Orestimba Creek Agricultural Drainage Study

Report 5.2.2

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December, 2013

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Introduction

The main objectives of this study were to expand the model domain of the 2012 Watershed Analysis Risk Management Framework model of the upper San Joaquin River (SJR-WARMF 2012) to include the Orestimba Creek watershed in order to simulate the inflows to the San Joaquin River (SJR) and to demonstrate how specific agricultural practices and changes in those practices affect pollutant loading. The WARMF model can be used as a tool to evaluate the effect of different wetland management practices on the mitigation of agricultural pollution under different scenarios. Specifically, changes in land use, conversion of row crops to orchards, and nitrogen based fertilizer use reduction in the Orestimba Creek watershed were investigated. In addition, nitrate removal was assessed under different land use scenarios based on the amount of land that would need to be allocated to treatment wetlands to achieve target nitrate effluent concentrations.

Background

Agricultural drainage is a major source of diffuse pollution worldwide and is an important factor contributing to the widespread eutrophication of anthropogenically impacted rivers and estuaries (Heathwaite, Johnes, and Peters 1996; Smith, Tilman, and Nekola 1999; Smith 2003; Diaz and Rosenberg 2008; Stringfellow and Jain 2010). Technological advances in modern agriculture and the application of nitrogen-based synthetic fertilizers and manure to agricultural crops have increased crop yields and food production for the world's growing population. However, a significant portion of the applied nitrogen is in excess of crop needs. Excess nitrogen applications result in leaching of nitrate into the groundwater and eutrophication of surface water systems via surface runoff (Viers et al. 2012). Total nitrogen levels greater than 0.5 mg L^{-1} in surface waters can result in large masses of nuisance algae, while nitrate concentrations above 2.0 mg L^{-1} can cause toxicity in a variety of freshwater organisms (Camargo, Alonso, and Salmanca 2005).

A recent study revealed that nitrate contamination in groundwater from fertilizer and animal manure is severe and getting worse, impacting drinking water sources that supply water to hundreds of thousands of residents in California's farming communities (Harter, Viers, and Lund 2012). According to the study, 10 percent of the 2.6 million people living in the Tulare Lake Basin and Salinas Valley are currently at risk because their drinking water supplies are contaminated with nitrate. Approximately 96% of this nitrate contamination comes from agriculture, while only 4% can be attributed to wastewater treatment plant effluents, septic systems, food processing industries, landscaping and other sources (Harter, Viers, and Lund 2012). Elevated nitrate levels in drinking water have been linked to thyroid cancer, skin rashes, hair loss, birth defects and methemoglobinemia (blue baby syndrome), a potentially fatal blood disorder in infants (Galaviz-Villa et al. 2010; Ward et al., 2005).

Widespread occurrence of elevated nitrate concentrations has been reported in the Eastern San Joaquin Valley, CA (Dubrovsky et al. 1998). California's Central Valley is one of three regions in the US that are most impacted by nitrate contamination, and where the US Environmental Protection Agency's (EPA) maximum contaminant level (MCL) for nitrate (10 mg L^{-1}) is frequently exceeded in public drinking water wells (SWRCB 2011). During the period 1993-1995, 24% of the wells sampled exceeded the US EPA's MCL for nitrate (Dubrovsky et al.

1998). The number of wells with water exceeding the MCL increased to 29% in the same region during the sampling period 2001-2002. During the period 2001-2002 nitrate concentrations ranged from 0.05 mg L^{-1} to 75 mg L^{-1} with a median of 6.4 mg L^{-1} (Burow, Shelton, and Dubrovsky 2008).

High flux of nitrate and other sources of nitrogen are indications that the level of functional ecosystem services in that watershed is low (Heathwaite, Johnes, and Peters 1996; Smith 2003; Halpern et al. 2008; Rabalais et al. 2009; Stringfellow and Jain 2010). The SJR Watershed is one of the most productive agricultural regions in the world and agricultural runoff has been identified as an important factor contributing to the eutrophication of the SJR (Gowdy and Grober 2003; United States Department of Agriculture National Agricultural Statistics Service 2005; Stringfellow et al. 2009). Agricultural runoff entering the SJR is characterized by high concentrations of nutrients, including nitrate as the predominant form of nitrogen (Kratzer et al. 2004; Stringfellow 2008).

Wetlands have been suggested as Best Management Practices (BMPs) for the treatment of return flows from irrigated agriculture (Comin et al. 1997, Braskerud 2002, Fink and Mitsch 2004, Hernandez and Mitsch 2007, Beutel et al. 2009, Budd et al. 2009, Diaz et al. 2010, Stringfellow 2010). In the San Joaquin Valley, construction of wetlands to mitigate agricultural impacts is being considered, but uncertainty in land requirements and environmental impacts are major impediments to full-scale implementation (Karpuzcu and Stringfellow 2012).

Methods

Model Calibration and Validation for Nitrate

The model calibration for Orestimba Creek was based on the calibration previously conducted by Systech. By focusing on Orestimba Creek, which is a well-monitored area, Systech was able to identify important sources of uncertainty and errors in model inputs, test the impact of key assumptions on model results, and ultimately improve model inputs and simulations (Systech 2012). The calibration for dissolved nitrate plus nitrite as nitrogen (NO_3-N) at Orestimba Creek was expanded and validated to include the study period. Key parameters adjusted for calibration of NO_3-N were nitrification and denitrification rates at catchments and rivers, adsorption coefficients, vegetation composition and initial pore water concentrations. Figure 1 and Figure 2 compare the time series of simulated and observed NO_3-N at two stations along the San Joaquin River. The stations presented here were selected based on the availability of the monitoring data for the calibration and validation period.

The acceptable standard for calibration is to have the relative error within 10% of the average observed value, although this criterion might not be easily met for constituents with observed data near the detection limit (Herr and Chen 2012). Realistic expectations for absolute error vary by parameter and watershed. According to Herr and Chen (2012), a reasonable absolute error is generally less than 30% for nutrients.

At Orestimba Creek, the relative error (5%) was within the calibration target of 10%, but the absolute error (50%) was higher than the calibration target for nutrients (30%) (Table 1). This is partly due to the several peak NO_3-N concentrations during storm events simulated by the model which did not match with the observed data (Figure 1). Another reason for the high absolute error might be the fact that only a few observed data points were available at this station. There were data gaps during the winter months and for the period between 2007 and 2009 (Figure 1). There were several other monitoring stations along the SJR, such as Crows Landing, Stevinson, Patterson, and Maze Road, which performed better during NO_3-N calibration (data not shown). Based on these results, NO_3-N calibration was considered satisfactory.

Model Configuration

Overview of Model Simulations

Two groups of scenarios were set up: land use change scenarios and wetland scenarios. In the land use change scenarios, the conversion of agricultural land to marshes of sizes ranging from 25 to 247 ac and the conversion of the other row crop land use to orchards were investigated. Table 2 contains a description of the groups of scenarios used in this study. In the Wetland scenarios, agricultural runoff was applied to 6 to 445 ac wetlands created in a non-productive part of the watershed in one group of scenarios and in a productive part of the watershed in another group of scenarios. In both groups of scenarios, NO_3-N removal was simulated to compare WARMF's representation of NO_3-N removal kinetics with the conclusions of the agricultural drainage study by Karpuzcu and Stringfellow (2012).

Watershed Model and Simulation Files

There are multiple file types that store model data. The WSM files contain information on the graphical interface of the model and COE files contain the model coefficients. Since both WSM files and COE files are needed to represent the physical attributes of catchments, rivers, and reservoirs, each COE file corresponds to a particular WSM file. Loading unrelated WSM files and COE files should be avoided, as conflicts may occur between elements in the model interface and information in the COE files. Table 3 and Table 4 contain lists of watershed model files and coefficient files used in the wetland scenarios. These files were generated by copying San_Joaquin_2012Apr30_Daily.COE included in the WARMF installation set and modifying coefficients as applicable to each scenario.

The San_Joaquin_2012Apr30.WSM watershed model file and the RowCropsToOrchards_3.COE coefficient file, which was a copy of San_Joaquin_2012Apr30_Daily.COE with modified coefficients, were used for the "row crop to orchard conversion" scenario. Since the objective of this analysis was to compare land use between the existing baseline scenario provided with the model and the "row crop to orchard conversion" scenario and the existing baseline scenario does not use a warm start file, no warm start file was used with the "row crop to orchard conversion" to maintain comparability. Both sets of scenarios involve calculating the amount of runoff generated by the model, creating irrigation FLO files from the model output to apply the runoff to the wetland catchment, running warm start simulations, and then running the final simulations to generate results. Table 5 contains a list of the irrigation files used in this study. The warm start simulations were used to improve the accuracy of the simulated results, as error often results early in a simulation period when the initial conditions are first applied. Once the simulations reach dynamic steady-state, the final variables from the warm start simulations are used as initial conditions for the final simulations that generate results so that model statistics do not incorporate error from the model warm-up period.

Land Use Change Scenarios

To evaluate the effect of agricultural land use change on NO_3-N removal in the Orestimba Creek watershed, nitrate land use change scenarios were created, where different amount of agricultural land areas in the Orestimba Creek watershed were converted to marshes by changing the agricultural land use to marsh land use in the model and by adjusting reaction rate coefficients. For nitrate land use change scenarios, tributary connections in the watershed were redefined to divert the flows from the subcatchments into the marshes and the marsh outflow back to Orestimba Creek near Crows Landing (River ID 165). The average first order NO_3-N removal rate of 10 cm d^{-1} (Karpuzcu and Stringfellow 2012) was used for the marshes. To compare the results of nitrate land use change scenarios to the original conditions, a control simulation named “nitrate base scenario” was run for the same period using the conditions from the calibration simulation.

To test the effect of converting row crops to orchards on NO_3-N concentrations in Orestimba Creek near Crows Landing, the “conversion of row crops to orchards” scenario was set up. Table 6 lists the land use changes for each catchment for the “conversion of row crops to orchards” scenario. The “new” orchard land use percentage was calculated as the sum of the existing orchard land use percentage and other row crop land use percentages from the default model configuration. In the default model configuration, there were 5,960 acres of orchards and 6,929 acres of other row crops; the land use conversion resulted in 12,889 acres of orchards. Since orchards require more water than row crops, adjustments were made to the irrigation coefficients to maintain the same areal water application rate from before the land use change. This was accomplished by developing an equation to calculate areal water application rates from irrigation rates, land use, and catchment area, and then using the equation to calculate the change in irrigation rate that resulted in the same areal application rate for the new land use. The areal water application rate was calculated using,

$$q = \frac{C}{AU}\sum_{i=1}^{n} Q_{avg,i} I_i \tag{1}$$

where q is the water application rate in ft yr^{-1}, n is the number of irrigation sources, Q_{avg} is the average flow rate of one or more water sources in cfs, I is the irrigation rate percentage, A is the size of the catchment in m^2, U is the land use percentage, and C is a conversion approximately equal to 2,931,797 m^2 s ft^{-2} yr^{-1}. For example, the orchard land use in catchment 959 in the base scenario was 13.4% and received 12.1% of diversions from GW Irrigation 959 and 10.7% of diversions from Oak Flat WD CAA. The catchment area was 8.77×10^6 m^2. GW Irrigation 959 and Oak Flat WD CAA had average flow rates of 4.91 cfs and 5.07 cfs, respectively. The areal water application rate was:

$$q = \frac{(4.91\ \text{cfs})(12.1\%)\left(2{,}931{,}797\ \frac{\text{m}^2\text{s}}{\text{ft}^2\text{yr}}\right)}{(8.77\times10^6\ \text{m}^2)(13.4\%)} + \frac{(5.07\ \text{cfs})(10.7\%)\left(2{,}931{,}797\ \frac{\text{m}^2\text{s}}{\text{ft}^2\text{yr}}\right)}{(8.77\times10^6\ \text{m}^2)(13.4\%)}$$
$$= 2.85\ \text{ft yr}^{-1}$$

The water application rates calculated using Equation 1 are shown in Table 7. These values match WARMF's reported values up to four decimal places.

Table 8 shows the change in irrigation for each catchment when other row crops are converted to orchards. Equation 1 was used as a ratio to scale land use rates, irrigation rates, and catchment areas, average flow rates, and water application rates. When catchment area, average diversion flow rate, and the water application rate remains constant, Equation 2 represents the change in irrigation needed with the land use change to maintain the same water application rate:

$$\text{I}_\text{f} = \text{I}_\text{i}\frac{\text{U}_\text{f}}{\text{U}_\text{i}} \qquad (2)$$

where subscripts i and f denote the initial and final values respectively. While the water application rate for orchards remains the same, the increase in orchard land use would result in an overall increase in irrigation.

Wetland Scenarios

Soil Coefficients

Soil coefficients for the wetland scenarios were selected based on wetlands previously studied in the San Joaquin River watershed (Karpuzcu and Stringfellow 2012). Table 9 contains soil data selected from the Natural Resource Conservation Service (NRCS) (2012) *Web Soil Survey* at the confluence of Orestimba Creek and the San Joaquin River, shown in Figure 3 under map symbol 153. This area was selected for its riparian soils that could exist if a wetland was created by creating a levee setback to expand Orestimba Creek's riparian zone. The soil coefficients used in the study are shown in Table 10. Horizontal and vertical hydraulic conductivity values of 12,200 cm d^{-1} and 244 cm d^{-1}, respectively, were selected based on the soil data and current model configuration. The soil erosivity factor and soil particle content data were not selected because the universal soil loss equation parameters in the current model had not been calibrated. In the absence of available literature on soil data for wetlands, the remaining soil coefficients were selected based on the current model configuration in nearby areas.

Hydrologic Connections

The default Orestimba Creek watershed is shown in Figure 4 with red arrows representing downstream catchment to upstream river connections. About 15,800 ac of the total 125,000 ac in the watershed consist of agricultural land. Catchments 979 and 983 support small amounts of agriculture (about 0.5% of the total agricultural land) relative to the remainder of the watershed. Table 11 and Table 12 contain a list of connected catchments and stream segments with their entity ID's that make up the Orestimba Creek watershed. Figure 5 shows the transition between

Orestimba Creek near Crows Landing and Orestimba Creek near Newman (River ID 165). Initial attempts to route agricultural runoff through the wetland catchment involved connecting all of the catchments except 983 to the wetland and connecting the wetland to Orestimba Creek near Crows Landing. Connecting the agricultural runoff to the wetland resulted in outflow from each soil layer of the routed catchments to be applied as inflow to each soil layer in the wetland, producing large fluctuations in pH and other constituents. The unrealistic variations in pH and other constituents were resolved by creating a “dummy” creek designed solely as a transfer mechanism to collect runoff and divert it to the wetland. Applying the water as irrigation to the surface of the wetland stabilized the constituent fluctuations in Orestimba Creek near Crows Landing and made it easier to control the depth of water in the wetland.

Wetland Formation

Figure 6 and Figure 7 illustrate the Orestimba Creek watershed with the wetland placed in an agriculturally productive region and in a non-productive agricultural region respectively. For the productive land scenarios, the wetlands were formed by splitting catchment 804 into pre-defined areas to represent different points on the P-k-C* curve presented in Karpuzcu and Stringfellow (2012). In the non-productive land scenarios, the wetlands were formed by drawing a polygon inside catchment 979 and converting it into a catchment. When splitting a catchment, coefficients from the original catchment are assigned to both subcatchments, whereas default coefficients are assigned to new catchments created when converting a polygon to a catchment. Thus, all of the coefficients were updated in the new catchment. Table 13 contains a description of the areas and widths of the wetland catchment in each scenario. The catchment width is the total length of all river banks on the downstream river segment parallel to the catchment that permits flow. This was calculated by measuring the wetland width parallel to Orestimba Creek near Crows Landing in the productive land scenarios and multiplying the result by two. Linear interpolation was used to estimate the remaining catchment widths in the non-productive land scenarios for land areas that did not have productive land scenario counterparts. In the non-agricultural scenarios, the detention storage was set to maintain an average depth of 2 ft to improve hydraulic retention time (HRT). The HRT is given by,

$$\theta = \frac{V}{Q} \tag{3}$$

where θ is the hydraulic retention time in days, V is the wetland surface volume in ft^3, and Q is the wetland surface outflow in $ft^3\ d^{-1}$.

Other Model Coefficients

Table 14 lists various physical parameters, initial concentrations, best management practices, and reaction rate coefficients for the wetland catchments in both the productive and non-productive land scenarios. Updated initial concentration coefficients and a shallower catchment slope were included to improve denitrification and improve the stability of the simulated results in Orestimba Creek near Crows Landing. Manning’s n was selected based on a range of values for free water surface wetlands, while the slope was selected based on an example calculation (Kadlec and Wallace 2008). A precipitation weighting factor of zero was used for the wetland catchments in the non-productive land scenarios so that the model would not double-count the area occupied by the wetland and catchment 979 for precipitation. All of the irrigation flow diverted from the "dummy" creek was applied to the marsh land use. (Table 14, Table 15, Table 16). River coefficients for the dummy creek are shown in Table 17. To eliminate flow attenuation and reactions to the extent possible, reaction rates, stream length, and Manning's n were set to zero or very small values. The downstream bed elevation was set to match the slope of Orestimba Creek near Crows Landing.

Results and Discussion

Land Use Change Scenarios

Conversion of 1.8% Agricultural Land (Scenario 1 for Nitrate)

To evaluate the effect of taking agricultural land out of production on NO_3-N concentrations in Orestimba Creek near Crows Landing, a simulation was run with 1.8% of the agricultural land in the Orestimba Creek watershed area converted to marsh by changing the agricultural land use to marsh land use in the model. Tributary connections in the watershed were redefined to divert the flows from the subcatchments into the marsh and the outflow from the marsh back to Orestimba Creek near Crows Landing. The average first order NO_3-N removal rate of 10 cm d^{-1} (Karpuzcu and Stringfellow 2012) was used for the marsh. The simulation for Scenario 1 was run from January 1, 2011 to January 31, 2012. To compare the results of Scenario 1 to the original conditions, a control simulation named "nitrate base scenario" was run for the same period using the conditions from the calibration simulation. The simulation results indicated a significant reduction in NO_3-N concentrations compared to the base scenario (Figure 8). The base scenario had peak NO_3-N concentrations of 18 mg L^{-1} and 10 mg L^{-1} during two storm events (Figure 8). Conversion of 1.8% of the agricultural land to marsh reduced these peak NO_3-N concentrations to 6 mg L^{-1} and 4 mg L^{-1} respectively (Figure 8). As mentioned previously, NO_3-N concentrations above 2.0 mg L^{-1} can cause toxicity in a variety of freshwater organisms and total nitrogen (TN) concentrations greater than 0.5 mg L^{-1} in surface waters can result in large masses of nuisance algae (Biggs 2000, Camargo et al. 2005). A statistical comparison of land use scenarios for NO_3-N is presented in Figure 9. In the base scenario, 91% of the time, simulated NO_3-N concentrations exceeded 0.5 mg L^{-1}, while 77% of the time, NO_3-N concentrations exceeded 2.0 mg L^{-1}. In Scenario 1, taking 1.8% agricultural land out of production was effective in removing NO_3-N with only 9% of the simulated NO_3-N concentrations exceeding 2.0 mg L^{-1}, while 53% of the simulated NO_3-N concentrations were above 0.5 mg L^{-1} (Figure 9).

