THE IMPACT MEMBRANE BIOREACTOR ON THE DESIGN OF BIOLOGICAL NUTRIENT REMOVAL AT MALMESBURY WWTW

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ABSTRACT

The application of Membrane Bioreactor (MBR) technology for solid-liquid separation has been increasing recently due to declining costs, increasing requirements for pristine effluent quality and higher premiums attached to land. Malmesbury, located approximately 70 km from Cape Town, upgraded their existing treatment works with MBR technology. The upgraded Malmesbury WWTW is a hybrid MBR nutrient removal system that makes optimum use of the previously existing Pasveer Ditch-type activated sludge plant. Flow is split and recycled between the old and new units to create one integrated system, where the MBR has hydraulic capacity for the design peak dry weather diurnal flow of 20 Mλ/d. To accommodate the significant peak wet weather flows, the normally "idling and dormant" previously existing clarifiers are called into service automatically along with the disinfection system. To accommodate this and ensure the clarifiers do not fail in flux overloading, the recycles are carefully designed to achieve conventional lower mixed liquor concentrations in the Pasveer Ditch, whilst the MBR unit runs at 8 to 15 kg/m3 (depending on the reactor zone). The hybrid system made the use of MBR technology viable cost-wise, and allows the municipality to recycle virtually almost the full daily dry weather flow. Also, and important in the client's decision to select MBR technology, the reduced footprint of the hybrid system (as opposed to conventional activated sludge) substantially increases the ultimate treatment capacity on the site; an important consideration to avoid the alternative of developing a second treatment site to meet the anticipated on-going growth of the town. This paper describes the design approach adopted for the MBR plant at Malmesbury as well as the preliminary five months operational results (since the introduction of raw sewage) of the recently implemented full scale MBR plant.

Keywords: MBR, hybrid process, optimum, mixed liquor concentrations, footprint, effluent re-use

1. INTRODUCTION

Malmesbury is a rapidly growing town and about three-quarters of an hour drive west of Cape Town. It is the largest town in the Swartland Municipality, which also encompasses Darling, Piketberg, Moorreesberg, and Riebeek West/Kasteel. Swartland Municipality is also responsible for the water supply and the wastewater reticulation and treatment in the town. The treatment works is sited at the south-west end of the town between the Cape Town–Malmesbury railway and the Diep River. The works treats both domestic and industrial wastewater (estimated to be about 30%) for Malmesbury town and discharges the treated effluent into Diep River.

The robust growth of residential and commercial development in Malmesbury, in recent years has put a strain of the existing treatment works. The existing treatment works has a maximum hydraulic capacity of 5.5 Mλ/d and is configured to achieve COD, Nitrogen and TSS reduction only. The existing plant has no allowance for phosphorus removal. In addition, the WWTW experiences significant sludge carry-over in the clarifier which escapes with the effluent. The works treatment capacity is also the limiting factor on additional growth and development. Demand is so strong that Swartland Municipality decided to have the plant capacity increased by nearly 2 times to 10 Mλ/d. This additional capacity allows for additional development to occur and also to connect many previously disadvantaged homes to the sewerage system. Meeting the increased flow from rapid development in the area was not the only challenge the municipality faced, new discharge standard/ regulations also call for lower nutrient discharge limits. In addition, due to high infiltration flow, the nutrient in effluent must be reduced to improve the percolation rate in the irrigation fields. Therefore, faced with an increasing population and robust growth of residential and commercial development, and concerns for environmental protection, the Malmesbury Wastewater Water treatment Works (WWTW) was upgraded (construction commenced in September 2010) to a wastewater re-use facility, with a membrane bioreactor (MBR) biological nutrient removal(BNR) process, and commissioned at the end of January 2013. The first set of comprehensive data gathering commenced in March 2013.

2. MALMESBURY WWTW DESCRIPTION PRIOR TO UPGRADE

Raw wastewater flowed by gravity to the raw wastewater pump station from where it was pumped into the main inlet works. In the inlet works the wastewater was screened, sand, stones and grit removed and the flow measured. Half of the flow was then directed to the biofilter plant, which operated as a "roughing" process to remove approximately 2 500 kg COD/d. The biofilter effluent was not suitable for discharge to the Diep River and was therefore discharged to the activated sludge (Pasveer Ditch) plant for further treatment. Flow from the inlet works that exceeds the capacity of the biofilter plant, passed directly to the activated sludge plant. The biofilter plant was loaded as highly as possible to facilitate the removal of a large organic load from the wastewater, as opposed to achieving a good final quality of effluent for a small quantity of wastewater.

