Performance of a Pilot Constructed Treatment Wetland For Membrane Concentrate Produced From Reclaimed Water

Rajat K. Chakraborti1*, James S. Bays2, Lou Balderrama3, Thien Ng3, and Mary L. Vorissis1

CH2M HILL Inc.
1325 E. Hillcrest Drive, Suite #125, Thousand Oaks, CA 91360
24350 West Cypress Street, Suite #600, Tampa, FL 33607-4178
3City of Oxnard, 305 W. Third Street, Oxnard, CA 93030
*Rajat.Chakraborti@ch2m.com

ABSTRACT

A pilot study was conducted for the City of Oxnard to assess treatment options for an advanced water purification facility using microfiltration and reverse osmosis to create high quality product water from reclaimed wastewater effluent to replenish groundwater. However, this process yields a concentrate with a high salt and ammonia content requiring disposal. The City is incorporating a constructed wetland into the facility to treat the concentrate as a demonstration project, with the long-term objective of using the treated concentrate for creating coastal wetland habitat. In a pilot study, a portable subsurface flow constructed wetland was used to evaluate the acceptability of this treatment method. Bulrush, a common wetland plant, was found to tolerate the high levels of total dissolved solids and provided significant mass removal of nitrogen, selenium, biochemical oxygen demand, phosphorus and other constituents in the concentrate. No evident objectionable color or odors were observed during the pilot study.

KEYWORDS: Membrane concentrate, reclaimed water, constructed wetland, groundwater recharge, microfiltration/ultrafiltration, reverse osmosis, wastewater treatment

INTRODUCTION

Membrane technologies for water treatment produce significant quantities of concentrate with elevated concentrations of metals, nutrients and inorganic ions. Common disposal methods for reverse osmosis (RO) concentrate include ocean discharge to coastal waters and deep-well injection or evaporation ponds inland. Stringent water quality regulations may further prohibit direct disposal and will mandate extensive treatment prior to disposal.

The City of Oxnard (City) has embarked on the Groundwater Recovery Enhancement and Treatment (GREAT) program to make efficient use of their water resources. This program develops additional sources of alternative water supply by combining wastewater recycling and reuse; groundwater injection, storage, and recovery; and groundwater desalination for water supply solutions to the Oxnard region (CH2M HILL 2004a). As part of its water resources master planning process, the City determined that additional alternative water supply sources should be developed to continue meeting the City's goal of providing current and future residents and businesses with a reliable and affordable source of high quality water. Limitations on both
the City’s local groundwater and imported water sources, plus the increased cost of imported water, prompted the City to conduct an advanced planning study of alternative water supply sources. The GREAT Program was developed to address the recommendations of the planning study. The plan calls for a wastewater plant to produce up to 5 million gallons per day (mgd) of tertiary treated water and up to 6.25 mgd of advanced treated water (primarily for agricultural irrigation). The recycled water will be used on the southern Oxnard Plain and Pleasant Valley areas where overdraft conditions and the effects of that overdraft are most severe. A portion of the 6.25 mgd of advanced treated water would be used for groundwater injection during times of low agricultural demand (approximately 3 months per year). The GREAT Program could potentially increase production of the existing City’s Water Pollution Control Facility (WPCF) of tertiary treated water up to a total of 25 mgd for agricultural irrigation and groundwater injection.

The existing WPCF currently treats the wastewater to secondary treatment levels and disinfects before discharging into the Pacific Ocean via an ocean outfall. The City will provide advanced treatment of the secondary effluent from the WPCF, thereby producing a very high-quality recycled water that meets the water quality criteria for groundwater recharge (GWR) and unrestricted irrigation as specified by the State of California, Department of Public Health Title 22 guidelines. To meet GWR water quality permitting requirements, the treatment options for the AWPF have been designed to include microfiltration/ultrafiltration (MF/UF), reverse osmosis (RO), and ultraviolet (UV) disinfection including advanced oxidation capabilities.

In general, it was assumed that the membrane concentrate to be generated by these treatment processes will be disposed of through the WPCF’s deep ocean outfall. A conceptual alternative to ocean disposal could be the use of membrane concentrate as a water source to create or restore brackish or salt marsh wetlands, if found to be compatible with the local environment.

Previously, the City conducted a detailed pilot study of the use of constructed wetlands for reuse of concentrate produced by membrane treatment of groundwater from the Port Hueneme Brackish Water Desalination Facility (Bays et al. 2007; CH2MILL 2004b, 2005). The conclusions of that study supported the prospect of using membrane concentrate for beneficial creation of new coastal marshes or for enhancing flow to existing marshes. The City was interested in applying this concept to the concentrate produced by the AWPF.

