Experiences on dual media filtration of WWTP effluent


ABSTRACT

This research is legislation driven by the European Water Framework Directive (WFD) and the Dutch Fourth Memorandum on Water Management. The objective of this research is to achieve the removal of total nitrogen and total phosphorus by Dual Media Filtration. The target value during this research for total nitrogen is 2.2 mg/L and for total phosphorus 0.15 mg/L. The results show that for NOx-N concentrations in the WWTP effluent up to 10 mg/L, a stable operation of the process can be reached with removal rates of 80% to 90%. The maximum nitrogen removal rate was 3.5 kg N/(m².d). Above 10 mg/L a risk of filter bed clogging occurred. When the orthophosphorus concentration in the WWTP effluent exceeds the maximum of 0.3 mg/L, the total phosphorus concentration in the filtrate water will exceed the target value of 0.15 mg P-total/L. Temperature has a large impact in the phosphorus removal; the optimum temperature range is within 13°C–18°C. In conclusion, Dual Media Filtration is capable of producing reusable water with total phosphorus concentrations of <0.15 mg/L, under the condition that the wastewater treatment plant produces WWTP effluent with steady concentrations for orthophosphorus (<0.3 mg PO₄-P/L). To reach total nitrogen concentrations in the filtrate water of <2.2 mg/L a NOx-N removal efficiency of nearly 100% is required.

Key words | WWTP Effluent, Dual Media Filtration, denitrification, phosphorus removal, reuse, advanced treatment

INTRODUCTION

The wastewater treatment plant (WWTP) Horstermeer has been in operation since 1985 and was originally designed for nitrification only. After several optimisation projects through the years, e.g. researching the application of online analyzers, the WWTP is now capable of removing nitrate (NO₃-N). In the near future the WWTP Horstermeer will be confronted with more stringent requirements; therefore research has been initiated to investigate the possibilities of simultaneous nutrient removal with (dual) media filtration. Results of other researches show that combined removal of nitrogen and phosphorus from WWTP effluent with sand filtration is capable of reaching low filtrate concentration for total nitrogen and total phosphorus. For example, at the WWTP Leiden Zuidwest (STOWA 2009), The Netherlands, research is conducted with simultaneous nutrient removal in a Dual Media Filter. This research showed that total nitrogen (N-total) concentrations in the filtrate of 2.2 mg/L and total phosphorus (P-total) concentrations of 0.15 mg/L could be reached steadily as long as the total nitrogen and total phosphorus concentrations in the feed water remained under 10 mg N-total/L and 0.75 mg P-total/L. Hultman et al. (1994) presents results of simultaneous nutrient removal in continuous sand filters. The results show that nitrate concentrations decreased from 7.3–20 mg/L to 0.5–2.2 mg/L and the total phosphorus concentration decreased from 0.6–5 mg/L to 0.1–0.5 mg/L.

Legislation

In 1998 the Ministry of Transport and Water Management introduced the fourth Memorandum on Water Management (NW4) which contains the water policy for the Netherlands until 2006 (Beesen 1998). The NW4 contains norms for the Maximum Permissible Risk (MPR) and target values, which need to be reached by the end of 2015. The MPR values are
preliminary and it is currently unknown which values will become effective. In 2000 the European Union (European Commission 2000) introduced the Water Framework Directive (WFD). The aim of the WFD is to achieve an ecological and chemical balance for all surface waters, coastal waters, transitional waters and groundwater in Europe by 2015. The ecological quality of water bodies is based on the status of biological, hydromorphological and physicochemical quality elements (Borja 2005).

Research objective

With dual media filtration of WWTP effluent low nutrient concentrations are expected to be reached in the filtrate water, which results in an improved surface water quality. The research objective is to reach the target values in the filtrate water of the Dual Media Filter of 2.2 mg/L for total nitrogen and 0.15 mg/L for total phosphorus. Advanced techniques like Dual Media Filtration can also be used for the production of process water or as pre-treatment technique for ultrafiltration and reverse osmosis to produce ultra pure water. Therefore practical research information about these techniques is interesting for both fields of interest. When advanced treatment is used to treat and upgrade WWTP effluent for example to use as process water, knowledge about the stability of the process within the range of working conditions is required. The results of this research give an estimation of this framework for operation aspects and the maximum allowable concentrations for inorganic oxidized nitrogen and orthophosphorus in the feed water.

