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# Linking Watershed and Reservoir Models

**K. L. White**

University of Arkansas, 203 Engineering Hall; Fayetteville, AR, klwhite@uark.edu.

**I. Chaubey, PhD**

University of Arkansas, 203 Engineering Hall; Fayetteville, AR, chaubey@uark.edu.

**B. E. Haggard, PhD**

USDA-ARS Poultry Production and Product Safety Research Unit, 203 Engineering Hall; Fayetteville, AR, haggard@uark.edu.

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***Abstract.*** Watershed nutrient management is essential in minimizing the eutrophication rate of reservoirs. A shortcoming in nutrient management of watershed-reservoir systems has been the lack of successful linking of watershed and water body models to evaluate impact of watershed management options on reservoir water quality. The objectives of this research were to 1) calibrate and validate a Soil and Water Assessment Tool (SWAT) watershed model for Beaver Reservoir Watershed; 2) calibrate and validate a CE-QUAL-W2 (W2) hydrodynamic and water quality model for Beaver Reservoir, 3) link the watershed and reservoir models, and 4) evaluate reservoir water quality changes with changing watershed management practices. Watershed management scenarios that were evaluated include: reductions in poultry litter application rates, reductions in commercial fertilizer rates, and reductions in waste water treatment plant (WWTP) effluent phosphorus (P) concentration. Scenarios were evaluated by comparing chlorophyll-*a* and $PO_4$-P concentrations at two locations within the reservoir. Results indicated that chlorophyll-*a* and $PO_4$-P concentrations were always greater at the transitional zone location than the lacustrian zone location. Predicted chlorophyll-*a* and $PO_4$-P concentrations from scenarios evaluating reduction in commercial fertilizer and reduction in WWTP effluent P indicated generally less than 1% change at both reservoir locations. Scenarios simulating reduction in poultry litter applied in the watershed predicted a substantial decline in $PO_4$-P concentrations. The linked SWAT and W2 modeling scheme provides a holistic approach to modeling nutrient sources, transport, and delivery in a watershed-reservoir system. The linked models can be used to assess the probable influence different watershed management schemes may have on reservoir water quality at targeted locations within the reservoir.

**Keywords.** CE-QUAL-W2 model, SWAT model, reservoir, nutrient, watershed

## Introduction

Management of reservoir water quality is needed to reduce eutrophication rates attributed to nutrient loading from cultural land use modifications and effluent discharges (Henderson-Sellers and Markland, 1987; National Research Council, 1996). Eutrophic reservoirs provide a poor drinking water source and are undesirable for recreation because of un-aesthetic characteristics such as algal abundance and unpleasant odors (Gibson, 1997). This is a concern since reservoirs have become a major drinking water supply, and in many areas, a major economic contributor through recreational dividends. To minimize the eutrophication rate in a reservoir, an understanding of nutrient sources, transport, and delivery in the particular watershed-reservoir system is needed.

A tool for simulating the processes influencing reservoir water quality requires temporal and spatial components, and computer models offer these capabilities (Cassell et al., 1998). However, no specific model is presently available that includes the source and transport of nutrients in a watershed and resulting influence on reservoir water quality (Sharpley et al., 2002). Therefore, in order to simulate watershed processes and resulting reservoir water quality impacts, available watershed and reservoir models must be linked.

Many investigators have attempted to link watershed and reservoir models. Summer et al. (1990) combined Agricultural Nonpoint-Source Model (AGNPS) (a watershed model) and FARMPND (a one-dimensional lake model) to evaluate the effect of land management changes on lake water quality. The linked models were used to assess the influence Conservation Resource Program (CRP) wetlands had on water quality of adjacent Eagle Lake, Michigan. In linking the models, FARMPND did not provide the level of detail and the capabilities needed to simulate these practices. A model with greater functionality was suggested for future research. Additionally, Mankin et al. (1999) combined AGNPS and EUTROMOD (watershed-scale nutrient loading and lake response model) on Melvern Lake, Kansas, to assess lake response to potential land management scenarios. Although several land management scenarios were evaluated, results indicated that predicted lake outputs did not differ substantially between scenarios. This corresponded with sensitivity analyses, which suggested that the models were not sensitive to the changes in land management evaluated in this study.

