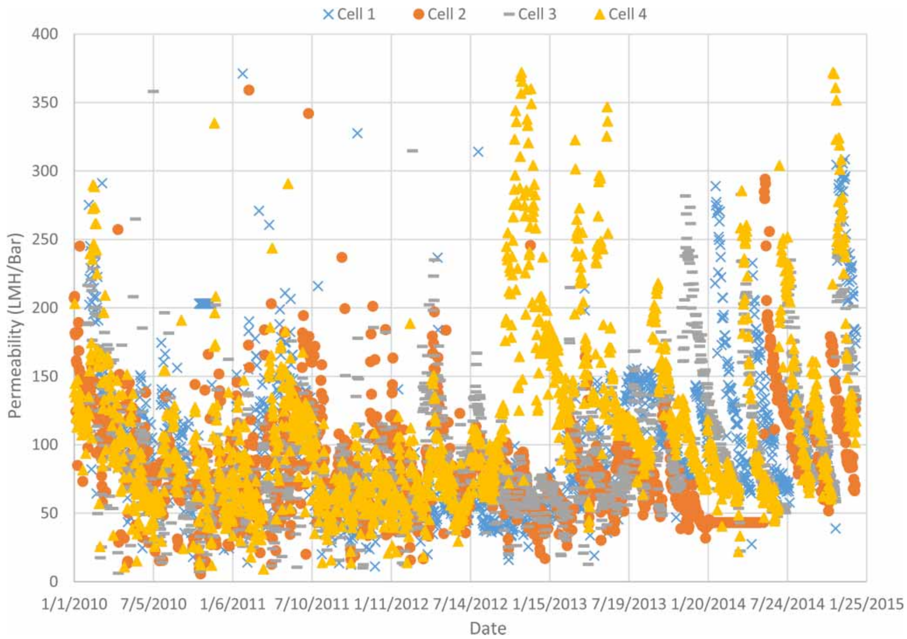


**Figure 6** | Time course of domestic MBR permeability.

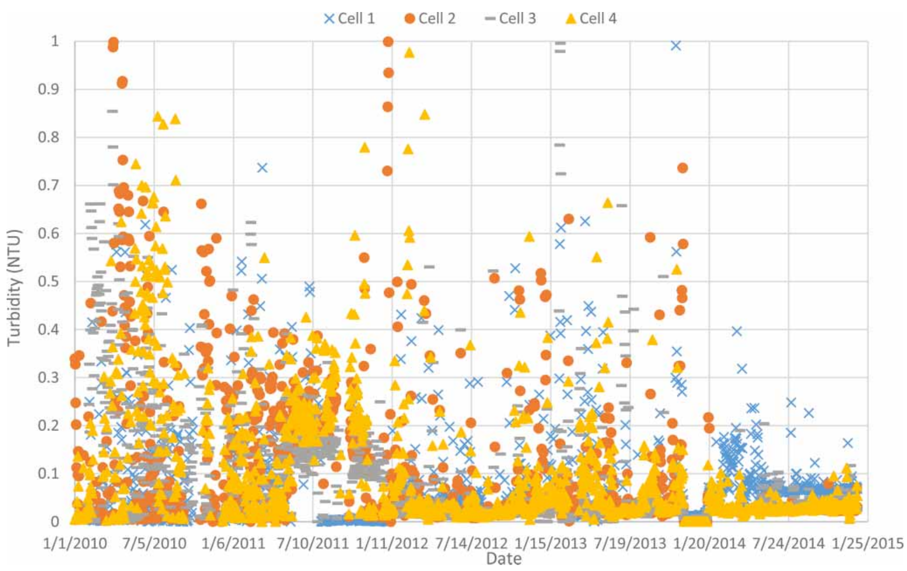


**Figure 7** | Domestic MBR effluent turbidity.

through 2014). Effluent turbidity improved throughout this period as filtration integrity issues were progressively dealt with. As noted above, the 12 Memjet racks initially installed in the four domestic membrane cells were replaced with 15 Mempulse racks by early 2011. Further, it was observed that filtration integrity was compromised by a number of systemic issues. These issues included manufacturing problems with potting, O-rings, incorrect torque settings on bolts, creep of plastic housing components, and filtrate hose washers and coupling clamp holding pressures. Comprehensive attention to the issues by the membrane supplier have resolved these issues, and reliable operation and easily acceptable turbidity performance is now routinely achieved. This is demonstrated by the reduced effluent turbidity during 2014, as shown in Figure 7.