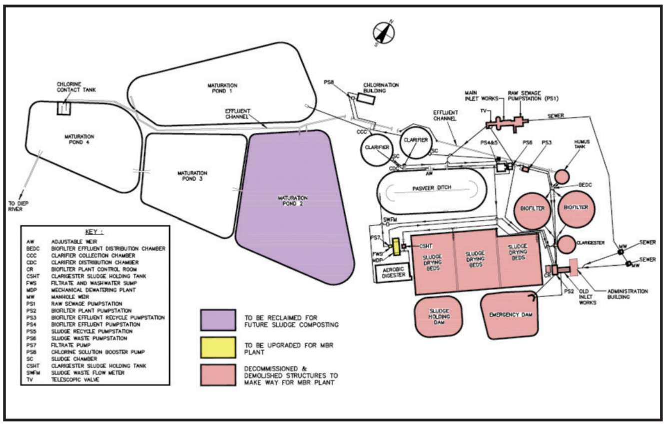

Figure 1: Process Flow Diagram of Malmesbury WWTW prior to the upgrade

The biofilter plant comprised the biofilter plant pump station followed by the clarigester (combination of primary settling tanks/anaerobic digester), two biofilters and finally a humus tank. Sludge from the humus tank was recycled to the biofilter plant pump station, from where it was pumped to the clarigester. The sludge from the clarigester was harvested periodically to the clarigester sludge holding tank (before being dewatered in the mechanical dewatering plant), or the sludge drying beds. The activated sludge plant comprised the Pasveer Ditch biological reactor (~3 000 m3); two clarifiers and sludge recycle pump station. The activated sludge from the Pasveer Ditch was settled in the clarifiers and recycled back to the Pasveer Ditch via the recycle pump station. The settled effluent from the clarifiers was chlorinated (disinfected) in the chlorine contact tank. The effluent then passed through a series of four maturation ponds for polishing before being discharged to Diep River. A fraction of the activated sludge that was recycled from the clarifiers to the Pasveer Ditch, was harvested to maintain the required solids retention time (sludge age). The waste sludge was then further treated in the aerobic digester which was equipped with two floating aerators. The waste sludge, along with any clarigester sludge from the clarigester sludge holding tank, was dewatered in the mechanical dewatering plant or dried on the sludge drying beds. The dewatered sludge was stored on site or carted away. Filtrate from the mechanical dewatering plant flowed either to the biofilter plant pump station, or pumped to the Pasveer Ditch, depending on whether clarigester sludge or aerobic digester sludge was being dewatered.

3. IMPLEMENTATION OF THE MBR PLANT AT MALMESBURY WWTW

The site of the treatment works is located on the Diep River which flow into the Milnerton Lagoon, and ultimately into the Atlantic Ocean. Apart from the fact that nutrient removal was required for the upgraded works, the Malmesbury WWTW had problems in the past with sludge that washed from the system into the river. Various options for upgrading the works had been presented to the Municipality. Amongst these options was the upgrading of the works using MBR technology. This technology was attractive to the Municipality, mainly for the following reasons:

- If the treatment works was to be upgraded using conventional activated sludge technology, the maximum treatment capacity that could be accommodated on the current site would most likely be limited to 15 Mλ/d. According to current flow forecasts this meant that an alternative site for a treatment works would most likely have to be identified within the next decade. Using MBR technology, the treatment capacity that could be accommodated on site could be increased two- to threefold.
- With an MBR plant the risk of solids carry-over into the environment was virtually eliminated.
- The quality of the effluent was such that disinfection was normally not required.

In a MBR plant, the membrane area is one of the major factors that determine the cost of the treatment works. Membranes can accommodate a defined increase in hydraulic flux for a limited period, but in areas such as the Western Cape, where the wet weather peak flows can last for an extended period, the required membrane area is directly related to the hydraulic load on the system. If the peak hydraulic load on the plant could be reduced it would have a direct impact on the capital cost of the plant.

A Pasveer Ditch normally does not lend itself easily to direct incorporation into a MBR plant. The reactor is normally shallow and can therefore not accommodate the membrane packs for which a minimum depth of about 3,5 m is required. Separate membrane tanks can be constructed, in which case the ditch can be used as a bioreactor before the membrane tanks. The shallow depth however limits the allowable contact time between the air bubbles and the mixed liquor, which limits the efficiency of oxygen transfer. This efficiency is reduced further by the high sludge concentration at which bioreactors operate in MBR systems.

During the design phase of the Malmesbury MBR plant various means of incorporating the existing Pasveer Ditch, as well as the downstream sedimentation tanks, into the upgraded works were considered. The two most likely options were:

- Option 1: To utilise the existing basin of the bioreactor as a buffer tank to store peak flows of screened wastewater, thus reducing the peak load on the membranes, or
- Option 2: To operate the existing basin in parallel with the MBR plant, allowing only the peak flow to effectively flow through the sedimentation tank of the existing works.

The first option of buffering the screened raw wastewater in the existing bioreactor had a few potential problems, of which the most important were:

- During the typical prolonged wet winter periods, the limited capacity of the tank would cause the tank to fill before the peak subsided following which it would not provide any effective buffering.
- The tank would be empty during average flow conditions which could lead to odour problems unless it was properly washed down every time after it had been used.
- Since the works did not have primary sedimentation, settable solids would accumulate at the bottom of the tank. The content would thus have to be continually mixed and the solids that had settled would have to be scoured from the tank during washing.
- The storage of raw wastewater normally gives rise to odour problems.

To limit some of the potential side-effects of buffering raw wastewater, covering the existing tank was strongly considered. This could give rise to corrosive conditions which would have to be countered with ventilation, concrete protection and/or treatment of the wastewater to prevent these conditions.

The second option, which has since been accepted for implementation, involved incorporating the existing Pasveer Ditch into the biological treatment stream of the upgraded works. The decommissioned and demolished process units are hatched and shown in Figure 1. The balance of the works comprises a new inlet works, MBR plant, additional aerobic digester and belt-press equipment and is shown in Figure 2 (see below for the upgraded works process description). The new bioreactor and inlet works are built in a position where there were sludge drying beds, the administration and control building in a position of the biofilter plant, and new additional aerobic digester in a location where there was an emergency dam/sludge holding dam. Figure 2 shows the aerial photograph of the new treatment works, while Figure 3 shows the process flow diagram of the upgraded works.

