Lake Marden Augmentation Capacity Rerating: A Water Resources Success!

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In 1997, Orange County Utilities (OCU) implemented a reuse feasibility study (RFS) in support of expanding the wastewater treatment system capacity at its Northwest Water Reclamation Facility (NWRF) from 3.5 to 7.5 mil gal per day (mgd) annual average daily flow (AADF). The reclaimed water management system at the NWRF at that time consisted of 13 rapid infiltration basins (RIBs) with a permitted capacity of 4.5 mgd AADF. The results of the 1997 study identified augmenting Lake Marden, an isolated karst lake located wholly within the limits of the NWRF property, as the preferred reclaimed water management expansion alternative. This alternative not only served to increase the reclaimed water management capacity of the NWRF, but it also served to recharge the underlying Floridan aquifer, thereby offsetting potential changes in groundwater levels due to regional pumping.

Implementation was begun by OCU of the recommendations from the 1997 RFS, and the Lake Marden system was permitted through the Florida Department of Environmental Protection (FDEP) in 2003 at an operational capacity of 3 mgd AADF. The Lake Marden project has been included in the groundwater flow modeling used in support of past OCU consumptive use permits as beneficial recharge that offsets potential changes in groundwater levels that may result from regional groundwater withdrawals.

In 2005, OCU completed construction and began operation of the Lake Marden treatment wetland and lake augmentation system at the NWRF. This system consists of approximately 67 acres of constructed wetlands used to further reduce nutrients in the reclaimed water produced at the NWRF prior to the direct augmentation of Lake Marden. From 2005 through 2008, flow to the wetlands was gradually increased to its permitted capacity of 3 mgd AADF, and flow, water level, and water quality data were closely monitored to ensure compliance with permitted and hydrologic limitations of the system. Based on field data, the system operated satisfactorily at its permitted capacity during this time.

In 2008, FDEP issued OCU a temporary (24-month) authorization to increase the loading of the Lake Marden wetlands above the permit limit of 3 mgd AADF, up to approximately 3.5 mgd AADF. The intent of the Lake Marden rerating study was to empirically determine the capacity of the Lake Marden augmentation system using operational data (e.g., flow, water level, and water quality) collected from 2005 through 2010. This evaluation had several key components as follows:

- An evaluation of the quantity of seepage occurring from the treatment wetlands.
- Estimation of the increase in Upper Floridan aquifer (UFA) potentiometric surface resulting from increased recharge through Lake Marden (a karst lake feature).
- Development of a continuous simulation model to determine the maximum potential capacity of the system that would not cause adverse impacts near the NWRF.
- An evaluation of the potential nitrate concentrations that would be anticipated from the treatment wetland discharge structure once the NWRF was at its full permitted operational capacity of 7.5 mgd AADF.

The analyses performed as part of the rerating study indicated that the Lake Marden system had been adequately functioning (quantity and quality) at its existing permitted capacity of 3 mgd AADF, and would continue to successfully operate at a higher recharge rate of 3.5 mgd under a wide array of climatic and operating conditions. Based on these analyses, OCU requested to increase the permitted capacity of the Lake Marden system with FDEP. In 2013, FDEP issued a permit to increase the capacity of the Lake Marden system from 3 to 3.5 mgd AADF, thereby increasing the reclaimed water management capacity at the NWRF and recharge to the underlying UFA in the area.

Lake Marden Wetland System

Reclaimed water from the NWRF is discharged into the Lake Marden treatment wetland system. As previously discussed, the Lake Marden wetland system was constructed to provide additional nutrient removal before reclaimed water is discharged into the lake. The treatment wetlands have a wetted area of approximately 67 acres and consist of three pairs of cascading cells (six total cells). The wetlands are encompassed by an exterior berm that contains a bentonite slurry wall to reduce the potential for seepage from the wetland. This was necessary because the wetland is located at the top of a sandy hill located in the karst region of central Florida. Stages within the wetland cells were controlled at higher elevations than the groundwater/surface water levels present in the area prior to construction of the wetland. The groundwater flow modeling results submitted to FDEP in support of the original permit application indicated that up to 0.3 mgd AADF of seepage from the wetlands laterally into the adjacent surficial aquifer system (SAS) and vertically to the underlying UFA would occur as a result of implementation of the project.