No single model is currently available that adequately represents the complex watershed-reservoir system. In addition, no one combination of models has been identified in published research as providing the best representation of the watershed-reservoir system. This shortcoming in successful linking of watershed and water body models has been identified as a substantial limitation in nutrient management (Sharpley et al., 2002). A watershed model sensitive to landscape changes and a reservoir model sensitive to changes in nutrient yields in receiving waters are essential for developing a watershed-reservoir linked model that predicts reservoir nutrient response to changes in watershed management. Based on this criterion, the

Soil and Water Assessment Tool (SWAT) watershed model and CE-QUAL-W2 (W2) reservoir model were chosen to be used in the linked modeling system in this study.

The SWAT model was selected to predict nutrient yields from the watershed because of its extensive applications in evaluating watershed management scenarios. For example, Santhi et al. (2001) applied SWAT to assess alternative management practices incorporating point and nonpoint sources, such as wastewater treatment plant (WWTP) phosphorus (P) limits, modifications to dairy manure application rates, reduction in animals' P diet, and removal of animal manure. King and Balogh (2001) investigated the conversion of agriculture and forestland into turf grass usage (e.g., golf courses and residential neighborhoods) with the SWAT model. The SWAT model was also used to develop a strategy for P yield reductions by simulating modifications in tillage practices and nutrient amendment application rates in Rock River Watershed, Wisconsin, USA (Kirsch et al., 2002).

The W2 model was selected to simulate reservoir water quality because of its previous applications in evaluating varying reservoir water quality concerns. Giorgino and Bales (1997) assessed different management scenarios, such as reductions in $PO_4$-P concentrations at the lake inflow, reduction in $PO_4$-P releases from bottom sediments, and changes in point source loads on the water quality of Rhodhiss Lake, North Carolina. A W2 model was also used to investigate management scenarios and land management changes in Lake Hickory, North Carolina (Bales and Giorgino, 1998). Model simulations included evaluation of stratification, reduced nutrient inflows, reduced release rate of nutrients from bottom sediment, and shoreline development. Green (2001) implemented the W2 model for Lake Maumelle, Arkansas to simulate the effects of nutrient yields and to predict trophic conditions in the reservoir. Green (2001) simulated scenarios such as a conservative spill, nutrient limiting status, nursery pond releases, and algal response to increases in nitrogen (N) and P yields with the W2 model. Haggard and Green (2002) developed a W2 model for Beaver Reservoir, Arkansas to simulate increased releases at the dam and its impact on temperature and dissolved oxygen (DO) values in the reservoir.

The utility of the SWAT model to predict nutrient yields from a watershed with various management schemes and the utility of the W2 model to simulate reservoir water quality based on nutrient inputs have been established by previous investigators. However, their combined ability to investigate watershed-reservoir nutrient management has not been evaluated. The objectives of this research were to 1) calibrate and validate a SWAT watershed model for Beaver Reservoir watershed; 2) calibrate and validate a CE-QUAL-W2 reservoir model for Beaver Reservoir, 3) link the watershed and reservoir models, and 4) evaluate reservoir water quality changes with changing watershed management practices.

## Study Site

This study was conducted in the Beaver Reservoir watershed (Beaver watershed) located in Northwest Arkansas. The Beaver watershed contains approximately 3,000 km of streams with the main tributaries being Richland Creek, War Eagle Creek, and White River (Figure 1). The watershed encompasses approximately 310,000 ha with land use distributions of 1.1% urban, 3.8% water, 69% forest, and 26% pasture (McKimmey and Scott, 1993; CAST, 2002).

Construction of Beaver Reservoir began in 1960 and ended in 1966. Beaver Dam was constructed by US Army Corp of Engineers (USACE) to control floods, generate electrical power, and supply drinking water. The hydraulic retention time in Beaver Reservoir is approximately 1.5 years with a conservation pool depth of 60 m and an average depth of 18 m (Haggard and Green, 2002). It contains 723 km of shoreline and stretches 80 km from White River at Highway 45 bridge to Beaver Dam. The total storage capacity at current conservation pools (341.4 m above sea level) of the reservoir is 2,040,000 $m^3$ with an ultimate water supply capacity of 120 MGD (Market, 1973; Haggard and Green, 2002). Beaver Reservoir is the major drinking water supply for Northwest Arkansas servicing more than 300,000 persons through the Beaver Water District, Carroll-Boone County Water District, and Madison County Water District.