Conversion of 9% Agricultural Land (Scenario 2 for Nitrate)

To test the effect of increasing the amount of area taken out of agricultural production on NO_3-N removal rates, the amount of area converted in Scenario 1 (conversion of 1.8% agricultural land use to marsh use) was increased to 9% of the agricultural land in the Orestimba Creek watershed. As expected, simulated NO_3-N concentrations significantly decreased as a result (Figure 10). In this scenario, simulated NO_3-N concentrations exceeded 2.0 mg L^{-1} only 1% of the time, while NO_3-N concentrations exceeded 0.5 mg L^{-1} 32% of the time (Figure 9). Moreover, increasing the marsh area further reduced the peak NO_3-N concentrations to 3 mg L^{-1} and 2 mg L^{-1}, respectively, for the two storm events (Figure 10).

Fertilizer Use Reduction (Scenario 3 for Nitrate)

To test the effect of reducing the amount of fertilizer applied, the base scenario was run after reducing the nitrogen-based fertilizer applications by 30%. In this scenario, the simulated NO_3-N concentrations exceeded 2 mg L^{-1} 36% of the time. This is a significant improvement in comparison to the baseline scenario, where simulated NO_3-N concentrations exceeded 2.0 mg L^{-1} 77% of the time. However, there was no improvement in reducing NO_3-N concentrations to below 0.5 mg L^{-1}, as 90% of the time, simulated NO_3-N concentrations exceeded 0.5 mg L^{-1}, almost the same as in the baseline scenario (Figure 9). The simulation results indicate that Scenario 3 (fertilizer use reduction) was less effective in reducing NO_3-N concentrations compared with Scenario 1 (conversion of 1.8% agricultural land use to marsh use) and Scenario 2 (conversion of 9% agricultural land use to marsh use) (Figures 8 through 12). Additionally, the 30% reduction in nitrogen-based fertilizer use alone may be insufficient to reduce NO_3-N concentrations below 0.5 mg L^{-1}.

Combination of Agricultural Land Conversion and Fertilizer Use Reduction (Scenario 4 for Nitrate)

From a management perspective, it would be of interest to see the results for the combined effect of two different best management practices, i.e., conversion of agricultural land use to marsh land use and fertilizer use reduction. For this purpose, Scenario 4 was run, which was a combination of Nitrate Scenario 1 (1.8% of agricultural land converted to marsh) and Nitrate Scenario 3 (30% fertilizer use reduction) (Figure 12). In this scenario, only 3% of the simulated NO_3-N concentrations exceeded 2 mg L^{-1}, while 39% of the simulated NO_3-N concentrations exceeded 0.5 mg L^{-1} (Figure 9). These concentrations were close to the NO_3-N concentrations observed in Nitrate Scenario 2 (9% of agricultural land converted to marsh).

A statistical comparison of the five nitrate scenarios is presented in Figure 9. At a significance level of 0.05, the mean NO_3-N concentration values for the base scenario (2.9 mg L^{-1}), Nitrate Scenario 1 (0.8 mg L^{-1}), Nitrate Scenario 2 (0.5 mg L^{-1}) and Nitrate Scenario 3 (2 mg L^{-1}) were significantly different from each other. However, the difference between the mean NO_3-N concentration values for Nitrate Scenario 2 (0.5 mg L^{-1}) and Nitrate Scenario 4 (0.5 mg L^{-1}) was not statistically significant (Figure 9). These results suggest that the combination of Nitrate Scenario 1 (1.8% of agricultural land converted to marsh) with Nitrate Scenario 3 (30% fertilizer use reduction) could potentially have a similar effect to Nitrate Scenario 2 (9% of agricultural land converted to marsh).

Conversion of Row Crops to Orchards

Table 18 shows summary statistics for both the base scenario and the "conversion of row crops to orchards". There was a mean 1.7% increase in flow from the base scenario from 27.7 cfs to 28.2 cfs in the "conversion of row crops to orchards" scenario, and a corresponding median increase of 10.8% between 6.29 cfs and 6.97 cfs, indicating skew towards high flow values. There was a mean increase in NO_3-N concentrations of 8.9% from 3.03 mg L^{-1} to 3.30 mg L^{-1} and a median increase of 13.8% from 1.88 mg L^{-1} to 2.14 mg L^{-1} between the base scenario and the "conversion of row crops to orchards" scenario after the other row crops land use was converted to orchards. The maximum flow for both scenarios was 1,099 cfs. Figure 13 shows a time series plot of both scenarios for flow. The flow rate is the same for both scenarios with nearly undetectable changes in base flow. Figure 14 shows a time series plot of NO_3-N concentrations for both scenarios. The NO_3-N concentrations for the "conversion of row crops to orchards" scenario were higher than the base scenario, particularly during the spring, summer, and fall months.

The results of the "conversion of row crops to orchards" scenario indicate that converting the other row crops land use to orchards in the Orestimba Creek watershed would increase water consumption and NO_3-N concentrations in Orestimba Creek near Crows Landing. The increase in NO_3-N is caused by land application rates from the orchard land use and to a much lesser extent, groundwater irrigation sources. Table 19 shows the monthly application rates for orchards and other row crops. According to WARMF's land use input, 38.4 kg N ha^{-1} of total ammonia plus ammonium nitrogen (TAN) was applied between April and October for orchards for a total of 269.0 kg N ha^{-1} while 43.6 kg N ha^{-1} of TAN was applied between May and September for a total of 217.9 kg N ha^{-1}. Table 20 shows the mean NO_3-N and TAN loading from irrigation sources between October 1, 2005 and December 31, 2010 at 100% allocation. Ammonia loading values ranged from 0.270 kg N d^{-1} to 1.40 kg N d^{-1} while NO_3-N loading values ranged from 6.03 kg N d^{-1} to 770 kg N d^{-1}. When multiplied by the percentage of water diverted for irrigation from Table 8, the TAN and NO_3-N loading for the base scenario and the "conversion of row crops to orchards" scenario was obtained. These values are reported in Table 21. Conversion of row crops to orchards resulted in an overall 4.7% increase in NO_3-N and TAN loading from 524 kg N d^{-1} to 549 kg N d^{-1} and 1.14 kg N d^{-1} to 1.19 kg N d^{-1} respectively.

Wetland Scenarios

Table 22 and Figure 15 show the summary statistics and a plot of outflow NO_3-N concentrations from the non-productive scenarios for wetland sizes ranging from 6.03 to 445 ac. The mean NO_3-N concentration ranged from 1.44 mg L^{-1} for no wetland to 0.482 mg L^{-1} for a 445 acre wetland. The maximum, minimum, mean, and median NO_3-N concentrations decreased with increasing wetland size. Comparing the effect of land area on NO_3-N concentration, the largest change occurred between having no wetland and having a 6.03 ac wetland; the maximum NO_3-N concentration decreased from 34.6 mg L^{-1} to 4.91 mg L^{-1} for no wetland and a 6.03 ac wetland respectively. Changes in NO_3-N concentrations were most pronounced during the irrigation season in April to August and rainy season in October through January. From February to April, NO_3-N outflows were greater for larger wetlands than smaller wetlands, ranging from an average of 0.726 mg L^{-1} to 1.08 mg L^{-1}. When no wetlands were present, large NO_3-N spikes of greater than 10 mg L^{-1} occurred between October and January with the largest peak occurring on November 19th at 34.6 mg L^{-1}. With a 6.03 ac wetland, this maximum decreased to 4.91 mg L^{-1}, an 86% reduction.

The trend of pronounced changes in NO_3-N concentrations during the irrigation season and the inversion of NO_3-N concentrations from February through April was also similar for TAN and TN, as shown in Table 23 through Table 24 and Figure 16 through Figure 17. As the wetland size increased, the mean, median, minimum, and maximum TAN and TN concentrations decreased, indicating the likely presence of NO_3-N decay and storage within the wetlands. Similar to NO_3-N, maximum TAN and TN concentrations decreased sharply from the base scenario to the 6.03 ac wetland scenario from 138 to 15.1 mg L^{-1} (Table 23) and 173 to

19.2 mg L^{-1} (Table 24), respectively. The same seasonal trends with NO_3-N were applicable to TAN and TN. In addition, TAN concentrations did not increase between January and February as they did with NO_3-N and TN. Figure 18 shows precipitation for Catchment 963, a catchment with substantial agricultural activity. The accumulation of nitrogen throughout the summer months and subsequent release in stormwater discharge from "first flush" precipitation events may have resulted in the NO_3-N peaks and NO_3-N storage in the wetlands.

Summary statistics and a plot of surface water outflow from wetlands in the non-productive scenarios are shown in Table 25 and Figure 19. The maximum, mean, and median flow tended to decrease with increasing wetland size, while minimum outflow tended to increase. Table 26 and Figure 20 contain summary statistics and a plot of hydraulic retention time (HRT) for wetlands of various sizes. The HRT was smallest between February and May when outflows were high. This suggested that the relationship between NO_3-N and wetland area may have inverted in this period due to washout. Summary statistics and a time series plot for dissolved oxygen (DO) concentrations in the modeled wetland are shown in Table 27 and Figure 21. Output noise and DO concentrations decreased with increasing wetland area. Summary statistics and time-series plot output for dissolved organic carbon (DOC) are shown in Table 28 and Figure 22. Only a gradual decrease in DOC occurred between June and October, which does not support the notion that denitrification was occurring.

While denitrification was simulated in the wetlands, reducing effluent NO_3-N concentrations, denitrification was not sufficient for complete conversion of NO_3-N originating in the agricultural runoff. Figure 23 shows a plot of wetland area versus mean NO_3-N effluent concentration for the non-productive land scenarios. The relationship between NO_3-N effluent and wetland area was only consistent with the P-k-C* relationship described in Karpuzcu and Stringfellow (2012) for areas up to 149 ac, indicating that the model did not adequately describe areal NO_3-N removal kinetics.

Suggested Improvements for the WARMF Model

Overland Flow in Wetlands

Based on a WARMF topical report by Systech (2001), the model uses Manning's equation to calculate overland flow for catchments. According to Kadlec and Wallace (2008), there is evidence suggesting that Manning's equation is inadequate for calculating flow in free surface wetlands. Manning's n is estimated based on characteristics of open channels, such as channel cross-section, alignment, and vegetation. Manning's n for various free water surface wetlands range from 0.18 to 7.6; values from the higher end of the range cannot be estimated using techniques in hydraulics literature that consider stream characteristics. Kadlec and Wallace found an inverse relation between Manning's n and depth in wetlands, contradicting the notion that friction increases as wetted perimeter increases. Lastly, as wetlands age, vegetation increases in density, resulting in an increase in Manning's n over time. Kadlec and Wallace present a collection of integrated equations from existing literature describing free water surface wetland hydraulics worth consideration for inclusion in WARMF.

Wetland Hydraulic Retention Time

While sufficient wetland depths were achieved with modifications to detention storage in the non-productive land scenarios, acceptable hydraulic retention times could not be achieved without unrealistically modifying other parameters in the model. Figure 24 shows a logarithmic plot of volume and flow for the 25 ac wetland in a non-productive scenario without modifications and with catchment 979 reconnected back to Orestimba Creek near Crows Landing. The average hydraulic retention time of the data (plotted as a line with long dashes) was 2.67 hr, which was insufficient to allow removal of NO_3-N to occur. The required hydraulic retention time shown with a solid black line is 1 d. Based on this plot, achieving a reasonable hydraulic retention time requires either an increase in surface volume by about a factor of 10 without outflow changing, a decrease in outflow by about a factor of 10 without volume changing, or a combination of the two. Since the wetland was already configured to have a mean depth of 2 ft, increasing the wetland volume was not practical. One possible remedy that was tested was to disconnect catchment 979 from the dummy creek and reconnect it to Orestimba Creek near Crows Landing since the catchment produced large peaks in Orestimba Creek in the default scenario included in the model. As shown in this plot, this approach slightly improved the hydraulic retention time, but was still not enough to meet the requirement. Other approaches tested during the development of the wetland scenarios to decrease flow included increasing Manning's n from 3 to 5, and decreasing the soil hydraulic conductivity, decreasing the catchment width, and decreasing the saturated soil moisture by an order of magnitude. None of these approaches resulted in a beneficial change in mean flow without an unreasonable increase in mean catchment volume.

A weir feature for catchments or a feature to set stage-outflow relationships is recommended for the WARMF model to improve hydraulic retention times for wetlands since weirs are used in treatment wetlands (Kadlec and Wallace 2008). This would enable a modeler to control both the flow and the volume within the catchment, making it possible to achieve desirable hydraulic retention times for wetlands. Systech has indicated that it is working on implementing a gate feature in a future release of WARMF that would offer similar functionality (Herr, personal communication).

Other Recommendations

Each of the productive scenarios required pre-calculation of the flow being applied to the dummy creek because the process of splitting catchment 804 resulted in hydrologic alteration upstream of the wetland. A recommended improvement to the diversion and irrigation feature in WARMF is to provide an additional option for a fraction of flow to be diverted from a river. This would make it possible to perform wetland simulations without the need for pre-calculating flow and creating additional diversion files. Sensitivity often occurred when flow reached zero in Orestimba Creek near Crows Landing during simulations; improvements to the model algorithms to improve numeric stability (such as reducing round-off errors) for low flow conditions would be useful for simulating pulse flow and loads.

Conclusions

WARMF is a powerful decision support system designed to support the watershed approach and Total Maximum Daily Load (TMDL) calculation. WARMF model was calibrated and validated for the San Joaquin River Watershed and used to simulate the effect of different best management practices on mitigation of nitrate in agricultural runoff. The kinetic parameters obtained from previous studies were used as input parameters in the simulations. The results of the nitrate simulations suggest that conversion of an area as small as 1.8% of the agricultural land in the Orestimba Creek watershed to marsh could significantly reduce NO_3-N concentrations. Increasing the marsh area further to 9% of the agricultural land reduced almost all of the simulated concentrations below the 2.0 mg L^{-1} target; however, taking such an amount of agricultural land out of production may be unrealistic. According to the model's predictions, if conversion of 2% of the agricultural land use to marsh use is combined with 30% fertilizer use reduction, a similar NO_3-N removal performance to a scenario, where 9% of the agricultural land use is converted to marsh use, could potentially be achieved.

Simulations also indicated that converting the other row crops land use to orchards in the Orestimba Creek watershed would increase water consumption and NO_3-N concentrations in Orestimba Creek near Crows Landing. Simulations of converting land uses from other row crops to orchards resulted in a 13.8% increase in median NO_3-N effluent concentrations, and an overall 4.7% increase in NO_3-N and TAN loading.

Based on the results of the wetland scenarios, while the model predicted increasing NO_3-N removal with increasing wetland area, it did not adequately describe the areal nitrate removal kinetic relationship described in Karpuzcu and Stringfellow (2012). Implementing areal nitrate removal kinetics, hydraulic equations that appropriately describe head loss in wetlands, and flow control structures for catchments will improve WARMF's accuracy and reliability for assessing treatment wetlands as a BMP for water quality improvement.

Acknowledgements

We gratefully acknowledge the Ecosystem Restoration Program and its implementing agencies (California Department of Fish and Wildlife, U.S. Fish and Wildlife Service, and the National Marine Fisheries Service) for supporting this project (E0883006, ERP-08D-SO3).

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Table 1. Model Errors for the Nitrate Calibration and Validation Simulations at Orestimba Creek near Crows Landing. A reasonable goal for calibration is a relative error of < 10% and an absolute error of< 30%.

USGS Monitoring Station	Parameter	Relative Error (%)	Absolute Error (%)
Orestimba Creek (Calibration)	NO_3-N	5	50
Orestimba Creek (Validation)	NO_3-N	1	47

Table 2. Overview of model scenario groups.

Study Group	Scenario Group	Description	Scenarios Used
Land use change	Scenario 1	1.8% of agricultural land in Orestimba Creek watershed converted to marsh land use, catchments connected to marsh and back to Orestimba Creek near Crows Landing.	See Karpuczu 2012
	Scenario 2	9% of agricultural land in Orestimba Creek watershed converted to marsh land use, catchments connected to marsh and back to Orestimba Creek near Crows Landing.	See Karpuczu 2012
	Scenario 3	Nitrogen-based fertilizer application reduced by 30%.	See Karpuczu 2012
	Scenario 4	Combination of Scenario 1 and Scenario 3.	See Karpuczu 2012
	Conversion of row crops to orchards	Other row crop land use converted to orchards.	Table 4
Wetland	Productive scenarios	25-247 acre wetlands created by splitting existing productive agricultural catchment, catchments connected to dummy creek, dummy creek applied to wetland as irrigation, wetland discharged to Orestimba Creek near Crows Landing.	Table 2
	Non-productive scenarios	6-445 acre wetlands created by creating new catchment in non-productive agricultural area, catchments connected to dummy creek, dummy creek applied to wetland as irrigation, wetland	Table 3

Table 3. Watershed model and coefficient files for the productive land scenarios. All files are copies of the 2012 base daily scenario provided in the WARMF installation with modifications to the model coefficients. Initial simulations were conducted throughout the durations of the warm start files and the simulation files to pre-calculate flow for application to the wetland. After the warm start simulations were complete, the simulations were conducted using the warm start files. See Table 5 for a list of irrigation flow files generated from the results of the pre-calculation simulations, Table 4 for a list of simulation files for scenarios with wetlands in a non-agricultural region, and Table 11 through Table 17 for descriptions of the coefficients modified in this study.

Percent of Catchment 804 Area	Watershed Model File	Pre-Calculation File Simulation Period: (1/1/09 – 1/31/11)	Warm Start File Simulation Period: (1/1/09 – 12/31/09)	Simulation File Simulation Period: (1/1/10 – 1/31/11)
0%	Wetland_Split_Base.WSM	-	new_kinetics_00_ws.COE	new_kinetics_00.COE
1%	Wetland_Split_01.WSM	new_kinetics_01_pc.COE	new_kinetics_01_ws.COE	new_kinetics_01.COE
2%	Wetland_Split_02.WSM	new_kinetics_02_pc.COE	new_kinetics_02_ws.COE	new_kinetics_02.COE
4%	Wetland_Split_04.WSM	new_kinetics_04_pc.COE	new_kinetics_04_ws.COE	new_kinetics_04.COE
6%	Wetland_Split_06.WSM	new_kinetics_06_pc.COE	new_kinetics_06_ws.COE	new_kinetics_06.COE
8%	Wetland_Split_08.WSM	new_kinetics_08_pc.COE	new_kinetics_08_ws.COE	new_kinetics_08.COE
10%	Wetland_Split_10.WSM	new_kinetics_10_pc.COE	new_kinetics_10_ws.COE	new_kinetics_10.COE

Table 4. Watershed model and coefficient files for the non-productive land scenarios. All files are copies of the 2012 base daily scenario provided in the WARMF installation with modifications to the model coefficients. The results of the wetland base scenario and warm start file were used to apply water to the wetland in the remaining scenarios. After the warm start simulations were complete, the simulations were conducted using the warm start files. See Table 5 for a list of irrigation flow files generated from the results of the pre-calculation simulations and Table 3 for a list of simulation files for scenarios with wetlands in an agricultural region.

