Modeling Sediment-Controlled TMDLs for the Branched and Braided Networks of Waterways in Louisiana: Model Development and Application to the Amite River Basin

Basic Information

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2. Deng, Z-Q., Scaling dispersion model for pollutant transport in natural rivers. The 2005 EWRI World Water and Environmental Resources Congress, Anchorage, Alaska, May 15-19, 2005.
3. Deng, Z., de Lima, João L.M.P., and Singh, V. P. (2005). Transport rate-based model for overland flow and solute transport: Parameter estimation and process simulation. Journal of Hydrology, 315(1-4), 220-235.
4. Mishra, P. K., and Z. Deng (2005). Sediment TMDL development for the Amite River. Submitted to the journal Hydrological Processes.

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Research

Problem and Research Objectives

An overview of current TMDLs by the EPA shows that over 40% of the United States assessed waters still do not meet the water quality standards which the states, territories, and authorized tribes have set for them. This amounts to over 20,000 individual river segments, lakes, and estuaries. These impaired waters include approximately 300,000 miles of rivers and shorelines and approximately 5 million acres of lakes -- polluted mostly by sediments, excess nutrients, and harmful microorganisms from nonpoint sources. In fact, the largest water pollutants in the United States, by volume, are instream suspended sediment (Fowler and Heady, 1981). In Louisiana, non-coal surface mining activities have been identified as a significant source of increased sediment loadings to rivers and streams, which continue well beyond the period of active industrial operations due to lack of proper restoration at most sites. The Amite River is identified as one of the 59 water bodies impaired by sediments in Louisiana. Fish and wildlife habitat has been directly degraded with significant loss of shoreline and aquatic habitat in approximately 25 miles of the upper reaches of the river above Denham Springs, with potentially many more miles indirectly impacted. This degradation is believed to have been caused by urbanization, sand and gravel mining, erosion, shallower water, faster flow, higher water temperature, increased turbidity, agricultural and forestry practices over the last 50 years. As the habitat deteriorates, wildlife that uses the river and floodplain ecosystem decreases in quantity, quality, and diversity. Another result of the sediment impairment in the river has been higher river stages downstream. The Amite's 1983 flood led to significant property damage, economic loss and disruption of lives in East Baton Rouge, Livingston and Ascension parishes. Therefore, a sediment TMDL calculation is required by EPA for the river. The overall goal of this project was thus to present the sediment TMDL calculation for the Amite River. The objectives of this project were (1) to develop a new sediment transport model for the Amite River, (2) to conduct steady and unsteady flow computation, (3) to estimate sediment loads (sources) produced by watershed erosion, and (4) to determine sediment TMDLs for the Amite River.

Methodology

Using the mass conservation principle and Reynolds transport theorem a new 1-D model has been developed for computation of suspended cohesive sediment transport in the Amite River. To solve the new sediment transport equation, a standard split approach by Sobey (1983) is used. Such an approach requires solving the advection and diffusion parts separately at each time step. The advection-dispersion equation is decomposed into the hyperbolic (pure advection) and the parabolic (pure dispersion with sink and source terms) partial differential equations. The two sub-equations are then solved separately in consecutive fractional steps by the corresponding numerical approaches that best fit the features of each PDE for one time step. Based on the split-operator algorithm it is commonly assumed that the pure advection process and the pure dispersion process alternate with time: the advection process occurs in the first sub-time step, the dispersion takes place in the second sub-time step, and the reaction is considered in the final sub-time step (Holly and Preissmann, 1977). A step size of 375 m is taken for distance and 10 seconds for the time step. The grid size was chosen carefully, so as to meet the stability criterion and also avoid being computationally expensive. The flow computation is performed under steady and unsteady conditions using the HEC-RAS software. The steady flow analysis is intended for calculating water surface profiles for steady gradually varied flow. The basic computational procedure is based on the solution of the energy equation. Effects of various obstructions such as bridges, culverts, weirs, spillways and other structures in the flood plain have been considered in the computations. Sediment erosion in the Amite River Basin is calculated by combining the USLE (Universal Soil Loss Equation) model with ARCVIEW GIS and the digital elevation model of the Amite River Basin. The entire Amite River basin is divided into 15 sub-basins. Digital elevation data was imported into the GIS which generated inputs for USLE. The GIS database provides inputs for land use, soil type, slopes and elevation as shown in Figure 1. Meteorological data from 1987 to 2004 from the USGS stations were used. Surface erosion from land catchments, settling, scouring, and bank erosion were considered.