4. UPGRADED MALMESBURY MBR WWTW DESCRIPTION

The treatment works consists of coarse screening inlet works (5 mm perforated drum screens, grit removal and separation), fine screening (with 1.5 mm contec perforated mechanical screens), new UCT type configuration bioreactor with four dedicated membrane tank/ trains, treated wastewater storage pond for non-potable use, sludge thickening and dewatering units. Several new pump stations were constructed as part of the project. The bioreactors have continuous inflow, but are intermittently aerated to achieve nitrogen removal. There are four membrane tanks in total and each membrane tank presently has four outside-in hollow fibre membrane modules installed. Each membrane surface module provides 34.37 m^2 of membrane area. Design average flux rate is 31 lmh, with a short-term maximum of 36 lmh acceptable during wet weather inflows. The permeate pumps are used to extract flow through the membranes by the maintenance of a 0.3 m to 0.5 m head of water across the membrane (this trans-membrane pressure is dependent on the flux rate and the condition of the membranes).The plant is provided with six positive displacement blowers (three for fine bubble diffused aeration and three for coarse scouring of the membrane, all arranged in a two duty, one standby mode). The hollow fibre membranes require continuous aeration (air scouring) to avoid fouling. Permeate extraction is critically interlocked with aeration as even a very short period of permeate flow under non-aerated conditions risks seriously fouling the membranes and potentially requiring a labour intensive chemical clean. Consequently, even with process adjustments made to reduce aeration rates during low flow periods, approximately 50 % of the total aeration power is consumed by the membrane modules on the Malmesbury WWTW.

The full plant process capacity was installed, except for the membrane bioreactor (MBR) tanks where only four out of five cassettes have been installed/ fitted in each of the four membrane tanks. Each of four MBR tank is sized for five membrane units (or packs), but initially only four have been installed in each tank, with the remainder of the membrane units available for later installation. The current available membrane capacity is sufficient for a hydraulic design capacity of 2 x ADWF (i.e. PDWF of 20 Mλ/d), with an allowance to ultimately increase total peak capacity of the MBR plant by a further 25% to 2,5 x ADWF (i.e. PDWF of 25 Mλ/d)with additional membrane units.

Figure 2: Aerial photograph of the upgraded Malmesbury WWTW

5. UPGRADED MALMESBURY WWTW FLOW DESCRIPTION

All flow arriving at the works is split after the inlet works (at the outlet chamber) in a ratio of 85:15 up to a total flow of 20 Mλ/d (i.e. peak dry weather flow) of which the smaller fraction is routed to the existing treatment works (see Figure 3). The diverted mixed liquor from the Pasveer Ditch–MBR recycle pumpstation in the existing works plus the raw flow from the inlet works outlet chamber flows into the MBR plant up to a total of 20 Mλ/d. Mixed liquor from the internal a-recycle of the MBR plant is diverted back to the Pasveer Ditch to retain the required sludge mass in the system. The rate at which the mixed liquor is recycled from the anoxic zone of the MBR plant to the Pasveer Ditch is designed to retain the sludge concentration in the Pasveer Ditch between 3 000 and 5 000 mgTSS/λ.

Flow above 20 Mλ/d arriving at the inlet works flows to the Pasveer Ditch plant. This configuration ensures that, up to the design peak dry weather flow, all treated effluent from the upgraded works flows from the works via the membrane trains/units. When the flow to the works exceeds the design peak dry weather flow rate, excess flow which is not diverted from the Pasveer Ditch to MBR plant (via the PD-MBR recycle pumpstation) will flow to the secondary sedimentation tank.

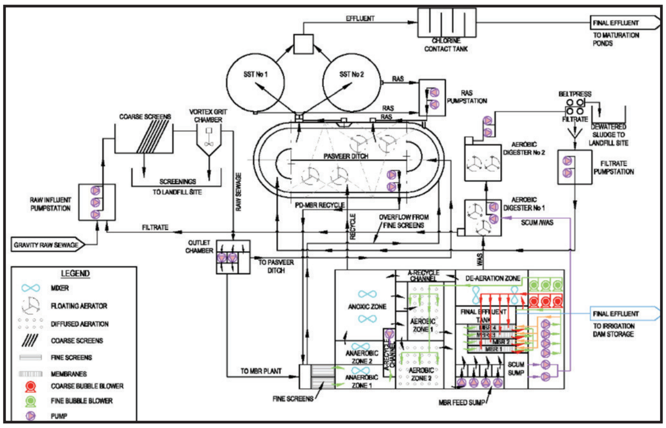

Figure 3: Process Flow Diagram of the upgraded Malmesbury WWTW

The treated flow from this tank is thus equal to the excess over the design peak dry weather flow. Modelling of the process indicated that the expected variation in mixed liquor suspended solids in the Pasveer Ditch will be within 10% of the design average value over the whole spectrum of hydraulic load variations. Even when the raw inflow is less than the peak dry weather flow, i.e. all flow from the existing Pasveer Ditch will be diverted to MBR plant, an internal s-recycle (i.e. return activated sludge) is retained at the Pasveer Ditch from the sedimentation tank to the bioreactor. The s-recycle rate is however equal to the flow rate of the sedimentation tank which means that there will be no flow over the weir of the secondary sedimentation tank. The benefits of the upgraded treatment works layout are:

- The existing Pasveer Ditch is incorporated into the overall treatment stream. Since the sludge mass required to treat the load on the works was a constant, the volume of the bioreactor of the MBR plant is reduced. The combined volumes of the two bioreactors are however more than if all sludge had been retained in a MBR plant.
- The reduced peak load on the MBR plant decreased the membrane area required.
- The disruption to the existing works during construction was limited to the construction of flow splitting between Pasveer Ditch and MBR plants.
- Most of the existing infrastructure was retained and incorporated into the future works (only the biofilter plant and sludge drying beds were decommissioned and ultimately demolished along with the inlet works which was not suitable and sufficient for the new upgraded treatment works).