Percent of Catchment 804 Area	Watershed Model File	Warm Start File Simulation Period: (1/1/09 – 12/31/09)	Simulation File Simulation Period: (1/1/10 – 1/31/11)
0.00	Wetland_Split_Base.WSM	new_kinetics_00_ws.COE	new_kinetics_00.COE
0.00	Wetland_const_flow_6.WSM	Wetland_const_flow_6_depth_ws.COE	Wetland_const_flow_6_depth.COE
0.50	Wetland_const_flow_12.WSM	Wetland_const_flow_12_depth_ws.COE	Wetland_const_flow_12_depth.COE
1.00	Wetland_const_flow_25.WSM	Wetland_const_flow_25_depth_ws.COE	Wetland_const_flow_25_depth.COE
2.00	Wetland_const_flow_50.WSM	Wetland_const_flow_50_depth_ws.COE	Wetland_const_flow_50_depth.COE
4.00	Wetland_const_flow_99.WSM	Wetland_const_flow_99_depth_ws.COE	Wetland_const_flow_99_depth.COE
6.00	Wetland_const_flow_149.WSM	Wetland_const_flow_149_depth_ws.COE	Wetland_const_flow_149_depth.COE
8.00	Wetland_const_flow_198.WSM	Wetland_const_flow_198_depth_ws.COE	Wetland_const_flow_198_depth.COE
10.00	Wetland_const_flow_248.WSM	Wetland_const_flow_248_depth_ws.COE	Wetland_const_flow_248_depth.COE
14.00	Wetland_const_flow_347.WSM	Wetland_const_flow_347_depth_ws.COE	Wetland_const_flow_347_depth.COE
18.00	Wetland_const_flow_446.WSM	Wetland_const_flow_446_depth_ws.COE	Wetland_const_flow_446_depth.COE

Table 5. Irrigation flow files used in the wetland scenarios. In the productive land scenarios the hydrologic characteristics change, requiring the need for multiple pre-calculation simulations and irrigation files. The same irrigation file is used for all of the non-productive land scenarios since the hydrology is the same upstream of the wetland between scenarios. See Table 3 and Table 4 for a description of the wetland scenarios and scenario files.

Percent of Catchment 804 Area	Wetland in Agricultural Region	Wetland in Non-Agricultural Region
0.25	-	wetland_kinetics_const.FLO
0.5	-	wetland_kinetics_const.FLO
1	wetland_kinetics_01.FLO	wetland_kinetics_const.FLO
2	wetland_kinetics_02.FLO	wetland_kinetics_const.FLO
4	wetland_kinetics_04.FLO	wetland_kinetics_const.FLO
6	wetland_kinetics_06.FLO	wetland_kinetics_const.FLO
8	wetland_kinetics_08.FLO	wetland_kinetics_const.FLO
10	wetland_kinetics_10.FLO	wetland_kinetics_const.FLO
14	-	wetland_kinetics_const.FLO
18	-	wetland_kinetics_const.FLO

Table 6. Change in land use percentage for catchments in the Orestimba Creek watershed in the "row crop to orchard conversion" scenario. The new land use percentage for orchards is the sum of the land uses for other row crops and orchards from the default model configuration. See Table 11 for catchment and river names.

Catchment	Other Row Crops	Orchards (default)	Orchards (new)
959	23.90%	13.40%	37.20%
963	15.80%	11.10%	26.90%
981	49.20%	34.50%	83.60%
853	21.10%	48.20%	69.40%
829	65.70%	14.10%	79.80%
980	47.30%	29.30%	76.60%
804	36.90%	45.70%	82.60%

Table 7. Calculated water application rates for catchments in the Orestimba Creek watershed for the "conversion of row crops to orchard" scenario. Water application rates were calculated using Equation 1 and compared with the water application rates reported in WARMF to test the validity of the equation for use in calculating new irrigation rates such that the new orchard land use has the same water application rate as the old orchard land use. These water application rates match WARMF's reported values up to at least four decimal places.

		Water Application Rates (ft yr^{-1})		
Catchment ID	**Catchment Name**	**Orchards**	**Other Row Crops**	**Orchards (New Scenario)**
959	Oak Flat WD S	2.85	2.63	2.85
963	Del Puerto (Sunflower S) WD	2.82	2.60	2.82
981	Del Puerto WD/Orestimba DD	2.82	2.60	2.82
853	Del Puerto (Foothill) WD	2.82	2.60	2.82
829	Crows Landing	2.99	2.79	2.99
980	Eastin WD	3.17	2.93	3.17
804	804 CCID North/ Orestimba DD	3.03	2.79	3.03

Table 8. Change in irrigation for catchments in the Orestimba Creek watershed for the row crop to orchard conversion. The resulting change in irrigation for the orchard land use (new) results in approximately the same areal applied water rate when row crops are taken out of production. For catchments (959, 963, 981, & 853) with multiple irrigation sources, all irrigation sources were scaled equally to match the ratio used for orchards in the default model configuration.

Catchment	Source	Other Row Crops	Orchards (default)	Orchards (new)
959	GW Irrigation 959.PTS	20.00%	12.10%	33.80%
	Oak Flat WD CAA.PTS	17.60%	10.70%	29.70%
963	GW Irrigation 963.PTS	5.76%	4.37%	10.60%
	DEL PUERTO WD DMC.FLO	2.37%	1.78%	4.37%
981	GW Irrigation 981.PTS	7.73%	5.87%	14.30%
	DEL PUERTO WD DMC.FLO	5.66%	4.30%	10.40%
853	GW Irrigation 853.PTS	4.17%	10.30%	14.80%
	DEL PUERTO WD DMC.FLO	1.76%	4.35%	6.26%
829	CCID Below OBanion.FLO	0.39%	0.09%	0.50%
980	GW Irrigation 980.PTS	36.20%	24.30%	63.50%
804	CCID Below OBanion.FLO	0.83%	1.11%	2.01%

Table 9. Soil data from NRCS (2012) *Web Soil Survey* selected to represent the Orestimba Creek wetland in the wetland scenarios.

Depth (in)	**0-14**	**14-60**
Sand %	70	67
Silt %	16	20
Clay %	10-14-18	8-13-18
K	0.32	0.32
Moist Bulk Density (g cm^{-3})	1.50-1.60	1.50-1.60
Saturated Hydraulic Conductivity (µm s^{-1})	14.11-42.34	14.11-42.34
Available Water Capacity	0.10-0.12	0.10-0.12
Organic Matter %	0.5-2.0	0.0-1.0
Classification	SC-SM, SM, SC	SC, SC-SM, SM

Table 10. Soil wetland coefficients for soil layers used for wetland scenarios. Values selected based on NRCS (2012) soil data for the Orestimba Creek confluence and existing values in the model. See Table 9 and Figure 3 for data selection.

Layer	1	2	3	4
Thickness (cm)	10	24.1	20.7	220
Initial Moisture	0.24	0.24	0.2	0.2
Field Capacity	0.24	0.24	0.228	0.2
Saturated Moisture Content	0.4	0.35	0.3	0.25
Horizontal Hydraulic Conductivity ($cm\ d^{-1}$)	12200	1200	0	0
Vertical Hydraulic Conductivity ($cm\ d^{-1}$)	244	20	0	0
Root Distribution	0.74	0.26	0	0
Density ($g\ cm^{-3}$)	1.3	1.3	1.3	1.3
Soil Tortuosity	10	10	10	10

Table 11. Catchments and rivers in Orestimba Creek watershed study area. Catchments and rivers in italics were created in the wetland study scenarios.

Catchment ID	Name
983	Orestimba Creek Headwater
979	Crow Creek Headwater
959	Oak Flat WD S
963	Del Puerto (Sunflower S) WD
981	Del Puerto WD/Orestimba DD
853	Del Puerto (Foothill) WD
829	Crows Landing
980	Eastin WD
804	804 CCID North/ Orestimba DD
976 (productive land) or 988 (non-productive land)	*Orestimba Wetland*
River ID	**Name**
164	Orestimba Creek near Newman
165	Orestimba Creek near Crows Landing
986	*Orestimba Dummy Creek*

Table 12. Catchment and river connections used in default model configuration and study in the Orestimba Creek watershed. Water from the dummy creek is diverted and applied to the wetland (Catchment 976 or 986) as irrigation. See Table 11 and Figure 4 through Figure 7.

Configuration	River ID	River Name	Upstream Catchments	Upstream Rivers
Default	164	Orestimba Creek near Newman	983	
	165	Orestimba Creek near Crows Landing	979, 959, 963, 981, 853, 829, 980, 804	164
Study	164	Orestimba Creek near Newman	983	
	165	Orestimba Creek near Crows Landing	976 (productive land) or 986 (non-productive land)	164, 986
	986	Orestimba Dummy Creek	979, 959, 963, 981, 853, 829, 980, 804	

Table 13. Physical data coefficients for the Orestimba Creek wetland in the productive and non-productive land scenarios.

	Productive Land		Non-Productive Land		
Percent of Catchment 804 Area	**Area (m^2) (ac)**	**Width (m)**	**Area (m^2) (ac)**	**Width (m)**	**Detention Storage (%)**
0.25	-	-	24,411.1 (6)	758	79
0.5	-	-	50,700 (13)	910	79
1	99,522.2 (25)	1,213	101,400 (25)	1,213	81
2	199,044 (50)	1,820	200,922 (50)	1,820	86
4	399,967 (99)	1,993	399,967 (99)	1,993	86
6	602,767 (149)	2,080	602,767 (149)	2,080	87
8	799,933 (198)	2,773	801,811 (198)	2,773	88
10	1,000,086 (247)	3,033	1,000,273 (247)	3,033	89
14	-	-	1,402,700 (347)	3,765	91
18	-	-	1,800,267(445)	4,496	92

Table 14. Catchment coefficients for the Orestimba Creek wetland. The wetland catchment was created by splitting Catchment 804 in the productive land scenarios and by converting a polygon to a catchment in the non-productive land scenarios. When splitting a catchment, the model assigns the original coefficient values to both of the new catchments created, whereas the model assigns default values when converting a polygon to a catchment. For this reason, all other coefficients for the non-productive land wetlands were copied from the productive land wetlands.

Scenario Set	Coefficient Type	Parameter	Value
Productive land	Physical Data	Detention Storage (%)	20
		Slope	0.0056
	Pumping	Pumping From	(removed)
Non-productive land	Physical Data	Slope	0.0005 [1]
	Meteorology	Precipitation Weighting Factor	0
	Soil Layers – Initial Concs.	Initial NH_4 Conc. (mg L^{-1})	0.2 (Soil Layer 1) [2]
		Initial NO_3 Conc. (mg L^{-1})	0.4 (Soil Layer 1) [3]
		Initial DOC Conc. (mg L^{-1})	7 (Soil Layer 1) [2]
		Initial BOD (mg L^{-1})	5 (Soil Layer 1) [1]
Both	Physical Data	Manning's n	3 [1]
	BMP's	Buffer Zone (%)	100
		Buffer Zone width (m)	100
	Soil Layers – Initial Concs.	Initial Nitrate Conc. (mg L^{-1})	1 (Soil Layer 1)
			0 (Soil Layers 2-4)
		Initial Dissolved Oxygen Conc. (mg L^{-1})	0 (Soil Layers 1-4)
	Land Uses	Grassland/Herbaceous Land Use (%)	3
		Shrub/Scrub Land Use (%)	6
		Marsh Land Use (%)	90
		Water Land Use (%)	1
	Reactions	BOD Decay (d^{-1})	0.50 (Surface and Canopy)
		Organic Carbon Decay (d^{-1})	0.50 (Soil, Surface, and Canopy)
		Denitrification (d^{-1})	0.16 (Soil, Surface, and Canopy)
		Nitrification (d^{-1})	0.02 (Soil, Surface, and Canopy)

[1] Kadlec and Wallace (2008)
[2] Stringfellow et al. (2008)
[3] Denver et al. (2004)

Table 15. Coefficients for catchments in the Orestimba Creek watershed for the wetland scenarios.

Catchment(s)	Parameter	Value
979, 983, 959, 963, 981, 829, 853, 980	Canopy Nitrification (d^{-1})	0.05
	Biozone	0.05
804	Double Crop DLA Irrigation (%)	0.167 (CCID Below OBanion)
	Farmstead Irrigation (%)	0
	Urban Landscape Irrigation (%)	0
	Buffer Zone Width (%)	0

Table 16. River coefficients for Orestimba Creek near Crows Landing (River 165) for the wetland scenarios.

Parameter	Value
Diversions to (from river)	(removed) (CCID Main Spill)
	(removed) (CCID Main Spill Summer)
BOD Decay Rate (d^{-1})	0.05 (Water)
	0 (Bed)
Organic Carbon Decay (d^{-1})	0.05 (Water)
	0.05 (Bed)
Nitrification (d^{-1})	0.05 (Water)
	0.05 (Bed)
Denitrification (d^{-1})	0.01 (Water)
	0.01 (Bed)
Clay Settling ($m\ d^{-1}$)	0.864 (Water)
Sand Settling ($m\ d^{-1}$)	0.864 (Water)
Nitrate Initial Conc. ($mg\ L^{-1}$)	0 (Water)
Organic Carbon ($mg\ L^{-1}$)	1 (Water)
BOD ($mg\ L^{-1}$)	5 (Water)
	5 (Bed)
DO ($mg\ L^{-1}$)	1 (Water)
Nitrate Adsorption Isotherm ($L\ kg^{-1}$)	400 (Water)
	400 (Bed)

Table 17. River coefficients for the "dummy" creek (River ID 986) in the wetland scenarios.

Parameter	Value
Length (m)	86.7
Downstream Bed Elevation (m)	42.5
Upstream Bed Elevation (m)	61
Manning's n	0.02
Aeration Factor	0.2
SOD ($g\ m^{-2}\ d^{-1}$)	0.1
Convective Heat Factor	1×10^{-6}
Precipitate Settling ($m\ d^{-1}$)	0
All other reaction rates	0

Table 18. Summary statistics for flow and nitrate plus nitrite as nitrogen (NO_3-N) at Orestimba Creek near Crows Landing in the "conversion of row crops to orchards" scenario with percent increases relative to the base scenario.

	Flow (cfs)			NO_3-N ($mg\ L^{-1}$)		
	With Land Use Change	**Base Scenario**	**Percent Increase**	**With Land Use Change**	**Base Scenario**	**Percent Increase**
Mean	28.2	27.7	1.7	3.3	3.03	8.9
Median	6.97	6.29	10.8	2.14	1.88	13.8
Standard	88.3	88.4	-0.1	23.5	23.5	0
Minimum	0.01	0.01	0	0	0	-
Maximum	1,099	1,099	0	36	35.7	0.7
Count	1,918	1,918	-	1917	1917	-

Table 19. Land application rates for orchards and other row crops in WARMF 2012.

Orchards	Ammonia (kg N ha^{-1})	Sulfate (kg ha^{-1})	Nitrate (kg N ha^{-1})	Phosphate (kg P ha^{-1})	Alkalinity (kg $CaCO_3$ ha^{-1})
Jan.	0	0	0	0	0
Feb.	0	0	0	0	0
Mar.	0	0	0	0	0
Apr.	38.4	125.8	0	3.8	6.2
May	38.4	125.8	0	3.8	6.2
June	38.4	125.8	0	3.8	6.2
July	38.4	125.8	0	3.8	6.2
Aug.	38.4	125.8	0	3.8	6.2
Sept.	38.4	125.8	0	3.8	6.2
Oct.	38.4	125.8	0	3.8	6.2
Nov.	0	0	0	0	0
Dec.	0	0	0	0	0
Total	269	880.3	0	26.9	43.4

Other Row Crops	Ammonia (kg N ha^{-1})	Sulfate (kg ha^{-1})	Nitrate (kg N ha^{-1})	Phosphate (kg P ha^{-1})	Alkalinity (kg $CaCO_3$ ha^{-1})
Jan.	0	0	0	0	0
Feb.	0	0	0	0	0
Mar.	0	0	0	0	0
Apr.	0	0	0	0	0
May	43.6	125.3	4.8	4.8	7.8
June	43.6	125.3	4.8	4.8	7.8
July	43.6	125.3	4.8	4.8	7.8
Aug.	43.6	125.3	4.8	4.8	7.8
Sept.	43.6	125.3	4.8	4.8	7.8
Oct.	0	0	0	0	0
Nov.	0	0	0	0	0
Dec.	0	0	0	0	0
Total	217.9	626.3	24.2	24.2	39

Table 20. Mean nitrate and total ammonia plus ammonium nitrogen (TAN) loading from irrigation sources in the Orestimba Creek Watershed from October 1, 2005 to December 31, 2010 for the "conversion of row crops to orchards" scenario.

	NO_3^--N (kg N d^{-1})	**TAN (kg N d^{-1})**
GW Irrigation 959	162	0.27
Oak Flat WD CAA	6.03	0.651
GW Irrigation 963	472	0.787
GW Irrigation 981	770	1.4
GW Irrigation 853	363	0.807
GW Irrigation 980	439	0.798

Table 21. Change in dissolved nitrate plus nitrite as nitrogen (NO_3-N) and total ammonia plus ammonium nitrogen (TAN) loading for irrigation sources between the base and "conversion of row crops to orchards" scenario. Land use (LU) values calculated by multiplying loading values from Table 20 and irrigation percentages from Table 8.

	NO_3 - N without LU Change (kg N d^{-1})	**NO_3 - N with LU Change (kg N d^{-1}) (alt. % increase)**	**TAN without LU Change (kg N d^{-1})**	**TAN with LU Change (kg N d^{-1}) (alt. %**
GW Irrigation 959	52.1	54.8 (5.2)	0.0867	0.0912 (5.2)
Oak Flat WD CAA	1.7	1.79 (5.2)	0.184	0.194 (5.2)
GW Irrigation 963	47.8	50.1 (4.8)	0.0797	0.0835 (4.8)
GW Irrigation 981	105	110 (4.8)	0.19	0.199 (4.8)
GW Irrigation 853	52.6	53.9 (2.4)	0.117	0.120 (2.4)
GW Irrigation 980	265	278 (5.0)	0.482	0.506 (5.0)
Total	**524**	**549 (4.7)**	**1.14**	**1.19 (4.7)**

Table 22. Summary statistics for wetland dissolved nitrate plus nitrite as nitrogen (NO_3-N) concentrations in mg L^{-1} for the non-productive scenarios. The simulated NO_3-N concentrations for the base scenario where no wetland exists represents the NO_3-N concentrations from the catchments connected to the "dummy" creek.