The first step taken in determining the operational capacity of the Lake Marden project was to estimate the seepage occurring from the wetland system. This was necessary for two reasons:

1) To determine the total capacity of the Lake Marden project, not just the amount of water discharged directly to the lake from the wetlands.
2) To allow the project biologists to properly design future planting schedules in support of maintenance of the wetland system.

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To determine the potential seepage from the wetland system, a water balance approach was implemented. The water balance for the wetland system was based on the continuity equation as follows:

$$\Sigma\ Inputs + \Sigma\ Outputs = \Delta\ Storage$$

The above equation was expanded as follows:

$$P + RW_{in} - ET - RW_{out} - Seep = \Delta\ Storage$$

where:

P = Precipitation within the footprint of wetland
RW_{in} = Observed discharge from the NWRF into the wetland
ET = Evapotranspiration (ET) within the footprint of the wetland (based on literature values)
RW_{out} = Observed wetland discharge to Lake Marden
Seep = Wetland seepage
Δ Storage = Change in storage within the wetland

The above equation was calculated in terms of mil gal (MG) for each daily time step.

Seepage from the wetlands was calculated as follows:

$$Seep = P + RW_{in} - ET - RW_{out} - \Delta\ Storage$$

Each wetland cell is controlled by a discharge structure similar to a typical ditch bottom inlet used in stormwater design. Boards are used within the discharge structures to control the water elevation of the wetlands. The NWRF operators have the ability to control the water elevation of the wetlands in response to climatic conditions, wetland maintenance, and various other operational factors. The change in storage or volume within the wetland on any given day was based on the historical stage and stage-storage relationship within each cell.

The water balance was performed on a daily basis from Jan. 1, 2005, through Aug. 31, 2011. Seepage was calculated on a daily, monthly, and annual basis. Calculated wetland seepage turned out to be highly variable on a daily, and even monthly, increment. As such, it was elected to base seepage on the annual average rates, which were calculated based on the daily water budget.

The average calculated seepage rate for the Lake Marden wetlands was 0.34 mgd AADF. These results are in reasonable agreement with the original estimate of 0.3 mgd AADF determined using the groundwater flow modeling performed in support of the permitting and design of the project.

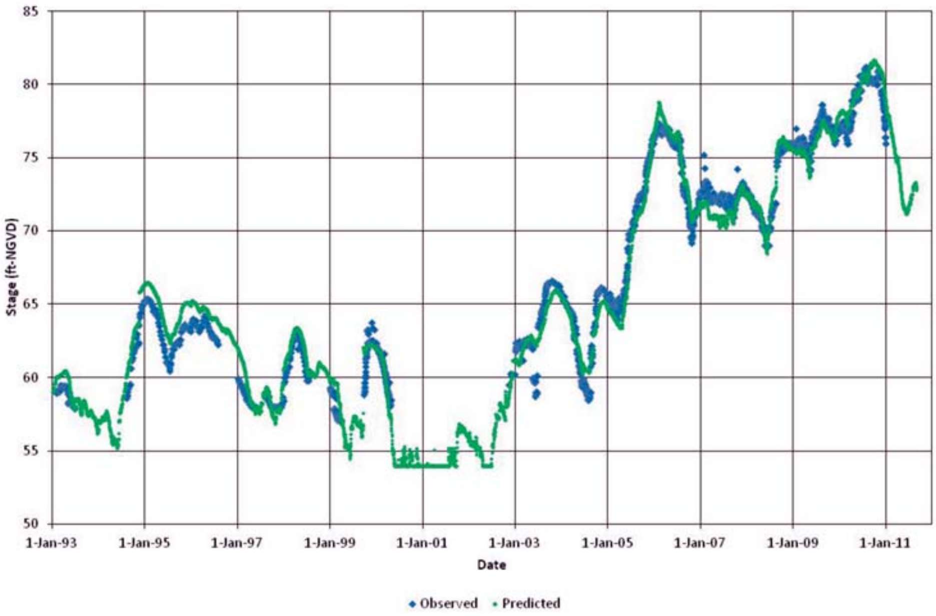

Figure 1. Model Calibration: Observed and Predicted Lake Marden Stage Versus Time

Lake Marden Capacity

The next step in this analysis was to determine the seepage capacity of Lake Marden. Reclaimed water that is discharged from the treatment wetlands to the lake is collected and stored within the depressional area associated with it. This depressional area is a karst feature with high leakance characteristics. Water stored in the lake recharges the UFA via diffuse leakance through the Intermediate Confining Unit (ICU), also referred to as the Hawthorn Formation, at the sinkhole feature that created Lake Marden. This results in both an increase in lake stage and UFA potentiometric surface elevation.

