Movement of water pollutants in Sardis Lake

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Comprising 39.9 million acres, lakes and reservoirs are a major water resource in this country. They provide drinking water and water supply for industry, irrigation, hydropower, and many recreational activities. Sardis Lake is a dammed reservoir in the state of Mississippi, located on the Little Tallahatchie River. This study is designed to evaluate the movement of water pollutants throughout Sardis Lake and to assess how different water quality parameters are related. The first part of this study is to compare levels of water quality parameters at different locations in Sardis Lake. A statistical package, SPSS, is used to analyze the data. The analyses of data were performed by two-tailed Pearson correlation. For the second part of this study a numerical model, CCHE2D, is used to examine the transport of pollutants in Sardis Lake. CCHE2D was developed by the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi. This two-dimensional system is used for unsteady, turbulent river flow, sediment transport, water quality evaluation, and chemical transport. Water quality data were obtained from the Mississippi Department of Environmental Quality (MDEQ). A digital elevation model for Sardis Lake developed by NCCHE was used to generate a structured mesh for the lake. By applying boundary conditions, initial conditions, and setting the model parameters, simulation is performed and the results are obtained.

Keywords: Surface Water, Water Quality, Water Use

I. Introduction

Background

Water quality is a description of biological, physical, and chemical characteristics of water with respect to its use (USGS, 2005). The uses of lakes, rivers, ponds, and streams are greatly influenced by the quality of their water. Activities such as fishing, swimming, boating, shipping, and waste disposal have very different requirements for water quality. For example fishing waters must have higher quality than shipping waters.

There are two important laws to protect the quality of surface and ground water in the United States. The Clean Water Act addresses surface waters, mainly to control point source discharges (USEPA, 2007a). The Safe Drinking Water Act protects underground sources of drinking water (USEPA, 2007b).

Pollutants that are of some concern and can be found in surface runoff are suspended solids, heavy metals, nutrients, oxygen demanding substances, organic compounds, and bacteria.

Lakes and reservoirs must meet water quality standards because they are important for fishing, supply of drinking water and water for industry, agriculture, and hydropower. They cover 39.9 million acres of land in the United States and support complex food web interactions, provide habitat for many species, and create recreational opportunities (U.S. ACE, 2007).

The productivity of a lake is a measure of its ability to support a food web. Algae form the base of this food web, supplying food for the higher organisms. A lake's productivity may be determined by measuring the amount of algal growth that can be supported by available nutrients. Lakes are classified based on their productivity as eutrophic, mesotrophic, and oligotrophic. Eutrophic lakes have high productivity due to abundant supply of algal nutrients, and oligotrophic lakes have low productivity due to deficiency of nutrients. Mesotrophic lakes are between these two types of lakes (PEARL, 2002 and

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Davis and Cornwell, 2006).

Algal growth is limited by the nutrient that is least available. Phosphorus is not readily available from the atmosphere or the natural water supply and it is the limiting nutrient in lakes (Chin, 2000). Therefore, the amount of phosphorus controls the quantity of algal growth, and as a result, the productivity of the lake. However, increased phosphorus generally results in reduced water quality because of undesirable changes that occur as algal growth increases (Ray, 1995). An example of that is the reduction of the most desirable fish as the population of undesirable fish increases. High productivity results in an abundant supply of algal nutrients, and algae cause the water to be highly turbid. Studies have shown that the phosphorus concentration should be below 10 to 15 µg/L to limit algal blooms (Davis and Cornwell, 2006).

Another important water quality parameter and nutrient in lakes is nitrogen. Nitrogen in lakes is usually in the form of nitrate (NO_3^-) and comes from external sources by way of inflowing streams or groundwater. In aerobic conditions, nitrogen changes from nitrate to organic nitrogen, then to ammonia, and back to nitrate (Mitch and Gosselink, 2000). Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen and ammonia (NH_3) as nitrogen in a water body. Total nitrogen concentration (TN) in a lake is equal to TKN plus NO_3^- plus NO_2^- as nitrogen.

Objective of the Study

This project has two objectives. The first objective is to analyze the relationship between selected water quality parameters at five different sites in Sardis Lake and to evaluate the lake's trophic state. The second objective is to computationally simulate the flow and transport of a hypothetical pollutant in Sardis Lake.

Study Sites

In the Yazoo Basin in northern Mississippi, there are four flood control reservoirs managed by the Vicksburg District of the U.S. Army Corps of Engineers. They are Enid, Arkabutla, Grenada, and Sardis Lakes. Sardis Dam was built on the Little Tallahatchie River to protect agricultural and industrial areas downstream by controlling its flow. Construction of Sardis Dam in 1940 resulted in the Sardis Lake System, an approximately 98,000-acre water resource development project. It extends into three counties: Union, Panola, and Lafayette. It serves a recreational use and has 5 million visitors annually (U.S. ACE, 2007).

Historical water quality data from five sampling sites in Sardis Lake were obtained from the Mississippi Department of Environmental Quality (MDEQ) in order to conduct the analyses in this project.