	Mean	**Median**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Sum**
Base	1.44	0.72	2.78	34.6	0	34.6	571
6.03 ac	1.24	0.889	1.07	4.87	0.0418	4.91	492
12.5 ac	1.12	0.816	0.975	4.5	0.0165	4.52	445
25.1 ac	0.928	0.764	0.868	3.96	6.29×10^{-3}	3.96	368
49.6 ac	0.762	0.733	0.773	3.4	3.99×10^{-3}	3.4	302
98.8 ac	0.636	0.608	0.682	2.87	2.51×10^{-3}	2.87	252
149 ac	0.579	0.507	0.621	2.48	1.92×10^{-3}	2.48	229
198 ac	0.551	0.406	0.586	2.2	1.57×10^{-3}	2.2	218
247 ac	0.527	0.353	0.556	1.98	7.02×10^{-4}	1.98	209
347 ac	0.501	0.279	0.524	1.68	3.51×10^{-4}	1.68	198.4
445 ac	0.482	0.233	0.505	1.45	1.87×10^{-4}	1.45	191

Table 23. Summary statistics for wetland total ammonia plus ammonium nitrogen (TAN) in mg L^{-1} for the non-productive scenarios. The simulated TAN for the base scenario where no wetland exists represents the ammonia from the catchments connected to the "dummy" creek.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
Base	2.29	0.233	10.7	138	0.0408	138	906
6.03 ac	1.49	0.412	2.33	15.1	0.0595	15.1	589
12.5 ac	1.28	0.428	1.84	11.2	0.0718	11.3	507
25.1 ac	1.07	0.46	1.49	8.33	0.0896	8.42	424
49.6 ac	0.759	0.38	0.972	4.84	0.0574	4.89	300
98.8 ac	0.52	0.27	0.619	2.87	0.0342	2.91	206
149 ac	0.395	0.208	0.451	1.92	0.0231	1.94	156
198 ac	0.358	0.2	0.4	1.64	0.0158	1.66	142
247 ac	0.307	0.183	0.338	1.34	9.62×10^{-3}	1.35	122
347 ac	0.238	0.169	0.256	0.989	3.58×10^{-3}	0.992	94.4
445 ac	0.21	0.164	0.225	0.864	1.62×10^{-3}	0.866	83.2

Table 24. Summary statistics for wetland total nitrogen (TN) concentrations in mg L^{-1} for the non-productive scenarios. The simulated TN concentrations for the base scenario where no wetland exists represents the total nitrogen concentrations from the catchments connected to the “dummy” creek.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
Base	4.06	1.22	13.3	173	0.536	173	1,609
6.03 ac	2.99	1.69	2.94	18.7	0.488	19.2	1,186
12.5 ac	2.64	1.63	2.36	13.9	0.315	14.2	1,047
25.1 ac	2.21	1.42	1.94	10.2	0.225	10.5	873
49.6 ac	1.68	1.36	1.41	6.05	0.143	6.2	664
98.8 ac	1.29	1.4	1.05	3.58	0.0941	3.68	510
149 ac	1.1	1.29	0.894	2.93	0.0686	3	435
198 ac	1.01	1.26	0.826	2.62	0.0619	2.68	400
247 ac	0.926	1.11	0.766	2.32	0.0426	2.37	367
347 ac	0.807	0.942	0.696	1.96	0.0183	1.98	320
445 ac	0.741	0.808	0.65	1.7	0.0104	1.71	293

Table 25. Summary statistics for wetland surface outflow in cfs for the non-productive scenarios. The simulated flow for the base scenario where no wetland exists represents the total flow from the catchments connected to the "dummy" creek.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
Base	22.2	3.72	51.1	377	0.024	377	8,776
6.03 ac	22	3.7	50.9	375	0.0771	375	8,717
12.5 ac	22	3.63	50.7	375	0.107	375	8,702
25.1 ac	21.9	3.5	50.3	371	0.166	371	8678
49.6 ac	21.8	3.48	48.9	350	0.29	350	8628
98.8 ac	21.5	3.4	45.8	302	0.429	302	8522
149 ac	21.2	3.17	42.2	251	0.566	251	8390
198 ac	20.9	2.81	40.4	228	0.574	229	8274
247 ac	20.5	2.42	37.8	198	0.612	199	8132
347 ac	19.8	2.82	33.5	150	0.567	150	7845
445 ac	19.2	3.23	30.7	121	0.435	121	7595

Table 26. Summary statistics for wetland hydraulic retention time (HRT) in hr for the non-productive scenarios.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
6.03 ac	0.792	0.735	0.55	3.38	0.104	3.49	313
12.5 ac	1.46	1.41	0.9	5.48	0.197	5.67	577
25.1 ac	2.67	2.69	1.48	8.87	0.394	9.26	1,056
49.6 ac	5.53	5.71	2.79	15	0.87	15.9	2192
98.8 ac	10.4	10.9	5.13	23.5	1.77	25.3	4133
149 ac	16.5	17.7	8.08	32.5	3.05	35.6	6540
198 ac	20.5	22.6	10.3	39	3.84	42.8	8131
247 ac	26.9	31	13.6	48.9	5.27	54.1	10645
347 ac	41.5	43.9	22.2	75	8.86	83.9	16417
445 ac	56.1	53.9	32.3	109	12.6	121	22199

Table 27. Summary statistics for wetland dissolved oxygen (DO) in mg L^{-1} for the non-productive scenarios. The simulated DO for the base scenario where no wetland exists represents the DO from the catchments connected to the “dummy” creek.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
Base	3.09	2.58	2.18	10.6	0.332	10.9	1,224
6.03 ac	7.07	6.74	2.73	11.5	0.714	12.2	2,798
12.5 ac	5.51	4.28	3.27	11.4	0.503	11.9	2,183
25.1 ac	4.01	1.82	3.44	11.1	0.271	11.3	1588
49.6 ac	2.76	0.887	3.07	10.3	0.123	10.5	1092
98.8 ac	1.94	0.476	2.67	10.1	0.0591	10.1	766
149 ac	1.55	0.296	2.45	9.83	0.036	9.86	614
198 ac	1.43	0.231	2.39	9.74	6.18×10^{-3}	9.75	566
247 ac	1.31	0.165	2.31	9.56	3.37×10^{-3}	9.56	517
347 ac	1.19	0.0971	2.24	9.15	1.55×10^{-3}	9.15	471
445 ac	1.17	0.053	2.25	8.82	1.17×10^{-3}	8.82	462

Table 28. Summary statistics for wetland dissolved organic carbon (DOC) in mg L^{-1} for the non-productive scenarios. The simulated DOC for the base scenario where no wetland exists represents the DOC from the catchments connected to the "dummy" creek.

	Mean	Median	Standard Deviation	Range	Minimum	Maximum	Sum
Base	4.16	4.09	1.14	14.3	0.02	14.3	1,647
6.03 ac	2.8	2.85	0.442	1.96	1.62	3.57	1,110
12.5 ac	2.33	2.29	0.441	1.9	1.49	3.39	924
25.1 ac	1.86	1.75	0.452	1.82	1.18	3.01	735
49.6 ac	1.31	1.2	0.384	1.53	0.754	2.28	517
98.8 ac	0.852	0.801	0.283	1.14	0.48	1.62	337
149 ac	0.58	0.549	0.201	0.825	0.275	1.1	230
198 ac	0.544	0.505	0.179	0.775	0.284	1.06	216
247 ac	0.434	0.382	0.153	0.617	0.242	0.86	172
347 ac	0.289	0.223	0.126	0.587	0.172	0.758	114
445 ac	0.229	0.156	0.125	0.711	0.101	0.812	91

Figure 1. Calibration results for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration at Orestimba Creek near Crows Landing (USGS station number 11274538).

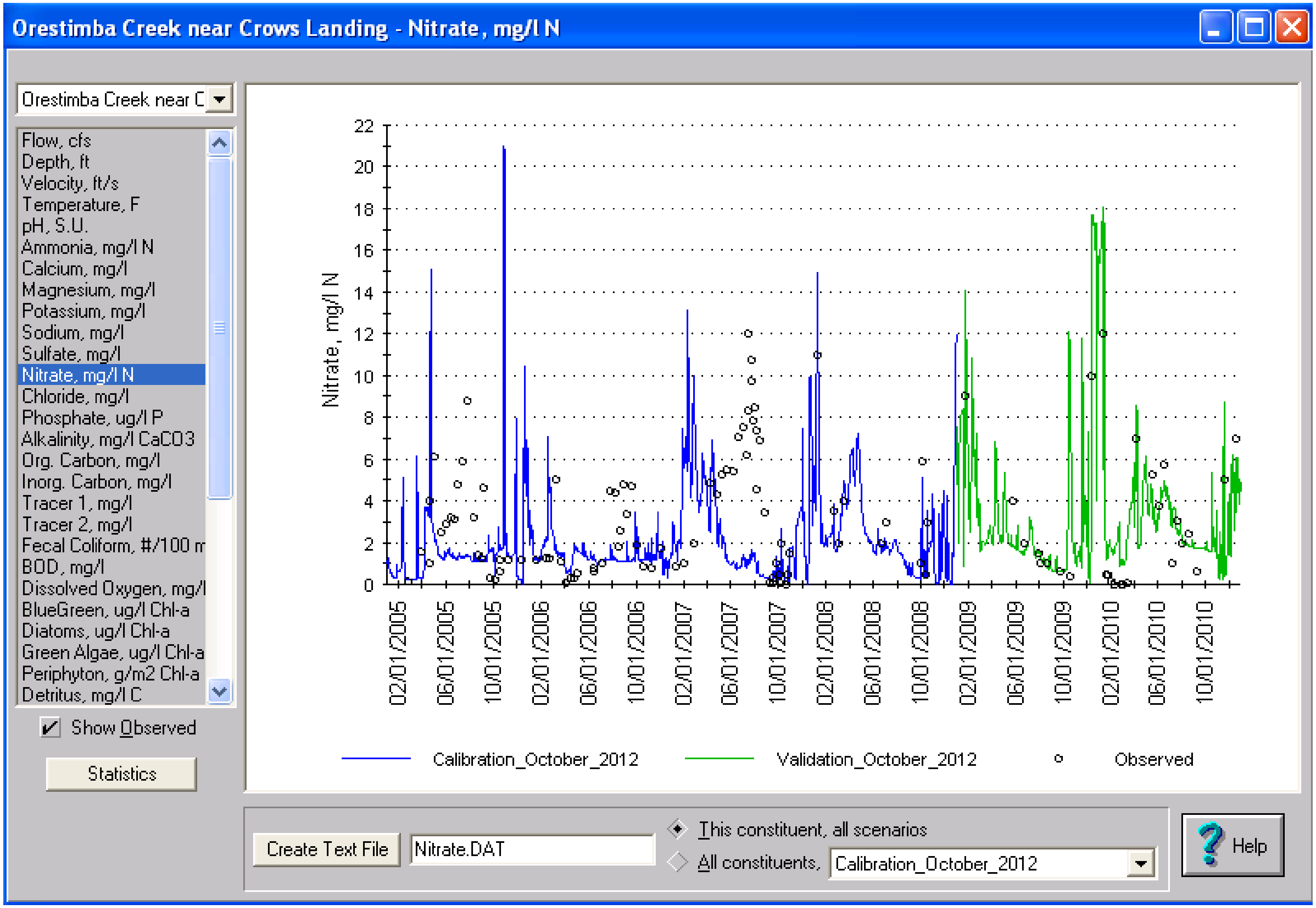

Figure 2. Simulated vs. observed dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentrations at Orestimba Creek near Crows Landing (USGS station number 11274538).

Orestimba Creek near Crows Landing - Nitrate, mg/l N

	Calibration October 2012	Validation October 2012	Observed
Mean	2.125	3.477	
Minimum	0	0.0649	
Maximum	20.97	18.04	
# Compare Pts	137	28	
Relative Error	0.0982	1.006	
Absolute Error	1.052	1.902	
RMS Error	1.9	2.783	
r squared	0.745	0.739	

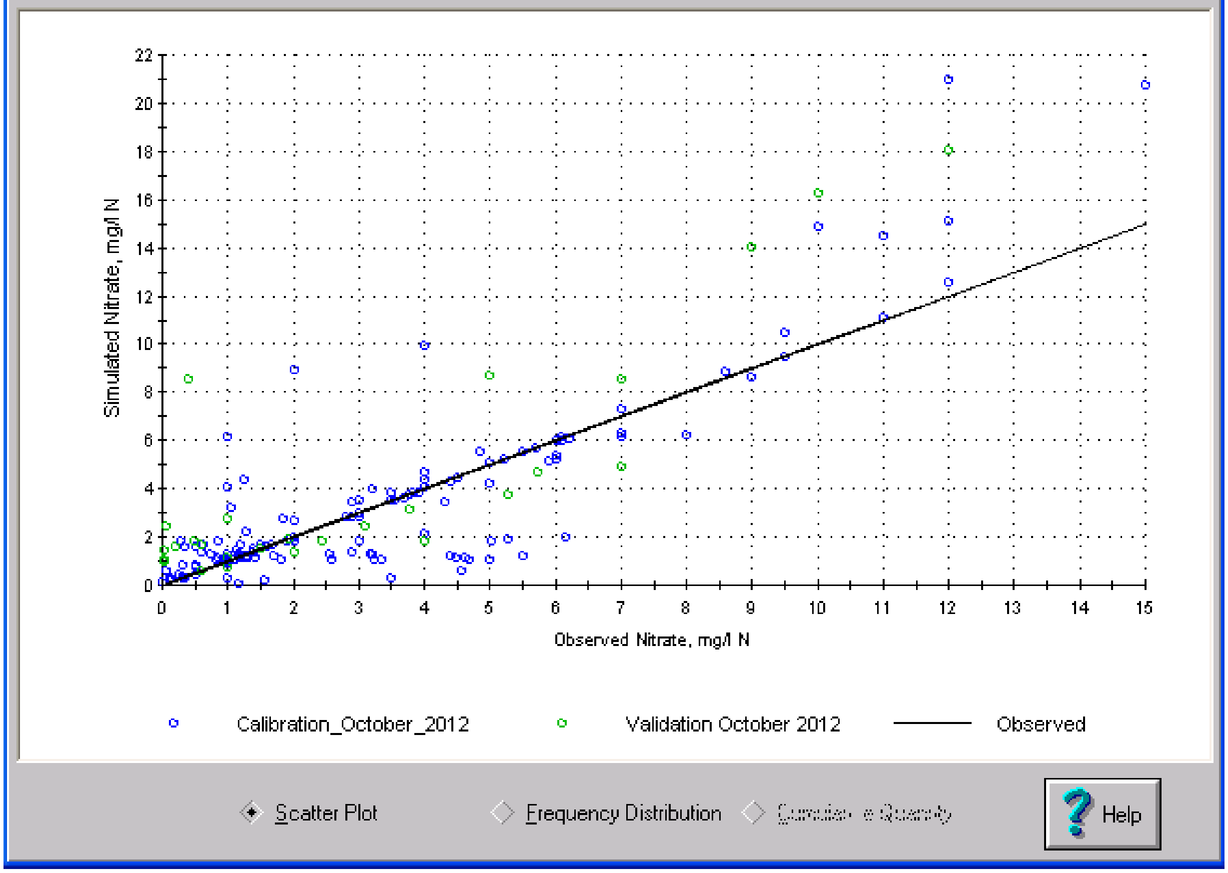

Figure 3. Soil map of the San Joaquin River confluence at Orestimba Creek from the NRCS (2012) *Web Soil Survey*. Map symbol 153 denotes soil selected to represent wetland. See Table A-8.

Figure 4. Orestimba Creek watershed with default catchment-to-stream connections. Catchment ID's are shown with tributary connections shown with red arrows. See Table 11 for catchment and river names.

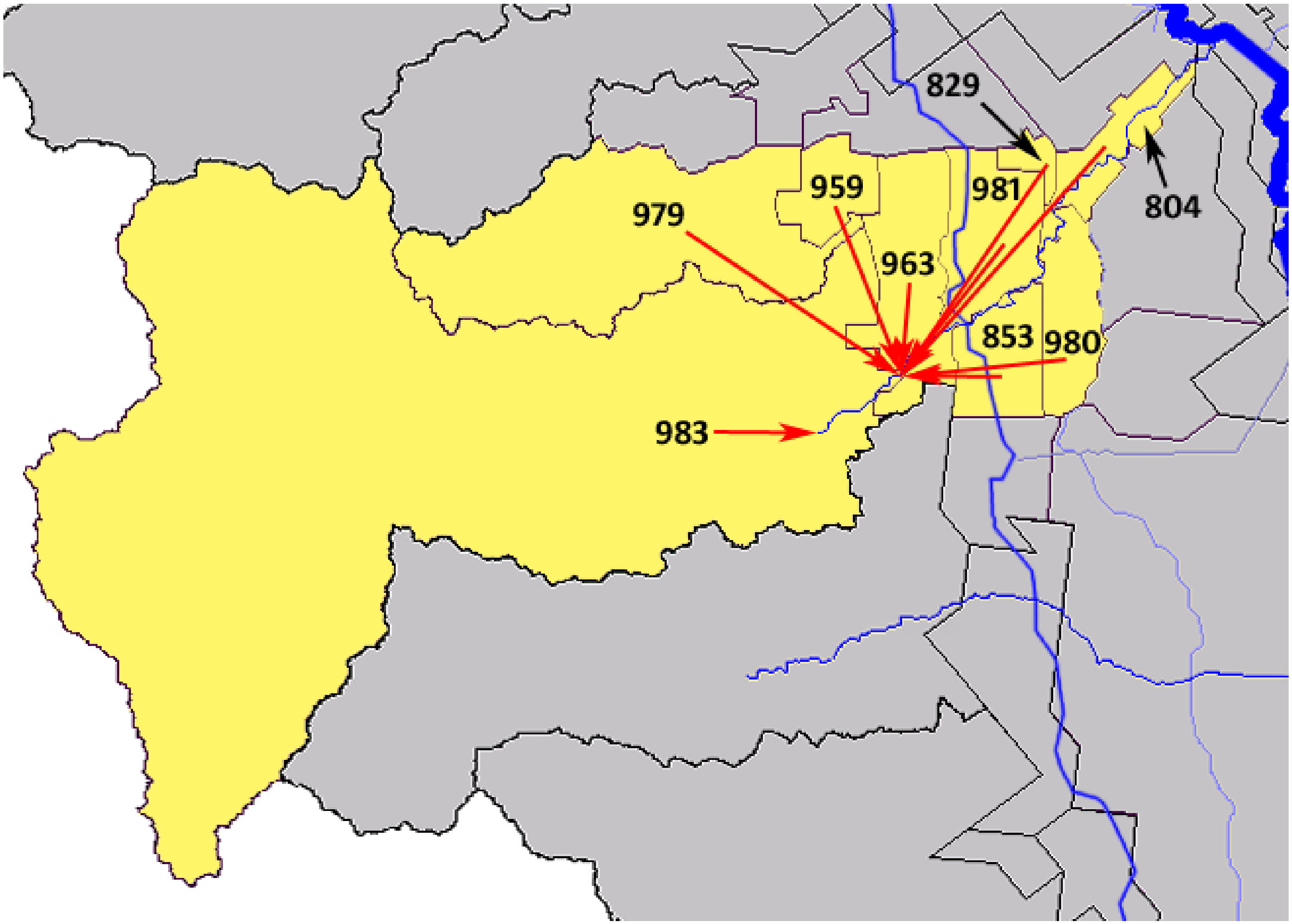

Figure 5. Location of river segments in Orestimba Creek watershed.