Lake Marden stage and the underlying UFA potentiometric surface had an equilibrium relationship before the project was implemented and will reach a new equilibrium relationship for a specific recharge rate. The intent of this portion of the study was to attempt to identify that relationship and determine what recharge rate will not result in unacceptable affects from the increase in water levels associated with the project.

Water Balance Approach

A water balance approach similar to that used for the analysis of average wetland seepage was used to determine the actual capacity of Lake Marden. The continuity equation previously discussed was expanded to assess lake seepage capacity as follows:

$$P + RO + SAS + RIBs + RW_{out} - ET - Q_L = \Delta\ Storage$$

where:

P = Precipitation
RO = Stormwater runoff contributing to Lake Marden
SAS = Lateral groundwater seepage from the SAS into Lake Marden
RIBs = RIB flow contribution to Lake Marden
RW_{out} = Wetland discharge to Lake Marden
ET = Evapotranspiration
Q_L = Diffuse leakage from Lake Marden to the underlying UFA
Δ Storage = Change in storage within Lake Marden

The above equation was calculated in terms of MG for each daily time step.

Precipitation

Direct precipitation on Lake Marden was based on the same rainfall series used for the treatment wetland water balance.

Runoff

Stormwater runoff contributing to Lake Marden resulting from rainfall on upland

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areas surrounding the lake was calculated using the Soil Conservation Service (SCS) method. Pervious and impervious area estimates were obtained from the original Environmental Resource Permit (ERP) application submitted to FDEP in support of the lake project.

Surficial Aquifer System Seepage

Lateral seepage from the SAS to Lake Marden is a component of the water balance of the lake. The Dupuit-Forchheimer formula was used as an approximation in the continuous simulation model to estimate lateral groundwater seepage to the lake.

Rapid Infiltration Basins

This parameter is an estimate of the quantity of reclaimed water applied to RIBs that percolates into the SAS groundwater system and contributes flow to the lake.

Wetland Discharge to Lake Marden

The volume of water conveyed from the treatment wetland to the lake was based on metered data.

Evapotranspiration

Evapotranspiration rates were based on literature values and were applied to the wetted area of the lake based on the historical stage and stage-storage relationship.

Leakance

Leakance from the lake to the underlying UFA was based on the following equation:

$$Q_L = L\ x\ (Stage_{LM} - UFA_{pot})$$

where:

L = Leakance (MG/ft)
$Stage_{LM}$ = Lake Marden stage (ft)
UFA_{pot} = UFA potentiometric surface (ft)

The UFA potentiometric surface was based on historical data collected from on-site UFA monitoring well MW-2. The stage of Lake Marden was calculated as part of the water balance model. The leakance term was used as a calibration parameter.

Calibration

The water balance model was calibrated based on lake stage data from Jan. 1, 1993, through Aug. 31, 2011. Calibration was achieved by adjusting the following parameters:

- SCS curve number (CN) II used in the calculation of stormwater runoff.
- SAS hydraulic conductivity (held within reasonable ranges derived from numerical groundwater flow models of the area).
- Lateral groundwater seepage (including the contribution from RIB flow).
- ICU leakance.

An iterative calibration process was implemented and an uncertainty analysis was performed to identify the best combination of these parameters. The calibration results of the lake water balance model are presented in Figures 1 and 2. Model error ranged between -3.3 ft and 3.6 ft, with an average error of 0.02 ft. The absolute error and root mean square error were 0.38 ft and 0.96 ft, respectively.

