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Modeling Water Quality in Rivers using the Branched Lagrangian Transport Model (BLTM)

by Harvey E. Jobson

The Branched Lagrangian Transport Model (BLTM) was developed by the U.S. Geological Survey (USGS) to simulate the unsteady movement, dispersion, and chemical reactions for any number of dissolved constituents moving through a system of one-dimensional channels (Jobson and Schoellhamer, 1987; Jobson, 1997). The model is applicable for rivers and well-mixed estuaries that can be approximated as a series of interconnected one-dimensional channels.

The BLTM solves the advective dispersion equation by using a Lagrangian reference frame in which the computational nodes move with the flow. This solution scheme minimizes numerical dispersion, which makes the model ideally suited for situations that contain steep concentration gradients and highly variable flow, such as occurs in estuaries (California Water Resources Control Board, 1996).

BLTM simulates transport using a series of line segments, called branches, connected by junctions. An example of a three-branch system is shown on figure 1. Any number of branches may be connected at a junction and flow can occur in either direction. Each branch is subdivided into reaches by nodes, and a branch must have at least two nodes, one at each end. Interior nodes identify the locations where withdrawals or additions to the flow are made and delineate locations where the channel properties, such as slope, width, area, or dispersion characteristics change. Channel properties, as well as chemical reaction coefficients, are assumed to remain constant within a reach between nodes.

Flow hydraulics for each node and time step of the model are supplied by a flow model. For estuaries, or low gradient streams, a fully dynamic model such as the BRANCH model (Weiss and others, 1994) or the Full Equations (FEQ) model (Ishii and Turner, 1996) is used. For steeper upland streams, a much simpler flow model, the Diffusion Analogy FLOW (DAFLOW) model (Jobson, 1989), is appropriate. As a general rule, the DAFLOW model provides an acceptable solution for a 1-hour time step as long as the slope is at least 1.5 ft/mile. By using a 12-hour time step, a slope of 0.1 ft/mile can be simulated.

Data Requirements

At least two general input data types are required by BLTM. First, the hydraulic information–discharge, cross-sectional area, top width, and tributary flow–are needed at each node and time step, as well as the boundary conditions that include the concentration of each constituent at each point of inflow for each time step. Second, general model and geometric information are needed, such as the number of branches, the connecting junctions, and between each set of nodes the distance, dispersion coefficient, and initial concentration of each constituent. If other than simple first-order decay is to be simulated, then additional input is needed, such as the kinetic rate coefficients or a time series of meteorological or other variables used to compute the rate coefficients.