II. MATERIALS AND METHODS

The sampling sites are shown in Figure 1. They are: (1) Near Sardis Dam, (2) Near Clear Creek Landing Public Use Area, (3) Toby Tubby Creek Embayment, (4) Near Hurricane Landing Public Use Area, and (5) at upper end of the Lake.

Two different methods were used for analyzing the data: statistical data analysis (using the software SPSS) and hydrodynamic simulation (using the software CCHE2D).

Statistical Data Analysis

The data obtained from MDEQ ranged from 1997 to 2004 for all five Sites. Site 1 data were also available for 1994. The water quality parameters were measured at different depths varying from 0.15 m to 15.54 m below the water surface. For the parameters of interest, the highest number of data points available was at the depth of 0.46 m. Therefore, most analyses were performed at this specific depth. Parameters that were used in this study were water temperature (T), chlorophyll *a* (Chl-*a*), total suspended solids (TSS), total phosphorus (TP), and nitrogen in three different forms: TKN, NH_3, and NO_3^- + NO_2^-. TN was obtained by the summation of TKN plus NO_3^- + NO_2^- as nitrogen. The highest number of sampling events at 0.46 m was for Site 1 (data points n = 28), Site 2 (n = 15), Site 3 (n = 14), and Site 4 (n = 15). Few data points were available for Site 5. Statistical analysis was not performed for this site. A two-tailed parametric correlation (Pearson Correlation) was performed between parameters of every site to determine the relationships between them.

One additional parameter used was chlorophyll *a* (Chl-*a*), found in all algae but not in other organic solids such as bacteria. Therefore, a criterion for the productivity of a lake is to determine the concentration of Chl-*a* in the lake. Table 1 shows the classification of a lake based on productivity (Wetzel, 1983).

The relationship between summer levels of chlorophyll *a* and measured total phosphorus concentrations for 143 lakes in the US can be estimated from Equation 1 (Jones and Bachmann, 1976).

$$\text{Log Chlorophyll } a = -1.09 + 1.46 \times \text{Log Total P} \quad \text{(Equation 1)}$$

Hydrodynamic Simulation

To analyze the movement of water pollutants and to assess the pattern of water quality parameters throughout the lake, a computational software package, CCHE2D, was used. This package was developed by the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi. CCHE2D is an integrated package for two-dimensional simulation and analysis of river flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport, and water quality. These processes are solved with the depth integrated Reynolds Equations, transport equations, sediment sorting equation, bed load and bed deformation equations. CCHE2D is composed of a graphical user interface (CCHE-GUI), a separate hydrodynamic numerical model (CCHE2D model), and a structured mesh generator (CCHE2D Mesh Generator). It is a two-dimensional structured and two-boundary algebraic mesh generator with graphical user interface (NCCHE, 2008).

III. RESULTS AND DISCUSSION

Statistical Data Analysis

Based on all the data available for Sardis Lake from 1994 to 2004 at all sampling depths, average concentrations of TP and Chl-*a* were 69 ± 56 μg/L and 4.8 ± 2.0 μg/L, respectively. The average concentrations for the depth of 0.46 m were 68 ± 53 μg/L for TP and 4.4 ± 1.4 μg/L for Chl-*a*. Comparison of the results with Table 1 shows that the lake is classified as eutrophic considering the average concentration of TP and mesotrophic considering the average concentration of Chl-*a*. Data points in Figure 2 show the measured TP vs. Chl-*a* in Sardis Lake. The straight line was obtained by substituting the measured TP in Equation 1 and calculating Chl-*a*. If Sardis Lake had followed the same pattern as the 143 lakes used to generate Equation 1, the points would be scattered about the line. This result shows that for the concentration of TP, the lake has produced less Chl-*a* than expected.

Correlation analyses were performed for the data on the five sites in Sardis Lake individually at the depth of 0.46 m below the surface water from 1997 to 2004. At Site 1 (Near Sardis Dam), temperature negatively correlates with TSS, TP, and TN ($-0.73 < r < -0.67$, $\alpha < 0.01$). r is correlation coefficient and α is the significance level. TSS positively correlates with TP and TN. Also, TN and TP positively correlate with each other ($0.56 < r < 0.73$, $\alpha < 0.01$). Figure 3 shows the values in a column chart. Figure 4 shows the water quality parameters versus water temperature at Site 1. As water temperature increases, the concentrations of TSS, TP and TN decrease. Chlorophyll *a* was not used in this data analysis because the number of data points was few.

Water temperature negatively correlates with TSS ($r = -0.71$, $\alpha < 0.01$) and TN ($r = -0.70$, $\alpha < 0.01$) at Site 2. It negatively correlates only with TSS at Site 3 ($r = -0.58$, $\alpha < 0.05$) and with both TSS ($r = -0.73$, $\alpha < 0.01$) and TP ($r = -0.81$, $\alpha < 0.01$) at Site 4. Figure 5 and Figure 6 show the concentrations of TSS, TP, and TN at different temperatures at Site 2 and Site 4, respectively. There is no strong correlation between temperature and TP at Site 2 or between temperature and TN at Site 4. TSS and TN correlate at Site 2 ($r = 0.58$, $\alpha < 0.01$). TSS and TP correlate at Site 4 ($r = 0.53$, $\alpha < 0.05$).

