Scale−Dependent Behavior and Modeling of Nitrogen Retention in Streams

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Publication

1. Deng, Z.−Q. and Jung, H.−S. (2008). “Variable Residence Time Based Model for Solute Transport in Streams: Part I. Model Development.” Water Resources Research (in review).
2. Deng, Z.−Q. and Jung, H.−S. (2008). “Variable Residence Time Based Model for Solute Transport in Streams: Part II. Model Application.” Water Resources Research (in review).
3. Deng, Z.−Q. and Jung, H.−S. (2008). “Scaling Dispersion Model for Pollutant Transport in Rivers.” Environmental Modelling and Software (in review).

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RESEARCH

Problem and Research Objectives

Streams play an important role in retaining and removing nutrients during passage through a stream network. A modeling tool for predicting nitrogen retention and uptake in streams is needed to understand how nitrogen loading from watersheds can be reduced in an efficient and cost-effective way. Although extensive investigations into in-stream nitrogen retention have been conducted, there are few mathematical models which are capable of reproducing nutrient attenuation process in natural streams without resorting to field tracer tests. The primary difficulty of developing such a model lies in the scale-dependent behavior of nutrient removal process in streams.

The overall goal of this project is to develop an efficient and effective mathematical model for predicting scale-dependent nitrogen retention and uptake in natural streams. Specific objectives of this project are therefore (1) to develop a mathematical model (VART) for predicting nitrogen transport and fate in river systems with transient storage zones, (2) to determine parameters involved in the model, (3) to test the model using conservative tracer (Rhodamine WT dye) experiment data and measured nitrogen concentration data, and (4) to apply the VART model to the Amite River, Louisiana.

Methodology

The control volume approach is employed in combination with mass conservation principle for the development of the VART model. In order to include the scale effect on solute transport, two types of transient storage zones, an advection-dominated transient storage zone in upper/shallow sediment layer and a diffusion-dominated transient storage zone (A_{dif}) in lower/deep sediment layer, are introduced in the VART model. The area A_{dif} is scale-dependent and calculable using the equation derived in the new model. The longitudinal dispersion coefficient involved in the VART model is determined using a modified version of the PI's method published in ASCE *Journal of Hydraulic Engineering* (Volume 127(11)). To estimate nitrogen removal in the Amite River hydrological, hydrometeorological, and water quality data for the Amite River were collected from various sources. Daily discharges at Darlington and Denham Springs for the periods of 1980 - 1990 were obtained from U.S. Geological Survey (http://la.water.usgs.gov/). Water quality data were gathered from the Louisiana Department of Environmental Quality. The water quality data included monthly average water temperature and monthly mean concentrations of total Kjeldahl nitrogen (TKN), nitrate-nitrogen (NO_3), dissolved oxygen (DO), and total organic carbon (TOC). The water quality data covered the period of 1980 - 1990 and were measured at the three stations Darlington, Grangeville, and Magnolia along the Amite River, as shown in Figure 1. It should be pointed out that the water quality data were obtained by taking water samples on a monthly basis or taking one sample per month. Therefore, the so called monthly mean concentrations are actually the measurements at the instant when the water samples were taken. In order to find more reasonable monthly mean concentration values for the water quality parameters, HSPF model was used to