A further issue is associated with the pressure decay rate (PDR). The Victorian water quality regulator required that the GWF demonstrate a log removal value for virus (LRV) of six when operating in the reclamation mode. This was partially accomplished in the initial design of the GWF by including a requirement to maintain the domestic MBR membrane PDR less than 7 kPa/min (GWF 2010). Experience demonstrated, however, that the frequency of membrane repair (pinning) required to maintain this level of integrity was neither practical nor necessary. With the full-scale plant in operation, it was demonstrated that the required level of overall reclamation treatment train LRV could be demonstrated by monitoring total organic carbon (TOC) removal across the downstream RO system, thereby gaining two logs of virus removal by the overall treatment system. This relieved some of the treatment performance validation requirement from the ultrafiltration system and the PDR requirement was relaxed to 70 kPa/min, which, although still an onerous performance requirement, permits a practicable level of membrane maintenance activity. Table 5 summarizes LRV values provided by the facility with this change.

**Table 5** | LRV values provided by the GWF with revised monitoring of RO system

| Process step | Virus | Bacteria | Protozoa |
|---|---|---|---|
| MBR (UF) | 0 | 4 | 4 |
| Chloramination | 0 | 4 | 0 |
| RO | 2 | 2 | 2 |
| Final chlorination | 4 | 1 | 0 |
| Total | 6 | 7 | 6 |

The progression of the PDR for the domestic membranes is summarized in Figure 8. This figure displays a stepwise pattern in which after periods of PDR increase the PDR then resumes at a reduced rate and again slowly rises. This behavior is indicative of the evolving maintenance and membrane management practices at GWF. More recently, some of the cells display an almost continuous

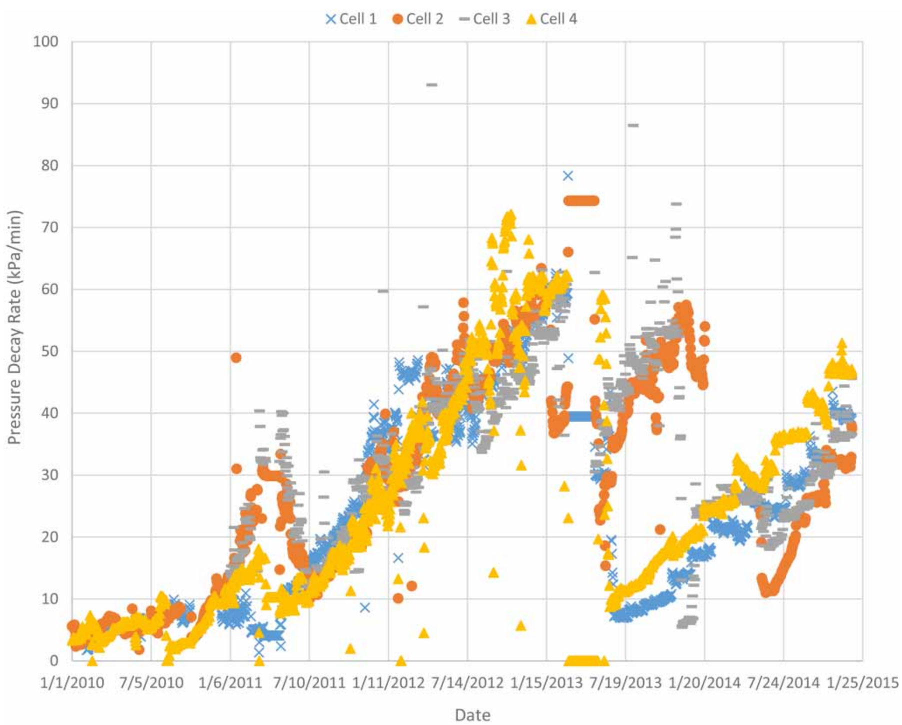


**Figure 8** | Time course of domestic MBR PDR.

PDR value, a sign of a stable and well-maintained cell. These latter periods of the PDR historical trend also illustrate a possibly unfortunate consequence of cell cleaning, which is that sometimes after a relatively stable period of PDR, the PDR increases sharply before stabilizing again. This phenomenon appears to correlate with cell cleaning events, although the exact reason for this result is not yet evident. As indicated by comparison of Figures 7 and 8, increased PDR did not adversely affect effluent turbidity. During filtration, the high level of suspended solids present on the feed side of the UF membrane quickly occludes defects in the membrane modules that result in the elevated PDR, preventing or limiting turbidity increases in the effluent.