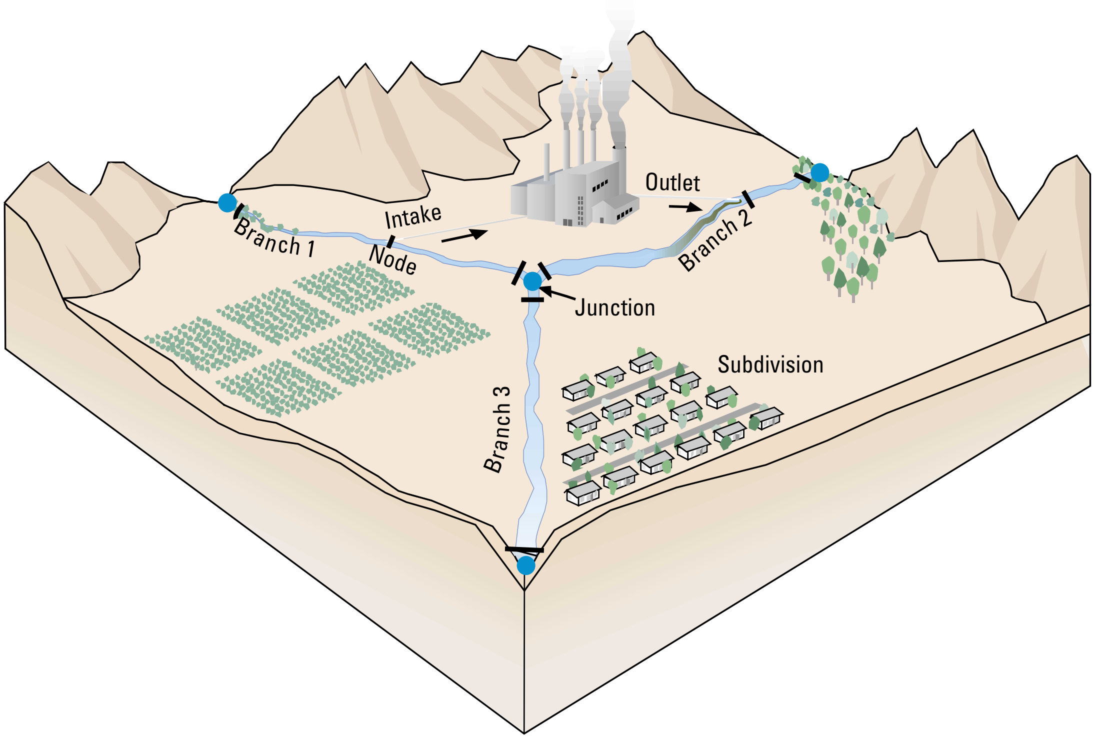


Figure 1. Example schematic of a three branch water-quality model with four junctions, one intake, and one wastewater outlet.

The BLTM transport model can be used for a wide variety of applications. The following examples demonstrate the model capabilities for simulating constituent transport and in-stream reactions.

Extent of the Dissolved Oxygen Sag as Affected by Macrophytes

Sand Creek is an ephemeral tributary of Caddo Creek in Oklahoma and drains 13.3 square miles. It receives wastewater discharges about 5.5 miles upstream from its mouth. Flow in Sand Creek is maintained in the summer by discharge from a petroleum refinery, by treated wastewater from the city of Ardmore, Oklahoma, and by some ground-water seepage. The Oklahoma Water Resources Board recently upgraded the beneficial-use designation of Sand Creek to warm water aquatic community and primary body contact recreation. Because the new use designation requires that aquatic life be protected, it was necessary to quantify the extent of the dissolved-oxygen sag (deficit below saturation) downstream of the treatment facilities before the waste load allocation could be made (Wesolowski, 1999).

A verified model of dissolved oxygen was used to determine how present and future treated-wastewater discharges affect the dissolved-oxygen sag in the unsteady flow of Sand and Caddo Creeks. For these streams, the dissolved-oxygen concentration is strongly influenced by varying densities of submerged macrophytes that are rooted in the bed of the stream. The growth rate of the macrophytes is influenced by the availability of nutrients, as well as by shading from trees that line the stream banks. Because the user can easily modify the kinetics of the BLTM model, the reaction kinetics of the water-quality model (QUAL2E) (Brown and Barnwell, 1987) were modified to simulate the effects of macrophytes and to allow the shading to vary with location (Wesolowski, 1999).

As shown in figure 2, the BLTM model is capable of simulating the observed dissolved-oxygen concentrations at four sites along a 12-mile reach of the two streams. During the study, the discharge varied from about 5 to 10 cubic feet per second (cfs) in Sand Creek and 8 to 20 cfs in Caddo Creek. The saturated value of dissolved oxygen (dashed curve on figure 2) varied with temperature. Dissolved-oxygen concentrations above saturation are the result of photosynthesis by algae and macrophytes. Generally, the density of macrophytes on the streambed defines the maximum dissolved-oxygen concentration, and the reaeration coefficient defines the minimum concentration. Bank shading controls the shape of the diurnal pattern. For example, the diurnal maximum is more peaked in the narrow shaded Sand Creek than in the wider less-shaded Caddo Creek (figure 2). For the loading imposed during the data collection, the minimum dissolved oxygen rebounds from 2.0 milligram per liter (mg/L) just downstream of the effluent pipe, to above the 4.0 mg/L limit before the water enters Caddo Creek.

After the model was calibrated and verified, it was used by the city of Ardmore, Oklahoma, to analyze the effects of discharging treated wastewater into Sand Creek under varying conditions. By using various flows, numerous simulations were conducted for different effluent discharges and concentrations of ammonia, ultimate carbonaceous biochemical oxygen demand and dissolved oxygen. The optimal strategy for effluent discharge was then selected on the basis of the recovery of dissolved oxygen in Sand Creek.