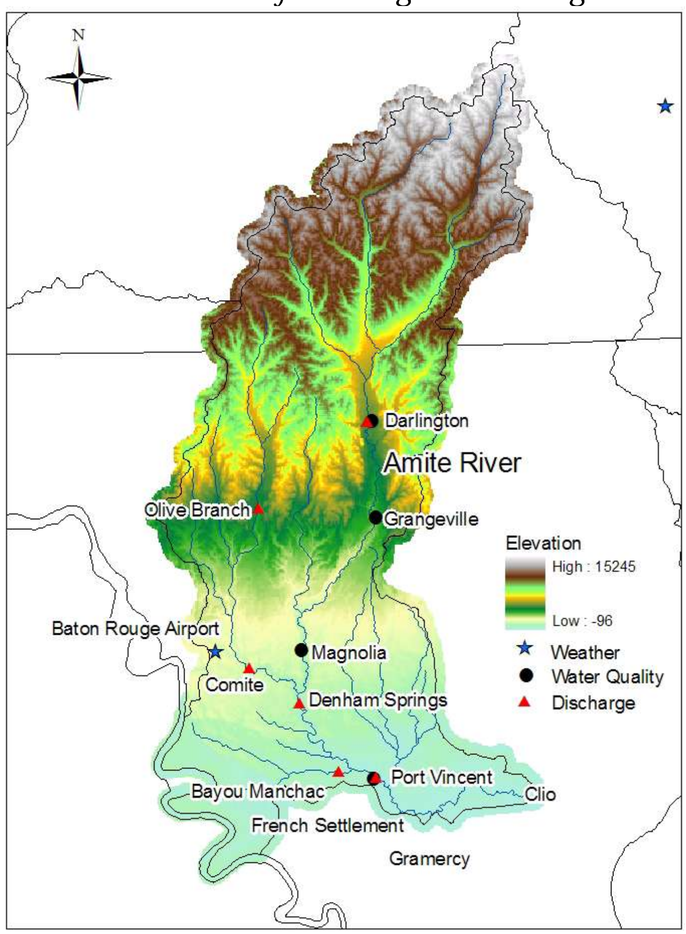


Figure 1. Map of the Amite River watershed.

generate more detailed water quality data for determination of the nitrogen removal rate involved in the VART model.

The HSPF Model, Hydrologic Simulation Program Fortran, is a U.S. EPA program for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. The HSPF modeling domain is the Amite River watershed including Darlington, Grangeville, and Magnolia stations. Application of HSPF involves the segmentation of the Amite River watershed, preparation of input data, and model calibration. The sub-watersheds were generated using the delineation tool in BASINS. Sub-watershed delineation and creation of river-reach segments utilized the NED (national elevation dataset) digital elevation model (DEM) for computing watershed boundaries, overland flow-path length and slopes, and stream segment slopes. The national land cover data (NLCD) representing land use type in 1992 was used for the determination of pervious and impervious surface areas and forested areas in each delineated sub-watershed, as shown in Figure 2.

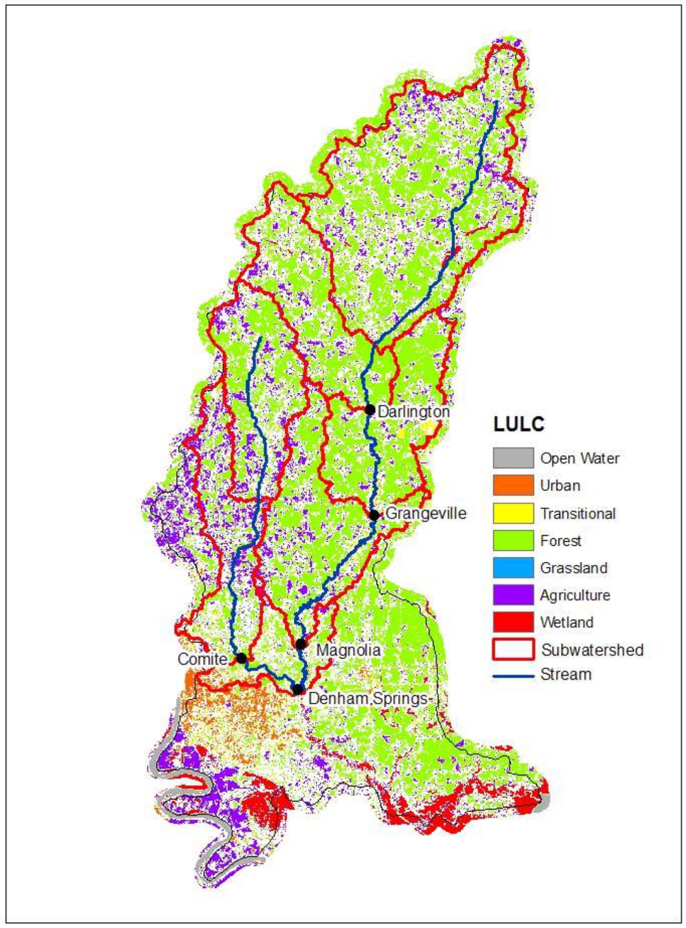


Figure 2. Land use and land cover data and sub-watersheds used in HSPF model

PRINCIPAL FINDINGS AND SIGNIFICANCE

1. Development of VART (Variable Residence Time-based) Model.

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = K_S \frac{\partial^2 C}{\partial x^2} + \frac{A_{adv} + A_{dif}}{A}\frac{1}{T_V}(C_S - C) - kC \quad (1a)$$