The designated uses of Beaver Reservoir for water supply and recreation are threatened by the increased rate of eutrophication from P loading (Runsick, 1967; Kirsch, 1973; Larson, 1983). Trophic conditions in Beaver Reservoir have historically been correlated to both watershed land use (USDA-SCS, 1986) and point sources dischargers (Runsick, 1967; Kirsch, 1973). Nutrient concentrations and yields in streams draining the Beaver Watershed are correlated to the fraction of pasture in each catchment (Haggard et al., 2003).

## Methods

### *The SWAT Model*

The SWAT model is a widely used, physically based, GIS-based watershed model developed by US Department of Agriculture – Agricultural Research Service (USDA-ARS). It functions on a continuous time step with input options for hydrology, nutrients, erosion, land management, main channel processes, water bodies, and climate data. The SWAT model predicts the influence of land management practices on constituent yields from a watershed. The model includes agricultural components such as fertilizer, crops, tillage options, and grazing and has the capability to include point source loads (Neitsch et al., 2001).

We used the ArcView interface with SWAT2000 in this application, which was the current version of the model at the beginning of the project. Mandatory GIS input files needed for the SWAT model include the Digital Elevation Map (DEM), land cover, and soil layers. The following GIS data were used to develop the Beaver Watershed model to simulate watershed response from 2001 to 2002: 30-meter DEM (US Geological Survey (USGS)), rf3 stream shape file (EPA BASINS), 28.5-m 1999 land use and land cover image file (CAST, 2002), and STATSGO soils shape file (EPA BASINS). Based on threshold specifications and the DEM, the SWAT ArcView interface was used to delineate the watershed into 55 subbasins. Point and nonpoint sources were included in the model such as, WWTP effluent, animal production, and commercial fertilizer usage. Weather data from stations within the region were incorporated to provide the most representative precipitation and temperature data available. The Beaver SWAT model was simulated with SWAT instream components active. The Beaver SWAT model was calibrated using data collected at three USGS gauging stations: White River near Fayetteville (USGS 07048600), Richland Creek at Goshen (USGS 07048800), and War Eagle Creek near Hindsville (USGS 07049000) (Figure 1). About twice-a-month water-quality sampling occurred at the USGS gauge, therefore daily measured constituent concentrations were not available. Daily concentrations were estimated from collected samples using LOADEST2 software (Crawford, 1991; 1996). The SWAT model was calibrated and validated for flow volume, sediment yield, total P (TP) yield, and $NO_3$-N plus $NO_2$-N yield for annual and monthly time steps.