Calibration of Transport Speed in Estuaries

The temporal variations in salinity were used to calibrate transport speed and dispersion in the Cooper and Wando Rivers of South Carolina (Conrads and Smith, 1996). A schematic of the river system that was simulated by using 37 branches is

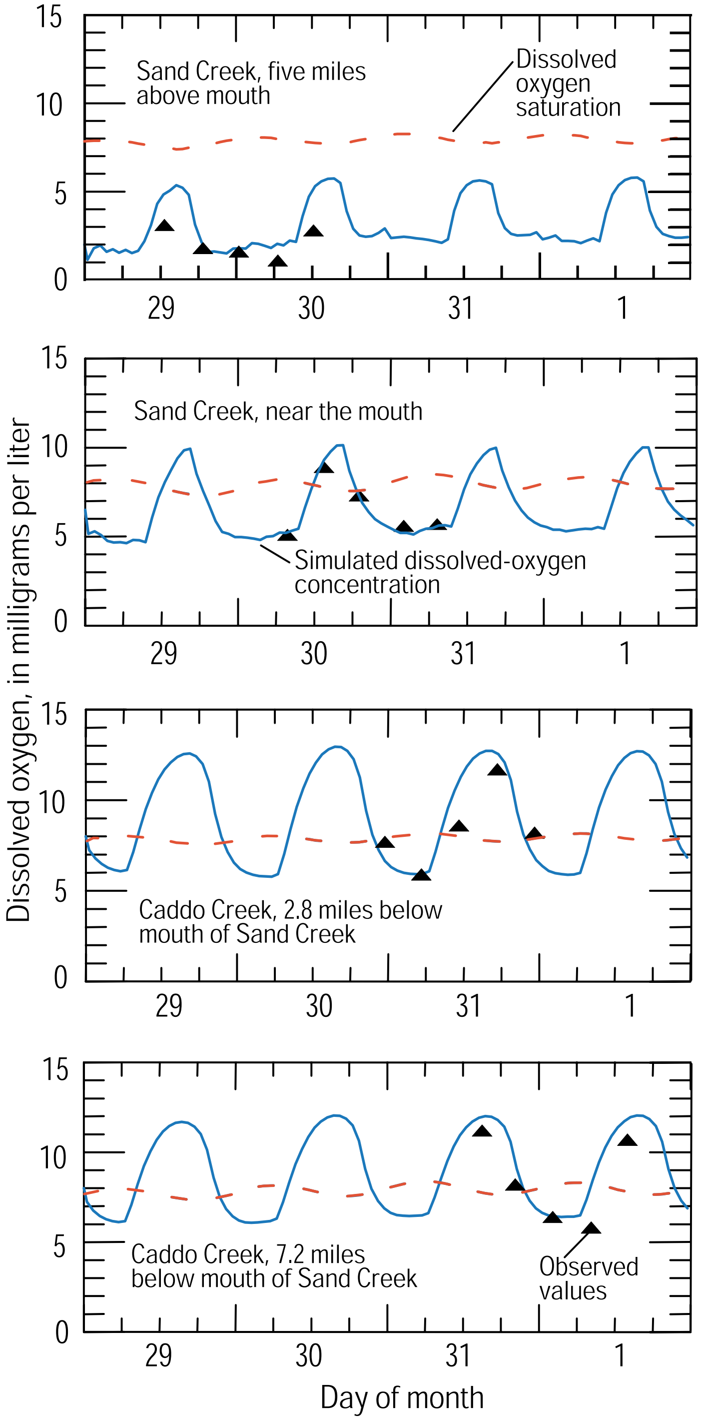
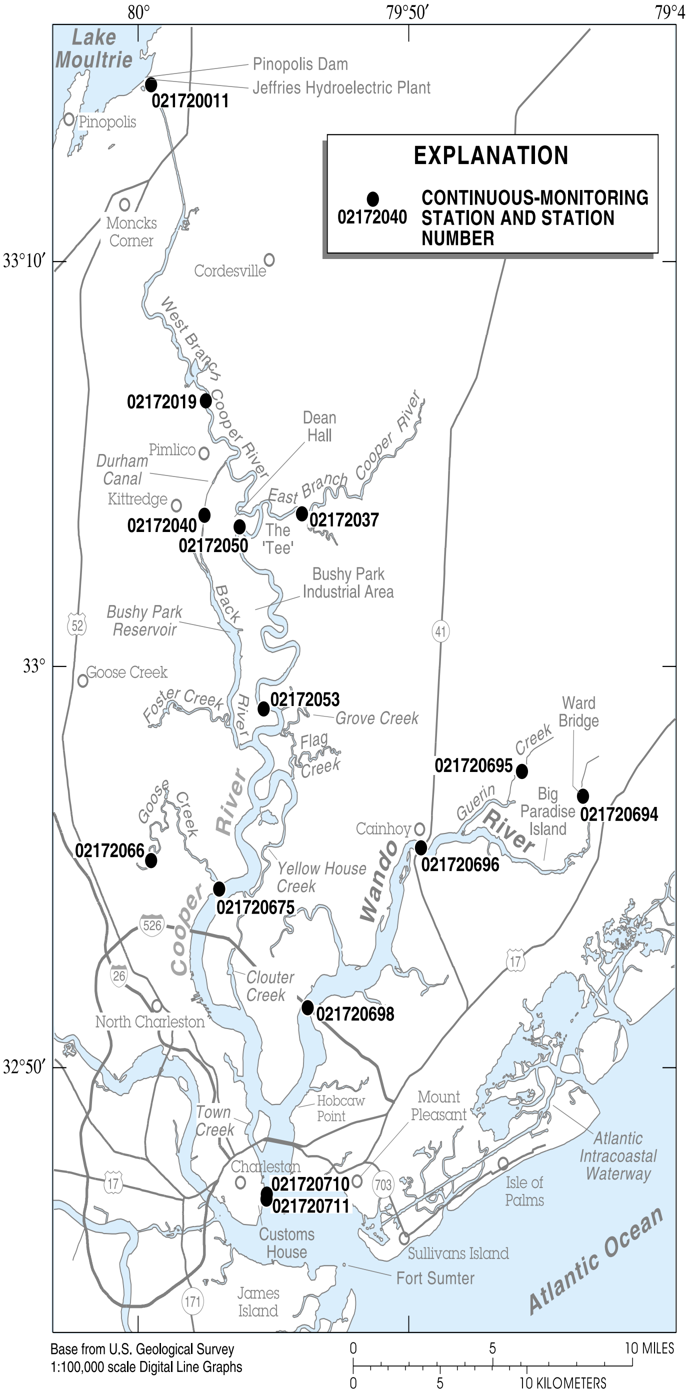