6. EFFLUENT DISCHARGE REQUIREMENTS

Driven by concerns for the long-term protection of the sensitive Diep River, Department of Water Affairs (DWA) indicated that they will impose a stringent effluent quality standard for the upgraded works. Thus the treatment works has been designed to comply with the target effluent discharge standard shown in Table 1. Swartland Municipality had further opted to conform to the DWA guidelines, targeting a clear effluent with <5 TSS (50%ile). At least 80% of the effluent was to be reused for irrigation of local farmers' crop, school fields and golf course as well as the treatment works site. This required low faecal coliform counts (50 No. per 100 mλ, geometric mean) for land application of the effluent.

Table 1: Treated Effluent Quality Target

Parameter	Unit	Effluent Quality Target	Requirement Type	Maximum Value
Chemical Oxygen Demand	mgCOD/ℓ	<50	80%	65
Free & Saline Ammonia	mgN/ℓ	1	50%	3
Total Kjeldahl Nitrogen (TKN)	mgN/ℓ	5	50%	10
Nitrate/Nitrite	mgN/ℓ	8	50%	12
Ortho-phosphate	mgP/ℓ	1	50%	2.5
Total Suspended Solids	mgTSS/ℓ	<5	80%	10
pH	-	5.5 - 7.5	Range	-
Faecal Coliform	(Count/100 mℓ)	5	Geomean	50

7. PRELIMINARY PERFORMANCE OF THE UPGRADED MALMESBURY WWTW

Five months of operational data has been recorded for the Malmesbury WWTW since the implementation of the MBR. Weekly laboratory tests (18 test days) have been conducted from March 2013 until July 2013. The raw sewage data is summarised in Table 2 and effluent results are summarised in Table 3. Data presented in these tables excludes the construction and early commissioning periods from September 2010 to February 2013.

The treatment works has a high strength COD, which is in line with the design values of (average of 1 000 mg/λ and peak of 1 400 mgCOD/λ).

Trends for effluent quality data are shown in Figures 2 to 5. Performance has met or exceeded the effluent target requirements since commissioning was completed (March 2013).

7.1 Reactor mixed liquor suspended solids (MLSS)

Variation in the MBR reactor concentration is depicted in Figure 4. Intermittent significant variations in the reactor MLSS concentrations were measured, due to initial approach to steady state. The variation in MLSS did not appear to exert any significant influent on the membrane performance and effluent quality. Also, operating the system at slightly higher MLSS concentrations (7 500 to

Table 2: Raw Sewage Data (Mar 2013 - July 2013)

Parameter	Unit	50th Percentile	80th Percentile	Maximum Value
Chemical Oxygen Demand	mgCOD/ℓ	1 068	1 277	1 403
Free & Saline Ammonia	mgN/ℓ	97	112	156
Total Kjeldahl Nitrogen (TKN)	mgN/ℓ	112	131	160
Total Phosphate	mgP/ℓ	15.9	17.9	20.8
Total Suspended Solids	mgTSS/ℓ	288	352	454
pH	-	7.3	7.5	7.7

Table 3: MBR Performance/ Effluent Data (Mar 2013 - July 2013)

Parameter	Unit	50th Percentile	80th Percentile	Maximum Value
Chemical Oxygen Demand	mgCOD/ℓ	31	36	39
Free & Saline Ammonia	mgN/ℓ	0.2	0.8	1.5
Total Kjeldahl Nitrogen (TKN)	mgN/ℓ	2.0	3.0	6.9
Nitrate/Nitrite	mgN/ℓ	5.9	8.4	10.6
Ortho-Phosphate	mgP/ℓ	1.0	1.4	2.1
Total Suspended Solids	mgTSS/ℓ	4	4	6
pH	-	6.5	6.8	7.0
Faecal Coliform	(Count/100 mℓ)	2	6	10