METHODS

The WWTP Horstermeer treats the wastewater of 140,000 inhabitants living in the area of Naarden-Bussum, Hilversum-West and Nederhorst den Berg. The mean flow of the WWTP is 26,000 m³/day. The treatment plant consists of grit removal, primary sedimentation, aeration and final sedimentation. In Figure 1 a schematisation of the WWTP Horstermeer is given.

The plant was originally designed for nitrification only, but after implementation of online analysers and the introduction of a denitrification zone, a considerable improvement of effluent quality was achieved. Total nitrogen decreased from 30 mg/L to <15 mg/L. Poly aluminium chloride (PACl) is added in the aeration tanks just before the final sedimentation tanks with a metal/total phosphorus ratio of 0.65 mol/mol. PACl is dosed to prevent the formation of filamentous sludge and to enhance the phosphorus removal. Ferric chloride sulphate is dosed at the primary sedimentation tank with a metal/total phosphorus ratio of 0.38 and at the outlet of the aeration tanks with a metal/total phosphorus ratio of 0.25. Ferric chloride sulphate is dosed for phosphorus removal only. With these dosing conditions the effluent concentrations fulfil the current discharge limit of 1.0 mg P-total/L.

Effluent quality and legislation for the WWTP Horstermeer

The WWTP Horstermeer effluent is discharged into the river Vecht, which is part of the river basin district Rhine. The WWTP Horstermeer has to improve the effluent quality, due to the River Vecht reduction program, from a yearly average concentration for total nitrogen from 14 mg/L to less than 5 mg/L and for total phosphorus from 1 mg/L to 0.5 mg/L by the end of 2009. Probably in a later stage the effluent quality needs to be improved further to MPR quality. In Table 1 the mean effluent quality parameters of the WWTP effluent Horstermeer for the year 2008 are given.

In order to reach these low effluent requirements in a cost effective way and to assess the viability of post-treatment techniques, pilot scale research started in March 2005 until December 2009 at the WWTP Horstermeer in co-operation with Witteveen + Bos Consulting Engineers, Waternet and Delft University of Technology.

Pilot plant

The pilot installation consists of a 0.8 m² Dual Media Filter (Figure 2), operated for denitrification and simultaneous phosphorus removal. The feed water of the filter, WWTP effluent, passes a 450 µm screen and is collected in the feed water buffer. Turbidity, orthophosphorus (P-ortho, PO₄-P), total phosphorus and inorganic oxidized nitrogen (NOₓ-N) in the feed water and in the filtrate water are measured continuously by on-line analysers. Total nitrogen concentration is measured by analysing grab samples.
The Dual Media Filter contains two filtration layers (top: anthracite, 80 cm height, 2.0–4.0 mm grain diameter, 1,400 kg/m³ density and bottom: quartz sand, 40 cm height, 1.25–1.5 mm grain diameter, 2,600 kg/m³ density). The filter is operated at a filtration rate of 10 m/h and is back-flushed with air and filtrate water collected in a filtrate buffer tank. A backwash is started when the upper water layer exceeds a maximum level or when the maximum filtration runtime of 12 hours has past. Bump cleaning is needed to release nitrogen gas formed during denitrification (Lemmer et al. 1997; Miska-Markusch 2009). A bump cleaning is conducted automatically every 3 hours. For denitrification, the methanol dosage is based on the actual inorganic oxidized nitrogen and free oxygen concentrations in the feed water. COD/NO₃-N ratios of 4.0–6.0 g/g are used. For the simultaneous phosphorus removal and removal of suspended solids PACl is dosed into the filter feed water. PACl is chosen for the effluent of the WWTP Horstermeer because in preliminary jar tests it showed a higher removal efficiency with regard to phosphorus removal in comparison to ferric chloride (FeCl₃). This is probably due to the low pH of the WWTP effluent, which is pH 6.8 in average. Coagulation takes place by a static mixer and flocculation takes place in the water volume above the filter medium, the flocculation time is approximately 8 minutes. Used ratios of Al³⁺/P-ortho for dual media filtration are 2–5 mol/mol.