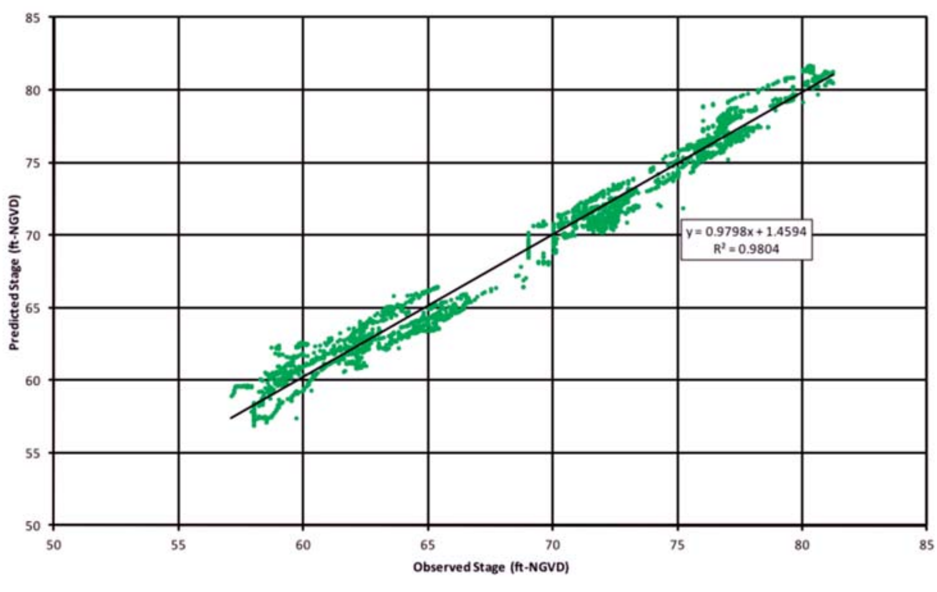

Figure 2. Model Calibration: Observed Lake Marden Stage Versus Predicted Stage

Simulations

Once the lake water balance model was calibrated, it was used to perform predictive simulations. The following changes were made to the model:

- Watershed information was updated to postdevelopment conditions (e.g., total acreage, impervious acreage, etc.) for the entire simulation.
- The historical UFA potentiometric surface data series used in the calibration simulation was updated to reflect the operation of the lake project in the predictive simulations. This was done by calculating a mounding factor, which for the purposes of this analysis, was defined as the change in UFA potentiometric surface elevation to change in reclaimed water application at the project. The mounding factor was estimated based on simple statistical evaluations of UFA potentiometric surface elevations observed in wells at the NWRF and wells far enough from the NWRF to likely not be affected by reclaimed water application at the NWRF, and on the results of the numerical groundwater flow model, developed in support of the original FDEP permit application for the project.

Based on the results of the evaluations performed to estimate the response in the UFA potentiometric surface resulting from recharge associated with the project, it was assumed that the UFA potentiometric surface elevation beneath the lake would increase approximately 0.7 ft/mgd AADF of recharge. The mounding factor was used to adjust the historical UFA potentiometric surface elevations used in the model to reflect what the elevations would have been if the project had operated at a higher target capacity from 1993 to 2010. If this adjustment to the UFA potentiometric surface was not made in the future simulations, the UFA potentiometric surface used in the model would be too low and would not fully include the effects of the project on the underlying potentiometric surface.

- The model was updated to automatically calculate the following results:
  - o Peak Lake Marden stage
  - o Normal high Lake Marden stage
  - o Average Lake Marden stage
  - o Lake Marden stage resulting from a design storm event

The normal high stage was calculated as the average of the peak stage for each year from 1993 through 2010. The stage resulting from a design storm event was calculated based on information contained in the original ERP submitted in support of the project.

The updated version of the model as described was then used to perform predictive simulations.

Results

The project was originally permitted for a capacity of 3 mgd AADF. The intent of this study was to determine if the capacity of the system could be increased above the original permitted capacity. This was achieved by performing predictive simulations with the Lake Marden water balance model to simulate higher project loading rates, which are summarized in Table 1. To determine if the predicted stages associated with higher loading rates were acceptable, the critical elevation evaluation performed in support of the original ERP for the project was reviewed. Based on this information, the evaluation submitted in support of the ERP for the project recommended a critical elevation of 90 ft-National Geodetic Vertical Datum (NGVD).

Based on the results of the lake water balance model and the constraint evaluation, a recharge capacity of 3.5 mgd AADF for the lake system (including wetland seepage), was selected as the rerating capacity to request from FDEP. A recharge capacity of 3.75 mgd was not selected for conservatism to allow greater freeboard between predicted peak stage and the identified constraint elevation of 90 ft-NGVD. The selected recharge capacity of 3.5 mgd AADF was further supported by the temporary loading test performed in 2010, during which the system successfully functioned at a capacity of approximately 3.5 mgd AADF. The predicted stage in the lake associated with a project loading capacity of 3.5 mgd AADF is presented in Figure 3, under the historical climatic conditions that occurred between 1993 and 2010.