Figure 2. Dissolved-oxygen concentrations in Sand and Caddo Creeks, Oklahoma, July 29-August 1, 1997.

shown in figure 3. The upstream boundary for the Cooper River was the Lake Moultrie tailrace at Pinopolis Dam, and the downstream boundary, in Charleston Harbor, was near the Customs House. The BLTM model was selected over other one-dimensional models because of its accuracy in simulating the temporal variations of salinity. As shown on figure 4, the average salinity in the Cooper River decreases in the upstream direction from about 25 parts per thousand (ppt) at the Customs House (Station 021720710) to less that 2 ppt near Station 02172053. The mean salinity at any point, like the travel time of water particles, is strongly influenced by the volume of water stored in the channel.



Base from U.S. Geological Survey
1:100,000 scale Digital Line Graphs

Figure 3. Location of continuous-monitoring stations on the Cooper and Wando Rivers and their tributaries, South Carolina (from Conrads and Smith, 1996).

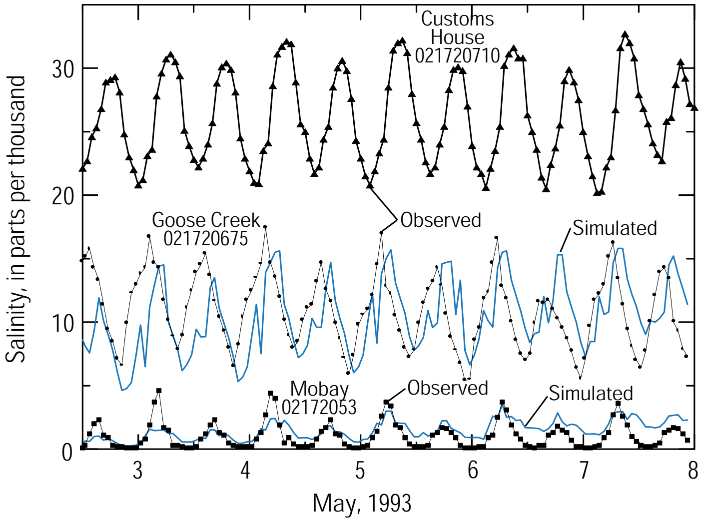


Figure 4. Verification of the hydraulic and mixing components of BLTM in the Cooper River by using salinity as a tracer.