Accordingly, the AWPF has been designed to integrate demonstration wetlands into the site plan to enhance visitor interest and educational opportunities as well as to minimize conveyance and management requirements (Figure 1). A series of constructed wetlands will treat up to 20,000 gpd (76 m³/d) of the concentrate in a three-stage process with specific treatment objectives:

- **Stage 1**: Horizontal Subsurface Flow Wetlands with supplemental aeration for nitrification of ammonia.
- **Stage 2**: Vertical Subsurface Upflow Wetlands for denitrification of nitrate-nitrogen and anaerobic removal of selenium.
- **Stage 3**: Surface Flow Marsh and Open Pond for final polishing and wetland habitat creation.

Because the water source for the membrane treatment process will be reclaimed water, with significantly greater concentrations of nitrogen, phosphorus, selenium, and TDS, instead of
groundwater, it was determined that a pilot wetland study would be conducted during the AWPF pilot study to confirm the treatability characteristics of the reclaimed water concentrate.

**Figure 1. Conceptual Overview of the AWPF Demonstration Facility.** *The AWPF is designed to be surrounded by different types of constructed wetlands converging on an open pond and wetland system.*

The pilot study was conducted during the final design with the following specific objectives: 1) Confirm the survival and growth of brackish marsh plants receiving the concentrate; 2) Assess the pollutant removal performance of wetlands treating the RO concentrate; and 3) Confirm that the aesthetics of the treatment wetland would be acceptable (i.e., no offensive odors or colors would be generated). A system installed to pilot the multiple advanced treatment technologies was used to generate a wastewater similar in quality to the full-scale AWPF. This paper provides a detailed summary of the methods, results and key findings of the pilot wetland study. A previous paper described the AWPF pilot system, with a brief summary of pilot wetland results (Chakraborti et al. 2009) and another paper compared the overall results with other concentrate treatment wetland studies (Kepke et al. 2009).

**MATERIAL AND METHODS**

The AWPF effluent was tested on a portable subsurface flow-type wetland developed by Mobile Environmental Solutions (MES) of Tustin, CA (Figure 2). The MES portable wetland is a trailer with a surface area of 8.9 m² (96 ft²) and an internal volume of 11.9 m³ (420 ft³) containing soil
and gravel as a substrate for growth of a mature stand of bulrush (*Schoenoplectus californicus*). The trailer, originally built and planted in the fall of 2006, was fully grown in with sufficient time for a microbial biofilm community to develop on the inert matrix and the root system.

**Figure 2. The MES Wetland System.** *The white trailer on the left is the AWPF pilot system.*

The portable wetland was installed in August 2008 adjacent to the AWPF pilot facility on the grounds of the City’s WPCF (Figure 3).

**Figure 3. Site and Facility Layout of the Pilot Study at the Oxnard WPCF.** *The red outline box is the pilot wetland and the white box is the AWPF pilot system.*

While the final components of the MF/RO pilot system were being installed, the MES wetland plant and bacterial communities were gradually acclimated to the TDS levels in the MF/RO
concentrate. Secondary effluent was recycled through the wetland for the first week. Over the next three weeks sea salt (Instant Ocean brand) was added to the wetland to attain a total dissolved solid (TDS) of 5 g/L and finally 11 g/L. During this time the water continuously recycled through the wetland at a rate of 1.9 L/min.

While the wetland was in the acclimation mode, the rest of the test site was assembled including the influent and effluent lines to and from the wetland (Figure 4). All components of the study were operational by the end of September 2008. Initially, the MES wetland was loaded at 317 gpd (1 L/min), yielding a hydraulic loading rate of 5 in/day (12.9 cm/day) and a theoretical residence time (HRT) of 2.5 days.