RESULTS AND DISCUSSION

Removal of oxidized inorganic nitrogen (NOₓ-N)

Hourly averages of the NOₓ-N concentrations in the WWTP effluent and the filtrate water of the filter in the period 10 July to 10 September 2008 are shown in Figure 3. The blue line represents the NOₓ-N concentration in the WWTP effluent and the green line represents the NOₓ-N concentration in the

![Figure 3](http://www.iwaponline.com/wst/article-pdf/63/10/2462/443717/2462.pdf)

**Figure 3** | Inorganic oxidized nitrogen removal of the Dual Media Filter.

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**Table 1** | Effluent quality in 2008 of WWTP Horstermeer compared with concentrations based on the River Vecht reduction program and MPR concentrations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Average</th>
<th>Discharge permit</th>
<th>River Vecht reduction program</th>
<th>MPR concentration</th>
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<tr>
<td>COD</td>
<td>mg/L</td>
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<tr>
<td>BOD</td>
<td>mg/L</td>
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<tr>
<td>Ntotal</td>
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<td>14.0</td>
<td>5.0</td>
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<td>NKj</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ptotal</td>
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<td>1.0</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>P-ortho</td>
<td>mg/L</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended solids</td>
<td>mg/L</td>
<td>11</td>
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<td></td>
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</tbody>
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filtrate water. The graph shows large variations, from 3 to 20 mg NO$_3$-N/L in the WWTP effluent. NO$_3$-N concentrations in the WWTP effluent up to 10 mg/L result in a stable operation of the process and removal rates of 80% to 90% can be reached. During four years of research the average nitrogen removal rate was 1.5 kg N/(m$^3$.day). The maximum nitrogen removal rate was 3.5 kg N/(m$^3$.day). The NO$_3$-N peak in the filtrate water around the 30 August was caused by a shortage of methanol. When, after a pause of a day or a weekend, the dosage of methanol continues, the removal of inorganic oxidized nitrogen increased within hours.

The process becomes unstable when NO$_3$-N concentrations in the WWTP effluent are above 10 mg NO$_3$-N/L. This is illustrated in the period 15 July to 28 July (Figure 3). During this period the NO$_3$-N concentration in the WWTP effluent was above 10 mg/L, resulting in an increased NO$_3$-N concentration in the filtrate water. At the same time the dosage of methanol is increased. The increase in methanol together with high NO$_3$-N concentrations, result in extra growth of biomass which leads to a rapid increase of the filter bed resistance and shorter filter run times, i.e. clogging of the filter bed. When after a period with high NO$_3$-N concentrations the NO$_3$-N concentration decreases, less substrate is available relative to the biomass. The possible consequence is inactivation, stress or maybe starvation of the biomass, which leads to a period of shorter runtimes even though the NO$_3$-N concentrations are below 10 mg/L.

Temperature influences on the denitrification

When comparing cold periods with temperatures around 10$^\circ$C and warmer periods with temperatures around 20$^\circ$C, it is observed that nitrogen is not removed completely in colder periods as it is mostly in warmer periods, but removal rates are still comparable. Figure 4 illustrates this, with on the left side a graph with an average temperature of approximately 20$^\circ$C and on the right side an average temperature of approximately 13$^\circ$C. The red line represents the temperature, the blue line the nitrogen load and the green line the nitrogen removal. These results are in contradiction to the results presented by Koch and Siegrist (1997) which describes methanol based denitrification in tertiary filtration. During this research the maximum nitrogen removal rate for temperatures between 10–15$^\circ$C was 1.0 kg N/(m$^3$.d).