After the hydraulics and mixing components of the model were calibrated, the water-quality constituents were simulated by use of a modified form of the Environmental Protection Agency (EPA) QUAL2E model (Brown and Barnwell, 1987). Longitudinal profiles of the simulated 24-hour minimum dissolved-oxygen concentration as a function of distance upstream (Conrads and Smith, 1997, p. 48) are shown in figure 5. Three loading conditions are shown; no effluent loading to the system (background conditions), fully permitted loading, and the loads as occurred on August 27, 1993.

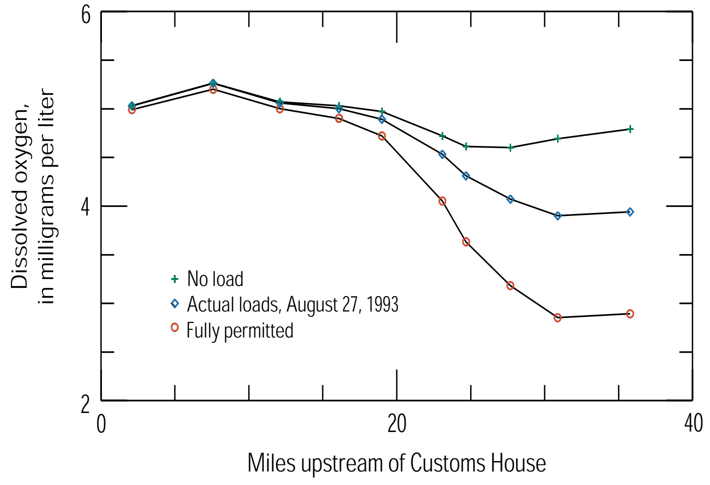


Figure 5. Longitudinal profiles of the 24-hour minimum dissolved-oxygen concentrations for three point-source loading conditions on the Cooper River, South Carolina.

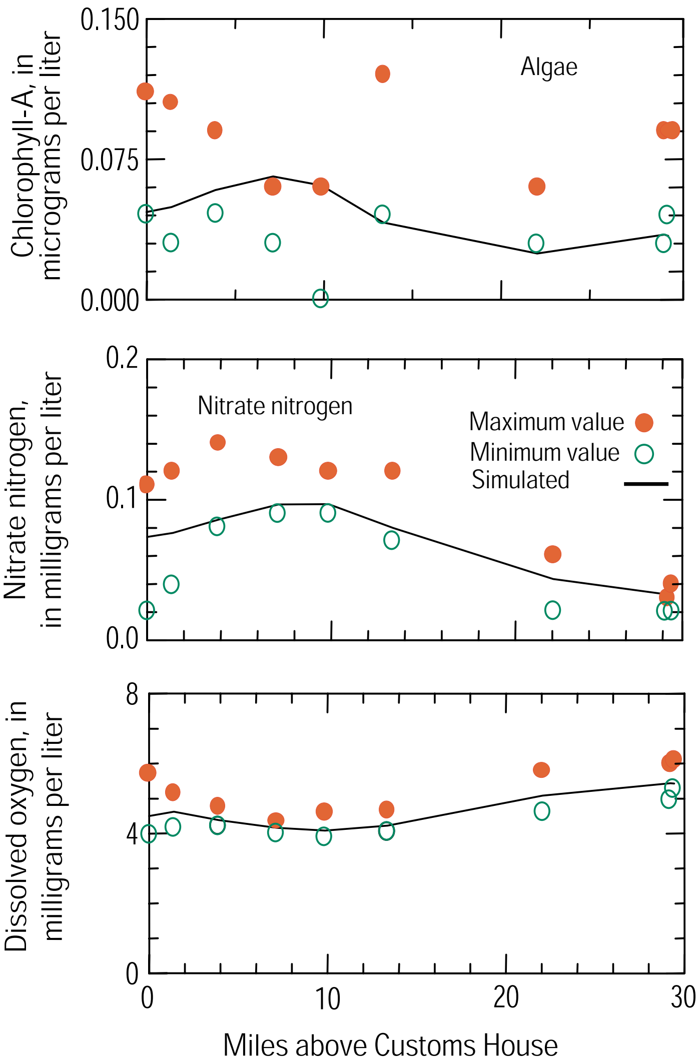


Figure 6. Simulated, and observed concentrations in the Cooper River.