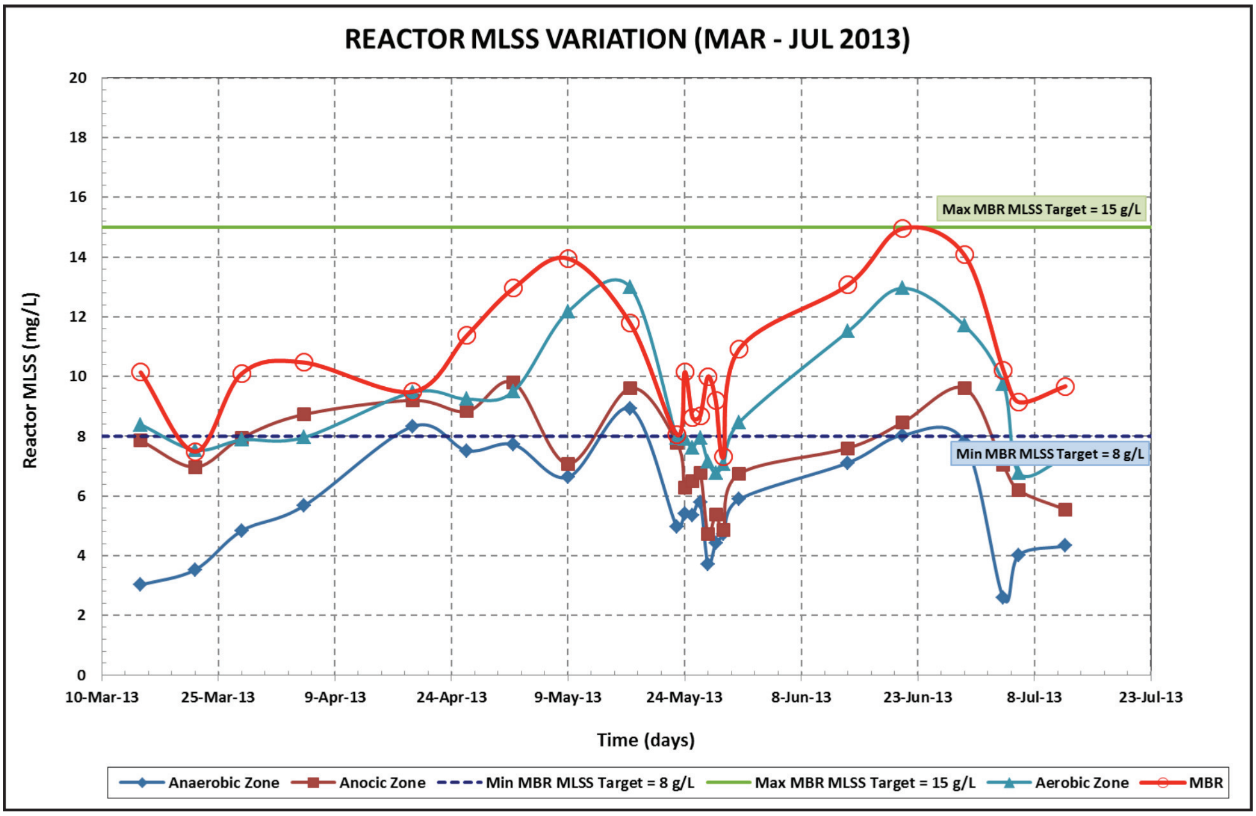

Figure 4: Reactor mixed liquor suspended solids (MLSS)

14 500 mgTSS/λ) than recommended (8 000 to 12 000mgTSS/λ) did not appear to impact negatively on the membrane performance. However, there may be a long term influence not obvious from the available data. The process is not sensitive to variations in the sludge qualities that can impact on the settleability of the sludge (as was previously the case with the conventional treatment works). The possibility of washing sludge out of the system to the downstream environment is therefore eliminated.

7.2 Effluent Data

Despite markedly high variability in influent parameters, the treatment works had consistent excellent removal efficiency (Figures 5 to 9) in excess of 97 % for COD, NH3-N, TKN and TSS, while P removal exceeded 93 %. Effluent TSS has been very good, with no results exceeding 6 mgTSS/λ, well below the discharge target of 10 mgTSS/λ, shown in Table 1. With inherent advantage of 0,04 μm pore size membranes used, the MBR completely retained all the solids within bioreactor, and generated solids free effluent (Table 3 and Figure 9), hence the lower effluent COD in comparison with the traditional 0,45 μm from a conventional activated sludge system. As anticipated, the ultrafiltration effluent contained soluble contaminants only, and no organic nitrogen or phosphorous.

Removal of indicator bacteria (faecal coliforms, F-Coli) has been good with only four out of eighteen samples (up to July 2013) exceeding the 80th percentile discharge requirement (> 6 F Coli/ 100 mλ). There is no clear explanation for these sporadic spikes in faecal coliform levels; however it is suggested that it may be due to sampling collection issues (i.e. dirty bottles). In theory there should be no transfer of faecal coliforms through membranes (unless there is an integrity breach, which would show up in effluent TSS data). However, from Figure 9, it is unlikely that there was an integrity breach.

8. CONCLUSIONS

The additional capacity provided by the new hybrid MBR plant allows for additional development to occur (i.e. especially that which was deferred because of lack of adequate treatment capacity), connect many previously disadvantaged homes and also to move many homes off septic system that are currently contaminating the surrounding water ways – a step which allows the Municipality to connect every home into the sewerage network system. Overall the upgrading of the treatment works to MBR was a success, satisfying all the objectives as set forth in the planning stage. By utilising the existing infrastructure optimally, keeping the existing Pasveer Ditch plant and digester – a significant cost saving was realised with minimal interruption to the operation of the existing