Nitrogen distribution

In the second part of 2008 (June to December) in total 60 nitrogen distributions are made for grab samples of the WWTP effluent and the filtrate water of the Dual Media Filter. The average concentrations are shown in Figure 5. The red bars represent the Nitrogen Kjeldahl (NKj) concentration, the blue bars the nitrite concentration and the green bars the nitrate concentration. Figure 5 shows an average nitrate removal of approximately 80%. The NKj concentration decreased with 50%, probably due to biomass growth. Nitrite is formed in the filter bed which can be caused by phosphorus limitation, methanol shortage, the presence of oxygen or other factors. The oxygen concentration after the sieve is about 4 mg/L, which leads to a high methanol dosage and it may lead to insufficient denitrification. The transfer of oxygen to the feed water may get reduced by using a submerged sieve instead of a sieve bow before the installation. Due to the nitrite formation and the

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high nitrate concentration in the filtrate water the target value of 2.2 mg N-total/L can not be reached in the period.

**Phosphorus removal**

The phosphorus removal of the Dual Media Filter in months June and July 2008 is shown in Figure 6. In the graphs the blue line represents the orthophosphorus concentration (<0.45 μm) in the WWTP effluent, the red line represents the orthophosphorus + metal bound phosphorus, i.e. unfiltrated orthophosphorus measurement, in the filtrate water. The green line represents the total phosphorus concentration in the filtrate water, which should stay below the target value (black line) of 0.15 mg/L. The graph shows that the filter can fulfil the target value for total phosphorus under normal conditions. Every now and then when a peak load occurs, the target value is exceeded.

It is important to know the maximum orthophosphorus concentration in the WWTP effluent for which the target value still can be reached. The maximum orthophosphorus concentration is determined for different temperature ranges; this is shown in Figure 7. The concentrations shown are average values. The online data of 2007 and 2008 are used. Data are selected with Al³⁺/P-ortho ratios between 3 and 5 mol/mol.

The figure shows the orthophosphorus concentration in the WWTP effluent (dark blue bars, on the left of each group of four), the total phosphorus concentration in the filtrate for T ≤ 13 °C (red bars, second from the left of each group of four), for 13 °C < T ≤ 18 °C (green bars, second from the right of each group of four) and for T > 18 °C (light blue bars, on the right of each group of four). The black line shows the target value of 0.15 mg/L for total phosphorus. Error bars show the 95% confidence interval. These results show that for T < 13 °C the total phosphorus concentration in the filtrate water directly increases with increasing orthophosphorus in the WWTP effluent. The best results are reached within the temperature range of 13 °C–18 °C. The total phosphorus concentration in the filtrate water increases with an increasing orthophosphorus concentration in the WWTP effluent up to 0.4 mg P-ortho/L. When the orthophosphorus concentration further increases to 0.9 mg P-ortho/L the total phosphorus concentration in the filtrate water remains stable at approximately
0.25 mg/L. For temperatures above 18°C, the total phosphorus concentration increases rapidly when the orthophosphorus concentration in the WWTP effluent is higher than 0.4 mg/L. This is probably caused by floc formation. According to Fitzpatrick et al. (2004) warmer temperatures produce larger flocs which break more easily and reform less well than lower temperatures do. The average results of 2007 and 2008 show that the Dual Media Filter will fulfil the target value with incoming orthophosphorus concentrations up to 0.3 mg/L.

**Phosphorus distribution**

From March to November 2008, 14 phosphorus distributions are made in total. The average results over the Dual Media Filter are shown in Figure 8. All phosphorus distributions are made with an Al$^{3+}$/P-ortho ratio of 4 mol/mol and a filtration rate of 10 m/h. The results are shown in concentrations and in percentages. For more information about the phosphorus distribution technique, see Scherrenberg et al. (2008).

