Full-scale operating experience of deep bed denitrification filter achieving <3 mg/l total nitrogen and <0.18 mg/l total phosphorus

Joseph A. Husband, Larry Slattery, John Garrett, Frank Corsoro, Carol Smithers and Scott Phipps

ABSTRACT

The Arlington County Wastewater Pollution Control Plant (ACWPCP) is located in the southern part of Arlington County, Virginia, USA and discharges to the Potomac River via the Four Mile Run. The ACWPCP was originally constructed in 1937. In 2001, Arlington County, Virginia (USA) committed to expanding their 113,500 m³/d, (300,000 pe) secondary treatment plant to a 151,400 m³/d (400,000 pe) to achieve effluent total nitrogen (TN) to < 3 mg/l and total phosphorus (TP) < 0.18 mg/l. Key to this conversion was the implementation of deep bed denitrification filters to simultaneously achieve both low effluent TN and TP concentrations. A challenge with implementing this technology is maintaining a health denitrifying biomass within the denitrification filters while reducing an essential nutrient, phosphorus, to very low concentrations. This paper will review the steps from concept to the first year of operation, including pilot and full-scale operating data and the capital cost for the denitrification filters.

Key words | denitrification filters, nitrogen removal, phosphorus removal

INTRODUCTION

The Arlington County Wastewater Pollution Control Plant (ACWPCP) is located in the southern part of Arlington County, Virginia, USA. The ACWPCP was originally constructed in 1937 and has had several upgrades. The facility treats mainly domestic sewage and was converted to a biological nitrogen removal (BNR) facilities using step feed activated sludge with an average flow capacity of 113,500 m³/d and a peak treatment capacity of 189,500 m³/d during wet weather events in 2001. The facility was able to achieve annual effluent total nitrogen (TN) of 8 mg/l and total phosphorus (TP) of <0.18 mg/l. The facility consisted of influent screening, vortex grit removal, primary treatment (with ferric addition), off-line equalization, step-feed activated sludge with final settling tanks, lime reaction tanks (LRTs) for phosphorus removal (originally installed as a two-stage chemical precipitation process for phosphorus removal), gravity sand filters, carbon filters, chlorine disinfection and post aeration. In addition, the facility had the ability to blend screened raw wastewater and disinfected primary clarifier effluent with the secondary-treated effluent, see Figure 1, prior to discharge to Four Mile Run.

The County finalized their 2001/2003 Master Plan (Master Plan 2003) and decided to expand their existing 113,500 m³/d facility to provide 151,400 m³/d average daily flow capacity (178,000 m³/d including internal plant recycles). Peak flow capacity was expanded to treat 363,400 m³/d (including internal plant recycles) through the facility for several days due to wet weather events. Effluent quality requirements were also increased to achieve a 3 mg/l TN discharge on a monthly basis, while still achieving an effluent < 0.18 mg/l TP, as part of the revitalization effort for the Chesapeake Bay, which the Potomac River discharges. Severe plant site space constraints prohibited conventional expansion of the existing facilities to achieve these extremely low nutrient goals. Virtually every process and structure at the facility was renovated. The expansion and upgrade of the facility included additional primary effluent equalization tanks, increasing biological reactor volume, replacing the LRT units with additional secondary

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clarifiers and the replacement of the carbon filters with deep bed denitrification filters as shown in Figure 2. The total construction cost for the plant upgrade/expansion is approximately US$389 million.

**Nitrogen removal challenges**

As shown in Figure 1, the facility had limited space for expansion. Detailed process modeling indicated that the facility even with an expanded activated sludge system would require a downstream denitrification process to reduce the TN < 3 mg/L. This was due to colder and higher influent flows caused by wet weather periods in the spring. Modeling indicated that the entire step feed BNR system must be operated aerobically to sustain sufficient aerobic solids retention time to maintain full nitrification. Thus, denitrification filters were chosen to provide the second-stage denitrification process as these have the advantage of removing solids, nitrogen and phosphorus. These filters must have the capability of managing a highly variable oxidized nitrogen loading caused by a significant flow increase and reduced TN removal in the activated sludge system during wet weather conditions. This approach will require that sufficient populations of denitrifying microorganisms are retained in the filters to respond to significant nitrate load variations that can more than double during wet weather events.