Figure 6 shows the computed longitudinal distribution of the mean concentration of Chlorophyll-A, nitrate, and dissolved oxygen, as well as the maximum and minimum observed values (Conrads and Smith, 1997, p. 30). Figures like 5 and 6 are useful in the permitting process.

Point-source Reductions in Fecal Coliform Bacteria

The Cuyahoga River flows through a national park in Ohio and is affected by high bacteria levels following runoff. To evaluate actions needed to maintain acceptable water quality for body-contact recreation, Myers and others (1998) used the BLTM model to evaluate the effects of point-source reductions on the bacteria concentrations in the river. Once the model was calibrated for travel time and mixing, the bacteria decay rate was the only unknown model parameter. By use of field experimental data, bacterial decay rates were determined to be 0.0195 per hour, as shown by the slope of the straight line in figure 7.

The BLTM model was verified by a comparison of the simulated and observed fecal coliform concentrations in the Cuyahoga River at Botzum, Jaite, and Independence, Ohio during a 40-hour monitoring period starting September 2, 1993. Finally, the reduction in bacteria count in the river that would result from reducing the bacteria count in point discharges was evaluated. As can be seen from figure 8, even a 90-percent reduction in the concentration of fecal coliform bacteria in the effluent of the Akron waste-treatment plant will not reduce the concentration in the river below the standard for secondary contact recreation. This indicates that, either other point sources, such as combined-sewer overflows, or non-point sources, such as urban runoff, contribute a major part of the bacteria found in the river.

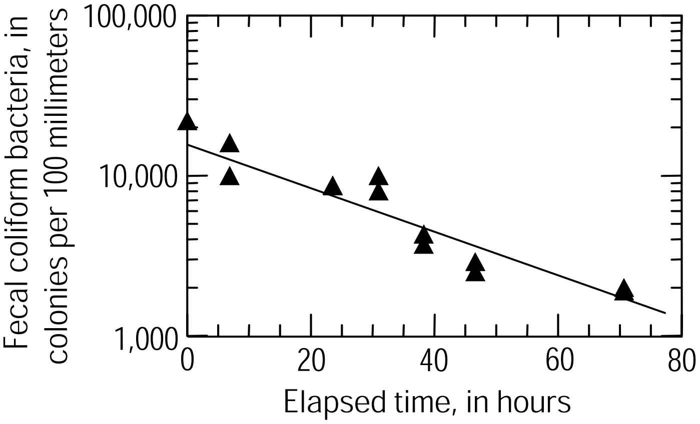


Figure 7. Decay rate of fecal coliform bacteria in water samples collected from the Cuyahoga River at Peninsula, Ohio, June 1992.

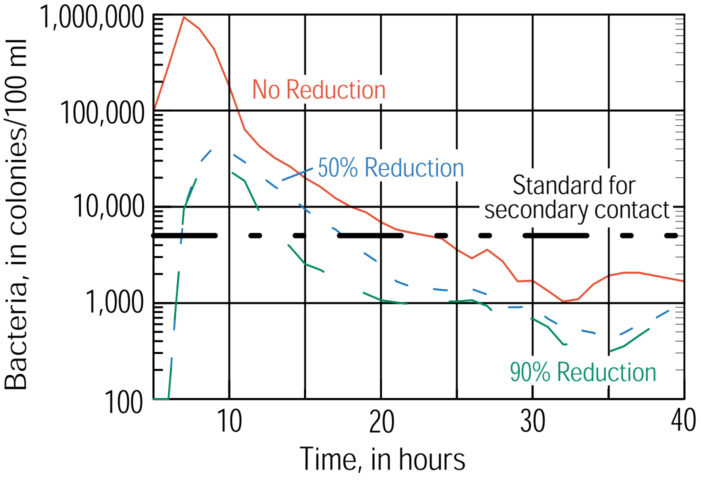


Figure 8. Predicted fecal coliform bacteria counts in the Cuyahoga River at Botzum that result from reductions in bacteria counts of the waste effluent from the Akron wastewater treatment plant.