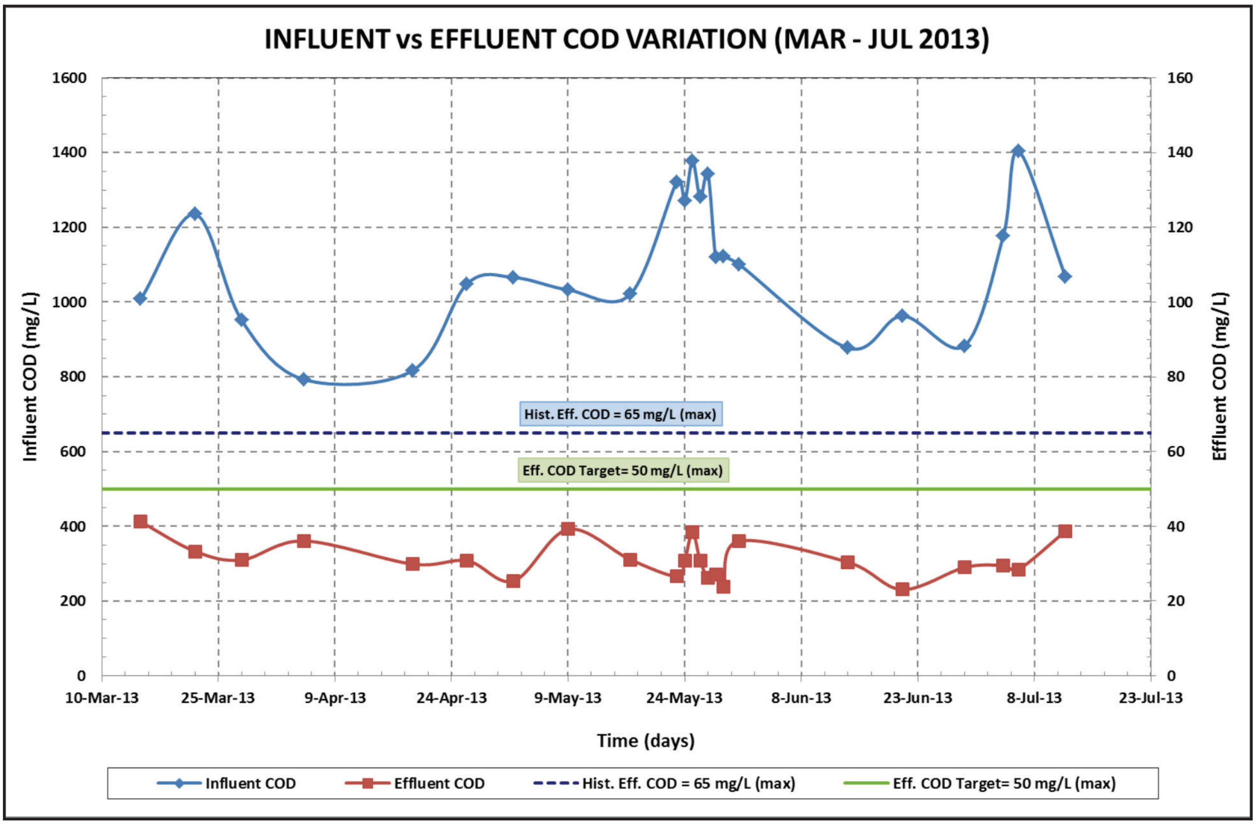

Figure 5: COD removal at Malmesbury WWTW (March 2013 to July 2013)

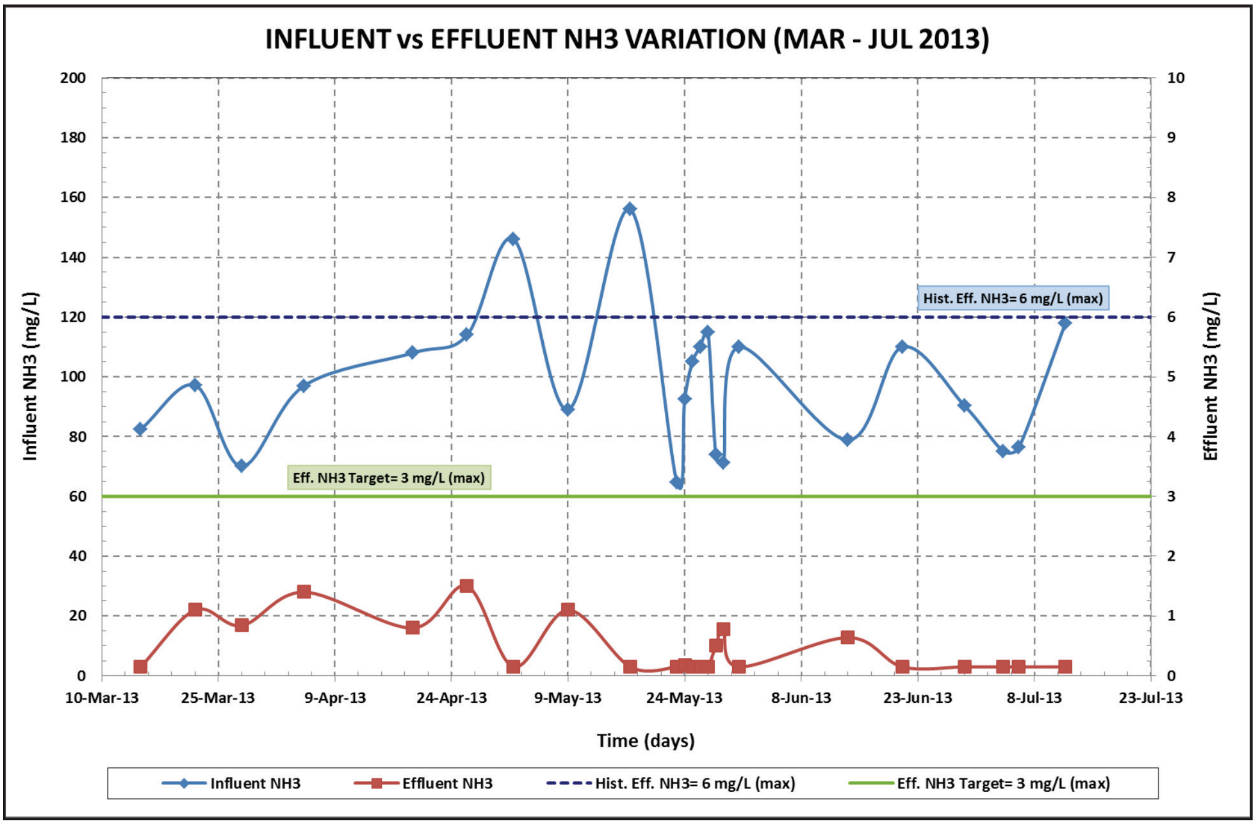

Figure 6: Ammonia removal at Malmesbury WWTW (March 2013 to July 2013)