![Figure 4. Pilot Wetland System Setup with Pre-Treatment Aeration Tank.](image)

The AWPF Demonstration Wetlands will contain aeration lines in the first series of subsurface flow wetland cells which will meet the biochemical oxygen demand (BOD) in the concentrate and the conversion of ammonium to nitrate. A small aeration tank in the pilot study held approximately 185 gal (700 L) and at a flow rate of 380 gpm (1 L/min), the residence time was about 12 hours. This pre-treatment system allowed site visitors to be able to smell the concentrate to assess for objectionable odors. In order to inactivate the chlorine a solution of sodium bisulfite was added to the aeration tank. The 6 mg/L addition of sodium bisulfite inactivated the free and combined chlorine which was estimated to have a concentration of 4 mg/L or less. As a consequence, wetland influent and effluent alkalinity were significantly reduced below the requirements for nitrification to occur. This was discontinued on January 17 2009.
Between 9/17/2008 and 3/5/2009, the inflow and outflow to the MES wetland was sampled weekly for analysis of ammonia-N, nitrate-N, total kjeldahl nitrogen (TKN), orthophosphate (OP), biochemical oxygen demand (BOD), total organic carbon (TOC), total nitrogen (TN), and total selenium (Se). Weekly samples of concentrate were also analyzed which essentially represented the characteristics of the wetland influent. Field measurements of temperature, specific conductance, pH, and ammonia-N were taken periodically throughout the study.

RESULTS AND DISCUSSION

The results of the AWPF Pilot Wetlands Study are presented in the areas of operating conditions and aesthetics, plant survival and growth, and water quality performance.

Operating Conditions and Aesthetics

The wetland received RO concentrate continuously with average HRTs estimated to range from 1 to 5 days (Table 1). During the initial acclimation period of 23 days, an HRT of 1.3 days was achieved. The HRT was increased to 2.5 days during the first period of sampling for 110 days, followed by a 5-day HRT during the final period of sampling of 40 days.

Table 1

Hydraulic Data Summary

<table>
<thead>
<tr>
<th>Dates</th>
<th>Duration (day)</th>
<th>Flows (L/min)</th>
<th>HRT (day)</th>
<th>HLR (cm/day)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/1/08-9/24/08</td>
<td>23</td>
<td>1.9</td>
<td>1.3</td>
<td>24.5</td>
<td>Initial acclimation period - no sampling</td>
</tr>
<tr>
<td>10/1/08-1/19/09</td>
<td>110</td>
<td>1</td>
<td>2.5</td>
<td>12.9</td>
<td>First period of sampling</td>
</tr>
<tr>
<td>1/20/09-3/5/09</td>
<td>40</td>
<td>0.5</td>
<td>5</td>
<td>6.5</td>
<td>Final period of sampling</td>
</tr>
</tbody>
</table>

HLR = Hydraulic Loading Rate  
HRT = Hydraulic Residence Time  

Since the demonstration wetlands will be part of a public display, one of the initial concerns was that concentrate will generate unpleasant odors in the aerated wetland cells. In the first aeration test of the MF/RO concentrate, there were no foul or noxious odors coming from the aeration tank as shown in the figure below. Throughout the study, no unpleasant odors were given off by the water in the aeration tank.

Concentrations of parameters measured at laboratory for the first period of sampling and final period of sampling are presented in the following section.

Plant Growth and Survival

As a preliminary step in the pilot study, in the summer of 2008, clusters of bulrush were tested in the summer of 2008 in barrels containing nutrients and TDS levels of 0.3, 5 and 11 g/L. Plants
showed no indications of plant mortality or injury. Qualitative observations of the MES wetland plant condition were made throughout the pilot study. At no point in time were indications of stress evident, including tip browning, shoot necrosis, shoot pigment loss, or other indications of plant mortality or injury. Normal flowering and fruiting characteristics were observed. The bulrush thrived and grew throughout all conditions with no indication of adverse health at the conclusion of the study (Figure 5).

Figure 5. MES Wetland System at the Conclusion of the Study.
Side view of the MES wetland shows the high plant density and vigorous growth.

Water Quality Analysis

Field Measurements

Temperature, pH, and specific conductance data are summarized in Table 2 for samples collected in the final sampling period when HRT was set to 5 days. Values of pH ranged slightly above neutral. Mean pH decreased marginally through the wetland by 3% from 7.4 to 7.2, indicating alkaline water, as expected given the high inorganic ionic content of the concentrate. Influent temperatures during this period were warm, ranging from 14°C to 22.5°C. Specific conductance in the influent water varied between 11,460 and 16,210 µS/cm, indicative of the concentrate source, while effluent values averaged between 16,320 µS/cm and 19,150 µS/cm during the pilot study. This 17% increase in inorganic solids content through the wetland is attributable to evapoconcentration caused by water loss through plant evapotranspiration. Ammonium concentrations showed an apparent decrease of 38% from 150 mg/L to 94 mg/L during this same period. Actual concentration reductions may be greater, given the significant water loss and evapoconcentration effect.
Table 2
Summary of Water Quality Field Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wetland Influent</th>
<th>Wetland Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>18.16</td>
<td>22.50</td>
</tr>
<tr>
<td>pH</td>
<td>7.37</td>
<td>7.47</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>15,103</td>
<td>16,210</td>
</tr>
<tr>
<td>NH4-N (mg/L)</td>
<td>150.00</td>
<td>180.00</td>
</tr>
</tbody>
</table>

