Setting new low energy benchmarks for Australian Sewage Treatment with Plastic Media Trickling Filters and Constructed wetlands – a 1ML/day case study

Authors:
- Ian Kikkert – The Water and Carbon Group; i.kikkert@waterandcarbon.com.au
- Barrett Moulds – Water Corporation; barrett.moulds@watercorporation.com.au
- Vanessa Personnaz – The Water and Carbon Group; v.personnaz@waterandcarbon.com.au

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Abstract
Water Corporation recently upgraded the 1ML/day Narrogin Wastewater Treatment Plant (WWTP), 2.5hrs South East of Perth, involving the construction of a new plastic media trickling filter with a two hectare treatment wetland. The upgrade aims to improve the final effluent quality released to a stream to TN<5.8mg/L; TP<2mg/L, whilst still allowing reuse within the township.

This paper analyses the energy and economic inputs for the Narrogin WWTP upgrade relative to BOD and TN reduction, and compares the results to five other similar sized operational treatment plants within Water Corporation.

The paper demonstrates that the Trickling Filter / Wetland combination used at Narrogin, affords utilities with a solution that has significantly lower energy requirements to achieve high nutrient standards, compared to more common mechanical mainstream process choices.
Introduction

The Water Corporation is the principal supplier of water, wastewater and drainage services throughout the state of Western Australia. The corporation is owned by the Western Australian Government and manages an asset base over $15 billion (AUD). Water Corporation is responsible for operating 109 wastewater treatment plants (WWTPs) across Western Australia.

The township of Narrogin is approximately 4,000 people located in the Western Australian wheatbelt, 2.5hrs South East of Perth. Narrogin WWTP is one of the wastewater treatment plants operated by Water Corporation. It treats approximately 0.9ML/day of municipal effluent generated from the township. During the summer months, effluent from the WWTP is used to irrigate some of Narrogin’s parks and gardens. In winter months, effluent is released to the local Narrogin brook.

In 2015, Water Corporation commenced work to upgrade the Narrogin WWTP to improve its performance, particularly to meet lower nutrient discharge requirements of TN=5.8mg/L and TP = 2mg/L. Prior to the upgrade, limited nutrient treatment was achieved, resulting in effluent being a significant contributor to the overall nutrient loading to the local brook. The upgrade comprises:

- replacement of three stone media trickling filters with a new 290m$^3$ plastic media trickling filter, specifically designed to remove BOD and partially nitrify the effluent; and
- Construction a 20,000m$^2$ Free Water Surface (FWS) Wetland to remove nutrients prior to discharge to the environment.

Once completed in early 2016, the Narrogin WWTP will include:

1. Inlet screen – mechanical spiral sieve (existing)
2. 2 x primary aerated lagoons ~4,200m$^2$ total area for both (existing)
3. 1 x Plastic media Trickling Filter – 290m$^3$ (new)
4. 2 x humus clarifiers ~8m diameter. Includes aluminium chlorohydrate (ACH) dosing for P removal. (existing)
5. Effluent reuse lagoon / chlorination (existing)
6. 2 x 10,000m$^2$ high density FWS wetlands (new), prior to discharge to the Narrogin Brook
**Trickling Filter**

Trickling filters are fixed film bioreactors that typically comprise the following key components:

A. Media such as rocks, gravel or plastic that provides a structure for microbes to attach.
B. A distributor system to evenly disperse the wastewater over the media.
C. A containment tank to hold the media. This is not designed with water holding capacity, as media should be free draining.
D. Ventilation holes at the base of the containment tank to allow air (oxygen) to be drawn into the media to support aerobic microbial reactions.

![Figure 1– General schematic of Trickling Filter operation](image-url)
Treatment occurs as wastewater trickles from the top of the media to the bottom, interacting with the biofilms attached to the media as the water cascades down. Trickling Filters are usually designed as a fully aerobic reactor, and therefore are particularly effective at BOD removal (organics) and nitrification (ammonia to nitrate).