Principal Findings and Significance

(1) Using mass conservation and Reynolds transport theorem, the following 1-D sediment transport model has been developed for the sediment TMDL calculations. The new model is capable of predicting suspended sediment transport in the Amite River.

$$\frac{\partial S}{\partial t} + U\frac{\partial S}{\partial x} = \frac{1}{A_f}\frac{\partial}{\partial x}\left(A_f K_x \frac{\partial S}{\partial x}\right) + \frac{\alpha(u_* - u_{*c})(S_* - S)}{h} - \frac{\beta\omega_S S}{h} + \frac{q_L}{A_f}(S - S_L) \quad (1)$$

in which U = flow velocity, h = flow depth, S = sediment concentration (M/L^3), S_L = sediment concentration of lateral inflow (M/L^3), S_* = suspended sediment concentration under equilibrium conditions or suspended-load carrying capacity (M/L^3) which is determined using the formula proposed by WIHEE (Chien and Wan 1999), u_* = shear velocity (L/T), u_{*c} = critical shear velocity (L/T), ω_s = settling velocity of sediment particles (L/T) which is calculated using the equation presented by Cheng (1997), α = constant , β = constant, A_f = channel cross-sectional area (L^2), K_x = longitudinal dispersion coefficient (L^2/T) which is calculated using the method presented by Deng et al. (2001), x = longitudinal distance [L], t = time [T].

The main advantage of Eq. (1) over existing 1-D sediment transport models is that sediment erosion (described by the second term on the right hand side of the equation) and sediment settling (represented by the third term on the RHS) are treated as two different processes and thus modeled by two separate terms. The last term on the RHS of Eq. (1) stands for the influence of tributaries on sediment transport in the Amite River.

(2) The combination of USLE model and GIS technology is an efficient and effective approach for estimation of watershed sediment erosion. GIS is very useful compared to traditional methods by breaking up the land surface into many small cells which enables an analysis to be performed on both large regions as well as discrete areas. GIS not only generates inputs for USLE, but also displays outputs such as land use distribution, as shown in Figure 1.

Spatial variation of soil loss correlated with land use can be observed, as shown in Figure 2. Based on USLE and the average intensity rainfall of 1990, erosion rate of the Amite River Basin is found to be 5.41 tons/acre/year. This erosion rate represents the average annual erosion rate for the entire basin. This erosion value can be used for sediment TMDL calculations under steady flow conditions. The MUSLE model which is a single event model can be employed to determine the soil erosion for the TMDL calculations under unsteady flow conditions.