Note:
SD: Standard Deviation
N: Number of samples analyzed
Data is for samples collected in final sampling period with HRT = 5 days

Laboratory Measurements
A summary of concentration of selected constituents in wetland influent and effluent measured during the two sampling periods are presented in Tables 3 and 4, respectively. Mass removal percentages for various parameters measured during the entire sampling period of the pilot study are presented in Table 5.

Table 3
Concentration of Parameters in Wetland Influent and Effluent Measured during First Sampling Period (2.5-day HRT).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent</td>
</tr>
<tr>
<td>NO3-N</td>
<td>11.4</td>
</tr>
<tr>
<td>NO2-N</td>
<td>4</td>
</tr>
<tr>
<td>Orthophosphate</td>
<td>11</td>
</tr>
<tr>
<td>BOD5</td>
<td>10</td>
</tr>
<tr>
<td>Ammonia-N</td>
<td>165</td>
</tr>
<tr>
<td>TN</td>
<td>177</td>
</tr>
<tr>
<td>TKN</td>
<td>146</td>
</tr>
</tbody>
</table>
Table 4
Concentration of Parameters in Wetland Influent and Effluent Measured during Final Sampling Period (5-day HRT).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Concentration (mg/L)(^1)</th>
<th>Influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_3)-N</td>
<td>14</td>
<td>4.09</td>
<td></td>
</tr>
<tr>
<td>NO(_2)-N</td>
<td>14</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>165</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>TKN</td>
<td>116</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>TOC</td>
<td>72</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Selenium (µg/L)</td>
<td>34</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
These values are based on average values
1. Concentrations are in mg/L unless otherwise mentioned
2. Wetland influent concentrations presented in this table are measured at RO effluent

Table 5
Mass Loading and Removal Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Mass Loading Rates</th>
<th>Influent (g/m(^2)/day)</th>
<th>Effluent (g/m(^2)/day)</th>
<th>Mass Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_3)-N</td>
<td></td>
<td>1.99</td>
<td>0.49</td>
<td>75%</td>
</tr>
<tr>
<td>NO(_2)-N</td>
<td></td>
<td>1.18</td>
<td>0.57</td>
<td>51%</td>
</tr>
<tr>
<td>TN</td>
<td></td>
<td>28.00</td>
<td>14.56</td>
<td>48%</td>
</tr>
<tr>
<td>BOD(_5)</td>
<td></td>
<td>1.18</td>
<td>0.87</td>
<td>26%</td>
</tr>
<tr>
<td>Orthophosphate</td>
<td></td>
<td>1.84</td>
<td>1.32</td>
<td>29%</td>
</tr>
<tr>
<td>TOC</td>
<td></td>
<td>11.67</td>
<td>10.60</td>
<td>9%</td>
</tr>
<tr>
<td>Selenium</td>
<td></td>
<td>0.005</td>
<td>0.003</td>
<td>36%</td>
</tr>
<tr>
<td>Calcium</td>
<td></td>
<td>154.6</td>
<td>143.7</td>
<td>7%</td>
</tr>
</tbody>
</table>

Note: These values are based on average values measured during the study for each constituent
Values represent sampling for both first and final sampling periods
Nitrogen and Phosphorus

Average concentrations of total nitrogen decreased by 27% and 86% during the first and final sampling periods of this pilot study, respectively, indicating a greater removal rate with the longer HRT. Average concentrations of nitrate decreased 75% from 11 mg/L to 3 mg/L and 14 mg/L to 4 mg/L during the first and final sampling periods, respectively. Average concentrations of nitrite decreased 51% from 4 mg/L to 2 mg/L and 14 mg/L to 6 mg/L the first and final sampling period, respectively. Nitrite concentrations in the wetland effluent ranged from 1.0 to 12.2 mg/L, indicating incomplete denitrification, which can be attributed to the relatively low carbon influent supply (e.g., 5 mg/L BOD, 10 mg/L TOC). This reduction in nitrogen is consistent with the expectations of the literature on treatment wetlands (Kadlec and Wallace 2009), in that subsurface flow treatment wetlands reduce nitrogen through plant assimilation of nitrogen as ammonium and nitrate, biological nitrification of ammonium, and biological denitrification of nitrate (Kadlec and Wallace 2009).