At Site 1, TN concentration correlates positively with three types of nitrogen: TKN ($r = 0.93$, $\alpha < 0.01$) NH_3 ($r = 0.4$, $\alpha < 0.05$), and $NO_3^- + NO_2^-$ ($r = 0.8$, $\alpha < 0.01$). At Site 2, TN correlates positively with two types of nitrogen, TKN ($r = 0.96$, $\alpha < 0.01$) and $NO_3^- + NO_2^-$ ($r = 0.7$, $\alpha < 0.01$). TN correlates with TKN ($r = 0.99$, $\alpha < 0.01$) at Site 3. Also TN correlates with TKN ($r = 0.92$, $\alpha < 0.01$) at Site 4. Figure 7 shows the percentage of contribution of three types of nitrogen in total nitrogen at Site 1. On Sept. 97 and Oct. 98 the percentage of ammonia is highest.

Correlations between parameters are higher at Site 1 compared to the other sites. Site 1 is near the dam and downstream of mixing points with other water bodies. Therefore, at Site 1, the parameters may have interacted with each other for more time and may have reached steady state.

Simulation Model

To simulate the flow and chemical transport using the software CCHE2D, five steps were followed: 1) generating a mesh, 2) setting boundary conditions, 3) setting initial conditions, 4) setting model parameters, and 5) running simulations. For the first step, the bathymetry data for Sardis Lake developed by NCCHE were used. The data were in ASCII format.

Flow simulation

Before conducting a chemical transport simulation, it was necessary to conduct a simulation of the water flow through the lake. For the flow simulation, the following conditions were set. One inlet (Little Tallahatchie River) and one outlet (Sardis Dam) were assumed for boundary conditions. For the initial condition, the inlet flow was set at 80 m^3/s. This flow rate is an estimate of a high discharge flood situation, based on historical discharges at the United States Geological Survey (USGS) gauge station at the Little Tallahatchie River at Etta (approximately 30 km upstream of the lake) and estimates of tributaries to the Little Tallahatchie River between Etta and Sardis Lake. The water surface elevation at the outlet of the lake was set at 80 m, which is a summertime elevation. The simulation time was 30 days to ensure that steady state flow was reached before the chemical transport simulation. The simulation time is different from the water travel time. The output results of the simulation in the graphical interface were: water depth, velocity in the x and y directions, velocity magnitude, specific discharge in the x and y directions, total specific discharge, shear stress in the x and y directions, total shear stress, Eddy viscosity, and Froude number. Figure 8 shows the water depth after steady state was reached. The water depth ranges from 16 m near the dam (Site 1) to less than 1 m at upper end of the lake (Site 5).

Figure 9 shows the velocity magnitude of water flow in the lake after steady state was reached. The flow ranges from zero near the dam (Site 1) to 2 cm/s at the upper end of the lake (Site 5).

Chemical Transport Simulation

To understand how a pollutant, introduced into Sardis Lake from the Little Tallahatchie River, may spread in the lake, a chemical transport simulation was carried out. Specific conductance, though not a pollutant in itself but a possible indicator of pollution, was used as a conservative parameter (that is, one that does not react) for the chemical transport simulation. A specific conductance of 79 µmhos/cm at 25°C was assumed as a uniform initial condition in the lake. This number is a realistic initial condition for the lake and was taken from historical data from the lake obtained from the MDEQ. The input of a hypothetical pollutant was used as values of specific conductance from the Little Tallahatchie River into the lake. The input was modeled as a specific conductance of 202 µmhos/cm at 25^0C. Figure 10 shows the pattern and distribution of specific conductance throughout the lake 25 days after the initial high input of specific conductance. After 25 days, the hypothetical pollutant has traveled approximately 14,000 m along the length of the lake and has spread laterally through most of the lake's width. This output shows that it is possible to simulate the input of a conservative pollutant into the lake and obtain the concentration of that pollutant at a certain time at every point of the lake for different situations and initial conditions.

Simulation of water quality parameters in Sardis Lake allows a user to see the pattern and dilution of pollutants across the lake and to predict the concentration of pollutants in every point of the lake at any time. But to reach this goal, more data should be collected on potential pollutants, not only for the Little Tallahatchie, but also for other inlets to the lake.

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Lake Classification Based on Productivity			
Lake Classification		Chlorophyll a Concentration (μg/L)	Total Phosphorus Concentration (μg/L)
Oligotrophic	Average	1.7	8
	Range	0.3 - 4.5	3.0 - 17.7
Mesotrophic	Average	4.7	26.7
	Range	3.0 - 11.0	10.9 - 95.6
Eutrophic	Average	14.3	84.4
	Range	3.0 - 78.0	15.0 - 386.0