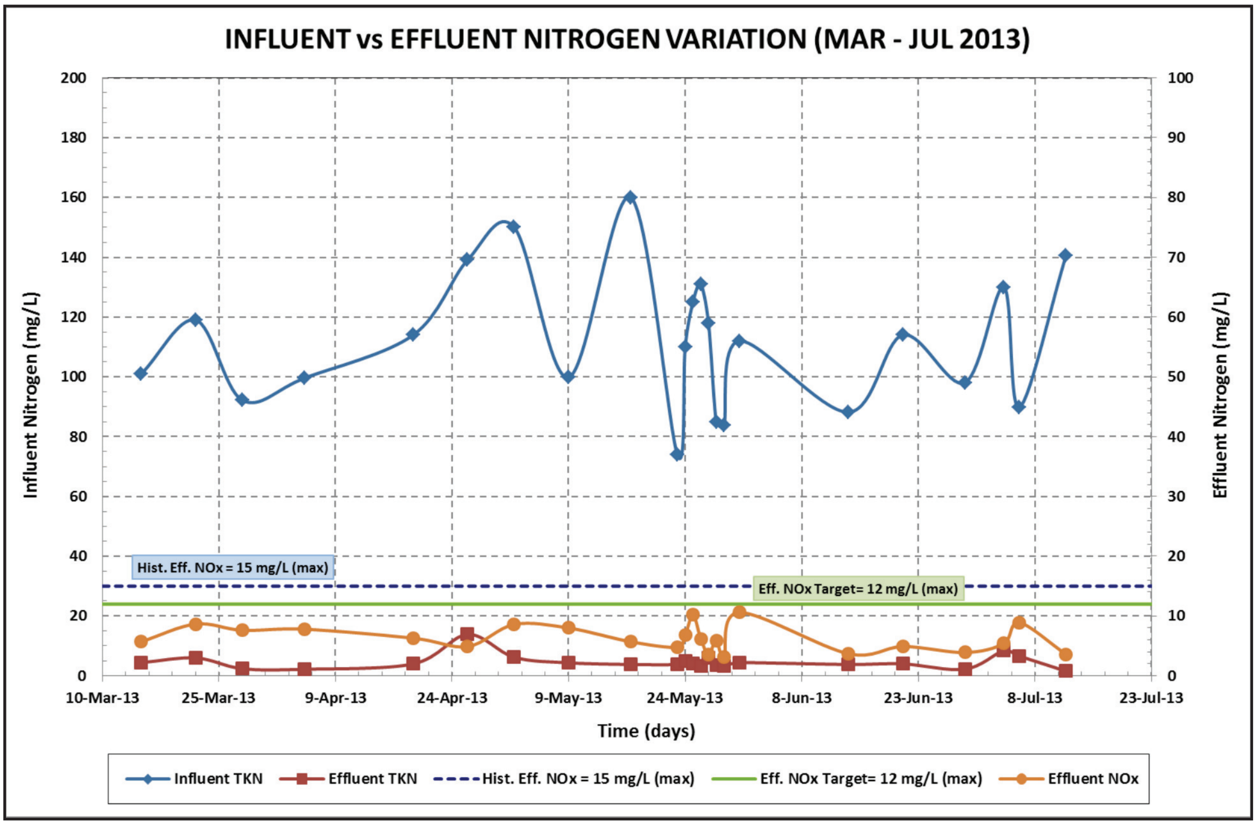

Figure 7: Nitrogen removal at Malmesbury WWTW (March 2013 to July 2013)