Energy requirements for the submerged membranes were initially on the order of 1 kWh/m$^3$ for operation with the Memjet system. However, the energy consumed declined to just under 0.4 kWh/m$^3$ as the Mempulse system became fully operational and the overall process was optimized. Although the Mempulse system does require less agitation blower energy, it should be noted that much of the energy saving reported here, although not all of it, is thought to be attributed to the optimization efforts.

## RO performance

The RO facility became operational in early 2010. However, addressing filtration integrity issues associated with the MBR was generally the focus during 2010 and 2011, and this led to infrequent RO operation through this period. Improved filtration integrity, and the resulting decrease in turbidity, was achieved by late 2011, allowing more consistent operation of the RO system for process proving and optimization purposes during 2012. The RO system was operated only intermittently during 2013 and 2014 as reclaimed water was not needed by GW to meet the overall water supply needs of its service area. Consequently, this analysis focuses largely on operation during 2012.

A detailed summary of RO influent quality is presented in Table 6 for the period of January through October 2012, compared to the specified design influent quality. Both 50th and 90th percentile values are presented. Influent values exceeding the specified design values are indicated

**Table 6** | Comparison of RO feedwater quality for 12 January through 22 October 2012 compared to specified design values

| Parameter, mg/L | Design 50th %tile | Design 90th %tile | Actual 50th %tile | Actual 90th %tile |
|---|---|---|---|---|
| Ca | 20.1 | 29.7 | **24.1**[a] | 28.1 |
| Mg | 6.6 | 9.5 | 7.4 | 8.9 |
| Na | 161 | 190 | 121.6 | 138 |
| K | 21.6 | 31.2 | 15 | 16.9 |
| Ba | 0.07 | 0.12 | < 0.01 | < 0.01 |
| Sr | 0.08 | 0.08 | < 0.01 | 0.1 |
| Al | 0.04 | 0.04 | NM[b] | NM |
| Fe | 0.07 | 0.11 | **0.2** | **0.37** |
| Mn | 0.06 | 0.06 | **0.26** | **0.35** |
| Alkalinity as $CaCO_3$ | 146 | 192 | 127 | 151 |
| Bicarbonate as $CaCO_3$ | 178 | 234 | 155 | 184 |
| Cl | 158 | 190 | 100 | 117 |
| $SO_4^{-2}$ | 72.2 | 94.4 | 55.0 | 65.9 |
| Fl | 0.95 | 0.95 | 0.22 | 0.28 |
| Br | 0.00 | 0.00 | **0.26** | **0.42** |
| $NH_3$-N[c] | 0.18 | 0.18 | **1.24** | **2.46** |
| $NO_2$-N | 0.39 | 0.45 | 0.00 | 0.09 |
| $NO_3$-N | 0.70 | 1.43 | **0.78** | **2.19** |
| Organic nitrogen | 2.06 | 1.27 | *1.89* | ***1.94*** |
| TN | 3.33 | 3.33 | **3.91** | **6.68** |
| $PO_4$-P | 1.00 | 1.00 | **2.00** | **4.45** |
| TP | 1.00 | 1.00 | **2.70** | **4.75** |
| Si | 17.1 | 17.27 | NM | NM |
| B | 0.22 | 0.23 | NM | NM |
| Conductivity, uS/cm | 1006 | 1247 | 758 | 859 |
| TDS | 644 | 804 | *485* | *554* |
| Total hardness, as $CaCO_3$ | 66 | 111 | ***91*** | *107* |
| pH, units | 7.01 | 7.00 | **7.18** | **7.53** |
| Temperature, deg C | 19 | 26 | **17.1** | **21.2** |
| Turbidity, NTU | NE[d] | NE | 0.030 | 0.080 |
| SDI, 15-min | NE | NE | 2.4 | 3.28 |
| TOC | NE | NE | 13.3 | 19.5 |
| Total carbon | NE | NE | 52.6 | 63.8 |
| Colour, Pt Co | NE | NE | 51.5 | 77.1 |
| UV254, 1/cm | NE | NE | 0.35 | 0.50 |
| Chloramines, as $NH_2Cl$ | 3.0 | 3.0 | 1.52 | 2.14 |
| Chloramines, as $NH_3$ | 0.82 | 0.82 | *0.50* | *0.71* |

[a]Bold values represent measured values that exceed corresponding design values.
[b]NM, not measured.
[c]50th and 90th percentile $NH_3$-N levels in MBR filtrate prior to ammonia dosing were 0.20 and 3.6 mg/L, respectively.
[d]NE, none established.

in bold. The principal issues indicated by these data are iron and manganese (because of potential oxidation and fouling of the RO membranes), and nitrogen and phosphate species (because of the stringent reclaimed water discharge standards and potential for precipitation of calcium phosphate within the second stage of the RO system). Actual total dissolved solids (TDS) values were significantly less than the design value. Even considering that operating temperatures were generally lower than the 90th percentile design value of 26 °C, the head on the RO feed pumps was more than sufficient to achieve the specified flux and recovery at the observed TDS values.