**Planning for success**

The key implementation issue was to define the efficiency of the denitrification filters in a phosphorus limited situation. Discussion with manufacturers and a literature review indicated that there were a few facilities in Europe that indicated operational and effluent issues with low phosphorus concentrations (<0.5 mg/l TP). A pilot study conducted with a moving bed biological reactor denitrification process 'qualitatively showed that low phosphate concentrations had a negative effect on the denitrification rate' and full-scale operations indicated that around 0.3 mg/l of dissolved phosphorus was a crucial point for denitrification (Taljemark et al. 2004). A fluidized bed denitrification process study noted problems with uncontrolled biological growth when the influent feed to the unit was <0.5 mg/l phosphorus (Harri & Bosander 2004). Attempts to reduce upstream phosphorus removal prior to the denitrification process were not reliable, and that facility provided supplemental dosing of soluble phosphorus to the reactor. In the USA, vendors of denitrification filters were contacted and no applications with effluent TP of <0.5 mg/l were identified. Accordingly, based on the lack of information on operating denitrification filters to simultaneously achieve high levels of denitrification (oxidized nitrogen <1 mg/l) and total phosphorus removal to less than 0.3 mg/l in a denitrification filter, a demonstration study was required.

The Master Plan (Master Plan 2003) identified two denitrification processes to be evaluated for the facility expansion: deep bed denitrification filters (DBF) and continuous backwash filters (CBF). The DBF process has been used since the early 1970s to provide denitrification at a number of large wastewater treatment facilities. However, the need for backwash holding tanks to equalize the periodic filter cleanings increased cost for this units operation.
To reduce the volume and magnitude of numerous internal recycles at the ACWPCP, the CBF technology was of particular interest to the County due to the potentially easier management of a constant fixed-rate filter backwash flow. Not requiring a backwash holding/equalization tank and potentially lower backwash flow under peak conditions when the plant is already stressed hydraulically was desirable. However, unlike DBF, the use of CBFs for denitrification had a very limited track record.

A three month, side-by-side on-site demonstration study (Husband et al. 2005) of the two filter technologies was conducted in order to:

- Evaluate the two filter technologies ability to achieve permit limits.
- Determine the ability to denitrify under very low soluble phosphorus conditions.
- Identify the need for supplemental phosphorus addition.
- Provide information to aid in the life-cycle cost analysis, including backwash, methanol use, and general operational requirements.

Details of this testing were reported by Husband et al. (2005). In summary, the DBF technology was selected based on the following findings:

- The CBF filter was not able to achieve equivalent performance as the DBF under low phosphorus concentration. It was suspected that the high intensity backwash in the CBF could be contributing to a high phosphorus demand versus the DBF.
- At the average influent flows and loads, with influent nitrate-nitrogen typically 6 to 8 mg/l and without supplemental phosphorus addition, the DBF filter was able to meet the effluent TSS, TP and TN goals. The CBF did not meet these effluent goals.
- At peak conditions with high influent solids, the DBF system exceeded future targeted effluent (<1 mg/l nitrate-nitrogen) and TSS goals. However, the vendor for the DBF reviewed the data and believes there are reasonable explanations for the pilot system performance not meeting effluent goals.
- Pilot testing indicated that the DBF was able to significantly reduce influent nitrate loads under average conditions without supplemental phosphorus and required from approximately 0.01 to 0.02 g Ortho-P/g nitrate versus the theoretical demand of 0.04 g Ortho-P/g nitrate (deBarbadillo et al. 2006). The filter responded slowly to rapid increase in nitrate loads and did show a higher uptake of soluble phosphorus during the step increase in nitrate loading (approximately 0.03 mg OrthoP/mg NO$_3$-N removed).

After reviewing the pilot study data and based on the history of full-scale applications of the technology, the vendor submitted a process guarantee for the DBF system, to meet the ACWPCP effluent goals under both average and peak filter influent conditions.

**Facility design**

The design criteria and performance guarantees for the DBF are shown in Tables 1 and 2.

A supplemental phosphorus feed system was provided in case the influent Ortho-P dropped too low and affected performance. This situation was a concern for wet weather

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**Table 1 | Deep bed denitrification final design criteria**