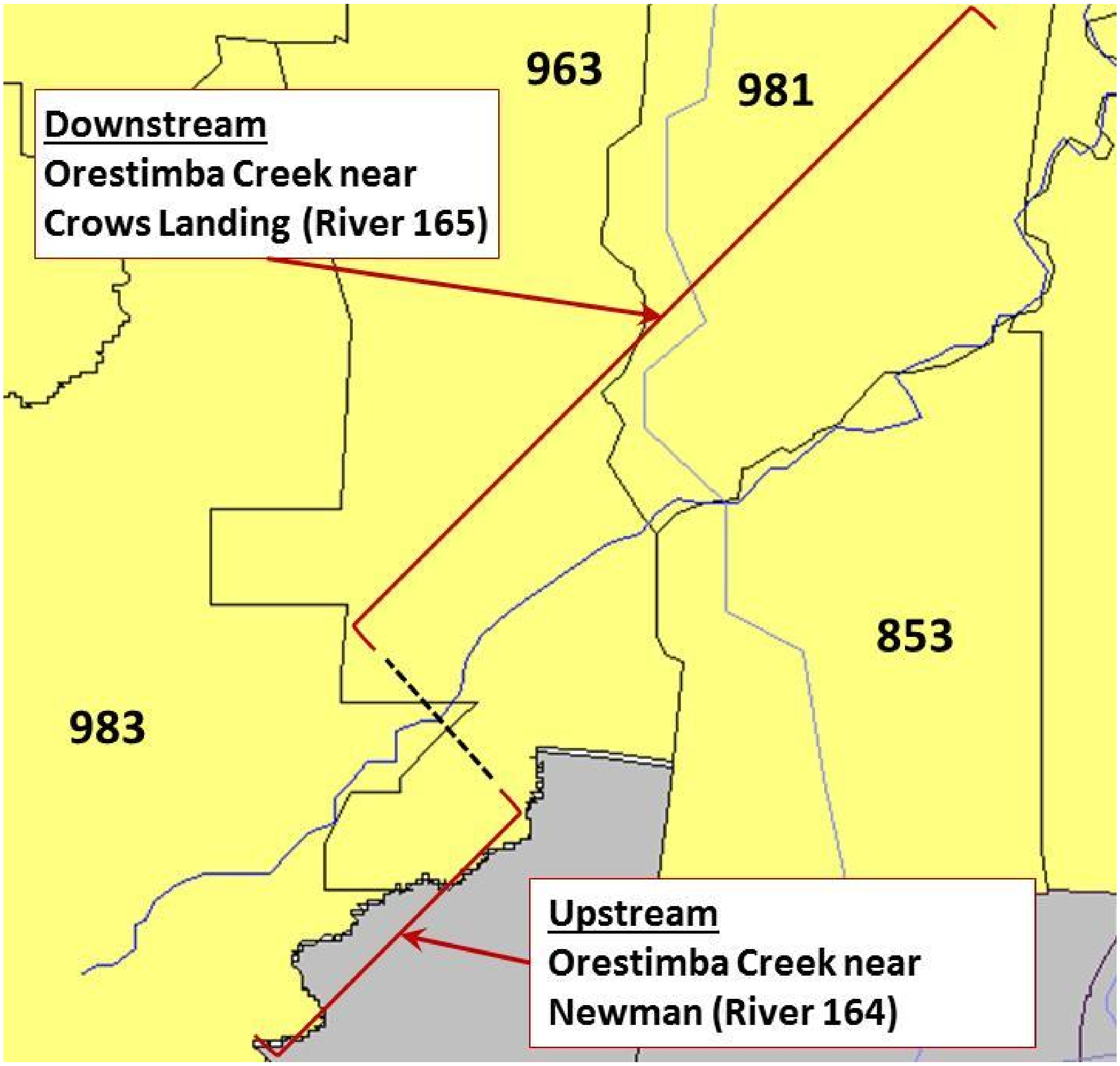

Figure 6. Connections from catchments in the Orestimba Creek watershed to the "dummy" creek used to apply water to the wetland for the productive land scenarios. Water from the "dummy" creek is diverted and applied to the wetland as irrigation.

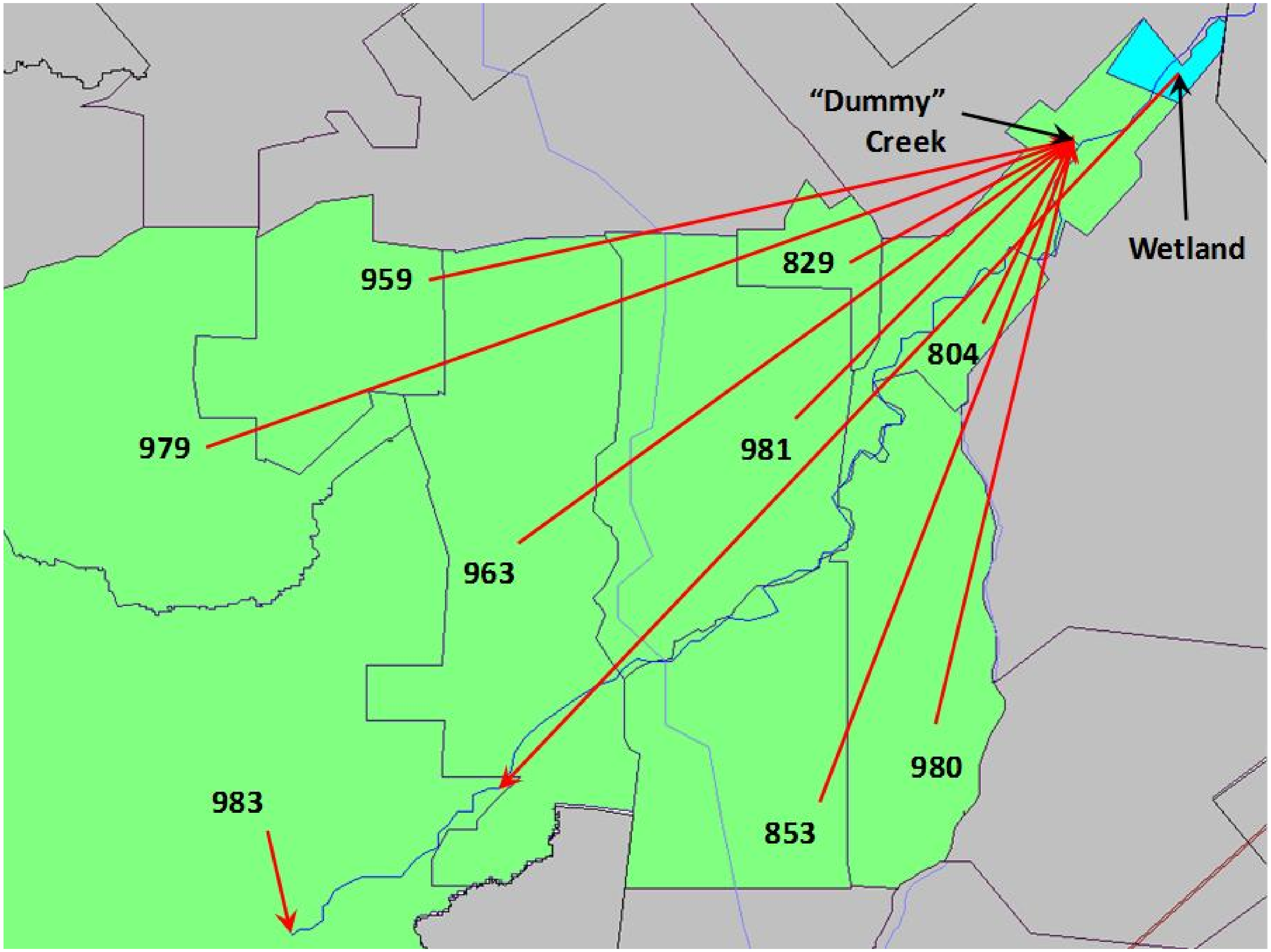

Figure 7. Connections from catchments to rivers in the Orestimba Creek watershed for the non-productive land scenarios. Water from the "dummy" creek is diverted and applied to the wetland as irrigation.

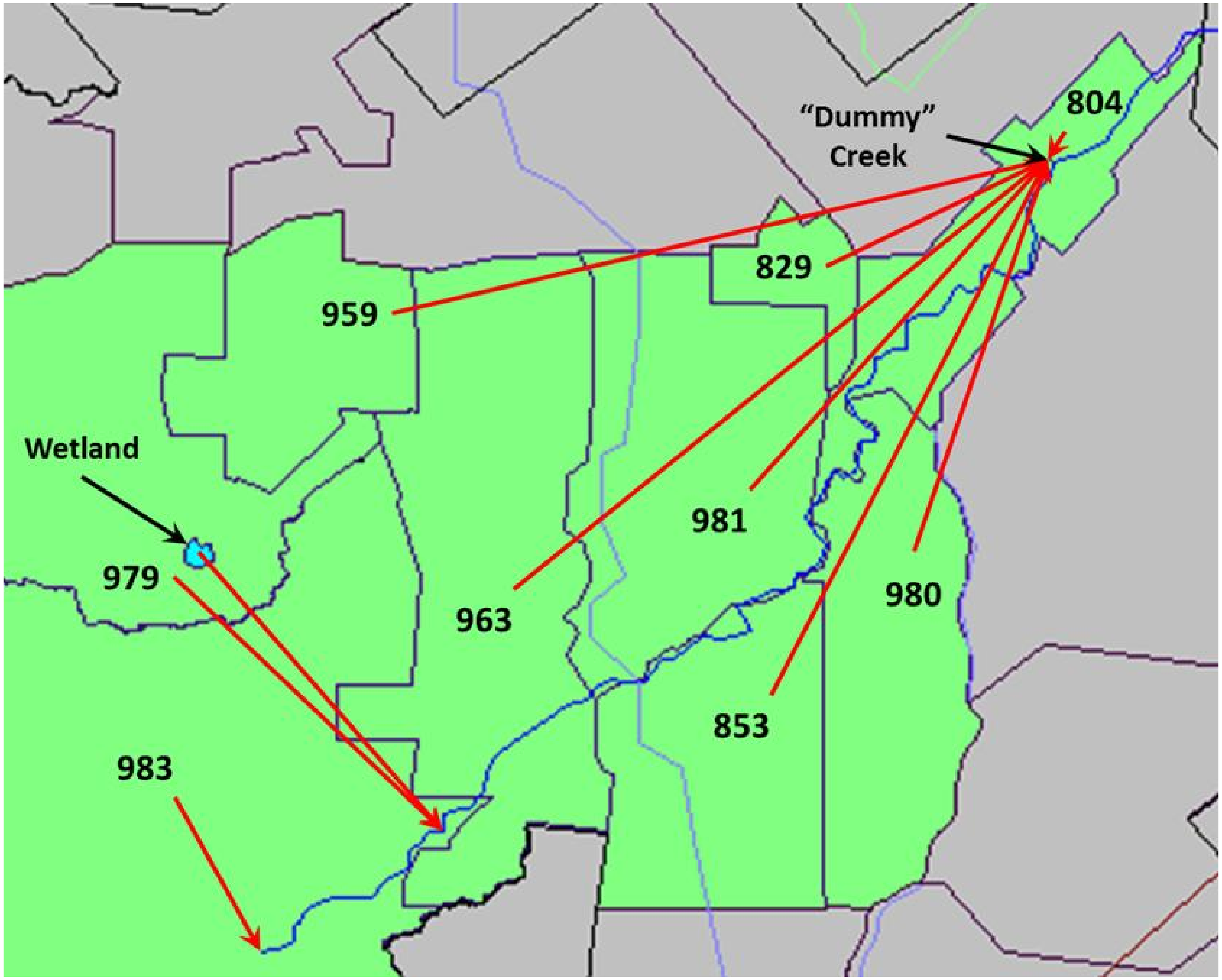

Figure 8. Comparison of Nitrate Scenario 1 (1.8% agricultural land converted to wetland) with the base scenario (no wetland) for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration at Orestimba Creek near Crows Landing.

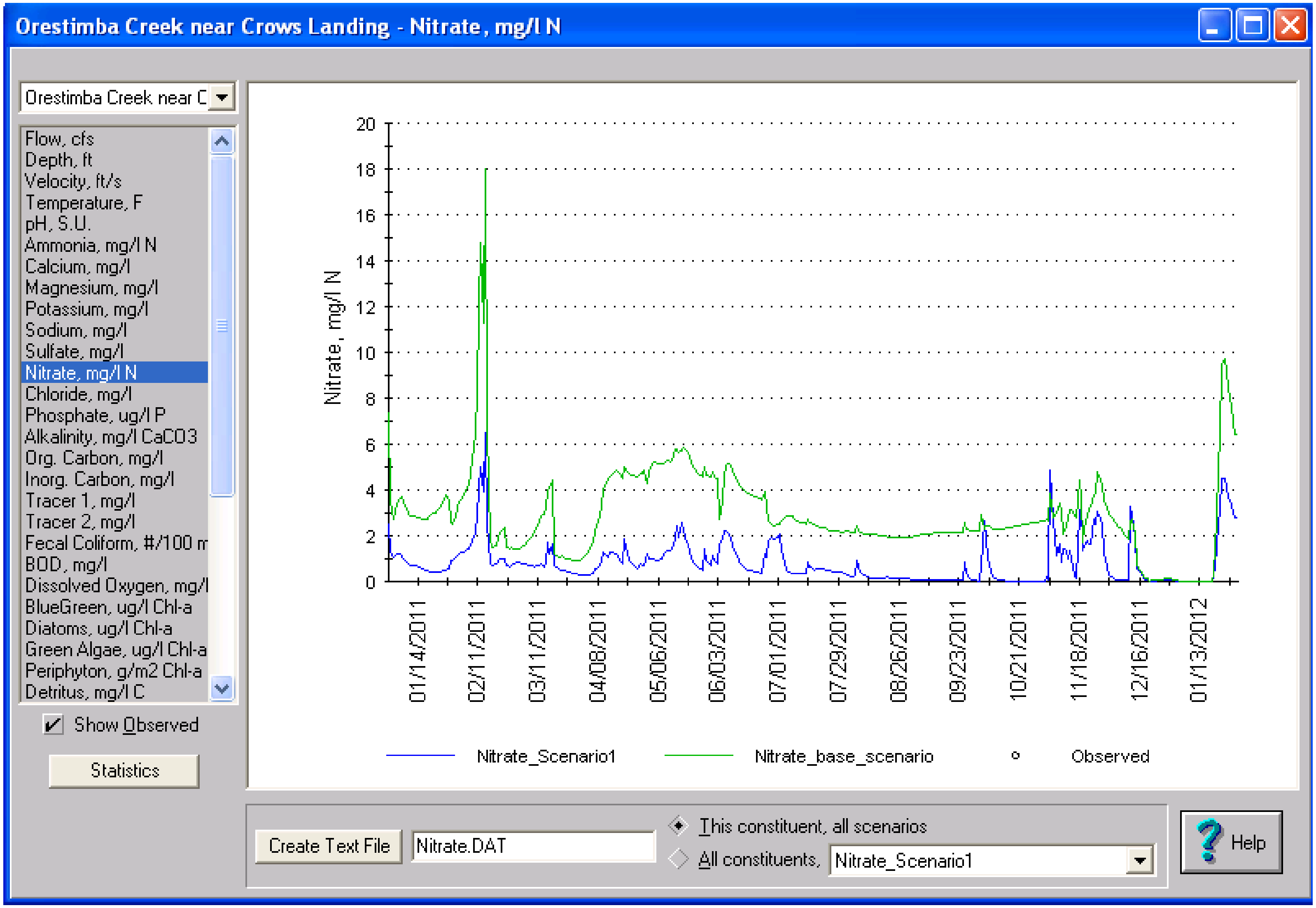

Figure 9. Comparison of nitrate simulation scenarios (green lines represent the means; while quantiles are indicated by red lines) for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration. For Student's t test, the overlapping circles are not significantly different from each other at a significance level of 0.05. The scenario descriptions are as follows: (Nitrate Scenario 1 - 1.8% Ag land conversion; Nitrate Scenario 2 – 9% Ag land conversion; Nitrate Scenario 3 – 30% nitrogen fertilizer reduction; Nitrate Scenario 4 – combination of 1.8% Ag land conversion plus 30% nitrogen fertilizer reduction).

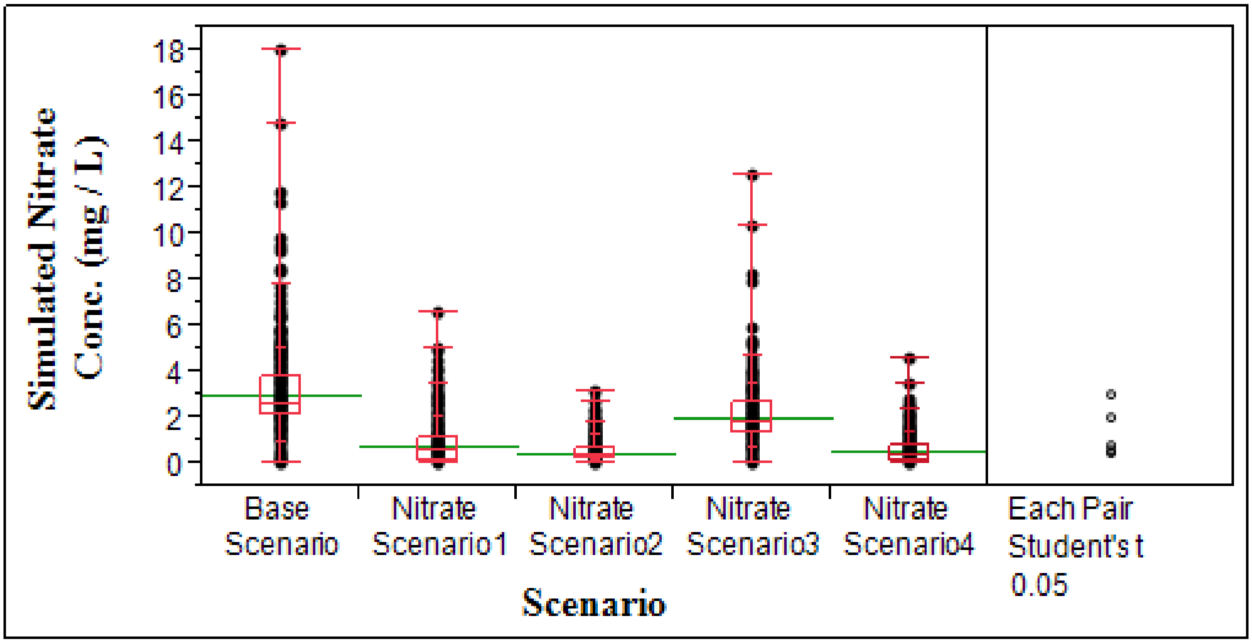

Figure 10. Comparison of Nitrate Scenario 2 (9% agricultural land converted to wetland) with the base scenario (no wetland) and Nitrate Scenario 1 (1.8% agricultural land converted to wetland) for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration for Orestimba Creek near Crows Landing.