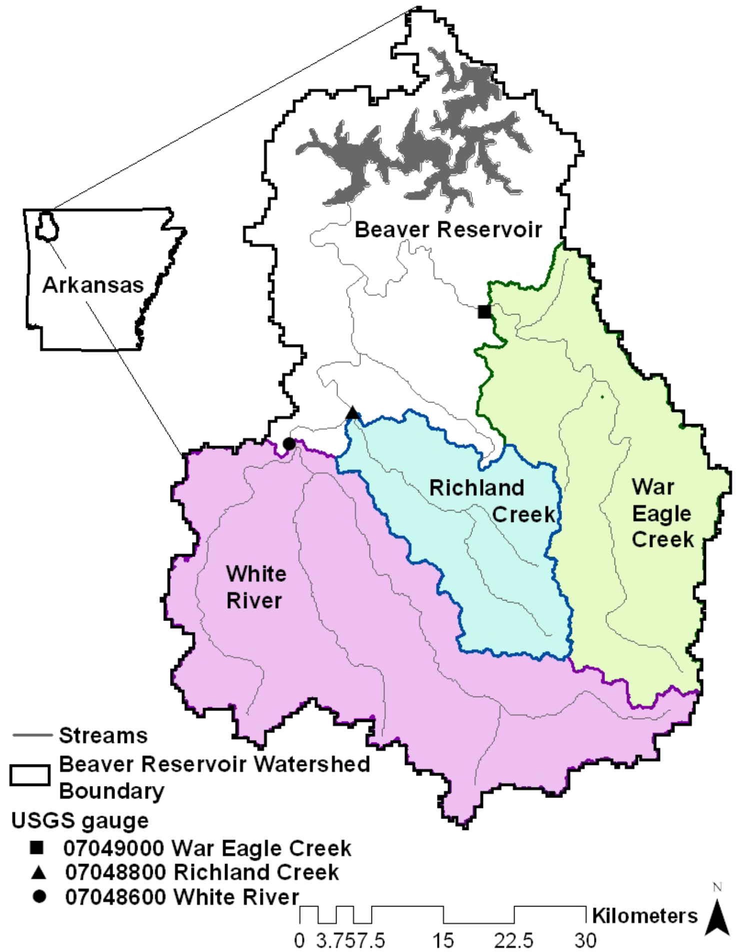


Figure 1. Beaver Reservoir Watershed with main tributaries and USGS stream gauging locations identified

The SWAT model was calibrated and validated using 1999-2002 gauge data (USGS 07049000). For the calibration of the Beaver SWAT model, three statistical measurements were included. We defined the multi-objective function as the optimization of the following three statistics for each of the identified variables (flow, sediment, TP, and $NO_3$-N plus $NO_2$-N).

SWAT model annual calibration was performed by minimizing the relative error (RE, %) at the gauge locations:

$$RE(\%) = \left| \frac{(O - P)}{O} \right| * 100 \tag{1}$$

where O was the measured value and P was the predicted output. The SWAT model was further calibrated on monthly time scale using the Nash-Sutcliff model efficiency ($R_{NS}^2$) defined as (Nash and Sutcliffe, 1970):

$$R_{NS}^{\ 2} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - O_{avg})^2} \tag{2}$$

where O was measured values, P was predicted outputs and i = number of values. Monthly coefficient of determination ($R^2$) was also calculated since $R_{NS}^2$ is sensitive to outliers (Kirsch et al., 2002). The $R^2$ was calculated as:

$$R^2 = \left( \frac{\sum_{i=1}^{n} (O_i - O_{avg})(P_i - P_{avg})}{\left[ \sum_{i=1}^{n} (O_i - O_{avg})^2 \sum_{i=1}^{n} (P_i - P_{avg})^2 \right]^{0.5}} \right)^2 \tag{3}$$

### *The CE-QUAL-W2 Model*

The W2 model is a two-dimensional, hydrodynamic, water quality, reservoir model developed by the USACE. Reservoir dimensions are described by segment width, layer height, and latitudinal length. A limitation to the model is that the governing equations are laterally and layer averaged. The W2 model's basic input data needs are geometric data, initial conditions, boundary conditions, hydraulic parameters, kinetic parameters, and calibration data (Cole and Wells, 2002).

In order to correctly simulate conditions at a particular reservoir, geometric data are input into the model through the bathymetry file. A previously developed bathymetry file for Beaver Reservoir was used in this study (Haggard and Green, 2002). The model extends downstream 80 km to the Beaver Dam. Reservoir bathymetry was designated with 1 waterbody, 6 branches, 61 layers, and 70 segments. Reservoir inflow was distributed on a drainage area basis into two major branches, War Eagle Creek and White River, and one tributary, Richland Creek. Four additional branches were modeled further down-reservoir (Figure 2). Other tributaries not included in the model were lumped to respective larger branches to account for their contribution to reservoir volumes.