$$\frac{\partial C_S}{\partial t} = \frac{1}{T_V}(C - C_S) - kC_S \quad (1b)$$

$$A_{dif} = 4\pi D_S t_S \quad (1c)$$

$$T_V = \begin{cases} T_{\min} & \text{for} \quad t \le T_{\min} \\ t & \text{for} \quad t \ge T_{\min} \end{cases} \quad (T_{min} \ge 0) \quad (1d)$$

$$t_S = \begin{cases} 0 & \text{for} \quad t \le T_{\min} \\ t - T_{\min} & \text{for} \quad t \ge T_{\min} \end{cases} \quad (1e)$$

where C denotes solute concentration; U refers to cross-sectionally averaged flow velocity in x direction; t stands for time; C_S = solute concentration in storage zones; K_S = longitudinal Fickian dispersion coefficient excluding the transient storage effect; k is the first-order decay coefficient for non-conservative solute (NO_3 removal rate in this application); D_S is the effective diffusion coefficient for solute within the sediment/hyporheic zone; and T_V is the actual varying residence time of solute. The parameter T_{min} is the minimum net residence time at which solute starts releasing from the transient storage zone. Due to the adoption of the actual residence time, T_V, there is no need to assume a power-law or exponential or lognormal residence time distribution (RTD), avoiding the use of user-specified RTDs. This is an essential advantage of the VART model over the models requiring user-specified RTDs. The second term on the right hand side of Eq. (1) represents the combined effect of the advection, dominated in the upper bed sediment layer, and the diffusion, dominated in the lower bed sediment layer, on mass exchange between the surface stream flow and subsurface hyporheic flow. The VART model reduces to the widely used transient storage model (TSM) if A_{dif} = 0 and T_V = a constant. The VART model was tested using 181 data sets of tracer experiments conducted on 51 river reaches by USGS. Figure 2 shows comparisons between tracer concentration breakthrough curves simulated using the VART model and observed in a natural stream. The VART model was also compared with three other representative models (TSM, Advective-Storage-Path, and STAMMT-L). Results of the testing and comparisons show that the VART model is a simple yet effective tool for predicting solute dispersion and transport in natural streams and rivers.