Table1. Classification of lakes based on productivity

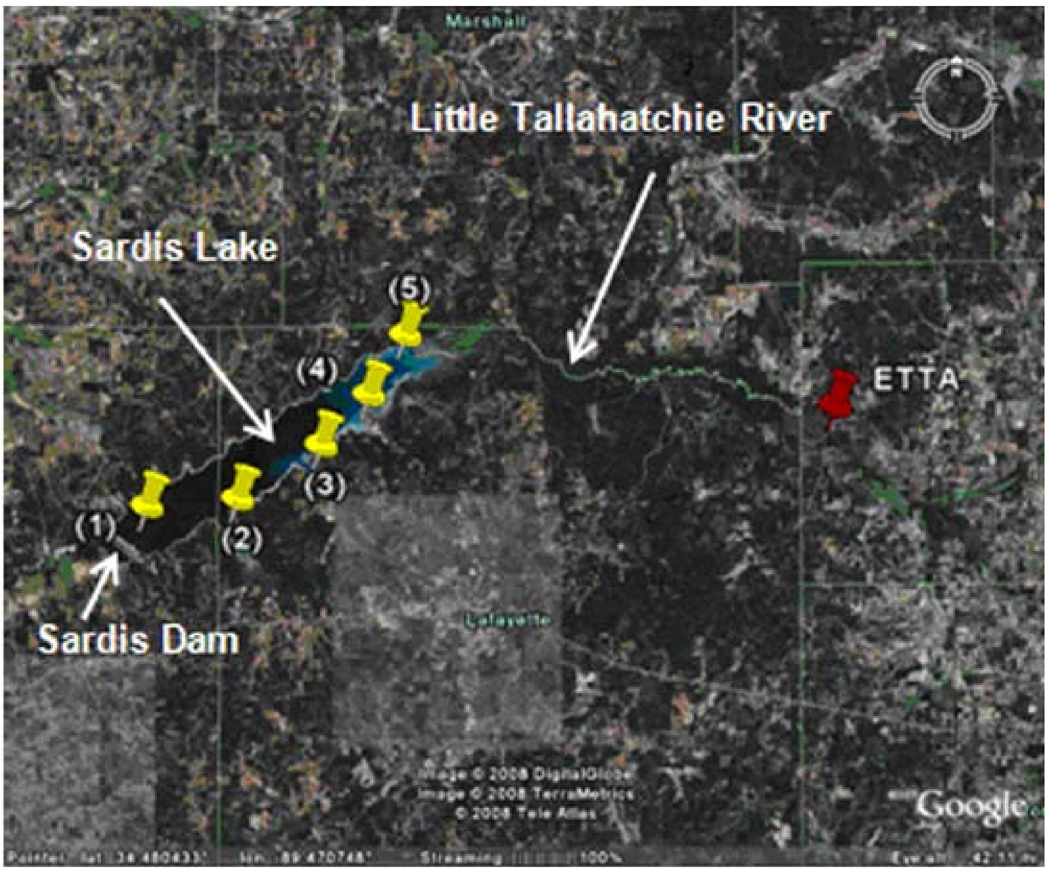

Figure 1. Satellite view of study area and study sites in Sardis Lake

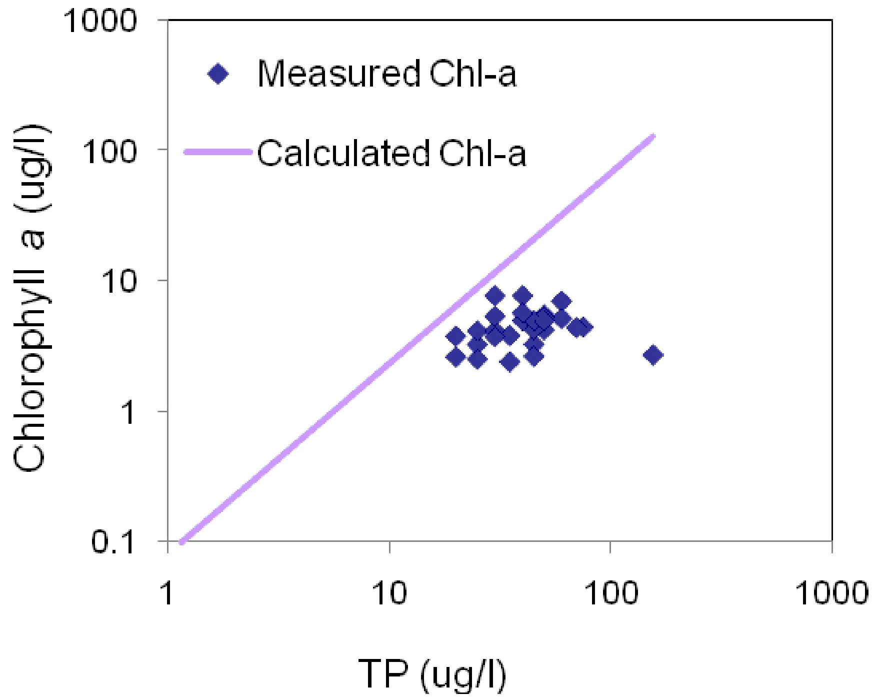

Figure 2. Relationship between TP and Chl-a

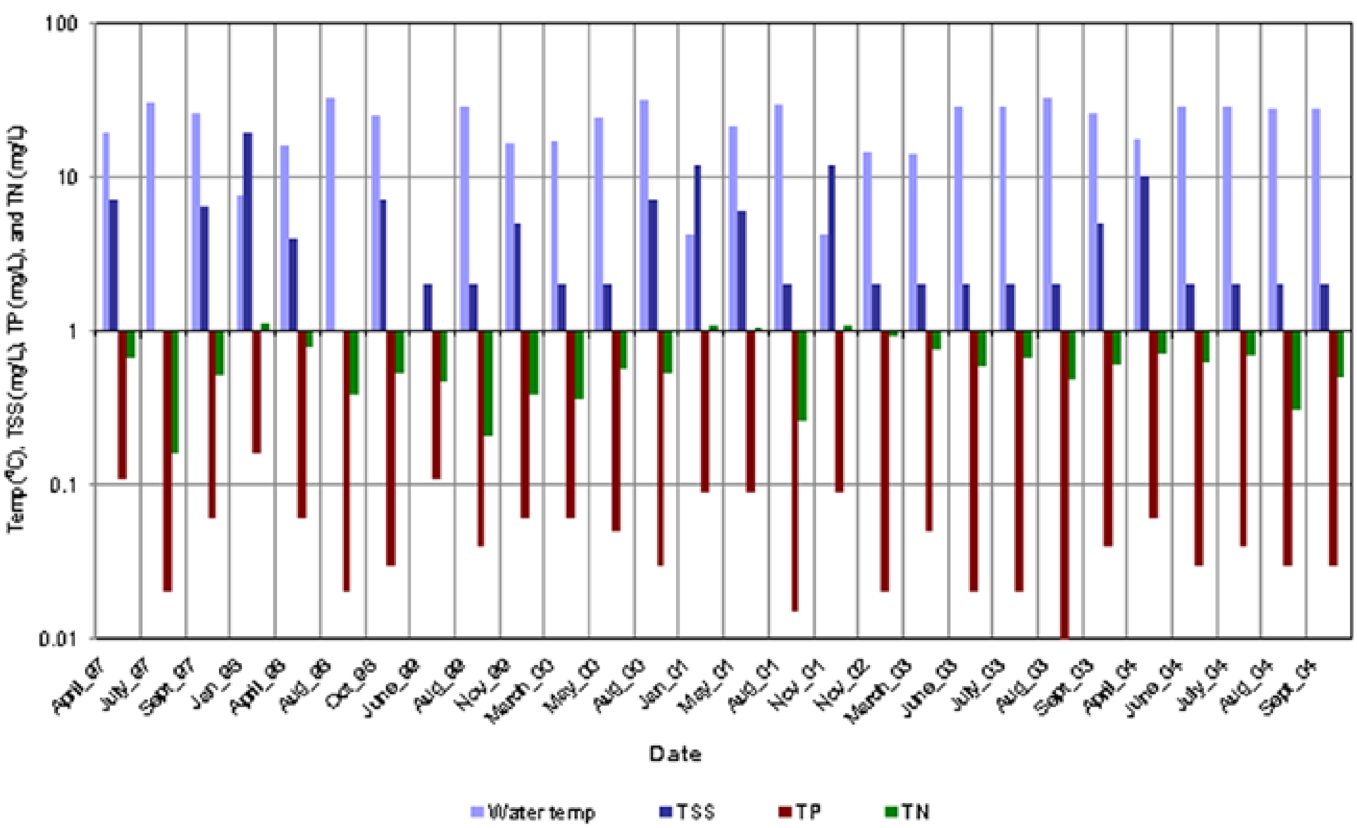

Figure 3. Variation of water temperature, TSS, TP, and TN at Site 1 from 1997 to 2004