<table>
<thead>
<tr>
<th></th>
<th>Monthly average influent</th>
<th>Effluent</th>
<th>Maximum week conditions influent</th>
<th>Effluent</th>
<th>Peak conditions* influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, m$^3$/d</td>
<td>178,000</td>
<td></td>
<td>363,400</td>
<td></td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>Hydraulic loading rate, m/h</td>
<td>5.2</td>
<td></td>
<td>10.6</td>
<td></td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>TSS (max), mg/l</td>
<td>25.0</td>
<td>5</td>
<td>30</td>
<td>8</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>BOD$_5$ (max), mg/l</td>
<td>15</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Nitrate-N, mg/l</td>
<td>11.3</td>
<td>1.0</td>
<td>9.0/6.0$^b$</td>
<td>1.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Nitrate-N, kg/d</td>
<td>2,010</td>
<td></td>
<td>3,270/2,180$^b$</td>
<td></td>
<td>–</td>
<td>–</td>
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<tr>
<td>Loading, kg/m$^3$/d</td>
<td>0.77</td>
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<td>1.25/0.83</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>TP, (max), mg/l</td>
<td>0.6</td>
<td></td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP, (min), mg/l</td>
<td>0.1$^c$</td>
<td>0.18</td>
<td>0.1$^c$</td>
<td>0.27</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

$^a$The duration of the peak condition is 4 h.

$^b$Summer (> 20.4 C) and winter (> 14.7 C) maximum week influent nitrate-N concentrations.

$^c$Minimum influent soluble phosphorus of 0.01 mg/l is required.
Table 2 | Effluent denitrification filter sizing criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of units</td>
<td>17</td>
</tr>
<tr>
<td>Dimensions, length × width, m</td>
<td>22.1 × 3.8</td>
</tr>
<tr>
<td>Gravel depth, m</td>
<td>0.46</td>
</tr>
<tr>
<td>Media</td>
<td></td>
</tr>
<tr>
<td>Effective size, mm</td>
<td>2.0 to 3.0</td>
</tr>
<tr>
<td>Max. uniformity coefficient</td>
<td>&lt;1.4</td>
</tr>
<tr>
<td>Sphericity</td>
<td>&gt;0.80</td>
</tr>
<tr>
<td>Hardness (MOH scale)</td>
<td>6–7</td>
</tr>
<tr>
<td>Depth, m</td>
<td>1.84</td>
</tr>
<tr>
<td>Surface area/unit, m²</td>
<td>84</td>
</tr>
<tr>
<td>Volume/unit, m³</td>
<td>154</td>
</tr>
</tbody>
</table>

periods when the step-feed BNR system may need to switch to full aerobic conditions to maintain nitrification.

The deep bed denitrification filters were TETRA filters supplied by Severn Trent Services. The external carbon source was methanol, which is fed and stored from an adjacent building. The methanol feed and storage facility was designed for potential alternative carbon sources with stainless steel construction for tanks, piping, and appurtenances to offer flexibility in the future. The methanol feed is diluted from 100% to <20% with plant effluent water prior to dosing at the filter influent junction box through a unique chemical diffuser system. The chemical diffuser system was required due to filter influent wastewater being discharged from three separate sources. Computational fluid dynamic modelling was performed to verify sufficient methanol and wastewater mixing was achievable under varying wastewater discharge sources.

Methanol dosing is controlled by the proprietary control system called TETRA Pace system supplied by Severn Trent Services. The TETRA Pace control system analyses filter influent and effluent NO₃-N concentrations in conjunction with influent flow to determine the methanol-dosing requirements. The TETRA Pace control system has the flexibility to operate on feed forward control, feed back control, combined feed forward/ feed back control, or manual control for methanol-dosing control. The preferred methanol control strategy is the feed forward/ feed back control, which provides methanol-dosing control based on a preset desired effluent nitrate concentration and applied influent nitrate load.

Additional controls supplied by Severn Trent Services included the filter backwash scheme and the proprietary SPEED BUMP backwash. The filter backwash scheme included air only, air/water, and water only sequences to remove retained influent solids and excess biomass growth. Filter backwashes are scheduled by filter run time, high filter headloss, or time of day sequences. The SPEED BUMP backwash is initiated to remove nitrogen gas bubbles retained within the filter media voids to eliminate headloss across filter and increase filter run time.

Facility construction

The tight space requirements required demolition of the existing carbon filters and installation of the new 17 denitrification filters. One unique feature of this facility was locating the effluent chlorination facility below the effluent filters due to the limited space. The plan was to initiate construction of the denitrification filters as soon as possible to provide the best effluent quality possible prior to completion of the entire project. Accordingly, as noted below, there were some issues with the start-up of these units. Demolition of the carbon filters was initiated in 2004, construction was initiated in October 2006, and the filters were available for operation in December 2009. The overall cost for the denitrification filter complex was in the order of US$55 million.