Table 7 summarizes 50th and 90th percentile flux and recovery values for the two RO trains for 2012, indicating that they were generally operated at reasonable flux and recovery values. Analysis of sparingly soluble salts indicated that calcium carbonate, calcium phosphate, barium sulfate, and silica were supersaturated in the RO concentration at 75% recovery for both the 50th and 90th percentile feed water concentrations, but this was controlled by anti-scalant addition (GWF 2012). Analysis of feed water data indicated some concern related to iron precipitation. An analysis of normalized product flow, normalized differential pressure, and normalized salt passage for the entire period of operation (2010 through 2012) indicated little evidence of fouling or increased salt passage (GWF 2012), although it was decided to clean the membranes with both sodium hydroxide and citric acid in mid-2011 to facilitate commissioning of the RO cleaning systems. Biofouling of the RO membranes is controlled by continuous dosing of chloramines which acts to suppress biological growth within the RO system.

**Table 7** | RO operating conditions for 2012

| | 50th %tile | | 90th %tile | |
|---|---|---|---|---|
| **Train** | **Flux ($L/m^2$-hr** | **Recovery (%)** | **Flux ($L/m^2$-hr)** | **Recovery (%)** |
| Train A stage 1 | 18.1 | 51.0 | 19.3 | 54.0 |
| Train A stage 2 | 17.0 | 49.5 | 19.1 | 53.1 |
| Train A overall | 17.8 | 75.3 | 19.2 | 77.8 |
| Train B stage 1 | 18.4 | 53.7 | 19.9 | 56.3 |
| Train B stage 2 | 16.3 | 52.1 | 18.3 | 53.1 |
| Train B overall | 17.7 | 77.2 | 19.1 | 78.5 |

A total of 49 effluent quality parameters are specified for the RO product water, but not all must be routinely monitored because many are expected to be consistently below the specified values as long as design influent values are not exceeded and membrane integrity is maintained as demonstrated by compliance with critical control points. Table 8 summarizes performance for the parameters routinely monitored and generally demonstrates routine compliance with the required performance.

While product water quality requirements (i.e., chemical quality) did not require it, two LRV credits (i.e., 99%) removal of TOC is required by the Victorian Department of Health (DoH) to demonstrate RO membrane integrity and ensure the effective rejection of viruses. This performance requirement is complemented by challenge testing using Rhodamine WT fluorescent dye prior to full-scale operation and on a yearly basis. Online instrumentation (Sievers, 5310 C) to monitor both RO feed and permeate TOC is used for this purpose and generally demonstrated compliance with the 'two log' removal requirement. Figure 9 presents the LRV removal achieved during the 2012 testing period. Opportunities for improved analytical and operational control procedures were identified during a mid-2012 detailed review. Breakpoint chlorination of RO effluent with a minimum value of 10 mg-min/L is further required to ensure sufficient disinfection and was achieved. Of particular importance is excellent removal of the nutrients nitrogen and phosphorus, as indicated by reliable compliance with the stringent effluent requirements listed in Table 8.

Energy use for RO averaged 0.73 $kWh/m^3$ of product water in 2012. The total energy usage for both MBR and RO treatment was calculated including the bioreactors, MBR membranes, and the RO system. It averaged 3.04 $kWh/m^3$ of product water for the same period.

## DISCUSSION

Performance results for the MBR-RO water reclamation train at the GWF demonstrate the robustness and resilience of this process combination. In spite of significant membrane filtration system integrity issues experienced with the domestic MBR during its initial operating phase, reliable