Although Trickling Filter technology is over 100 years old, it is only in recent decades the advent of high surface area structured plastic media has reshaped the expectations of treatment outcomes from Trickling Filters. Structured plastic media that has >97% void, and surface areas greater than 125m²/m³ is 2-3 times more efficient compared to the equivalent volume of traditional stone/rock trickling filters. The continuous flow path afforded by the structure of the plastic media has significantly overcome risk of operational problems associated with stone/rock media trickling filters, such as clogging and filter flies.

One of the major operational benefits that Trickling Filters afford wastewater treatment is the lower energy requirements compared to conventional suspended growth bioreactors (e.g. activated sludge). In Trickling Filters, oxygen is supplied to the microbial reactions through passive ventilation, without the need for energy intensive mechanical blowers as is required with conventional activated sludge systems. Consequently, the only energy required is for delivering the wastewater to the top of the trickling filter vessel (typically by pumping).

The upgraded Narrogin Trickling Filter has the following design features:

- 10m diameter, Epoxy coated panel tank, ventilation holes cut into lower panels - 500mm diameter.
- 125m²/m³ cross-flow structure media, 3.6m deep, raised 0.9m above the base slab to allow free ventilation.
- A rotating distributor that is hydraulically driven
- Design based on achieving full BOD removal and partial nitrification
- 100% recirculation back to primary aerated ponds.

**Free Water Surface (FWS) Wetland**

FWS wetlands also operate as fixed film bioreactors; however, instead of the plastic or stone providing the fixed structure for biofilms to grow and deliver treatment to wastewater, it is the plants whose leaves, stems and detritus provide this substrate. FWS wetlands operate as shallow water bodies where water flows through the wetland plants e.g. figure 2 below.

When fully established, plant densities are several hundred stems per m². Water depth can temporarily increase or decrease as part of the ongoing management, but it is crucial that water depth does not rise above 0.5m for more than several weeks to avoid affecting plant health.

A number of treatment mechanisms occur within FWS wetlands: physical sedimentation, adsorption of heavy metals and other compounds, carbonaceous degradation and denitrification. They can be designed to achieve different outcomes for many different size
operations. An example of a large FWS wetland application is the Nimr Treatment Wetland in Oman which treats 115ML/d and is over 700ha in size.

![Figure 2 – schematic of free water surface (FWS) wetland.](image)

The Narrogin FWS wetland is designed with 2 x 10,000m² bentonite geofabric lined cells (235m x 43m). It will be operated at 200-300mm depth, which is an environment conducive to denitrification reactions with lower oxygen and a ready supply of natural carbon from the plants. The design has been developed to gravity feed the water from the Trickling Filter to the wetland inlet, and then from the end of the wetland to the environmental discharge point (stream).

FWS wetlands require a similar amount of operator attention as facultative pond treatment systems, with the primary activities being to ensure appropriate water levels and monitoring of vegetation health. Maintenance is minimal: no harvesting is required since nitrogen removal is facilitated by bacteria rather than relying on biomass uptake. Dead plant material does not require removal – it forms part of the substrate for the fixed film of bacteria, plus is the carbon source for bacteria-mediated denitrification.

**Low Energy Design for Narrogin**

Plastic Media Trickling Filters and Constructed Wetlands are often dismissed by the wastewater industry as viable treatment solutions for WWTP upgrades because individually they are generally unable to meet modern nutrient licence conditions. However, by combining these processes - as has been done for the Narrogin WWTP upgrade - they become complementary technologies with many advantages.
Treatment Plant Descriptions
To benchmark Narrogin’s performance, economics and energy use, five Water Corporation WWTPs of similar size have been selected to compare Narrogin against. All are located in similar climate but use different process treatment technologies. The five benchmark sites are (described further below):

- Manjimup
- Harvey
- Dunsborough
- Margaret River
- Busselton

Manjimup
Manjimup is an inland town, about 300km south of Perth. The Manjimup WWTP consists of a series of ponds; two aerated and a non-aerated primary pond (~1.1ha), two facultative secondary ponds (0.6ha), and a tertiary pond (0.4ha) with alum dosing. The WWTP currently treats on average about 0.95ML/day, with the final chlorinated wastewater being irrigated onto a woodlot and the golf course.