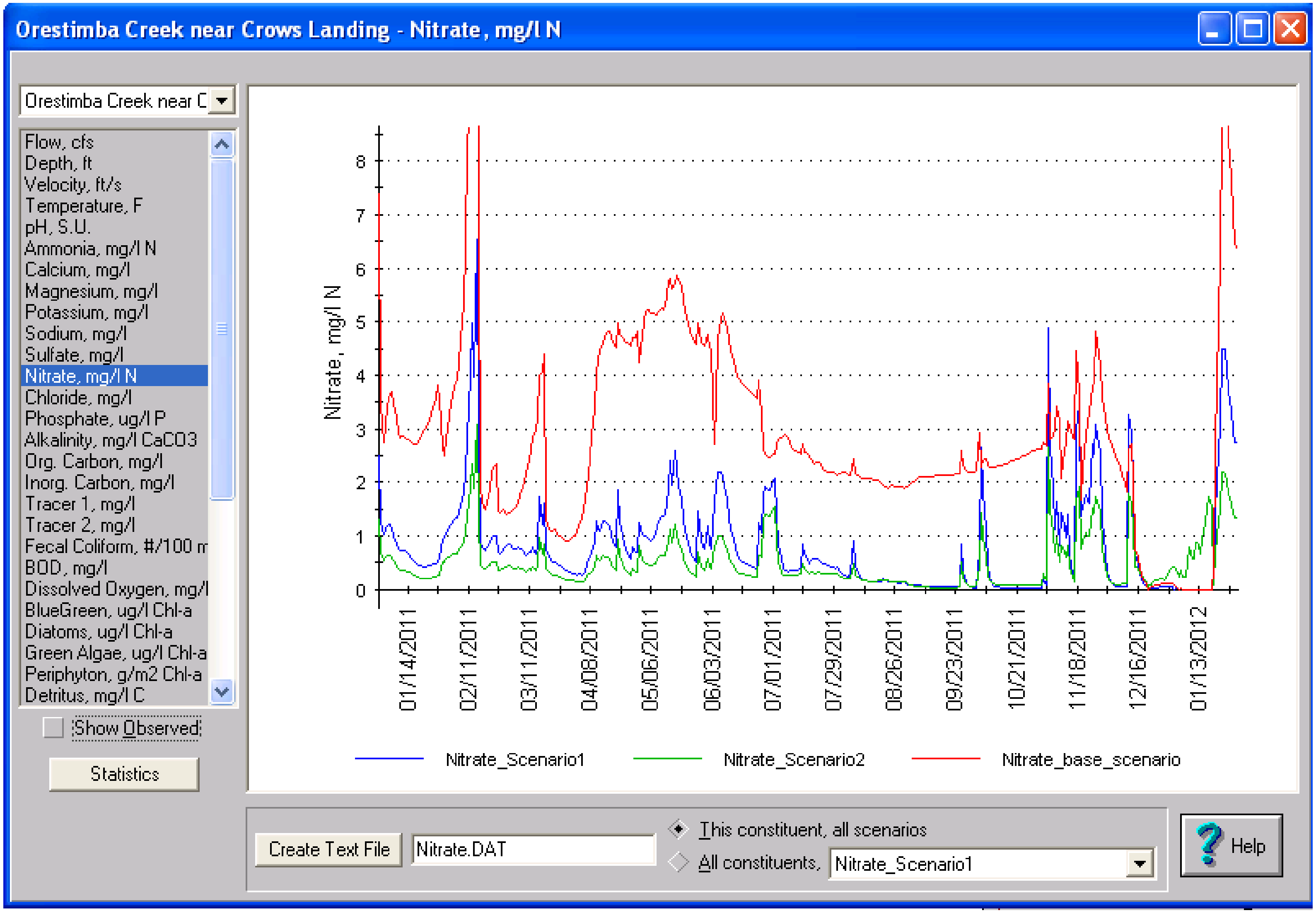

Figure 11. Comparison of Nitrate Scenario 3 (30% fertilizer use reduction, no wetland) with the base scenario (no wetland) for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration for Orestimba Creek near Crows Landing.

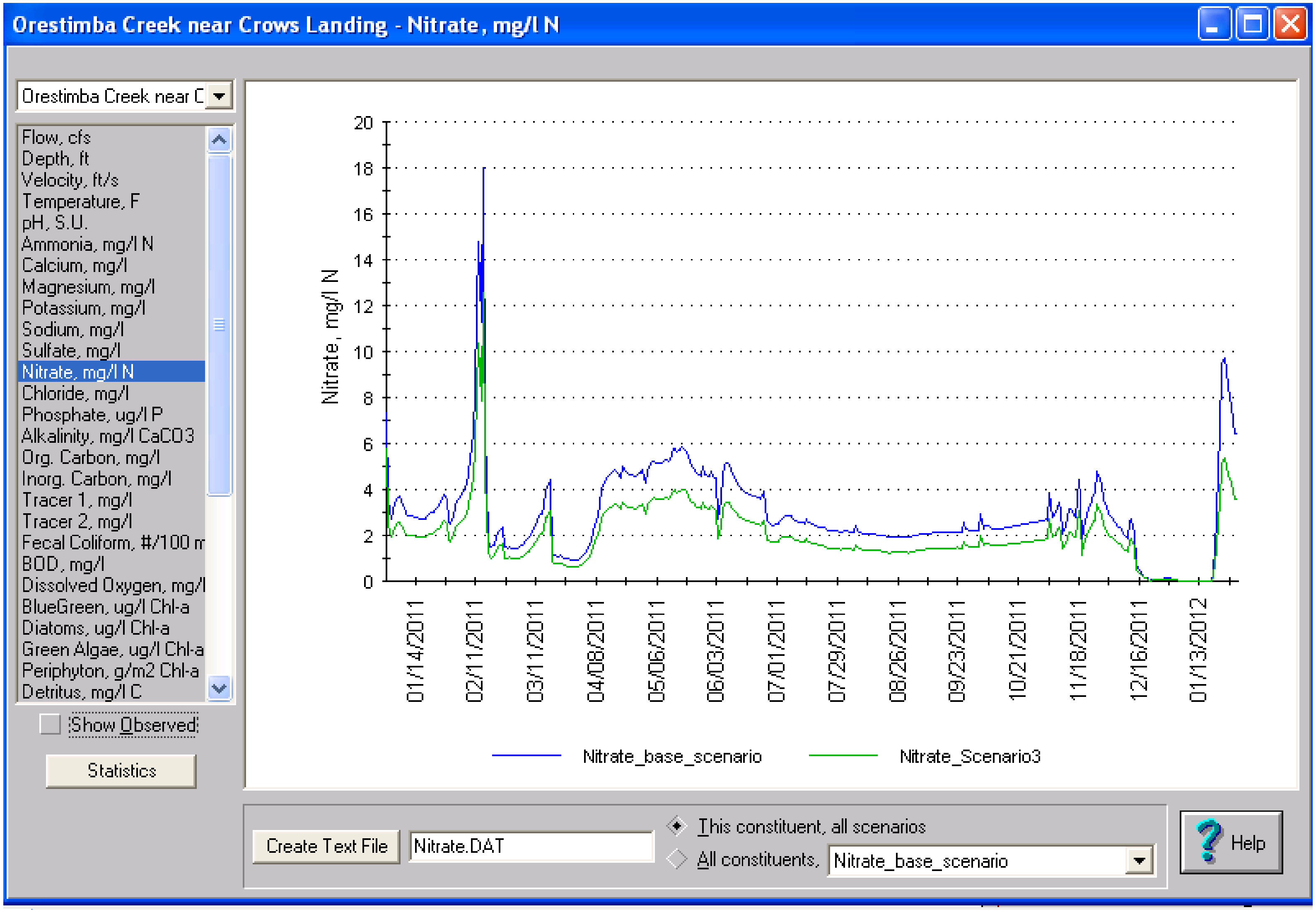

Figure 12. Comparison of Nitrate Scenario 1 (conversion of 1.8% of agricultural land to wetland) with Nitrate Scenario 4 (conversion of 1.8% of agricultural land to wetland combined with 30% fertilizer use reduction) for dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration for Orestimba Creek near Crows Landing.

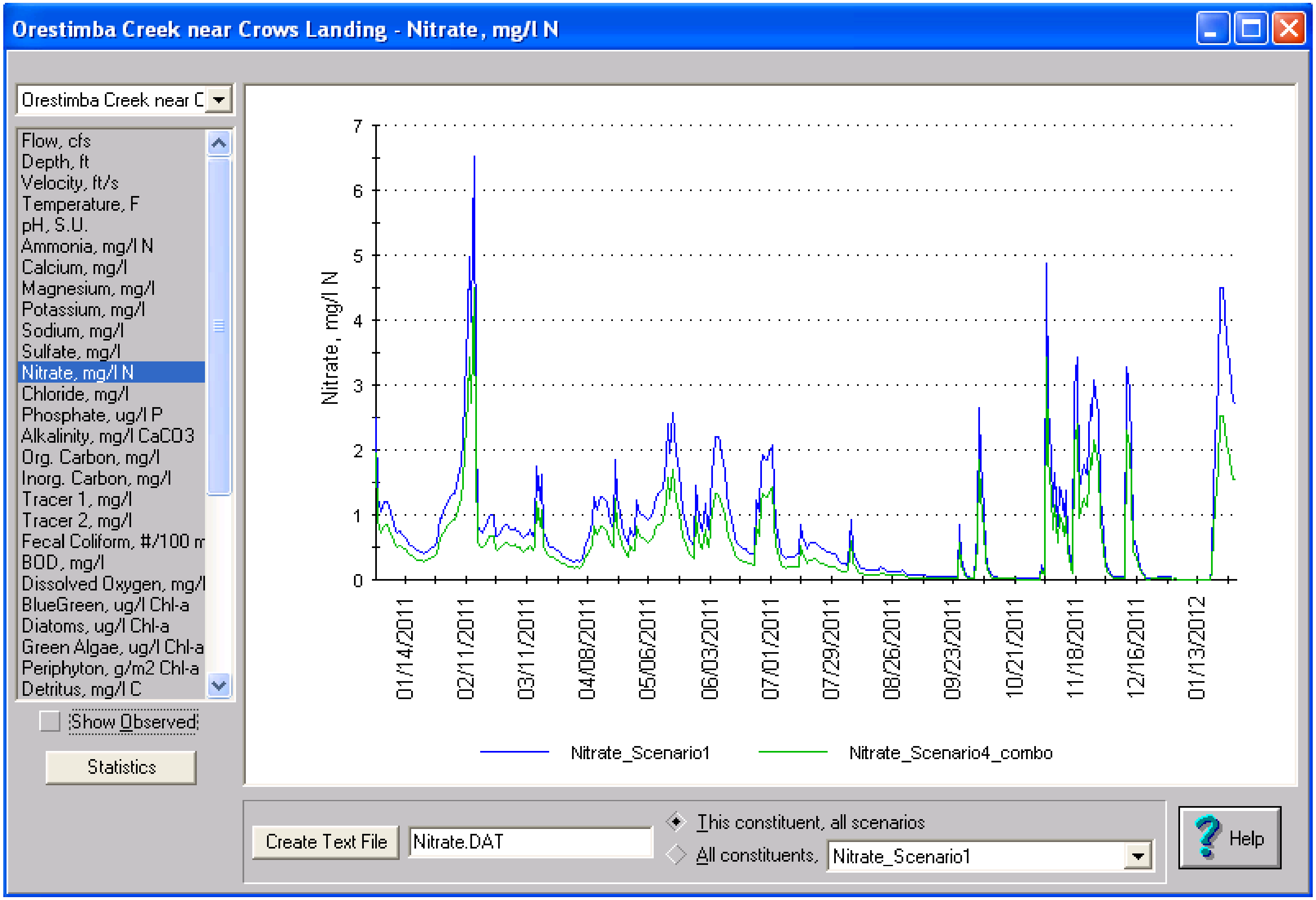

Figure 13. Time series plot of flow at Orestimba Creek near Crows Landing for the “conversion of row crops to orchards” scenario.

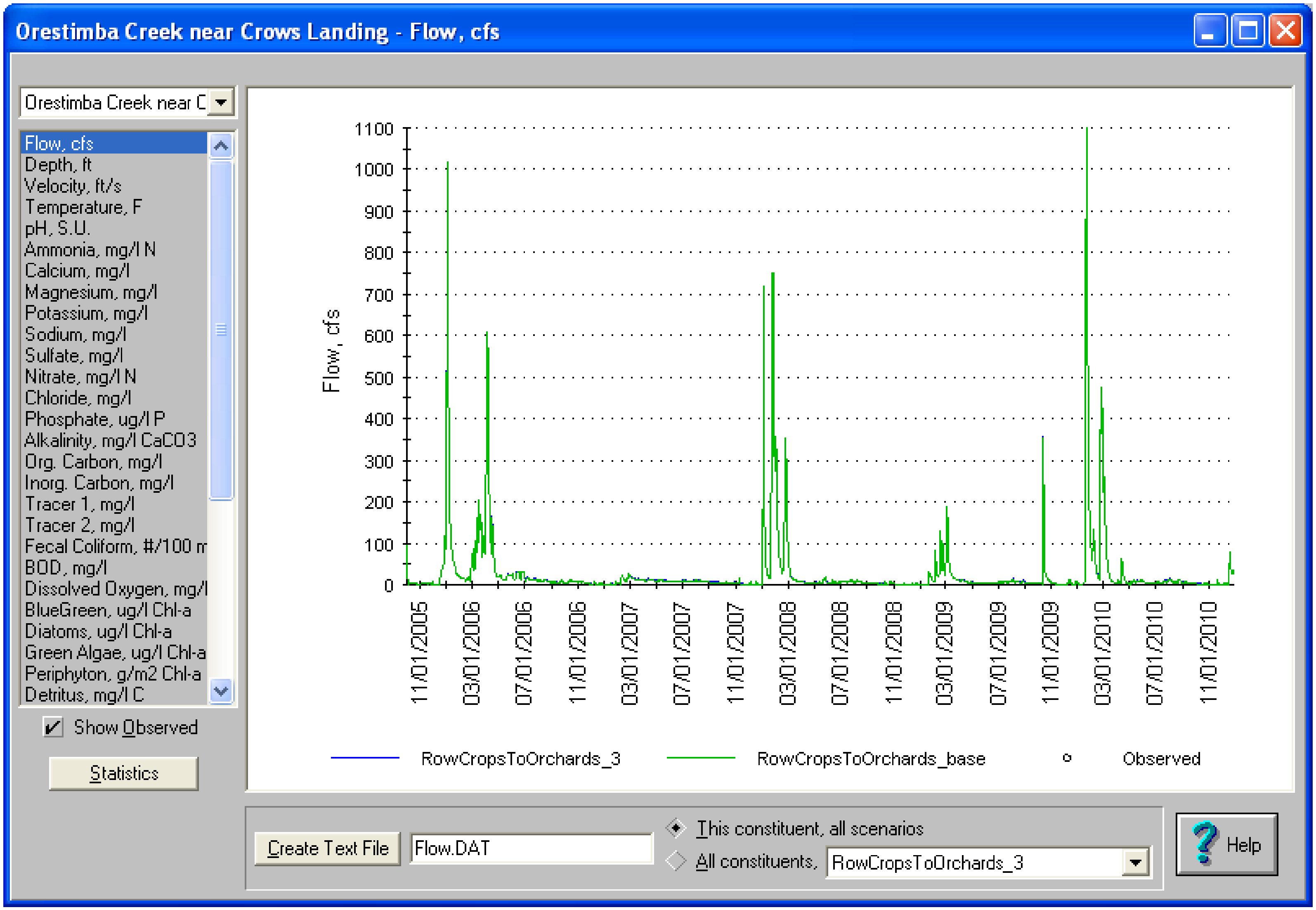

Figure 14. Time series plot of dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration at Orestimba Creek near Crows Landing for the "conversion of row crops to orchards" scenario.

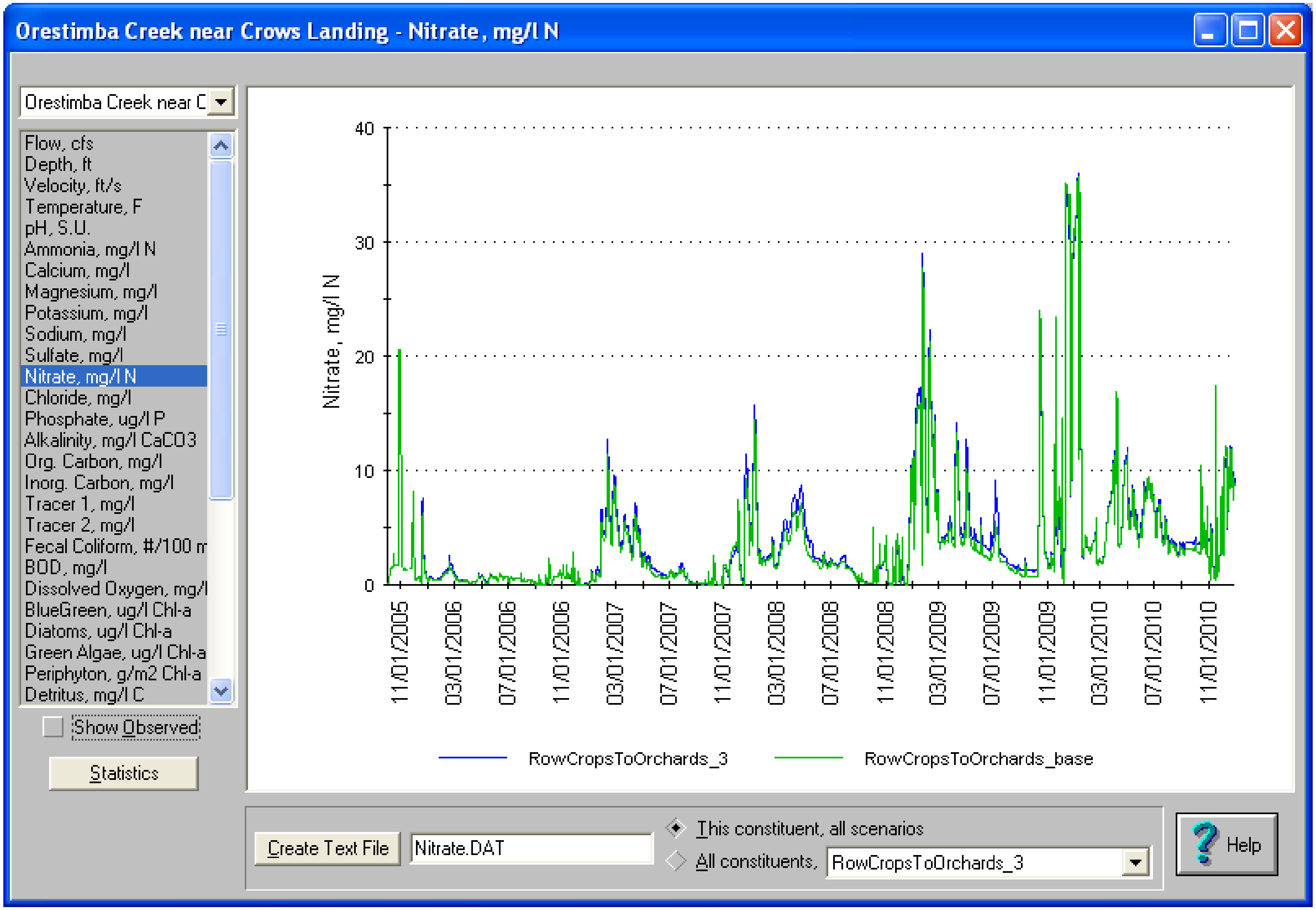

Figure 15. Wetland dissolved nitrate plus nitrate as nitrogen (NO_3-N) concentration for the non-productive scenarios. The simulated NO_3-N concentrations for the base scenario where no wetland exists represents the NO_3-N concentrations from the catchments connected to the "dummy" creek. Note the February-April period where increasing wetland size results in higher NO_3-N concentrations as shown in the inset.