Table 1. Lake Marden Water Balance Model Results

Result	Lake Marden Project Total Capacity[1] (MGD AADF)			
	3.0	3.25	3.5	3.75
Peak Stage (ft)	84.8	86.5	88.1	89.7
Normal High Stage (ft)	81.1	82.7	84.3	85.9
Average Stage (ft)	79.1	80.8	82.5	84.1
Normal High Stage Plus 12-in. Design Storm (ft)	83.1	84.6	86.1	87.6

[1] Wetland influent flow delivered from NWRF.

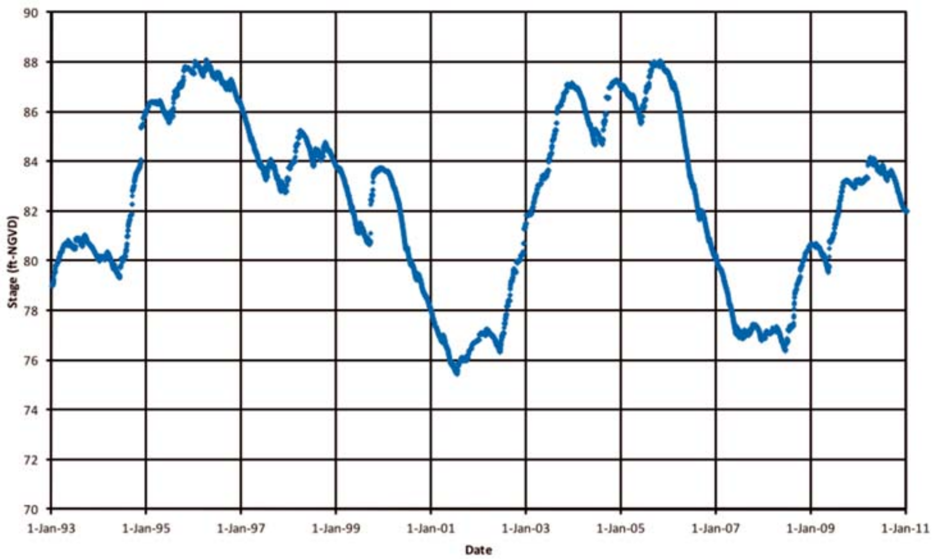

Figure 3. Predicted Lake Marden Stage at a 3.5 mgd AADF Operating Capacity

Water Quality

In addition to the hydraulic acceptance capacity of the lake system, the quality of the water conveyed to the lake was also evaluated. The FDEP wastewater operational permit for the NWRF has the following limitations (pertinent to this project) with regard to water quality:

- Reclaimed water generated at the NWRF (e.g., plant effluent): 12 mg/L nitrate (as nitrogen).
- Water conveyed from the lake treatment wetland to Lake Marden: 3 mg/L nitrate (as nitrogen).

The lake treatment wetland system was originally designed for a capacity of 3 mgd AADF. As part of this effort, it is proposed to increase the capacity of the lake system; it is not proposed as part of this effort to increase the size of the treatment wetlands. As such, a brief analysis was performed to determine if a higher flow rate could be accommodated within the existing footprint of the treatment wetland.

Nitrate concentration (in mg/L) was measured in the treatment wetland influent and effluent from December 2004 through December 2010. The historical average nitrate concentration in the reclaimed conveyed to the treatment wetlands was 4.8 mg/L. The historical average nitrate concentration in the water discharged from the wetlands to the lake was 0.35 mg/L. Though the historical nitrate concentration data were not continuous, nor were wetland influent and effluent data always collected on the same days or at the same frequency, this summary data provides a general indication that the wetlands removed approximately 93 percent (e.g., removal efficiency) of the nitrate in the water conveyed to the system. The nitrate removal efficiency of the wetlands varied between 92.0 and 96.5 percent from 2005 through 2010. The wetlands were operated above their permitted capacity of 3 mgd AADF in 2009 and 2010. The resulting percent nitrate removal rates observed in those two years were similar to the removal rates observed from 2005 through 2008, during which the wetlands were operated near or below their permitted capacity.