The figure shows the phosphorus distribution into particulate “organic” phosphorus (dark blue bars, lowest section), dissolved “organic” phosphorus (light blue bars, second lowest section), metal bound phosphorus (red bars, second highest section) and orthophosphorus (green bars, highest section) for the WWTP effluent, the upper water layer of the filters and the filtrate of the filters. The top graph in Figure 8 shows an increase of the total phosphorus concentration in the upper water layer compared to the WWTP effluent. Although this phenomenon is frequently observed, the cause of this increase is not clear. Hach Lange states in the product information (Hach Lange, 2009) Al$^{3+}$ does not cause interference for concentrations up to 50 mg/L. The used concentrations Al$^{3+}$ never exceeded 50 mg/L, therefore the increase which is measured after coagulation, is most likely not caused by the coagulant dosage. Another option for the increase of the total phosphorus concentration in the upper water layer may be a form of accumulation. Apart from this, the top graph shows that the orthophosphorus (green bar left column) is partly bound to metal ions after coagulation and flocculation (see the remaining green bar in the middle column). Almost all the metal bound phosphorus is removed in the filter bed (see the remaining red bar right column). The dissolved “organic” phosphorus decreases after flocculation and the particulate “organic” phosphorus increases after flocculation which suggests that it may be colloidal or associated with colloidal material (Stevens and Stewart, 1982). The particulate “organic” phosphorus is partly removed in the filter bed. Dissolved “organic” phosphorus will pass the filter bed. The bottom graph in Figure 8 shows that the total phosphorus in the filtrate water of the Dual Media Filter consists for 20% of orthophosphorus (green bar right column), for 40% of metal bound phosphorus (red bar right column) and for 40% of “organic” phosphorus (total of the dark and light blue bars right column). An insufficient removal of total phosphorus in the filter bed leads mostly to increased concentrations of metal bound and orthophosphorus in the filtrate. Information about the removal of the different phosphorus forms in the filter bed profile measure-
when measurements are made, these results are presented in Scherrenberg et al. (2009b).

CONCLUSIONS

NOx-N concentrations in the WWTP effluent up to 10 mg/L result in a stable operation of the process and removal rates of 80% to 90% can be reached. The maximum nitrogen removal rate was 3.5 kg N/(m³.day). Above 10 mg/L a risk of filter bed clogging occurs. When, after a pause of a day or a weekend, the dosage of methanol continues, the removal of inorganic oxidized nitrogen increases within hours. Periods with temperatures around 10°C show that nitrogen is not removed completely. The nitrogen distribution shows that nitrite is formed in the filter bed. The target value of 2.2 mg N-total/L is not reached, mainly because of insufficient NOx-N removal, possibly due to carbon shortage, high dissolved oxygen concentrations or nutrient deficiencies (Gayle et al. 1989; Scherrenberg, 2009a).

The online data shows that total phosphorus the filter can fulfil the target value of 0.15 mg/L. Every now and then when a peak load occurs the target value is exceeded. Temperature has a large impact in the phosphorus removal; the optimum temperature range is within 13°C–18°C. The average results of 2007 and 2008 show that the Dual Media Filter will fulfil the target value with incoming orthophosphorus concentrations up to 0.3 mg/L. When the orthophosphorus concentration in the WWTP effluent exceeds 0.3 mg/L, the total phosphorus concentration in the filtrate water may exceed the target value.

In conclusion, Dual Media Filtration is capable of producing reusable water with total phosphorus concentrations of <0.15 mg/L, under the condition that the wastewater treatment plant produces WWTP effluent with stable concentrations of orthophosphorus (< 0.3 mg PO₄-P/L). To reach total nitrogen concentrations in the filtrate water of <2.2 mg/L a NOx-N removal efficiency of nearly 100% is required.

Finally, some design parameters can be derived from this research. The optimal average flow rate is 10 m/h and the rain water flow rate 15 m/h. For the filter medium sand (1.5–2.25 mm) and anthracite (2.0–4.0 mm) should be used with an effective bed height of 2 meter. The runtime of the filter should be 12 hours with bump cleansings every 3 hours. The backwash of the filter takes approximately 15 minutes (2.2 m³ backwash water/ m² filter bed). A bump cleaning takes approximately 5 minutes (0.44 m³ backwash water/ m² filter bed).
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