Transport of Pesticides in Large Rivers

Understanding the transport of synthetic organic compounds in the Mississippi River Basin is essential for the wise management of natural resources in our nation's largest watershed. The Mississippi River drains about 40 percent of the continental United States. Our understanding of how to manage land use can be improved by integrating the analyses of data from stream gaging and water-quality sampling within a water-quality model. In an attempt to address the problem of low dissolved oxygen in the Gulf of Mexico, the DAFLOW/BLTM models were used to simulate transport of pesticides and nitrate in the Mississippi River below Thebes, Illinois (Broshears, and others, 2000), figure 9.

Daily mean streamflow data were assembled from the records of the USGS and the U.S. Army Corps of Engineers. Discharges of each tributary were obtained from USGS streamflow records at the most downstream gaging site. These discharges were increased by a constant factor to account for ungaged inflow.

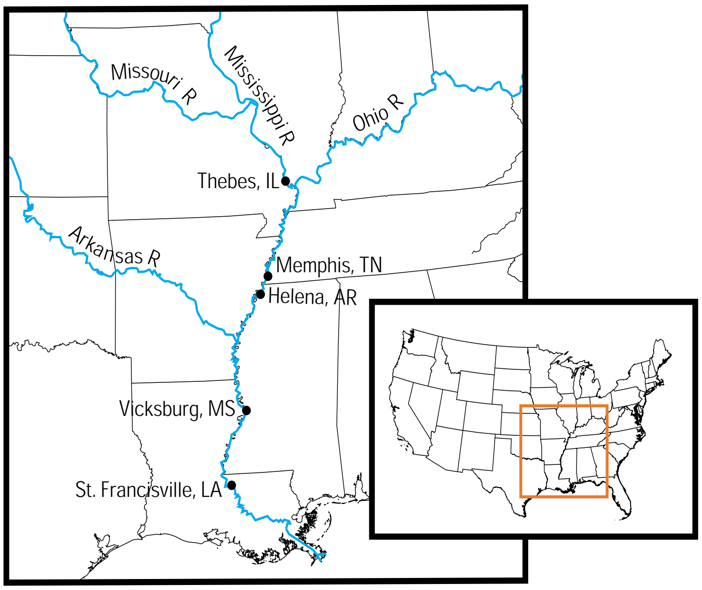


Figure 9. The Mississippi River and major tributaries.

Hydraulic coefficients for DAFLOW were calibrated to provide an optimum fit between simulated and observed discharges for the 1996 water year at gaging stations along the mainstem (Helena, Arkansas, Memphis, Tennessee, Vicksburg, Mississippi, and St. Francisville, Louisiana, figure 9). Discharge was simulated for water years 1992-94; this period included a major flood in the upper Mississippi and Missouri Basins in 1993. A comparison of simulated and observed discharges at St. Francsisville, Louisiana (figure 10) indicates that the range of transport velocities predicted by the models was similar to the observed water velocities (Moody, 1993; Moody and Goolsby, 1993).

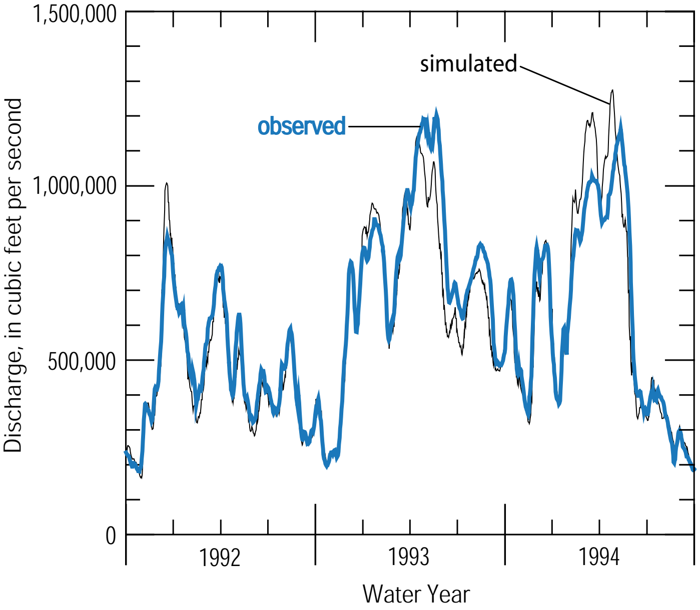


Figure 10. Observed and simulated flow in the Mississippi River at St. Francisville, Louisiana.