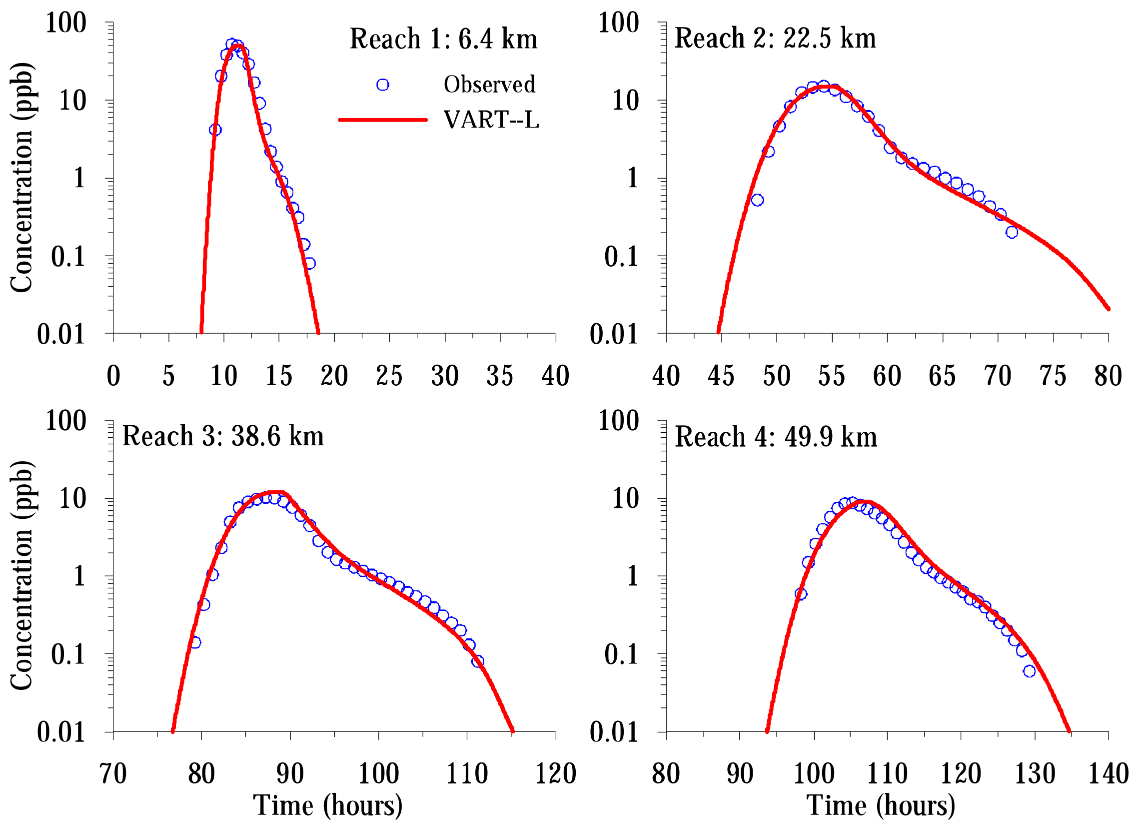


Figure 3. RWT concentration breakthrough curves observed on October 8, 1968 in four sampling reaches in series along the Tickfau River, Louisiana and simulated using the VART model for an instantaneous dye addition.

2. Equation for Estimation of Longitudinal Dispersion Coefficient Ks:

$$\frac{K_S}{Hu_*} = \frac{0.04}{8\varepsilon_{t0}}\left(\frac{B}{H}\right)^{5/3}\left(\frac{U}{u_*}\right)^2 \quad \text{or} \quad \frac{K_S}{Hu_*} = \frac{0.005}{\varepsilon_{t0}}\left(\frac{B}{H}\right)^{5/3}\left(\frac{U}{u_*}\right)^2 \tag{2}$$

where u_* = shear velocity, ε_{t0} = transverse mixing coefficient, B = surface width of flow, H = cross-sectionally averaged flow depth. The parameter Ks is involved in the VART model.

3. Method for Determination of Nitrate-Nitrogen Removal Rate *k*:

$$k = 0.14\ln(T_W) - 0.28 \qquad (R^2 = 0.82) \tag{3}$$

where T_W is water temperature. The equation is established based on monthly mean nitrate-nitrogen concentration data and monthly mean water temperature data measured at Darlington, Grangeville, and Magnolia.

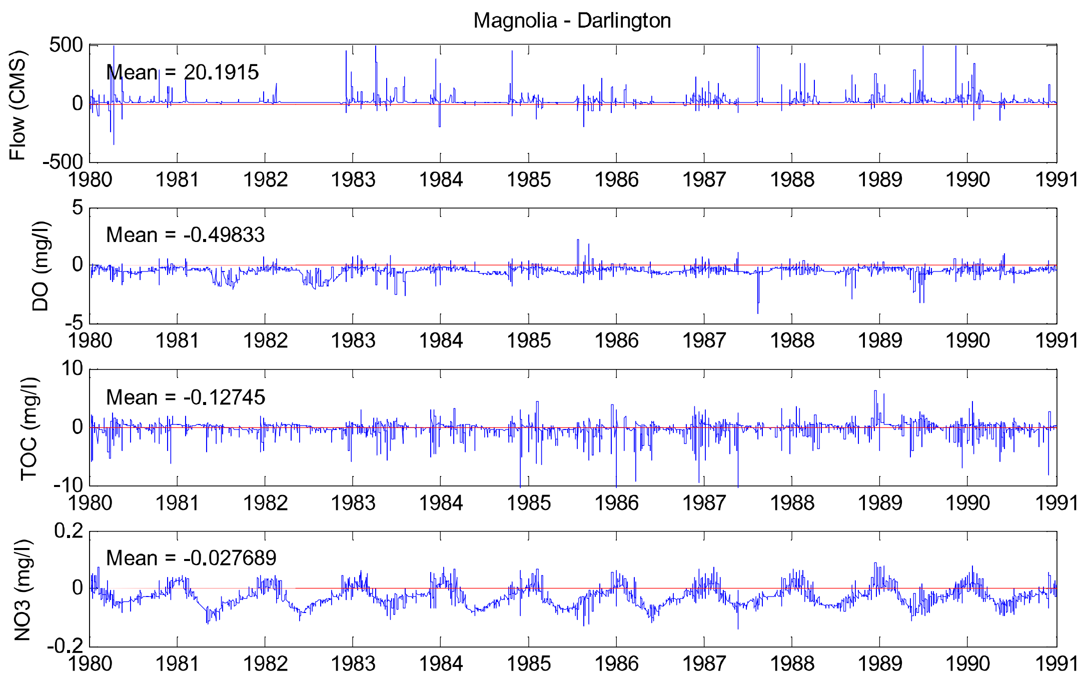


Figure 4. Changes (concentration value at Magnolia - concentration value at Darlington) in flow and water quality parameters (determined using HSPF model) along the Amite River.