Average concentrations of orthophosphate decreased by 29%. Significant removal of phosphorus is not normally expected in subsurface flow wetlands because phosphorus removal in this type of wetland is due to bacterial and plant uptake and the formation and precipitation of various phosphate salts including calcium phosphate (apatite or hydroxyapatite) (Kadlec and Wallace 2009). Both surface flow and subsurface flow treatment wetlands have limited abilities to remove phosphorus. The modest removal of orthophosphate is consistent with the possibility of some export of organic matter in the form of bacterial biomass, root exudates and material, compounded by an evaporative increase in parameter concentrations.

Table 3 summarizes estimates of mass loading, outflow and mass removal percentage. The nitrate loading rate of 1.99 g/m²/day and the outflow rate were 0.49 g/m²/day, indicating about 75% mass of nitrate is removed. About 51% and 48% mass of nitrite and total nitrogen was removed by the constructed wetland.

Total Organic Carbon (TOC) and Biochemical Oxygen Demand (BOD)

Average concentrations of TOC decreased by 19% from 72 mg/L to 58 mg/L and BOD decreased by 50% from 10 mg/L to 5 mg/L. The concentrations of BOD in the wetland effluent are well within the background concentrations expected for treatment wetlands, particularly those receiving similar highly-enriched effluents.

Selenium

Average concentrations of total selenium decreased 36% from 34 μg/L to 22 μg/L during the second 5-day HRT operational period. Additional removal could be anticipated with a reduction in hydraulic loading rate and further increase in HRT, given the understanding that nitrate will be used as an electron source preferentially by the bacteria that create the anaerobic conditions appropriate for selenium reduction before oxidized selenium. As with the other parameters, the
concentration of selenium may increase in part due to the evaporative concentration caused by the plants.

**Calcium**

Calcium showed no significant change through the wetland. On average, by mass estimate, about 7% from 154.6 g/m²/day to 143.7 g/m²/day calcium is removed by the wetland treatment (Table 3).

**CONCLUSIONS**

The following key findings of the AWPF pilot wetlands study are useful to the implementation of the AWPF demonstration wetlands:

1. The wetland plants were found to tolerate the high levels of salts and grow in the ammonium rich water from the MF/RO plant.
2. No odor was detectable from the RO concentrate influent to the wetlands.
3. Significant reductions in nitrate, nitrite and total nitrogen concentration and mass were measured consistently throughout the study at levels consistent with findings from other studies. Nitrite concentrations were detectable in the wetland effluent, indicating carbon limitation, hydraulic short-circuiting, or carbon limitation in the test wetland.
4. Ammonium concentrations decreased significantly but given the high inflow concentrations, additional removal will be required to complete nitrification. Because this was anticipated, the proposed design includes provision of aeration of the subsurface flow horizontal wetlands, which will support the microbial conversion of ammonium to nitrate and subsequently to gaseous nitrogen in the anaerobic second-stage wetlands.
5. Limited reduction in selenium concentration was observed in the pilot test. Mass removals were estimated to be on the order of 36%. The pilot system was configured differently than the proposed demonstration wetland, which includes anaerobic wetlands. The reducing conditions in the vertical flow cells of the demonstration wetland are designed to remove the selenium to meet the 5 µg/L regional limits.
6. The final TDS in the effluent is projected to fall within a range of 15-25 g/L. Consistent with the overall project vision, and assuming future testing in the demonstration wetlands continues to support these results, this effluent could possibly serve as a water source for the Ormond Beach Brackish Wetland Restoration Program that is under development by the City of Oxnard and the Coastal Conservancy.
7. The pilot test demonstrated the importance of the hydraulic loading rate and hydraulic retention time as the key operational controls over wetland performance. The full-scale wetland system will be designed such that the HRT can be as short as 7 or as long as forty days.
While the proposed wetland will improve the water quality of the concentrate, the created wetland habitat will benefit local species of birds, mammals, and plants, along with a myriad of other living organisms. Moreover, the results of the pilot wetlands study indicated that the elevated concentrations of nitrogen and phosphorus and selenium in the reclaimed water concentrate were found to be treatable consistent with expectations from the treatment wetland literature. This study demonstrates that treatment wetlands can be used for the management of RO concentrate from reclaimed water through reduction in concentration or reduction in volume through evapotranspiration.

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