The BLTM model was used to simulate the conservative transport of atrazine, metolachlor, and nitrate below Thebes, Illinois (fig. 9). The simulated and observed concentrations of atrazine at St. Francisville are shown on figure 11 and indicate that arrival and departure times for seasonal pulses in atrazine generally are well depicted. Most apparent discrepancies between simulated and observed values can be explained by the difficulty in defining peak concentrations of individual pulses with a weekly sampling interval.

The transport model is being used to track sources of contaminants in the basin and to investigate their behavior and fate within the drainage network. The model also is being used to evaluate the potential efficacy of programs to reduce loadings of nutrients and pesticides throughout the basin.

To determine where land-use changes would be most effective in improving the quality of the water delivered to the Gulf of Mexico, it would be helpful to know the percentage of the flow in the lower Mississippi River that originates from each major upstream basin. As shown in figure 12, a transport model provides an effective tool in determining this percentage.

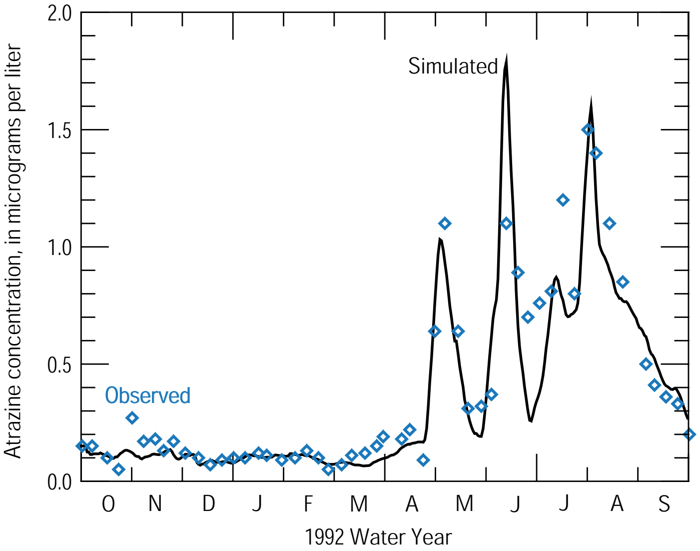


Figure 11. Observed and simulated atrazine concentrations in the Mississippi River at St. Francisville, Louisiana.

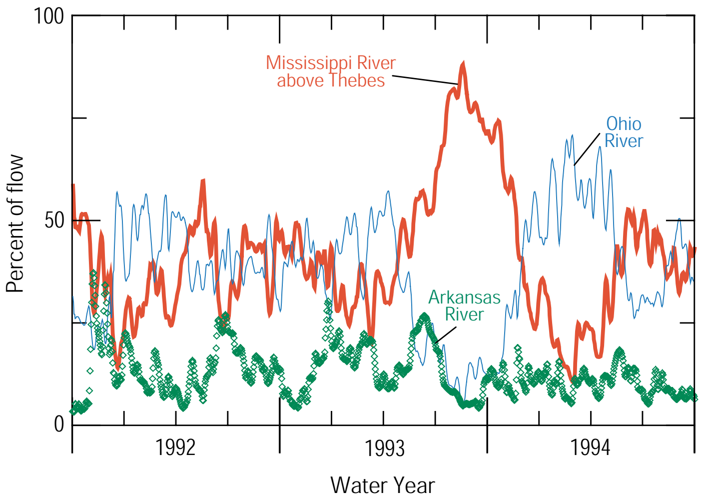


Figure 12. Percentage of the total flow in the Mississippi River at St. Francisville, Louisiana, that originates from major upstream river basins.

During most of the 3-year period shown in figure 12, about one-half of the flow in the Mississippi River at St. Francisville is contributed by the Ohio River. The major flooding in the upper Mississippi and Missouri River Basins during 1993 caused these areas to contribute a maximum of 88 percent of the flow. In early 1994, flooding of the Ohio River caused that river to provide up to 70 percent of the total discharge at St. Francisville. Generally, the Arkansas River provides a relatively minor contribution. In early 1992, however, it contributed as much as 37 percent of the total flow at St. Francisville.

Summary

The BLTM transport model has been used for the analysis of many different water-quality constituents in rivers with a wide range of sizes. The model can be used to identify major contaminant source areas, travel times, and mass loading, and to simulate the effects of water-resource management actions.

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