Harvey
Harvey is located approximately 140km south of Perth. The Harvey WWTP comprises an aerated oxidation pond, followed by 3 facultative waste stabilisation ponds (~2ha area) and alum dosing. The WWTP currently treats on average about 0.81ML/day, with the final chlorinated wastewater being irrigated onto a woodlot and the golf course. The Harvey sewer system experiences a high amount of stormwater infiltration with the result that wastewater flow per EP is relatively high – this may make Harvey WWTP performance (per ML) appear better than the treatment process is capable.

Dunsborough
Dunsborough is a coastal town, located about 250km south of Perth. Dunsborough WWTP consists of an activated sludge system - Intermittently Decanted Extended Aeration (IDEA) plant - with alum dosing. It treats an average daily flow of 1.36 ML/day. Treated wastewater is used to irrigate a plantation woodlot during summer and is discharged to ‘Station Gully Drain’ during winter months.

Margaret River
Margaret River is located approximately 270km south of Perth. The Margaret River WWTP consists of an activated sludge system - Intermittently Decanted Extended Aeration (IDEA) plant - with alum dosing. It treats an average daily flow of 1.29 ML/day. The treated wastewater is recycled to irrigate public open space, school ovals, a golf course and a woodlot.
**Busselton**

Busselton is a coastal town approximately 220km south of Perth. The Busselton WWTP treats wastewater by an activated sludge system (oxidation ditch), treating on average 4.46ML/day. Treated wastewater is reused for public open spaces and private land in summer. A major upgrade was completed on the Busselton plant in 2013.

**Basis of Data**

Historical operating data was collated from Water Corporation databases. Water quality data was based on monthly samples. Flow data was determined from magnetic flow meters. Cost data were the total operating costs recorded against each WWTP inclusive of maintenance, repairs, operating labour, chemicals and electricity. The costs include support expenses such as supervision, vehicle fleet, administration, IT charges, etcetera. Costs related to reuse varied between each WWTP due to reasons such as whether filtration was included and the pumping energy required to convey the recycled water to offsite reuse locations. This study did not attempt to normalise variability in reuse costs or remove the reuse costs from the operating cost estimates – Narrogin WWTP’s reuse conveyance and disinfection costs are borne by the Shire not the Water Corporation.

Although costs for different studies are difficult to accurately compare because of the underlying assumptions, the important aspect to appreciate is that that this study uses a relative base (being costs taken from the one utility). Analysis was taken over full years 2013, 2014, and 2015. Busselton taken over 2014/15 to account for upgrade.

Narrogin WWTP energy use and costs are based on past operational information plus projected (modelled) energy usage and operational costs associated with the new trickling filter and new treatment wetland. Process modelling of the Trickling Filter was based on Velz equation for BOD (Veltz, 1948) and Boller and Gujer for nitrification performance (Gujer W., Boller M., 1985). The FWS wetland performance was based on design algorithms using first-order areal rate coefficients (Kadlec and Wallace, 2009). The FWS wetland model coefficients were based on Australian experience of similar FWS design (Personnaz V.C et al, 2014).
Results and Analysis
The data extracted for each of the six WWTPs is shown in tabular and graphical form, focusing on:

- Energy use: kWh/ML and kWh/EP. Energy use is presented in terms of flow and Equivalent Population (EP) to allow further comparisons against different energy benchmarking data in literature. Some studies utilise kWh/ML e.g. Andriany S, Mulliss M, (2013) whilst other studies use kWh/EP.year (e.g. de Haas et al, 2015).
- Operational costs
- BOD removal efficiency: performance, cost ($ AUD) and kWh per kg BOD removal
- NH3 removal efficiency: performance, cost ($ AUD) and kWh per kg NH3 removal
- TN removal efficiency: performance, cost ($ AUD) and kWh per kg TN removal