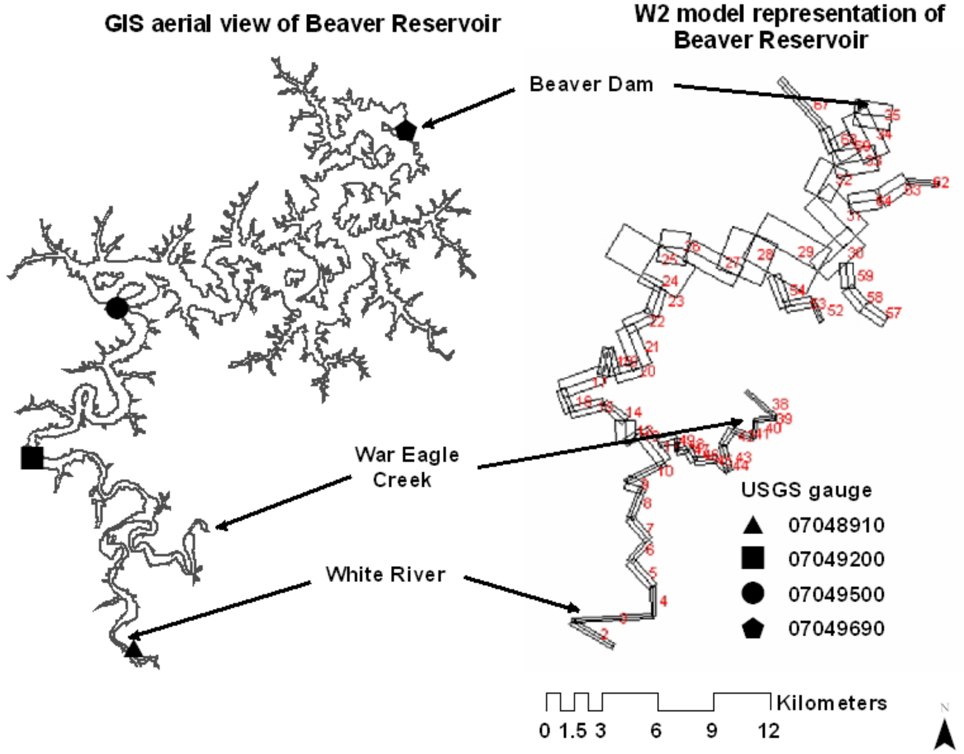


Figure 2. Beaver Reservoir presenting GIS overview and W2 model segmentation

To construct the water balance for the W2 model; withdrawals, dam release, and inflows were acquired for the study period (1999-2002). Water withdrawal data was obtained from the Arkansas Health Department (AHD) for the four municipal withdrawals, which include Beaver Water District, Carroll-Boone, Benton-Washington (or Two-Ton), and Madison County Regional. Release data for Beaver Dam was obtained from the USACE for 1999-2002. Tributary flows and main stem flow was estimated using USGS flow data and predicted flow values from the calibrated SWAT model. Constituent loads were also incorporated into the model from USGS data and SWAT model predictions. Meteorological data from the Bentonville, Arkansas, weather station was available on an hourly timestep and was input in the W2 model.

Water level calibration was conducted using the 'waterbalance' executable available with the W2 model. This executable reads in model predicted water level and measured water level, then the executable outputs a file with temporal flow values to accommodate for difference between the predicted and measured reservoir level. This flow output is then used as the indirect flow file or flow considered from nonpoint sources throughout the waterbody.

The W2 model was calibrated at 4 different reservoir USGS gauging locations for all data available between 1999 and 2002: Beaver Lake at Hwy 412 bridge near Sonora (07048910), Beaver Lake near Lowell (07049200), Beaver Lake at Hwy 12 (07049500), and Beaver Lake near Eureka Springs, AR (07049690) (Figure 2). The reservoir gauges include data on average, twice-monthly with values taken at different depths. The model was calibrated for temperature, DO, $NO_3$-N plus $NO_2$-N, and $PO_4$-P (when data were available). The objective function used to calibrate the W2 model was to minimize the average error for each of the four calibration locations for the identified output variables. Average error (AE) was calculated as:

$$AE = \frac{1}{n}\sum_{i=1}^{n}\left(\left|P_i - O_i\right|\right) \qquad (4)$$

### ***Model Linking and Scenario Analysis***

The purpose of linking the watershed and reservoir models was to predict changes in reservoir water quality resulting from different watershed management options. The calibrated SWAT watershed model and the calibrated W2 reservoir model were loosely linked so that output from the SWAT model became input for the W2 model. The SWAT model was used to determine daily flow volume and nutrient yields leaving the watershed and entering into Beaver Reservoir. The W2 model simulated the reservoir water quality response to the SWAT predicted nutrient yields entering the reservoir.