Based on this, it appears that the treatment wetlands were effectively removing nitrates from the reclaimed water conveyed to the wetlands, even at flow rates above the permitted capacity of the system. However, more detailed analyses were performed to provide additional reasonable assurance that the wetlands would effectively function under a wider range of operating conditions. This is discussed in more detail.

The NWRF was designed for a treatment capacity of 7.5 mgd AADF. It was also designed to meet a 12 mg/L nitrate concentration limitation. However, from 2005 through 2010, the NWRF was operated between 3.95 and 5.58 mgd AADF, below the plant design capacity. Because the plant was operating below its ca-

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pacity, higher nitrate production could occur than had been observed historically once the plant was operating at its full design capacity (depending on how the plant was operated). As such, a brief analysis was performed to determine potential nitrate production at the NWRF at its full design capacity and the associated treatment wetland system nitrate removal efficiency.

A synthetic flow series for the NWRF that simulates how the plant would operate on a daily basis under its full design capacity was developed. This was achieved by normalizing historical daily plant flows and then multiplying the normalized daily plant flows by the design capacity of the plant (7.5 mgd AADF). A synthetic nitrate series was then developed to simulate nitrate production at full design capacity of the plant. This is based on the following equation:

$$NO_3(syn) = Q(syn) \times P\text{-}NO_3(avg) \times NO_3(norm)$$

where:

$NO_3(syn)$ = Synthetic nitrate loading (kg)
$Q(syn)$ = Synthetic plant flow (mgd)
$P\text{-}NO_3(avg)$ = Average nitrate production rate (kg/mgd)
$NO_3(norm)$ = Normalized nitrate loading (based on observed data)

Historical nitrate concentrations were normalized in a similar manner used to develop the normalized plant flow series.

An average nitrate production rate of 20.2 kg/mgd was used based on historical data and operating conditions. A synthetic nitrate data series based on the synthetic flow series associated with the plant design capacity of 7.5 mgd AADF was developed based on this average nitrate production rate. This represents the daily nitrate concentration that might be expected in reclaimed water produced at the NWRF when the plant is operating at its full design capacity. This data series was then converted back to units of mg/L.

The next step was to develop a nitrate removal efficiency rate for the treatment wetland that could be applied to the synthetic nitrate series calculated previously. First, an estimate of the residence time of the wetland was developed. The difficulty with integrating residence time into the analysis is that residence time is constantly changing depending on the depth at which the wetlands are operated, flow into the wetlands, rainfall, and other parameters. The data exist to approximate the residence time of the wetland on a daily basis using the wetland water balance model previously discussed; however, the complexity of calculating the daily residence time would not significantly improve the results of the analysis. Furthermore, observed nitrate data are not available on a daily basis, nor are the influent and effluent observed nitrate data always available on the same day. As such, incorporating a calculation of daily residence time would be complex and likely beyond the level of complexity required for this analysis.

Instead, an approximate daily average residence time was calculated based on a wetland size of 67 acres and a typical operating depth of 2 ft, which are the approximate dimensions of the wetland. This equates to a wetland volume of 43.7 MG. This volume was divided into the daily flow rate conveyed to the wetlands to calculate a daily residence time. It was found that the average residence time for the period of record was approximately 19 days. The average residence time of 19 days is associated with an average flow rate of 2.76 mgd AADF. In 2009 and 2010, when the wetlands were operated above their permitted capacity of 3.0 mgd AADF, the calculated residence times were 18 days (3.24 mgd AADF) and 17 days (3.47 mgd AADF), respectively. This is not a significantly different residence time; therefore, 19 days was adequate for this analysis.

The typical residence time estimated for this project was used to develop moving average data series for the historical wetland in-

Table 2. Monthly Treatment Wetland Nitrate Removal Efficiency

Month	Year						
	2005	2006	2007	2008	2009	2010	Average
January	-	82.3	84.9	86.8	90.3	70.3	82.9
February	-	95.6	91.3	95.7	92.9	92.9	93.7
March	99.5	98.5	96.6	97.8	96.3	97.0	97.6
April	97.8	98.7	98.5	99.7	98.7	98.9	98.7
May	98.7	97.7	99.3	99.8	98.1	99.8	98.9
June	98.9	98.4	99.1	99.7	99.5	99.6	99.2
July	99.1	99.7	99.8	99.9	99.8	99.8	99.7
August	99.7	99.5	99.7	99.9	99.7	99.3	99.7
September	99.3	99.7	98.6	99.9	100.0	99.4	99.5
October	97.1	99.7	91.1	99.9	98.8	97.0	97.3
November	92.1	99.4	77.9	97.1	88.2	93.1	91.3
December	76.7	95.3	82.4	96.5	73.5	95.7	86.7