Both Eq. (3) and Figure 4 indicate that NO_3 removal is highly temperature-dependent. The highest NO_3 removal occurs in summer and NO_3 removal in winter is negligible. Eq. (3) is the first kinetics equation for description of denitrification in the Amite River watershed. Equation (3) in combination with the VART model provides a useful tool for estimation of seasonal variations in TMDLs and for BMP implementation.

4. Simulated and Measured Variations in Water Temperature and Concentrations of Water Quality Parameters at Darlington and Magnolia:

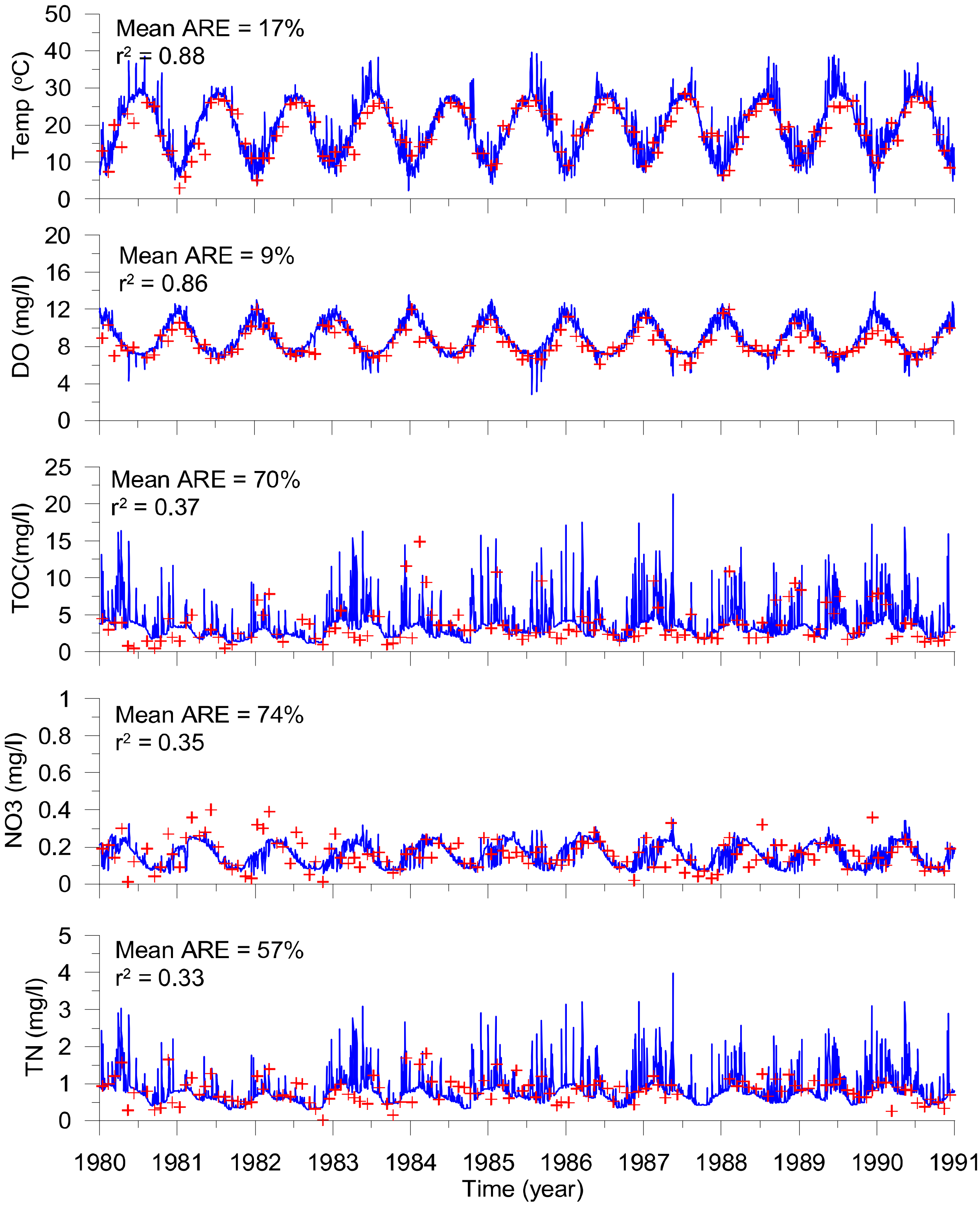


Figure 5a. Seasonal and annual variations in water quality parameters at Darlington.