**Table 8** | RO product water quality compared to required quality for 12 January through 22 October 2012

| | | **Required** | | **Actual** | |
|---|---|---|---|---|---|
| **Parameter** | **Units** | **Average** | **Maximum** | **Average** | **Maximum** |
| *Escherichia coli* | #/100 mL | NE | 10 | 0 | 0 |
| Ammonia (as N) | mg/L | 0.025 | 0.059 | 0.095 | **0.55**[a] |
| Calcium | mg/L | 1.66 | 1.8 | 1.53 | 2.94 |
| Chlorine residual | mg/L | NE | 1 | 1.94 | **0.0** |
| Colour, 465 nu | Pt Co | NE | 100 | 2.9 | 29 |
| Dissolved organic carbon | mg/L | 12.9 | 14.4 | *1.53* | *11.4* |
| Fluoride | mg/L | NE | 0.75 | 0.005 | 0.04 |
| Magnesium | mg/L | 1.66 | 1.8 | 0.39 | 0.87 |
| Organic nitrogen | mg/L | NE | 0.73 | *0.54* | ***0.91*** |
| pH (Lab) | | NE | 6.0 to 9.0 | 6.92 | **9.21** |
| Potassium | mg/L | 1.1 | 1.1 | 0.33 | 1.25 |
| TP | mg/L | NE | 0.1 | 0.001 | 0.010 |
| Sodium | mg/L | 7.8 | 8.4 | 7.41 | **54.3** |
| SUVA (254 nm) | m-L/mg | 4.6 | 4.7 | *1.3* | ***6.5*** |
| Temperature | deg C | NE | 22 | 17.3 | **22.9** |
| TDS | mg/L | NE | 200 | *41* | *63* |
| TN | mg/L | NE | 2 | 0.72 | 1.20 |
| TOC | mg/L | NE | 18 | 1.53 | 11.4 |
| UV absorbance (254 nm) | 1/cm | 0.595 | 0.651 | 0.011 | 0.106 |

[a]Bold values represent measured values that exceed corresponding design values.
SUVA: specific UV absorbance.

performance of the MBR-RO train was achieved when sufficient wastewater volume was available to allow for routine operation. Consistently good quality reclaimed water was produced, with occasional deviations from the desired 90th percentile values. Effluent nutrient (TN and TP) values were consistently below the very stringent limits specified, even though consistent performance by the MBR has not yet been achieved. Although the ability to add ferric chloride to the MBR for further TP control was provided, overall performance indicated that this was not needed and has not been practiced. While membrane integrity issues adversely impacted operation and performance initially, these issues are now considered resolved.

Operating experience with the RO system demonstrated the need to continuously maintain the analytical systems (instruments, SCADA, and controls) which support it. Intermittent operation of the RO system sometimes led to difficulties with these components of the system when it was started up after a period of inactivity. Operational procedures have been developed by plant staff to more routinely verify the readiness status of these system components, and they are now routinely returned to service with little difficulty. Comprehensive management of process assets for operational readiness should be a key component of the operational plan for any RO system, not only one following MBR. The DoH requirement to demonstrate membrane integrity via online TOC measurement adds an additional instrumentation requirement not typically required for RO systems utilized for removal of TDS or specific inorganic constituents. Likewise, RO systems are capable of removing a wide range of constituents to low levels. This does not mean that all constituents should be monitored as such a practice leads to excessive analytical costs and adds little value as the tendency is to not make use of the data collected. Routine operation demonstrating that RO membrane integrity is maintained (including