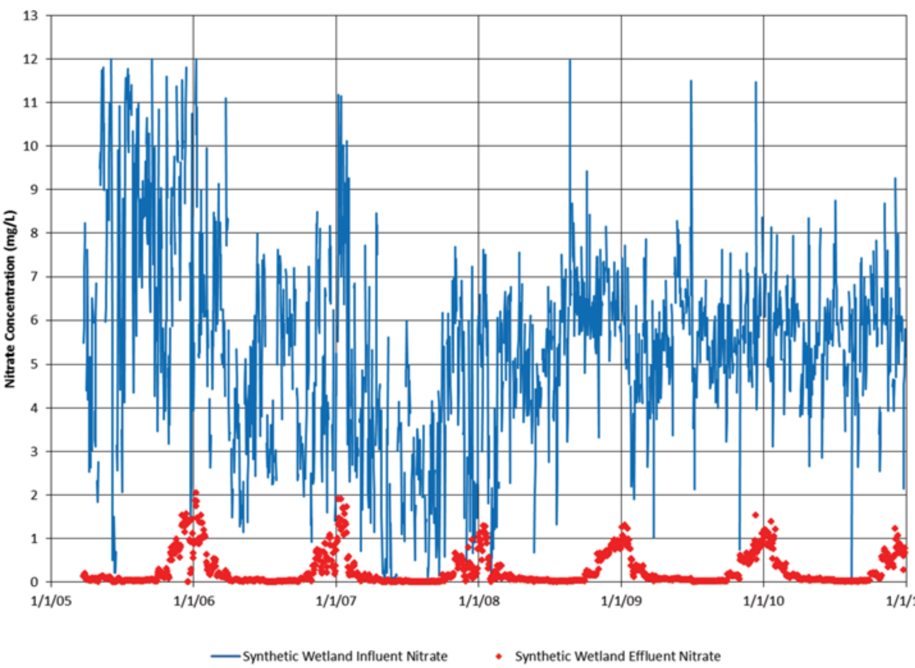

Figure 4. Synthetic Treatment Wetland Influent and Effluent Nitrate Concentrations

fluent and effluent nitrate data. The 19-day moving average influent nitrate series was then lagged 19 days. The daily percent removal efficiency was then recalculated based on the unlagged 19-day moving average influent nitrate series and the lagged 19-day moving average effluent nitrate series. In doing this, the average influent nitrate concentration on any given day is compared to the average effluent nitrate concentration that is observed 19 days in the future (approximately when the water leaves the wetland). The moving average approach was used to develop a continuous daily data series.

Once the new set of daily treatment wetland percent removal efficiencies was calculated, the monthly average removal efficiencies were recalculated, as presented in Table 2.

The average monthly percent removal efficiencies were applied to the synthetic nitrate series previously developed. The synthetic nitrate series represents the nitrate concentrations expected to be observed in the reclaimed water conveyed to the wetlands when the NWRF is operating at its full design capacity of 7.5 mgd AADF.

The average reclaimed water nitrate concentration predicted for the 7.5 mgd AADF design capacity of the plant was 5.4 mg/L. The predicted maximum daily reclaimed water nitrate concentrations were below the regulatory limitation of 12 mg/L. This synthetic nitrate series was assumed to be the nitrate concentrations in the reclaimed water conveyed to the Lake Marden wetlands.

Applying the average monthly nitrate removal efficiencies calculated for the treatment wetlands, the average and maximum nitrate concentrations predicted for the wetland effluent (e.g., the water conveyed to Lake Marden) were 0.25 mg/L and 2.58 mg/L, respectively. This is within the permit limitation of 3 mg/L. The predicted treatment wetland influent and effluent nitrate concentrations associated with a synthetic plant flow series of 7.5 mgd AADF are presented in Figure 4.

Based on this analysis, it is expected that nitrate concentrations in the treatment wetland effluent (e.g., the water conveyed to Lake Marden) will be well within the 3 mg/L permit limitation under expected operating conditions.