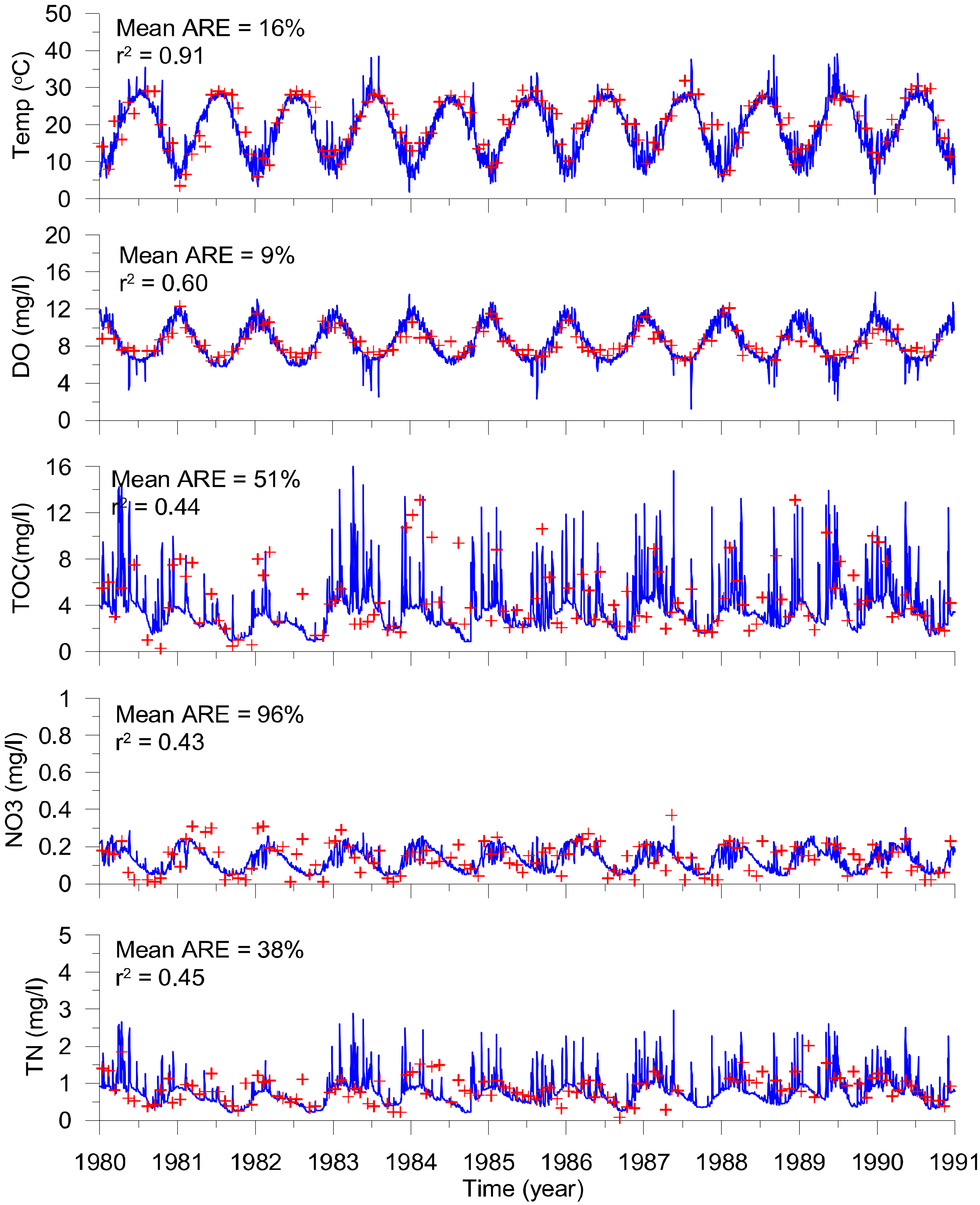
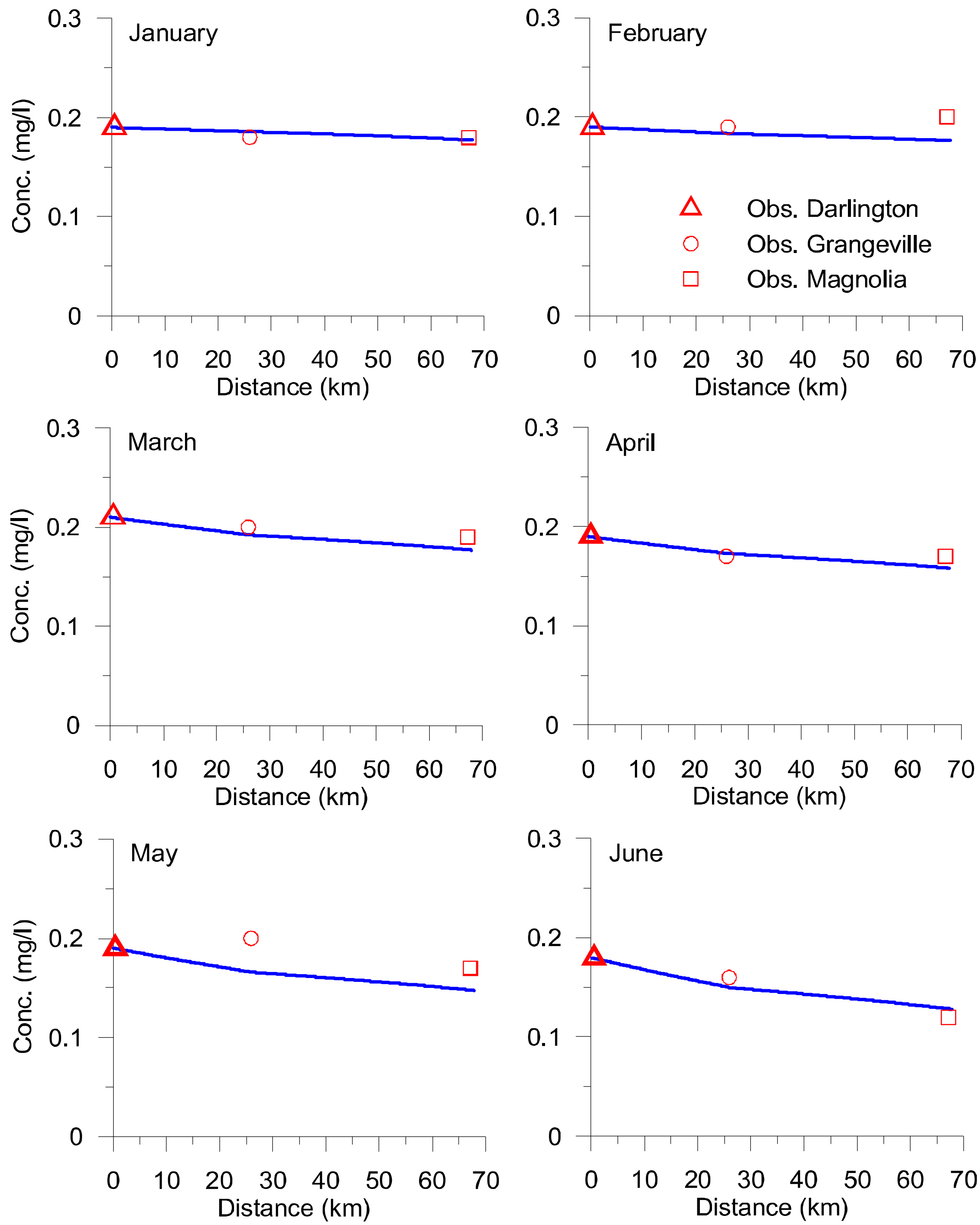


Figure 5b. Seasonal and annual variations in water quality parameters at Magnolia.

The results shown in Figures 5a and 5b were used in the determination of the nitrate-nitrogen removal rate *k*.