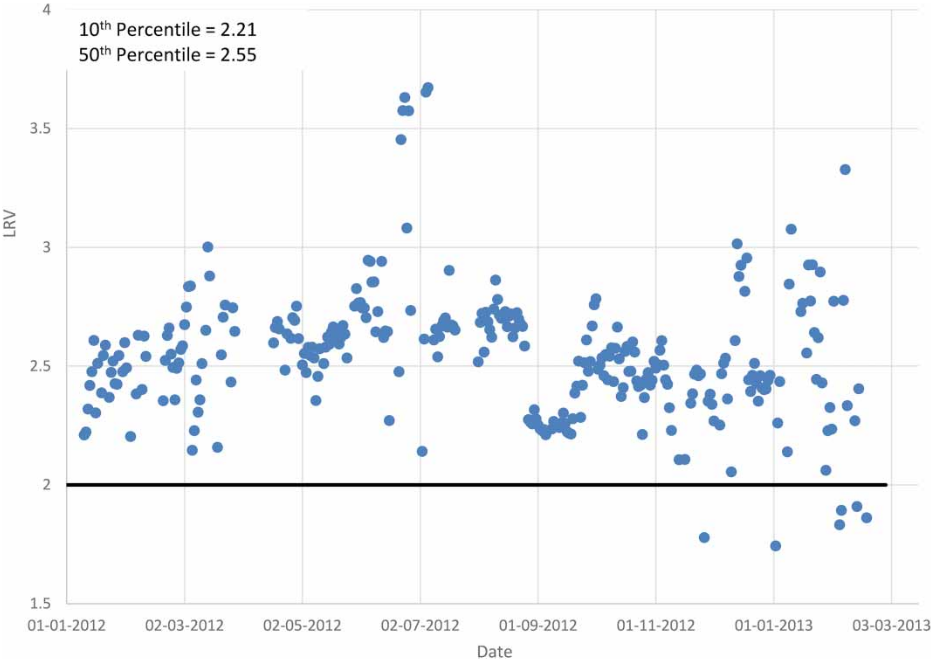


**Figure 9** | LRV for TOC for RO system.

online monitoring of both conductivity and TOC removal, as implemented at the GWF) can be supplemented by occasional confirmation of effluent quality.

## SUMMARY AND CONCLUSIONS

In spite of initial operational and performance issues, the GWF has operated successfully and met its performance requirements. Water reclamation is practiced only when required to supplement the regional water supply during periods of drought. Operation, to date, has allowed GW to gain a full understanding of the operational procedures required to achieve the intended capacity and performance. Consequently, the facility is fully available when needed as a drought-proof supplemental water supply. MBR membrane integrity issues were unexpected but have been successfully dealt with, and it is understood that the lessons derived from this experience have been applied elsewhere by the membrane supplier. GW owns and operates other wastewater treatment facilities which use activated sludge processes with clarifiers, and consequently has a basis for evaluation of the decision to use the MBR process at the GWF rather than a more conventional activated sludge process followed by tertiary membranes and RO. GW is fully satisfied with selection of the MBR process for the GWF, and on the basis of several years' operational experience at GWF, it is reasonable to conclude that the combination of MBR and RO is a viable means of producing reclaimed water from municipal wastewater at a very high quality standard.

## REFERENCES

CH2M HILL 2014 Phosphorus Study. Prepared for Gippsland Water.

Comerton, A. M., Andrews, R. C. & Bagley, D. 2005 Evaluation of an MBR-RO system to produce high quality reuse water: microbial control, DBP formation and nitrate. *Water Res.* **39**, 3982–3990.

Daigger, G. T., Hodgkinson, A., Burrowes, P. & Aquilina, S. 2013 Creation of a sustainable water resource through reclamation of municipal and industrial wastewater in the Gippsland Water Factory. *J. Water Reuse Desal.* **3** (1), 1–15.

Daigger, G. T., Hodgkinson, A., Aquilina, S. & Fries, K. 2015 Development and implementation of a novel sulfur removal process from $H_2S$ containing wastewaters. *Water Environ. Res.* **87**, 618–625.

Farias, E. L., Howe, K. J. & Thomson, B. M. 2014a Effect of membrane bioreactor solids retention time on reverse osmosis membrane fouling for wastewater reuse. *Water Res.* **49**, 53–61.

Farias, E. L., Howe, K. J. & Thomson, B. M. 2014b Spatial and temporal evolution of organic foulant layers on reverse osmosis membranes in wastewater reuse applications. *Water Reuse* **58**, 102–110.

Freeman, B. R., Peck, S., Jones, N., Kawashima, T., Franks, R., Oda, Y. & Itonaga, T. 2011 Advancing the use of integrated MBR-RO technology to reclaim wastewater through pilot testing. *Ultrapure Water J.* **20** (8), 16–21.

Gippsland Water Factory 2013 *Recycled Water Quality Management Plan and supporting documentation prepared for Gippsland Water by Gippsland Water Factory Alliance, submitted to Victorian Department of Health (DoH) July 2010*. Approved by DoH 16 July 2010. Gippsland Water Alliance, Traralgon, Australia.

Gippsland Water Factory 2013 *Technical Consolidation Report*. Prepared for Gippsland Water, Traralgon, Australia, December 2013.

Lozier, J. & Fernandez, A. 2001 Using a membrane bioreactor/reverse osmosis system for indirect potable reuse. *Water Supply* **1** (5–6), 303–313.

Moreno, J., Monclús, H., Stefani, M., Cortada, E., Aumatell, J., Afroer, N. & de Lamo-Castellyí, S. 2013 Characterisation of RO fouling in an integrated MBR/RO system for wastewater reuse. *Water Sci. Technol.* **67** (4), 780–788.

Qin, J.-J., Kekre, K. R., Tao, G., Oo, M. H., Wai, M. N., Lee, T. C., Viswanath, B. & Seah, H. 2006 New option of MBR-RO process for production of NEWater from domestic sewage. *J. Membrane Sci.* **272**, 70–77.

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