Energy

Table 1 – Comparison of Six Water Corporation WWTPs Energy Performance

<table>
<thead>
<tr>
<th>WWTP</th>
<th>EP</th>
<th>Process</th>
<th>Annual kWh</th>
<th>Annual Flow (ML)</th>
<th>Ave Daily Flow (ML/d)</th>
<th>kWh/ML</th>
<th>kWh/EP.year</th>
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<td>TF/Wetland</td>
<td>137,280</td>
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<td>409</td>
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<td>1,338</td>
<td>84.16</td>
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* Narrogin energy performance is a combination of historical information and projections.
**Fig 3** – Comparison of Six Water Corporation WWTPs Energy Performance kWh per ML/day

**Fig 4** – Comparison of Six Water Corporation WWTPs Energy Performance kWh/EP.year VS ML/day
Operational Costs

Table 2 – Comparison of Six Water Corporation WWTPs Annual Operational Costs

<table>
<thead>
<tr>
<th>WWTP</th>
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<th>Process</th>
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<th>$/kL</th>
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<td>Dunsborough</td>
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<td>461,635</td>
<td>0.93</td>
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<td>Margaret River</td>
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<td>IDEA</td>
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<td>Oxidation Ditch</td>
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* Narrogin costs are a combination of historical information and projections.

Fig 5 – Comparison of Six Water Corporation WWTPs Operational Costs

BOD Removal

Table 3 – Comparison of Six Water Corporation WWTPs BOD Removal Performance

<table>
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<tr>
<th>WWTP</th>
<th>EP</th>
<th>Process</th>
<th>BOD In (mg/L)</th>
<th>BOD Out (mg/L)</th>
<th>BOD removal (mg/L)</th>
<th>kg BOD remove d / year</th>
<th>kg BOD removed / kL</th>
<th>kWh / kg BOD removed</th>
<th>Annual $ / kg BOD removed</th>
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<td>Process</td>
<td>NH3 In (mg/L)</td>
<td>NH3 Out (mg/L)</td>
<td>NH3 removal (mg/L)</td>
<td>kg NH3 removed / year</td>
<td>kg NH3 removed / kL</td>
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<td>$/ kg NH3 removed</td>
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<td>15.51</td>
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*N Narrogin BOD removal is a combination of historical information and projections.

**Comparison of Six Water Corporation WWTPs**

$/$kg BOD removed Vs kWh/kg BOD removed

**Fig 6– Comparison of Six Water Corporation WWTPs BOD Removal Performance**

**NH3 Removal**

**Table 4– Comparison of Six Water Corporation WWTPs NH3 Removal Performance**
**Narrogin NH3 removal is a combination of historical information and projections.**

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**Fig 7– Comparison of Six Water Corporation WWTPs NH3 Removal Performance**

**TN Removal**

**Table 5– Comparison of Six Water Corporation WWTPs TN Removal Performance**

<table>
<thead>
<tr>
<th>WWTP</th>
<th>EP</th>
<th>Process</th>
<th>TN In (mg/L)</th>
<th>TN Out (mg/L)</th>
<th>TN removal (mg/L)</th>
<th>kg TN removed / year</th>
<th>kg TN removed / kL</th>
<th>kWh / kg TN removed</th>
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<tr>
<td>Narrogin*</td>
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* Narrogin TN removal is a combination of historical information and projections.
When comparing the different treatment processes it is important to not only consider, the energy used in treatment and the cost of operation, but also whether or not the treatment process is able to meet the final effluent quality required. For example, the two facultative pond systems (Harvey and Manjimup) would not be suitable to achieve high quality outcomes if required, irrespective of their energy or cost standing.