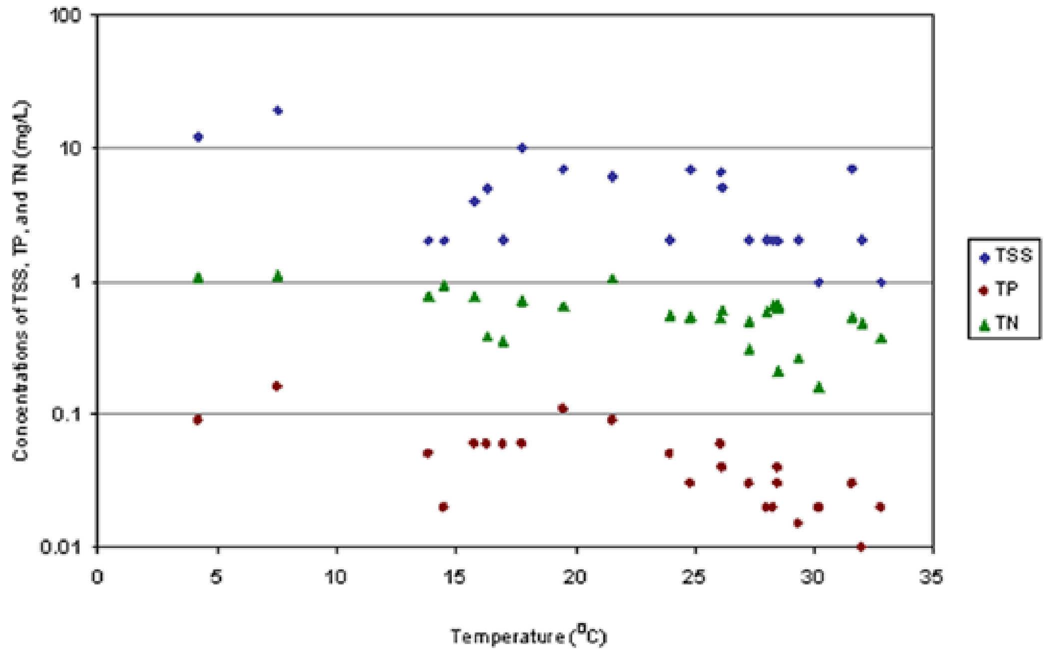

Figure 4. Variation of TSS, TP, and TN at different water temperatures at Site 1.