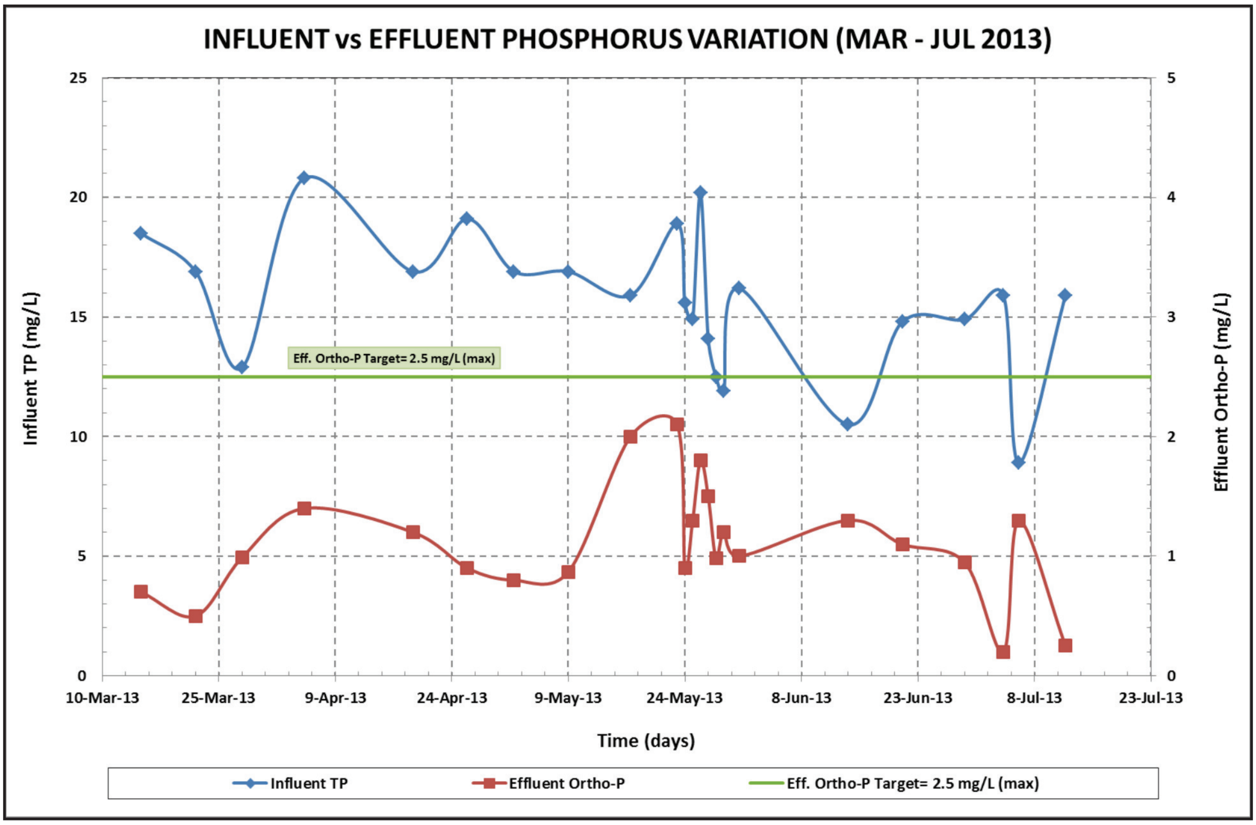

Figure 8: Phosphorus removal at Malmesbury WWTW (March 2013 to July 2013)

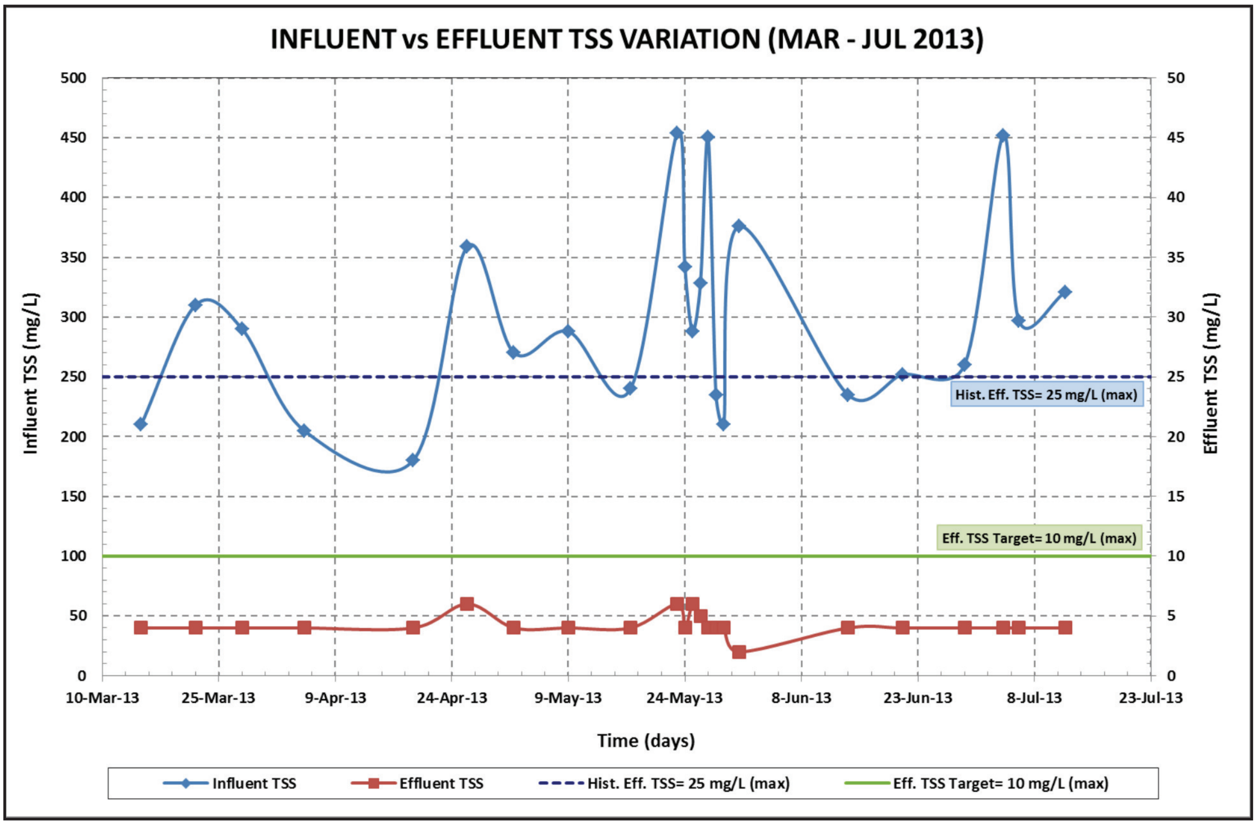

Figure 9: Solids removal at Malmesbury WWTW (March 2013 to July 2013)

treatment works. The system is designed to accommodate seasonal flow variation, and provide operational flexibility and energy saving. The upgrade increases the plant hydraulic capacity to a peak wet weather flow of 30 Mλ/d and PDWF of 20 Mλ/d, while achieving the most restrictive effluent requirements. The projects described in this paper represent the application of state-of-the-art membrane technology to wastewater treatment and water re-use for non-potable applications. The technology has proven reliable and robust for non-potable use applications and the process is relatively simple to operate. The Malmesbury WWTW has been operating successfully for over five months and has consistently met stringent effluent quality standard requirements, with excellent removal of COD, Nitrogen, TP, TSS, and faecal coliforms. Notable characteristics of plant performance over the five months have included:

- Continuous excellent COD, TN, TP, TSS and faecal coliform removal;
- Compliance with all design parameters over the last five months of operation;
- Ability to operate under low loads;
- Reliable performance of the membranes;

9. ACKNOWLEDGEMENTS

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