To take account of the performance aspects, the WWTP processes should therefore be considered in two groups:

- Low performing technologies – Facultative ponds (Harvey, Manjimup)
- High performing technologies – IDEA, Oxidation Ditch, TF/wetland (Busselton, Margaret River, Dunsborough, Narrogin)

Energy

Comparing against a kWh/EP.year basis, Narrogin WWTP has the lowest energy use of all the treatment plants analysed, including the facultative ponds. It uses 71% less energy per EP than the Busselton Oxidation Ditch and 74% less energy than the Dunsborough IDEA plant. The Margaret River IDEA plant had only slightly higher energy use than Narrogin on a per EP basis (12% higher), however comparing on a flow basis, the Margaret River IDEA used 60% more energy compared to the Narrogin WWTP.

It is possible that further energy reductions will be achieved at Narrogin WWTP once operation commences, as the aerators in the primary ponds could potentially be turned down with the addition of an internal recirculation stream of nitrified effluent, subject to managing
odour from the ponds (which is the reason aeration has historically been used at Narrogin WWTP).

Operational Costs
Operational costs are a factor of scale, plant location, and treatment process technology. Whilst the non-cost predictors of the Narrogin WWTP performance have a solid theoretical or design basis, the long term cost estimations are less certain, particularly until the Narrogin upgrade plant has a full year of operation, which will allow time for the wetland vegetation to become fully established and to observe seasonal effects.

The costs used for Narrogin WWTP analysis are projections based on recent past performance (2015). The nature of the processes used (Trickling Filters and Wetlands) are known for their simplicity and low operational requirements, so it is expected to see operational costs achieve below industry average in the future.

The Narrogin WWTP operating cost is projected as below average $/kL compared against the other three high performing plants, albeit acknowledging that the Margaret River IDEA plant was about double the $/kL of the other high performing plants, and that the Busselton Oxidation ditch is five times the capacity, so will have some economies of scale.

BOD Removal Efficiency

The Harvey WWTP Facultative pond system has the lowest cost/ kg BOD removed, which is not surprising given it is a pond based treatment process. The Busselton WWTP oxidation ditch has the next lowest cost to remove BOD / kg, which is reflecting of its larger size. The Narrogin WWTP is 26% higher operational costs than Busselton WWTP to remove BOD, reflecting that it is also five times smaller capacity. A Margaret River WWTP IDEA plant has the highest cost to remove BOD per kg, 93% more expensive than Narrogin / kg BOD removed.

Comparing the data against the higher performance plants, Narrogin WWTP has the lowest energy to remove each kg of BOD. It uses 67% less energy per kg BOD removed compared to Busselton, and an average of 51% less energy compared to the IDEA plants.

TN and NH3 Removal Efficiency
Analysis of NH3 and TN removal is only relevant for the Narrogin, Dunsborough, Margaret River and Busselton because Manjimup and Harvey WWTP processes do not effectively address NH3. Busselton has the least cost to remove each kg of NH3 and TN, which is also expected with the economies of scale that Busselton WWTP brings. Narrogin WWTP is next most cost effective plant to remove NH3 and TN, which will be due to efficiency of the passive Plastic Media Trickling Filter nitrification process.
On an energy basis, Narrogin WWTP uses the least amount of energy to remove each kg NH3 and kg TN compared to the other treatment plants. Its uses between 38%–75% less energy than the IDEA or Oxidation Ditch plants.

**Conclusion**

The Trickling Filter / Wetland arrangement developed for the Narrogin WWTP upgrade, is a significantly lower energy solution compared to all equivalent performing technologies on all measures of energy efficiency: kWh / EP.year; kWh / kg BOD removed; kWh / kg NH3 removed; kWh / kg TN removed.

It is too premature to draw any significant conclusions at this stage about Narrogin WWTP’s operational costs until the upgraded plant has been operating for several years. However the current operational forecasts are within expected range for this size of plant, and show promise, being about 48% cheaper than the more expensive IDEA operation of Margaret River.

This paper demonstrates a Trickling Filter/FWS wetland combination should be considered as one of the process choices for future utility upgrades and greenfield plants, especially where energy reduction of an overall treatment plant is a significant design criterion.

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**References**