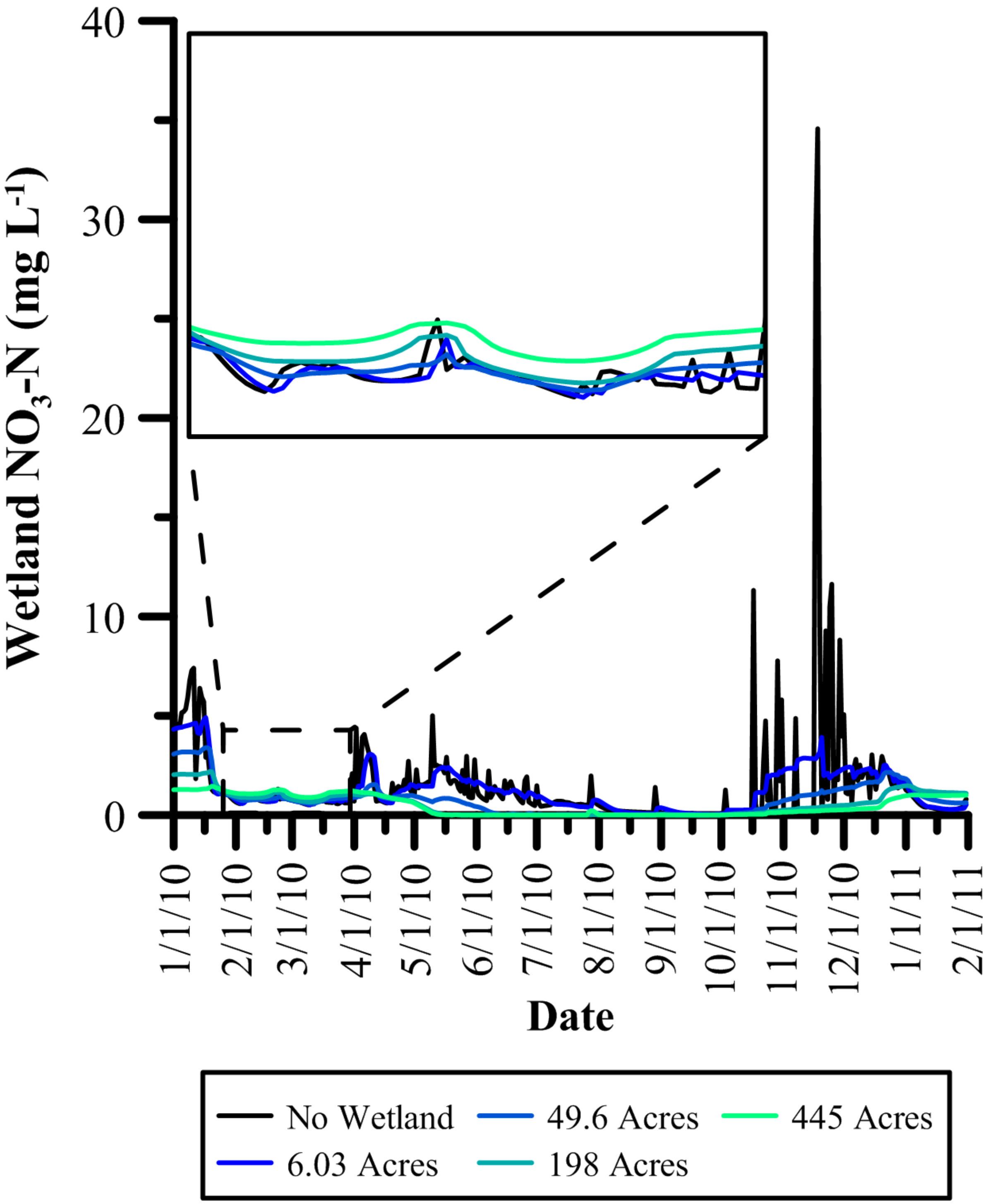

Figure 16. Wetland total ammonia plus ammonium nitrogen (TAN) concentration for the non-productive scenarios. The simulated TAN for the base scenario where no wetland exists represents the TAN from the catchments connected to the "dummy" creek.

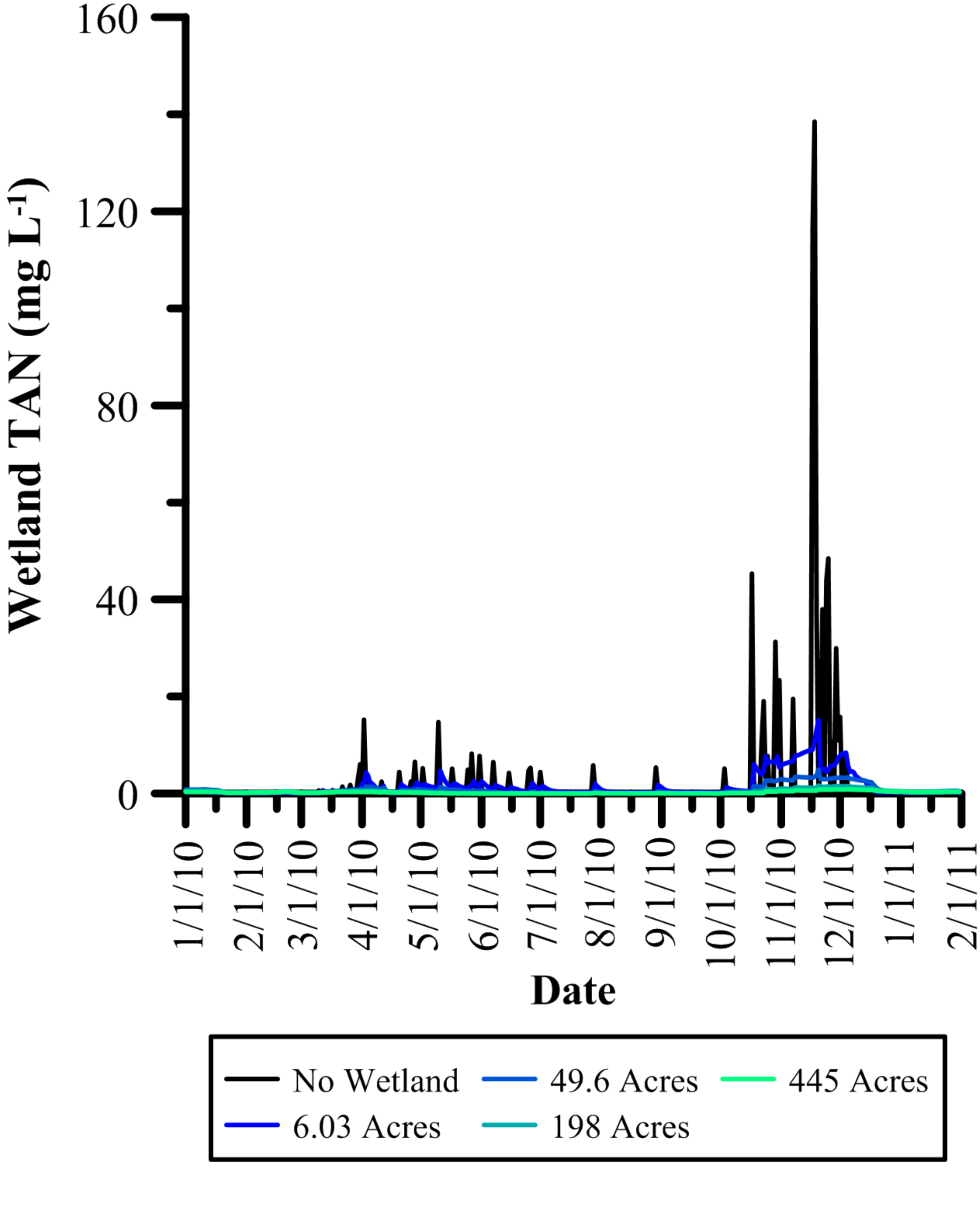

Figure 17. Wetland total nitrogen (TN) concentration for the non-productive scenarios. The simulated TN concentrations for the base scenario where no wetland exists represents the TN concentrations from the catchments connected to the “dummy” creek.

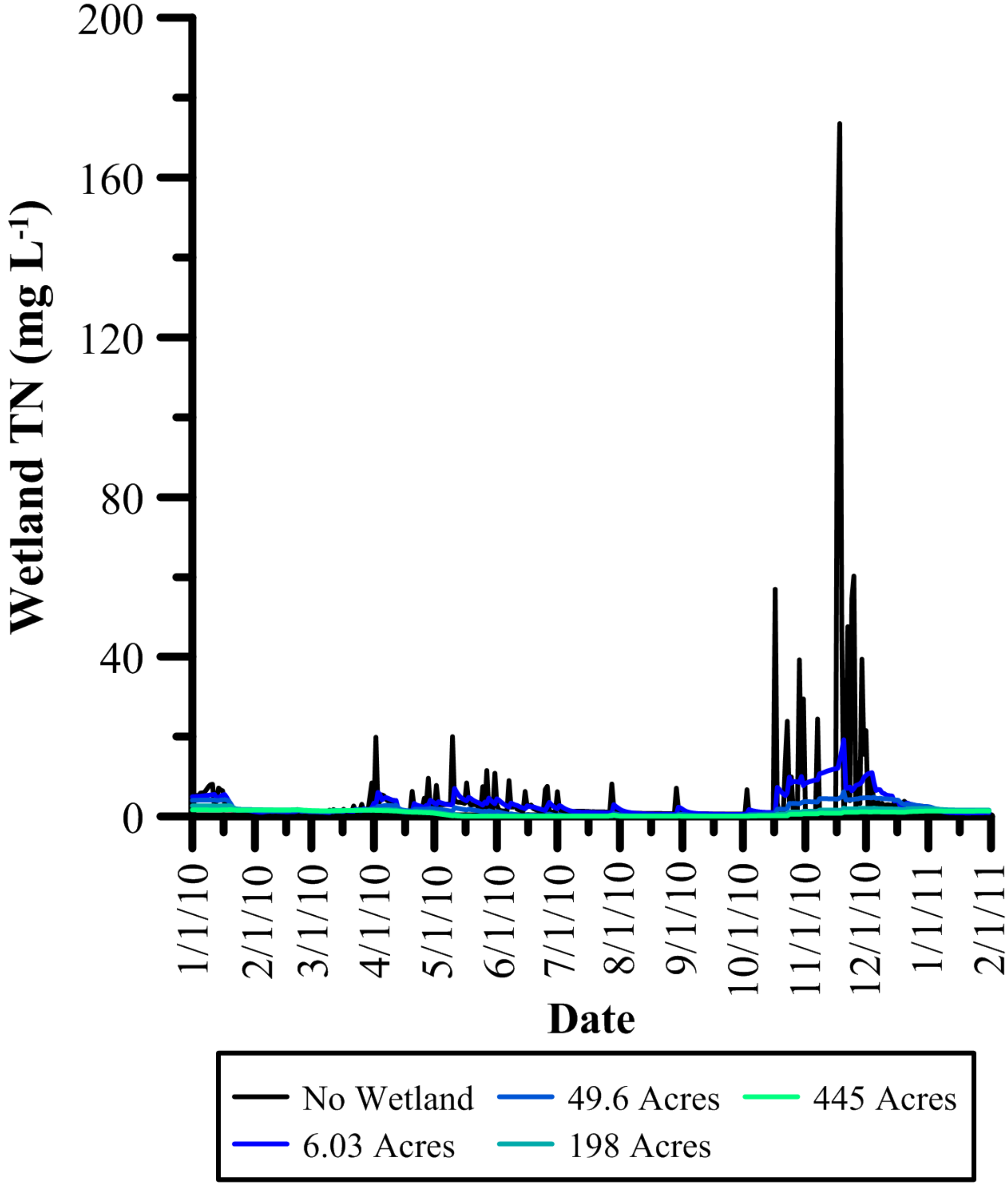

Figure 18. Time series plot of precipitation for Catchment 963 in the Orestimba Creek watershed.

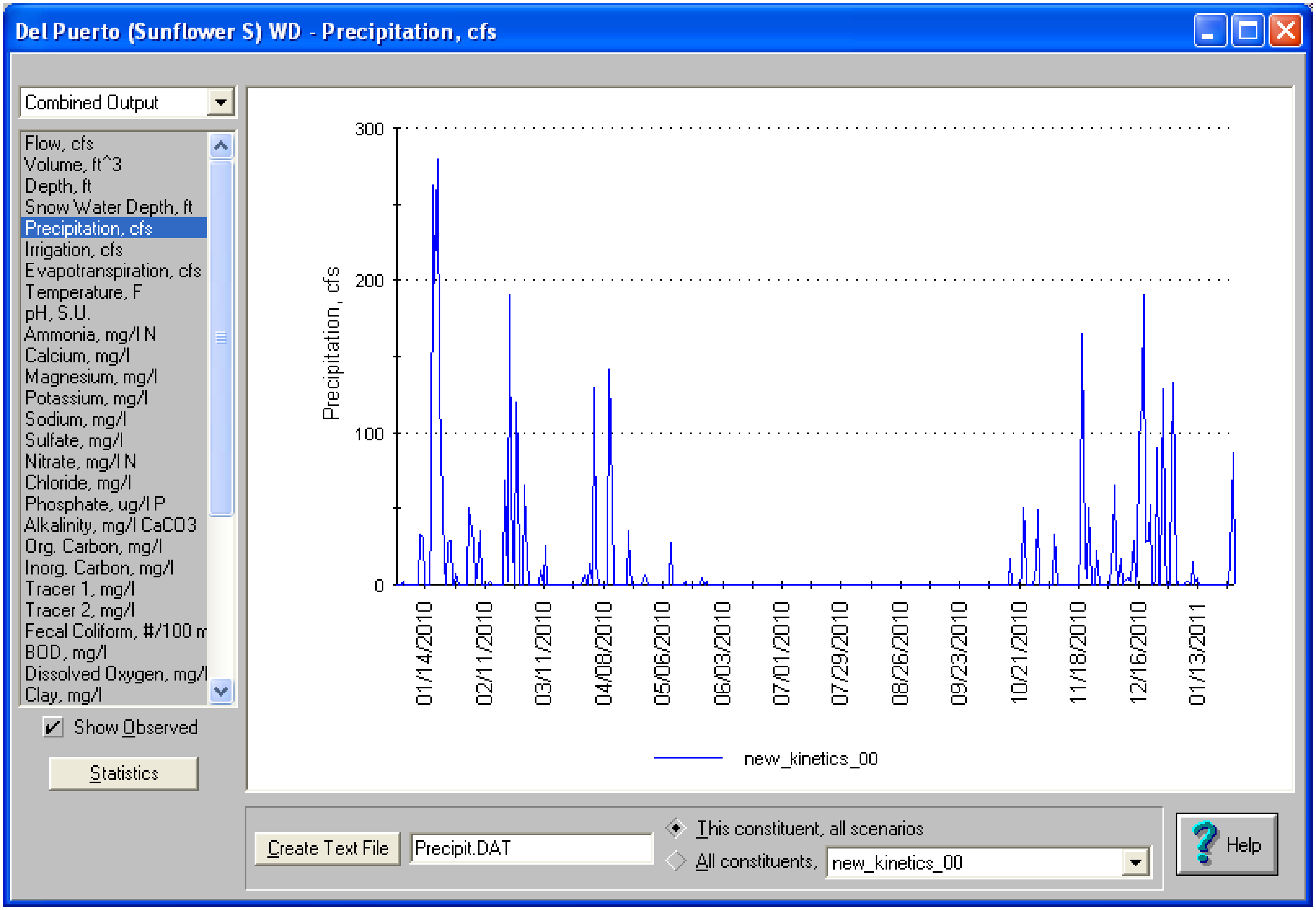

Figure 19. Wetland surface outflow for the non-productive scenarios. The simulated flow for the base scenario where no wetland exists represents the total flow from the catchments connected to the "dummy" creek.