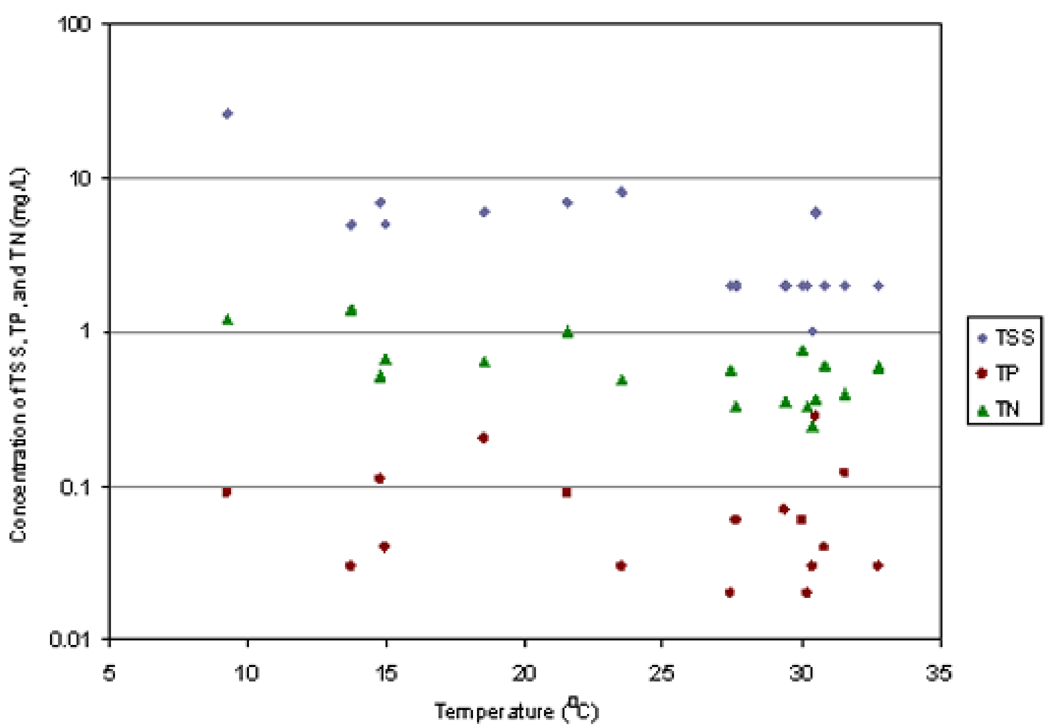

Figure 5. Variation of TSS, TP, and TN at different temperatures at Site 2

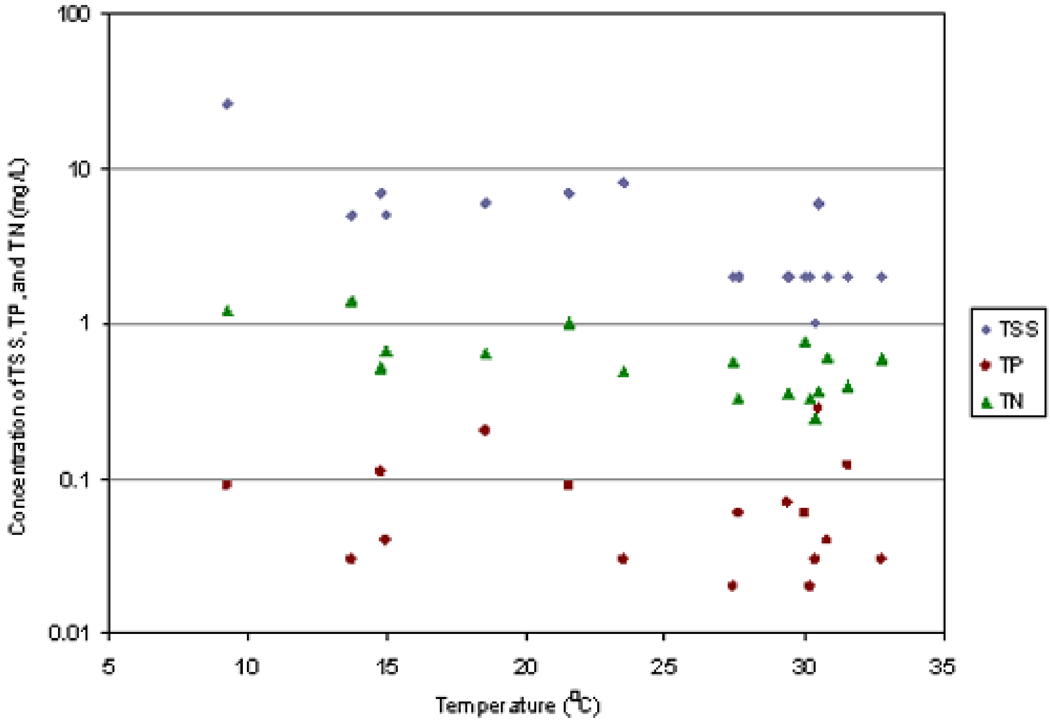

Figure 6. Variation of TSS, TP, and TN at different temperatures at Site 4