5. **Spatial (Longitudinal) and Temporal (Seasonal) Variations in NO_3 Concentration in the Amite River.**



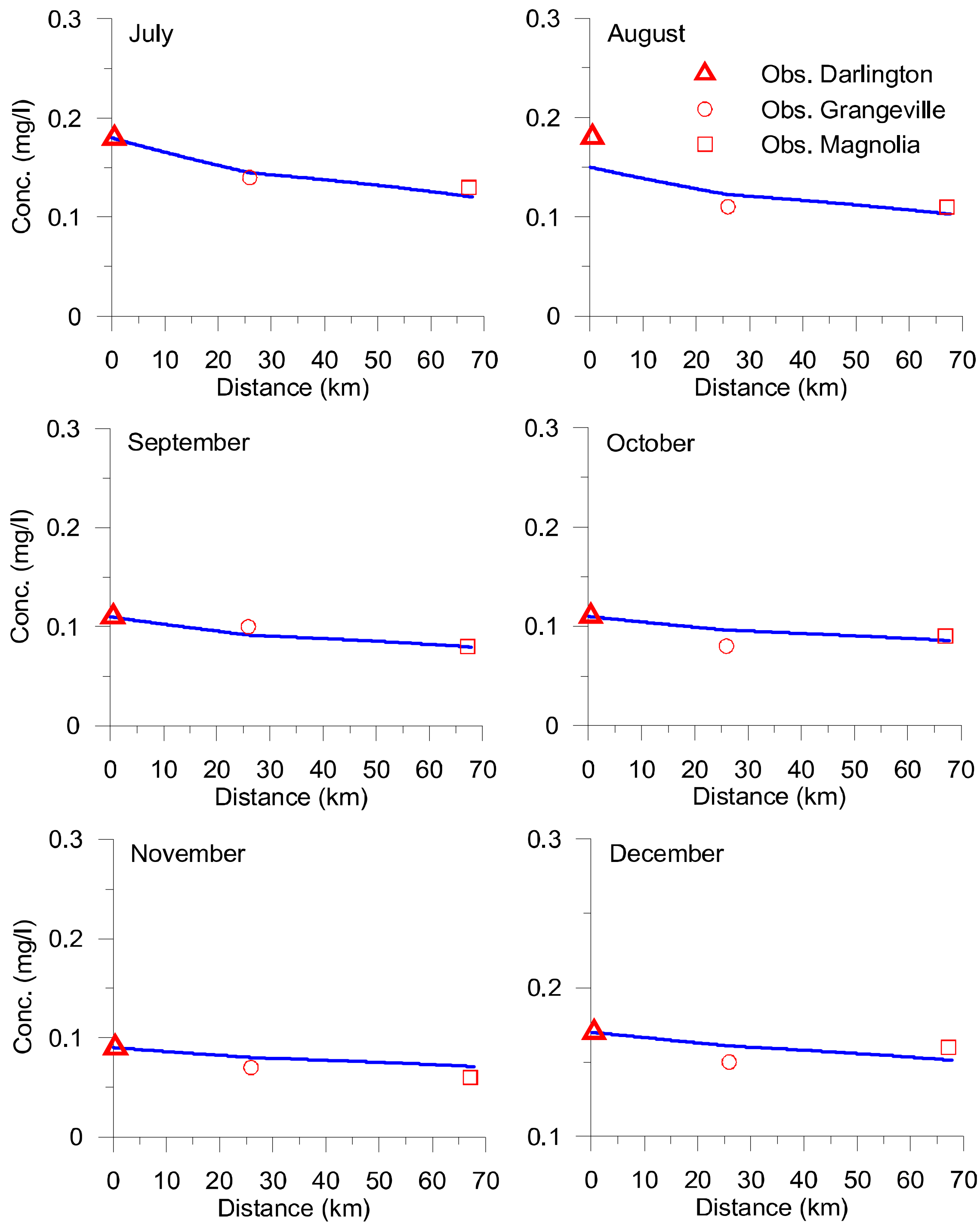


Figure 6. Monthly mean nitrate-nitrogen (NO_3) concentrations predicted using the VART model and measured at Darlington, Grangeville, and Magnolia along the Amite River. The vertical coordinate represents NO_3 concentrations and the horizontal axis denotes the longitudinal distance from Darlington.

This finding will provide useful data for establishment of water quality standard for nitrogen and for watershed restoration.