Start-up

The denitrification filters were started in late 2009 with a 30-day performance testing period in March/April 2010. During this performance testing, there were a number of start-up issues and influent loading variability that would not be consistent with normal facility operations. These abnormal conditions were due to construction activities with power outages, activated sludge tanks out of service for construction purposes and loss of return activated sludge (RAS) pumping, which resulted in sludge blanket washouts (excess TSS loadings), higher nitrate loading.

Table 3 | 30-day test period (5.74 m³/h (8 filters in-service))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Filter influent</th>
<th>Filter effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, m³/d</td>
<td>82,130</td>
<td></td>
</tr>
<tr>
<td>cBOD, mg/l</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>TSS</td>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>7.5</td>
<td>1.2</td>
</tr>
<tr>
<td>TP, mg/l</td>
<td>0.67</td>
<td>0.07</td>
</tr>
<tr>
<td>Ortho-P, mg/l</td>
<td>0.19</td>
<td>–</td>
</tr>
</tbody>
</table>
and loss of on-line instrumentation due to excessive solids loading.

The 30-day testing period results – including days when influent flow and TSS loading exceeded design criteria (due to construction issues) are summarized in Table 3. There were 8 effluent denitrification filters in-service. Throughout this 30-day period, the denitrification filters continued to perform very well when considering the above noted construction/operational related challenges.

The overall performance of the denitrification filters was impressive when considering that there were two days when the influent TSS concentrations were 96 and 134 mg/l due to loss of RAS pumps and power outages. This is reflected in the high TP feed to the filters. Also, there were some days that the methanol feed pumps failed. The overall methanol dosing was approximately 3.9 kg methanol/kg nitrate. This is a higher methanol dosing than desired, however the influent dissolved oxygen was high at 5 mg/l. Overall, when considering all of the equipment and loading variability, the filter performed well.

**Treatment performance**

The number of construction related interruptions decreased significantly in May 2010. Accordingly, the performance of the effluent filters is shown from June through the middle of February 2011 in Figure 3 and 4, and Table 4.

The influent TP ranged from 0.18 to 0.3 mg/l and Ortho-P ranged between 0.04 to 0.13 mg/l. The overall performance of the denitrification filters has been excellent with an average <2.2 mg/l TN and <0.07 TP for the June 2010 through mid November 2010 time frame.

Overall, the system has worked well without the addition of phosphorus to satisfy the biomass growth rate. While theoretical 0.04 g P requirement/g nitrate has been reported (deBarbadillo et al. 2006), values in the range of 0.01 g P/g nitrate have been reported as adequate for sustaining denitrification. Recent work has indicated that 0.0086 g Ortho-P/g nitrate (Boltz et al. 2011) may be the rate limiting concentration.

Phosphorus removal across the filters was 0.15 mg/l TP and 0.05 mg/l Ortho-P. This translated into 0.007 g Ortho-P/g nitrate removed and 0.021 g TP/g nitrate removed. At this point in time, no negative impact on the filter performance has been observed due to the low influent soluble phosphorus concentration.
Methanol demand

From June through February 2011, the methanol-dosing average was approximately 3.8 g methanol/g nitrate applied, which resulted in a methanol use of approximately 4.0 g methanol/g nitrate removed. As shown in the figure above, the operational staff have improved the denitrification filter performance through optimization of operations. Temporary construction impacts affected performance in September.

Lessons learned

- Maximum methanol feed pump set point needs to be carefully set to prevent over feeding methanol. The maximum methanol pumping rate is dependent on wastewater temperature, hydraulic and nitrate loading rates, and biomass depth in filter.
- High solids excursions from the final settling tanks can be removed through the denitrification filters, but increases backwashes that negatively affect nitrate removal.
- Instrumentation – reliable, accurate metering of all flows and critical wastewater constituents is critical to achieving very low effluent TN and TP. Proper sensors and analysers must be provided to avoid loss of these critical parameters.
- Monitor nitrite – impact on chlorine and dechlorination chemical.
- As of the first full eight months of operation, phosphorus addition was not required. Operation of the denitrification filters during the critical wet and cold spring season will define whether phosphorus addition will be required.

Future optimization

Plant staff continue to examine improving the efficiency and performance of the denitrification filter. Specific areas of further examination and improvements include:

- Developing standard operating procedures to maximize the biomass within the denitrification filters to manage expected high nitrate loadings in the coming spring (wet weather season).
- Reduce upstream ferric dosing to minimize chemical demand and increase P removal in denitrification filter.
- Optimization of the methanol feed strategy to eliminate over or under feeding of methanol through the use of on-line TOC analysers.

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REFERENCES


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