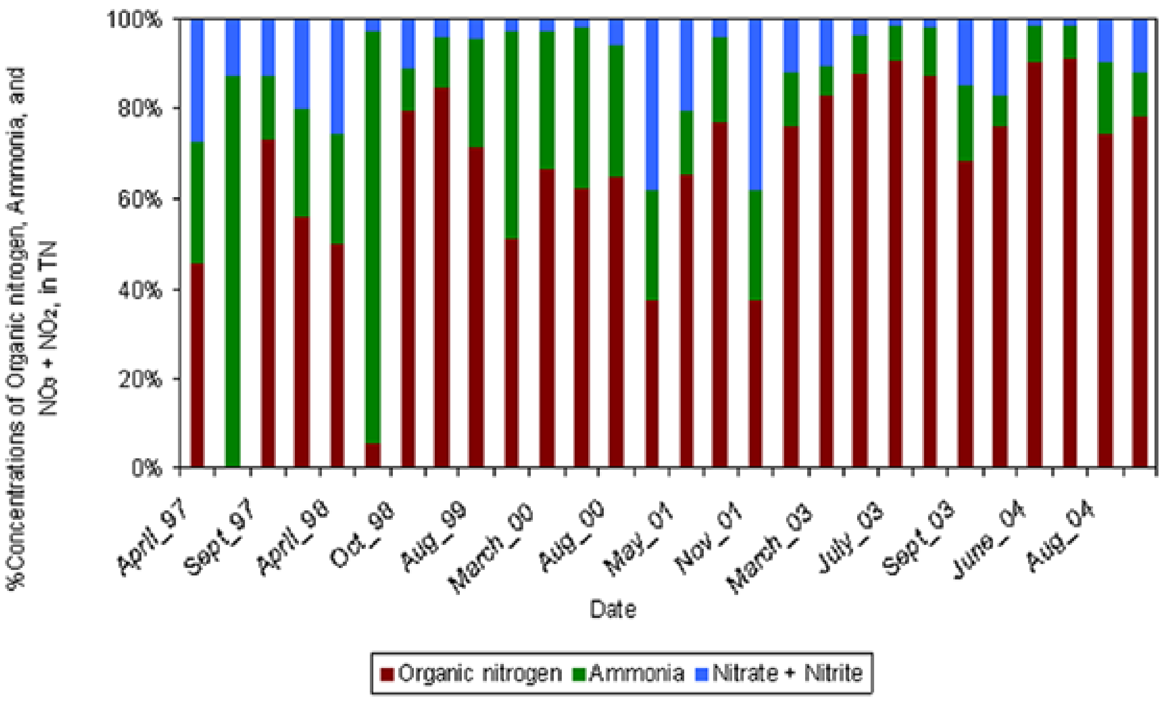

Figure 7. Contribution of three types of nitrogen in TN at Site 1

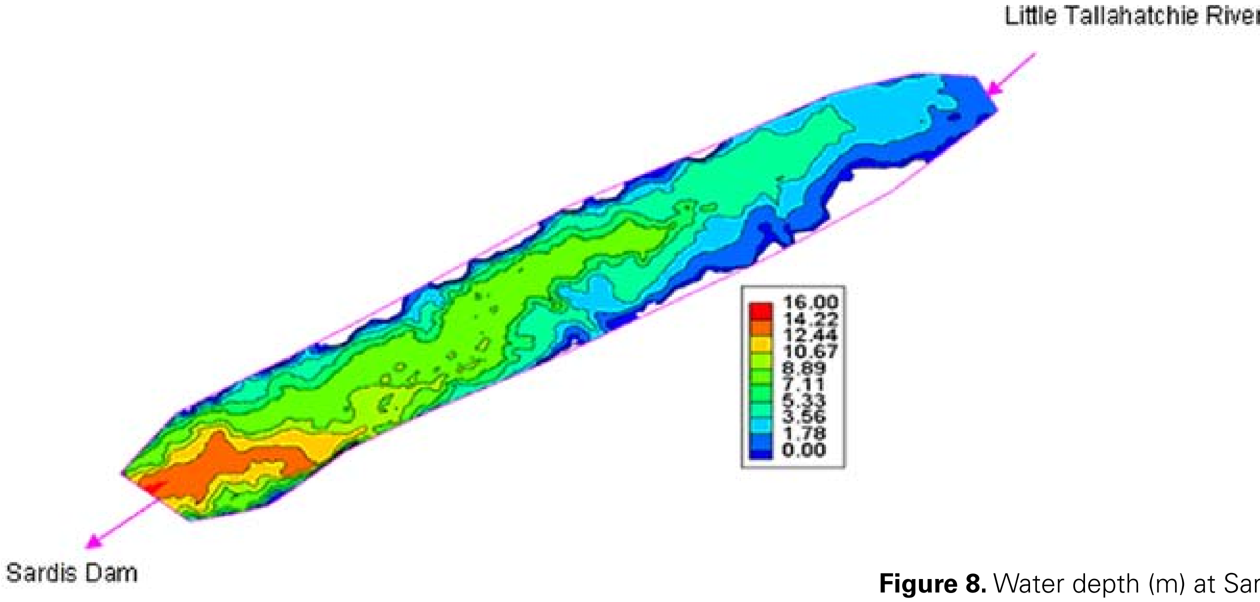

Figure 8. Water depth (m) at Sardis Lake