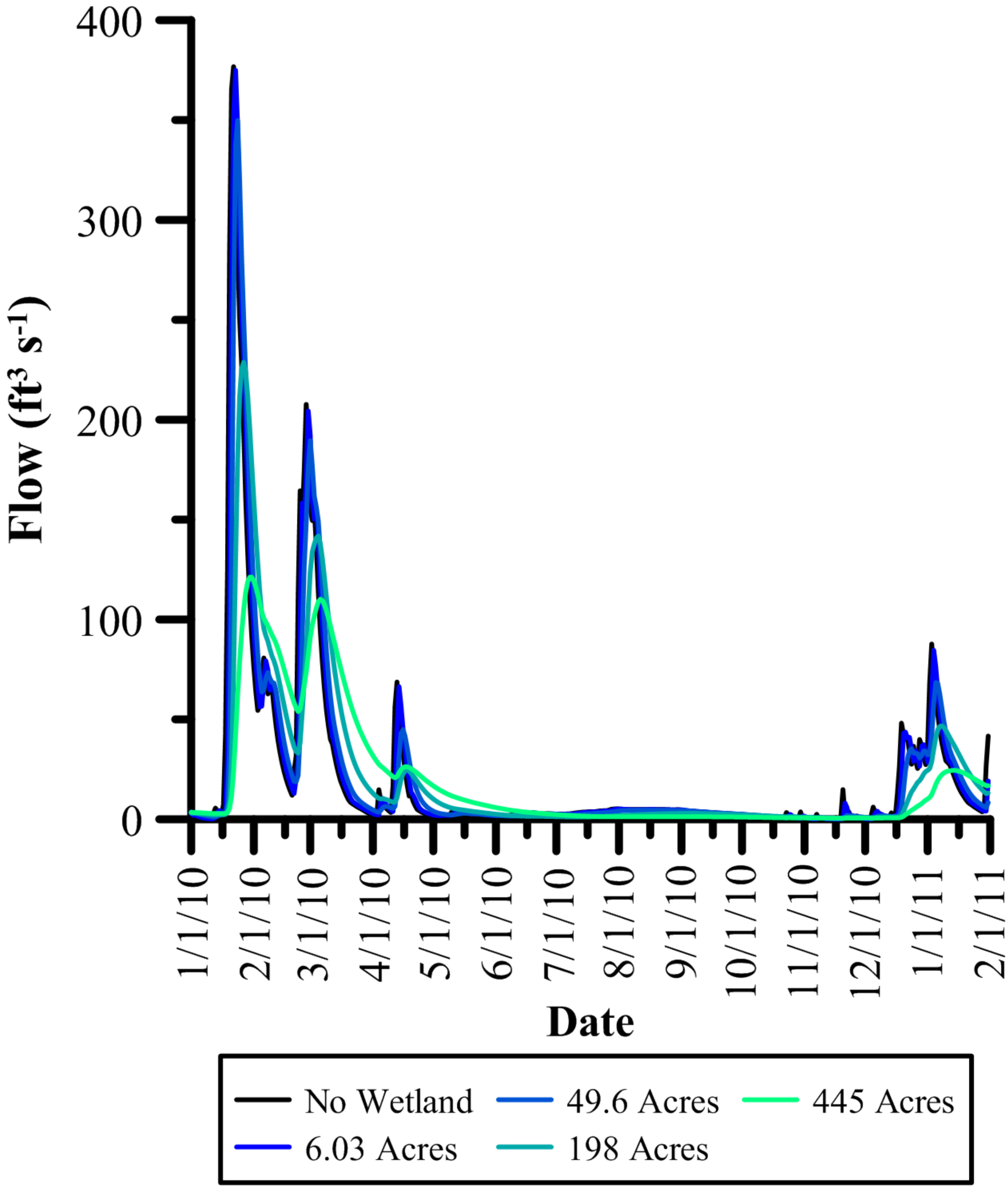

Figure 20. Wetland hydraulic retention time for the non-productive scenarios.

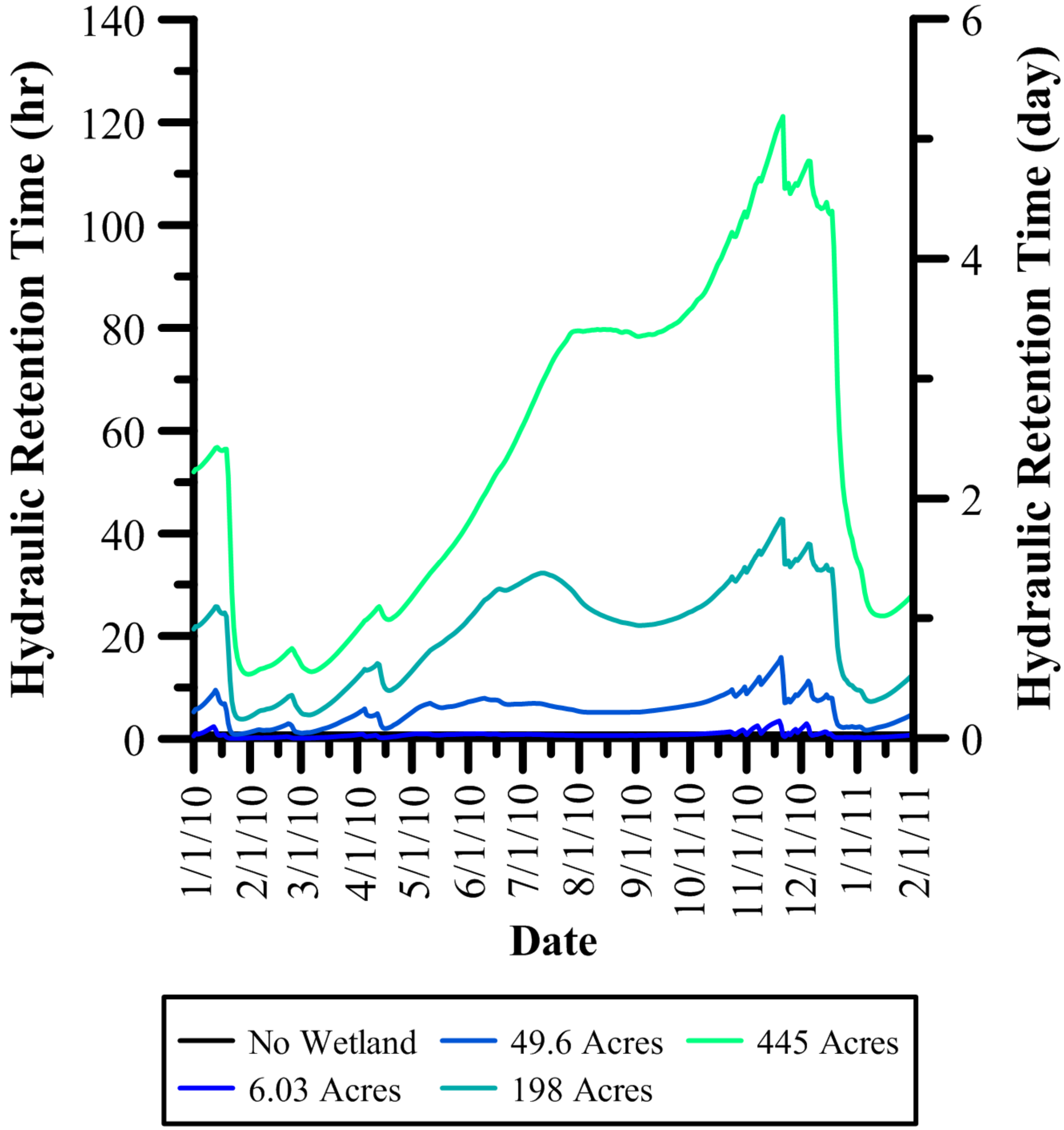

Figure 21. Wetland dissolved oxygen concentration (DO) for non-productive scenarios. The simulated DO for the base scenario where no wetland exists represents the DO from the catchments connected to the "dummy" creek.

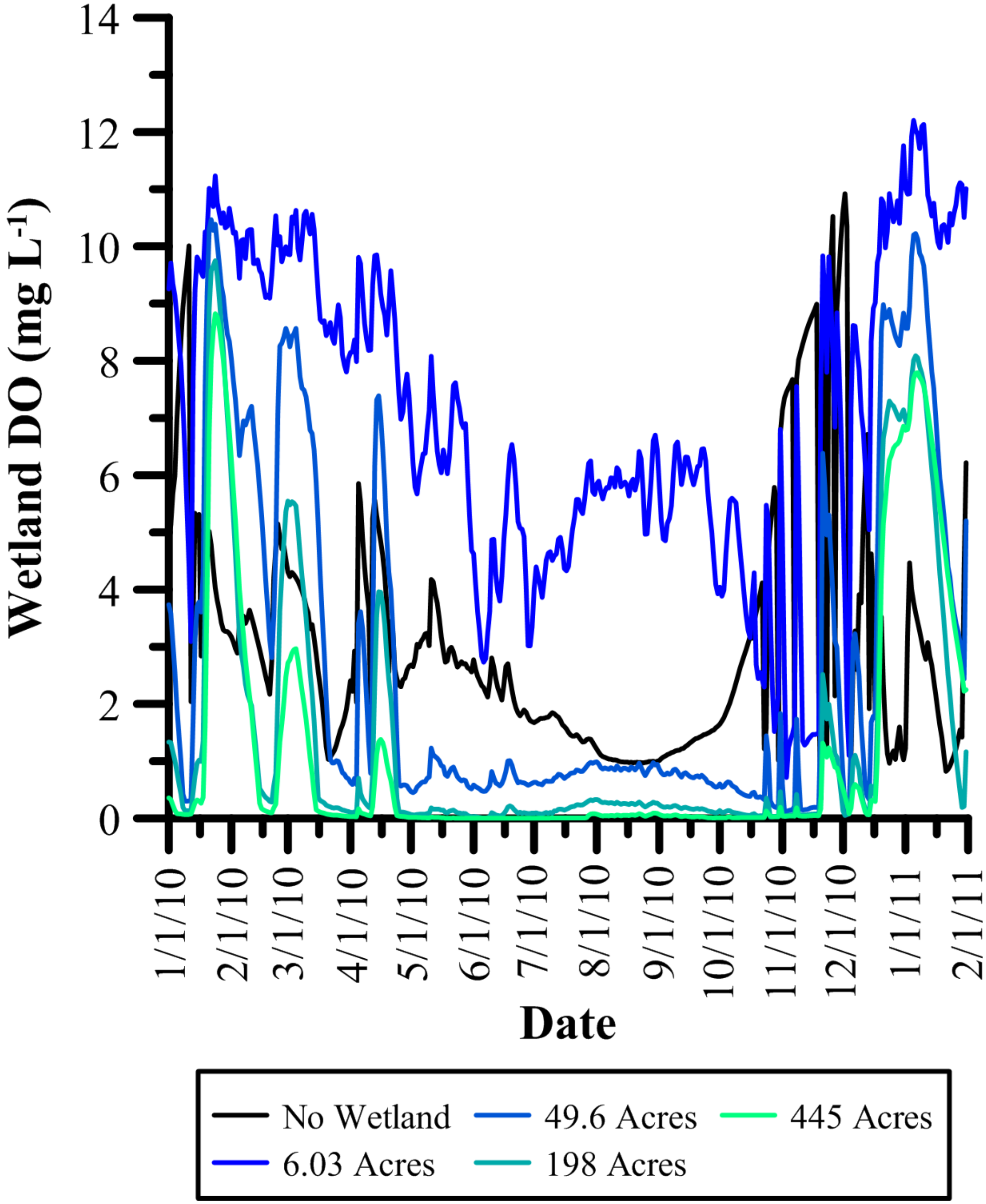

Figure 22. Wetland dissolved organic carbon (DOC) concentration for non-productive scenarios. The simulated DOC for the base scenario where no wetland exists represents the DOC from the catchments connected to the "dummy" creek.

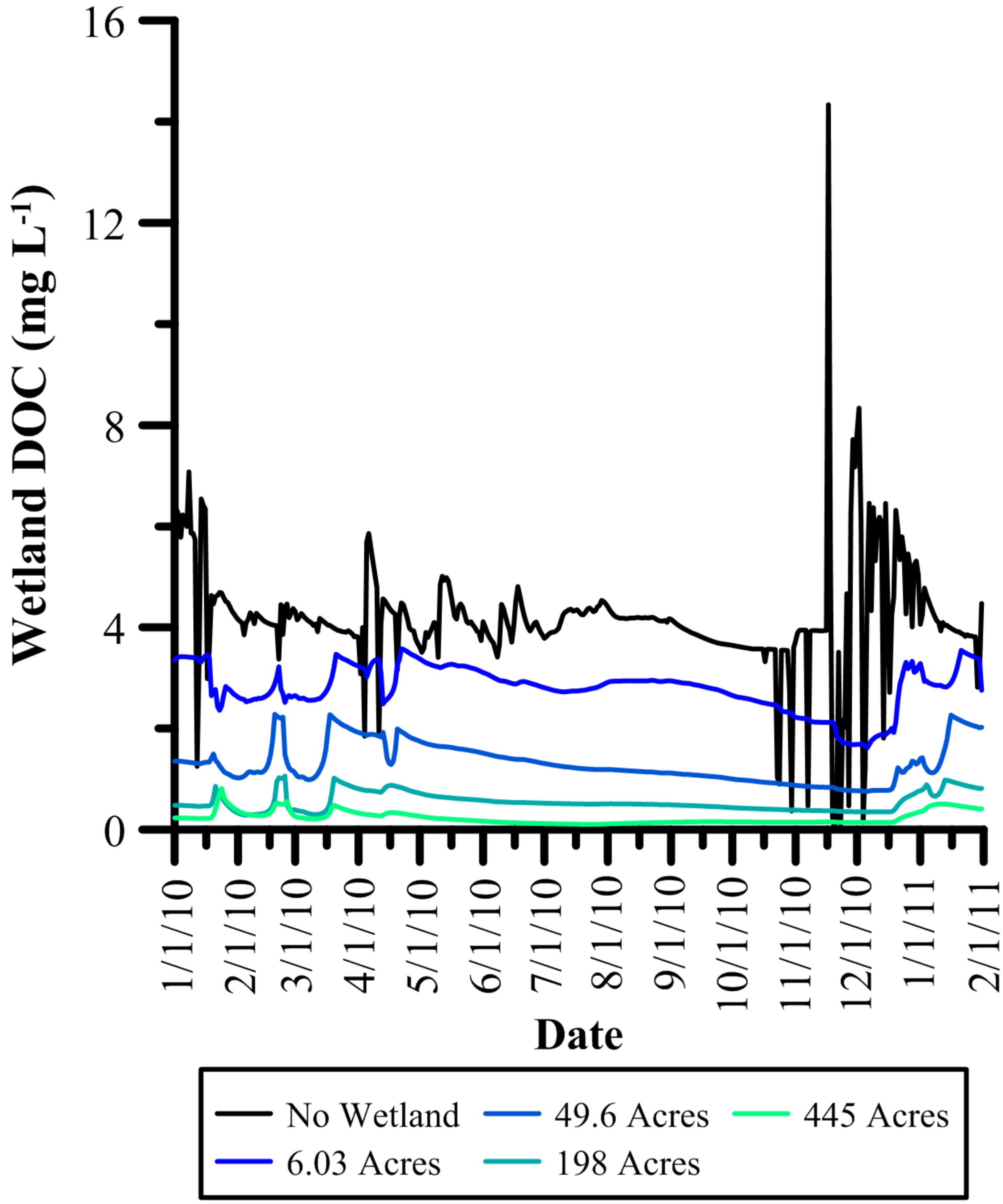

Figure 23. Kinetics plot for non-productive land scenarios.

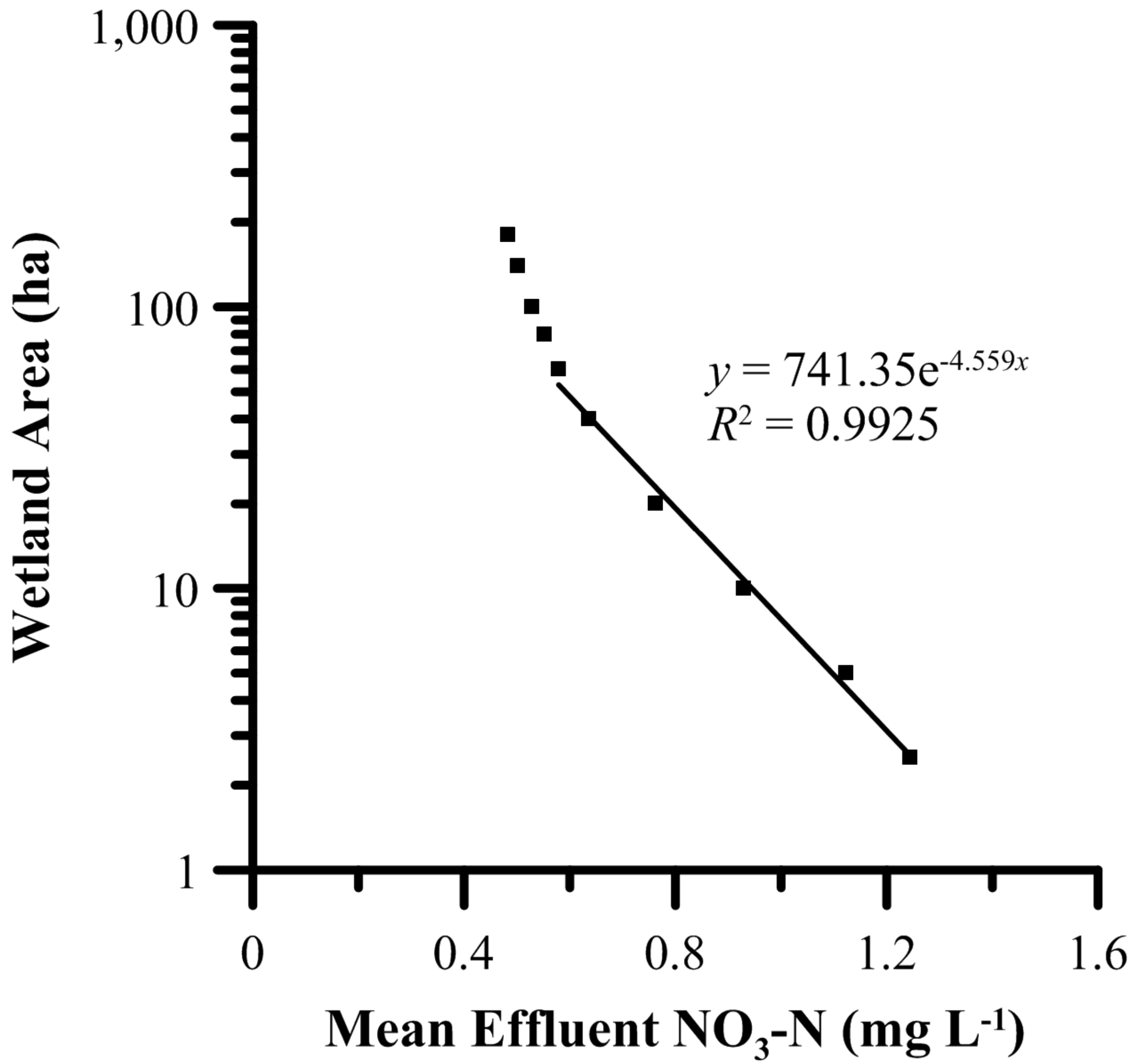

Figure 24. Logarithmic plot of surface water volume vs. surface outflow for 25 acre wetland non-productive land scenario without any modifications, indicated with blue squares, and with catchment 979 reconnected to Orestimba Creek near Crows Landing, indicated with red diamonds. The line with dashes represents outflow and volume values corresponding to the mean hydraulic retention time of the data for the 25 acre scenario without modifications, which is 2.67 hr. The solid line represents a volume and flow values needed to achieve a reasonable hydraulic retention time of 1 d.