Watershed management scenarios were evaluated using the linked models. Scenarios included reductions in litter application rates, reductions in commercial fertilizer rates, and reduction in WWTP effluent P concentration. Two reservoir locations (or W2 modeled segments) were evaluated during scenario analysis: segment 16 and segment 35. Segment 16 corresponds to a drinking water withdrawal in the transitional zone of the reservoir, while segment 35 corresponds to Beaver Dam which is located in the lacustrian zone of the reservoir. Scenarios were evaluated by comparing $PO_4$-P and chlorophyll-*a* concentrations in the photic zone. The photic zones for segments 16 and 35 were calculated on a seasonal basis using transparency depths reported by USGS for their respective locations. Concentrations were averaged on a seasonal and annual basis. The three seasons were chosen to account for differences in stream flow and nutrient dynamics that occur throughout the year (Haggard et al., 2003). The three seasons were summer (or low flow), fall (low flow after leaf abscission), and winter-spring (high flow). Summer, fall, and winter-spring were considered by months as July through September, October through December, and January through June, respectively.

## Results and Discussion

The SWAT watershed model and the W2 reservoir model were successfully calibrated to achieve their objective functions. The calibrated models were then linked so that constituent concentrations in the reservoir were a result of nutrient yields predicted by the SWAT model. Chlorophyll-*a* and $PO_4$-P concentrations were compared between the transitional zone location (drinking water withdrawal, segment 16) and the lacustrian zone location (Beaver Dam, segment 35). Chlorophyll-*a* and $PO_4$-P concentrations were always greater at the transitional zone location than the lacustrian zone location, which is an expected reservoir water quality response (Haggard et al., 1999; Kennedy and Walker, 1990).

Evaluation of predicted chlorophyll-*a* concentrations and $PO_4$-P concentrations from scenarios evaluating reduction in commercial fertilizer and reduction in WWTP effluent P indicated generally less than 1% relative difference for both sites and for all seasons. This was likely a result of the minimal amount of P contributed to the watershed from these sources. Relative contributions of P from commercial fertilizer, WWTP effluent, and poultry litter in Beaver Reservoir Watershed were 16%, <1%, and 84%, respectively.

Scenarios that evaluated reduction in poultry litter application in the watershed did predict reduced chlorophyll-*a* and $PO_4$-P concentrations. The transitional zone location was predicting a substantial decline in $PO_4$-P concentrations with decreased poultry litter application for all seasons. However, winter-spring predictions showed the greatest response to decreases in poultry litter application in the watershed in the transitional zone. This is possible due to the increased runoff events and poultry litter application timing during the winter-spring season. However, chlorophyll-*a* concentrations did not show as substantial of a response at the transitional zone as $PO_4$-P concentrations with decrease in poultry litter application in the watershed. The smaller response observed in chlorophyll-*a* concentrations might be an indicator of the nutrient status of the transitional zone of the reservoir. This portion of the reservoir may not be as immediately impacted by reduced $PO_4$-P yields from watershed because of the concentration of $PO_4$-P already available in this zone. In addition, chlorophyll-*a* may not be limited by $PO_4$-P, but instead by light due to turbidity in the transitional zone (Thorton, 1990).

For the lacustrian site, small reductions in chlorophyll-*a* and $PO_4$-P concentrations were observed with increased reduction in poultry litter application in the watershed. However, these chlorophyll-*a* and $PO_4$-P reductions were less than those predicted in the transitional zone. This difference is expected partially because of the length of the reservoir, which promotes settling of suspended particles (sediment attached P) in the transitional zone. In addition, dissolved P that is present in the photic zone will continually be assimilated by biota as it is transported down-reservoir; this results in a decreasing trend in available dissolved P as water moves further down-reservoir. The ability of the combined models to predict reservoir water quality characteristics, such as these $PO_4$-P trends, validates the functionality of the linked-models in assessing impact of land management scenarios.

## Conclusion

Objective 1: The SWAT model was successfully used to estimate monthly flow and nutrient yields in the Beaver Reservoir Watershed.

Objective 2: The W2 model was successfully used to simulate daily water quality concentrations in Beaver Reservoir.

Objective 3: The SWAT model representing Beaver Reservoir Watershed and the W2 model simulating reservoir water quality were loosely linked so that output from the watershed model became input into the reservoir model.

Objective 4: Different watershed management scenarios were evaluated using the linked models to determine changes in chlorophyll-*a* and $PO_4$-P in the photic zone of the reservoir.

The loosely linked SWAT and W2 modeling scheme provides a holistic approach to looking at nutrient dynamics in a watershed-reservoir system. The linked models can be used to assess the probably influence different watershed management schemes will have on reservoir water quality concentration at targeted locations within the reservoir. This approach will assist watershed managers in protecting reservoir drinking water supplies.

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