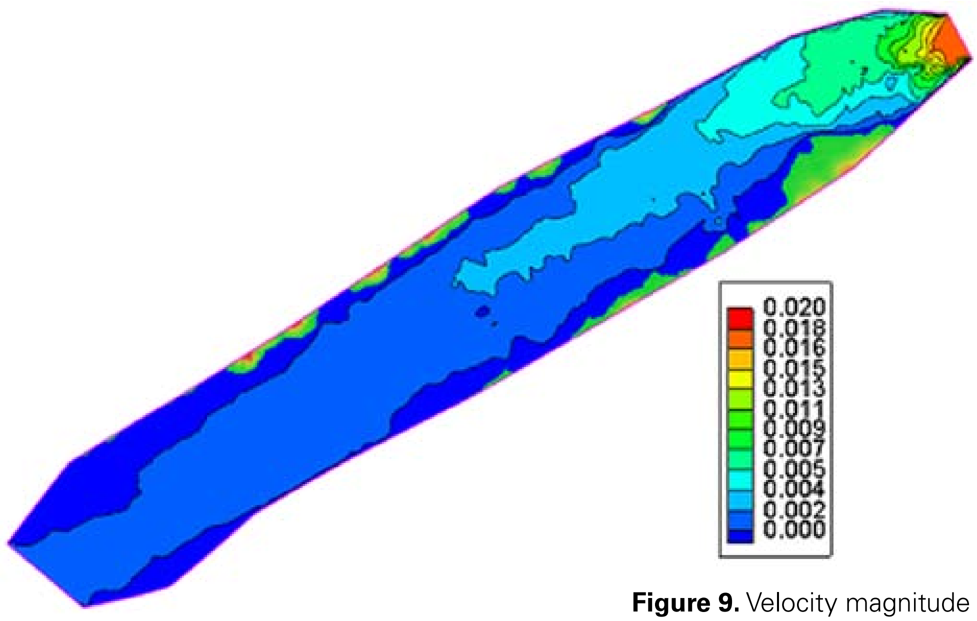

Figure 9. Velocity magnitude (m/s) at Sardis Lake

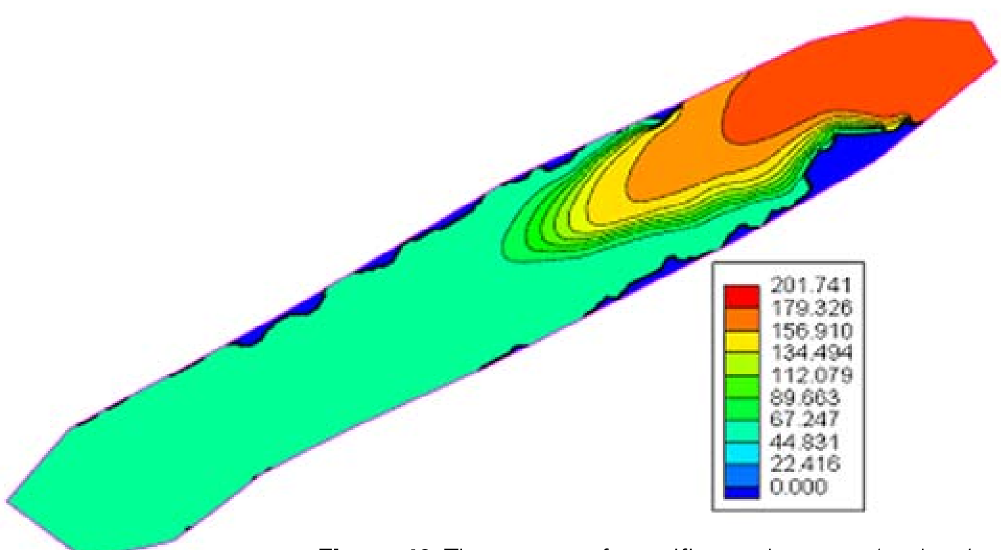

Figure 10. The pattern of specific conductance (μmhos/cm at 25°C) after 25 days