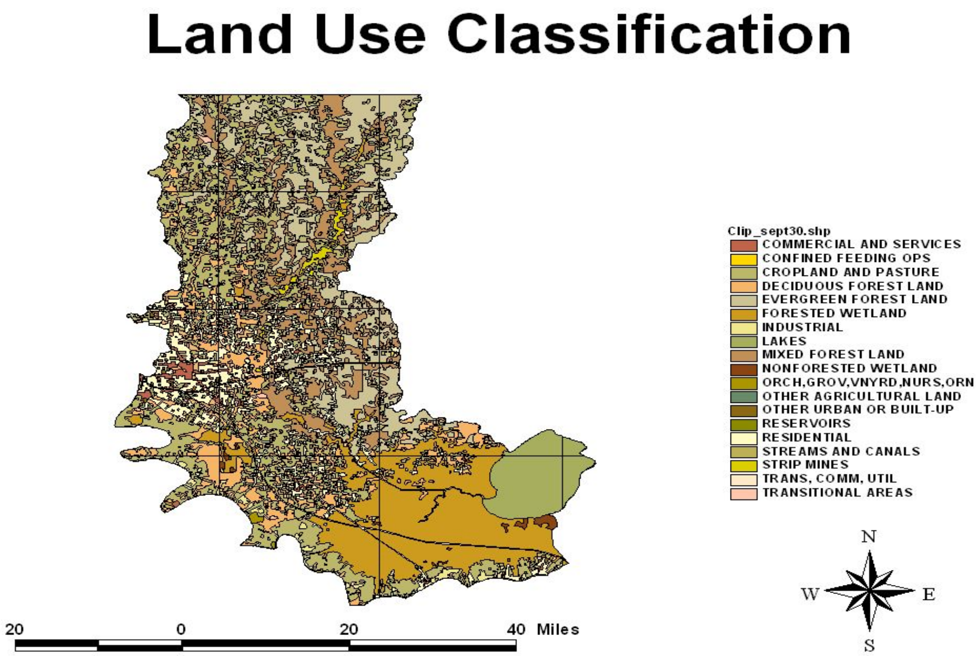

Figure 1: Land Use distribution in the Amite River Basin

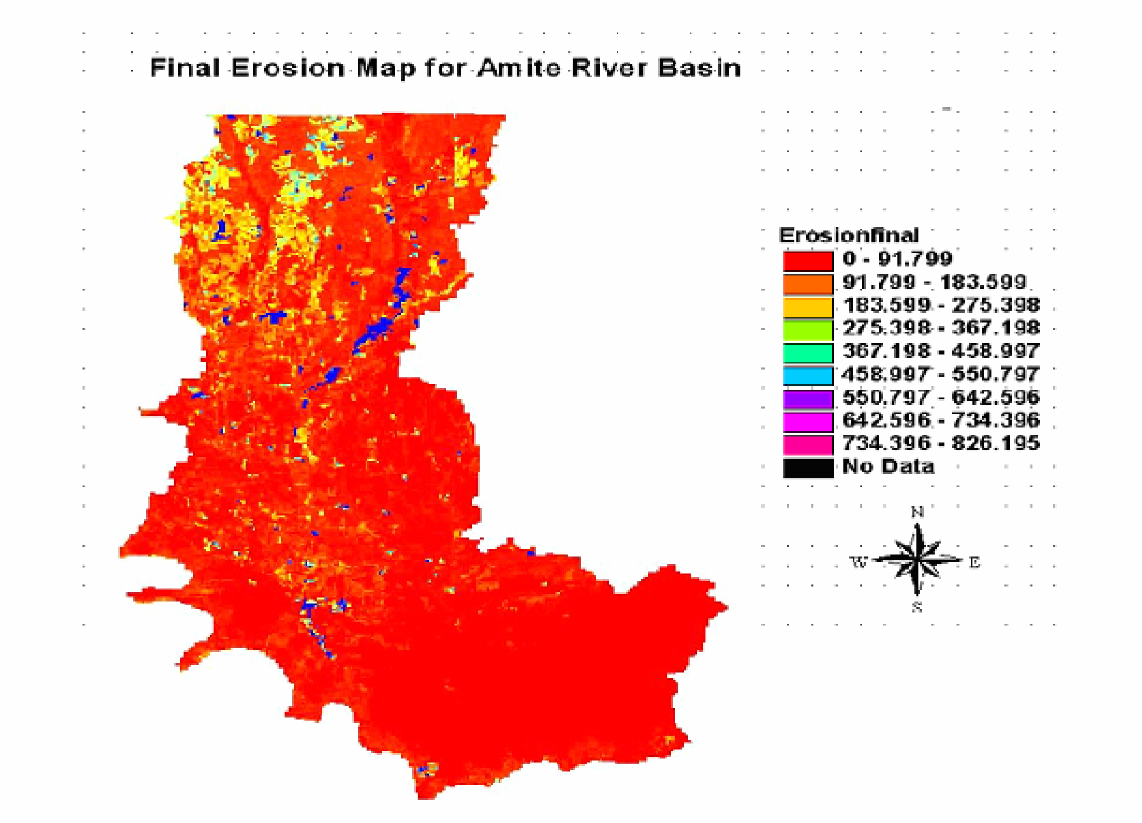

Figure 2. Spatial distribution of computed soil erosion in the Amite River Basin

(3) The flow parameters for both the steady and unsteady flow conditions can be efficiently computed using the HEC-RAS. The calculated discharge and flow velocity of the Amite River vary in the range of 285 – 771 m^3/sec and 0.34 – 2.4 m/s, respectively, as shown in Figures 3 and 4.

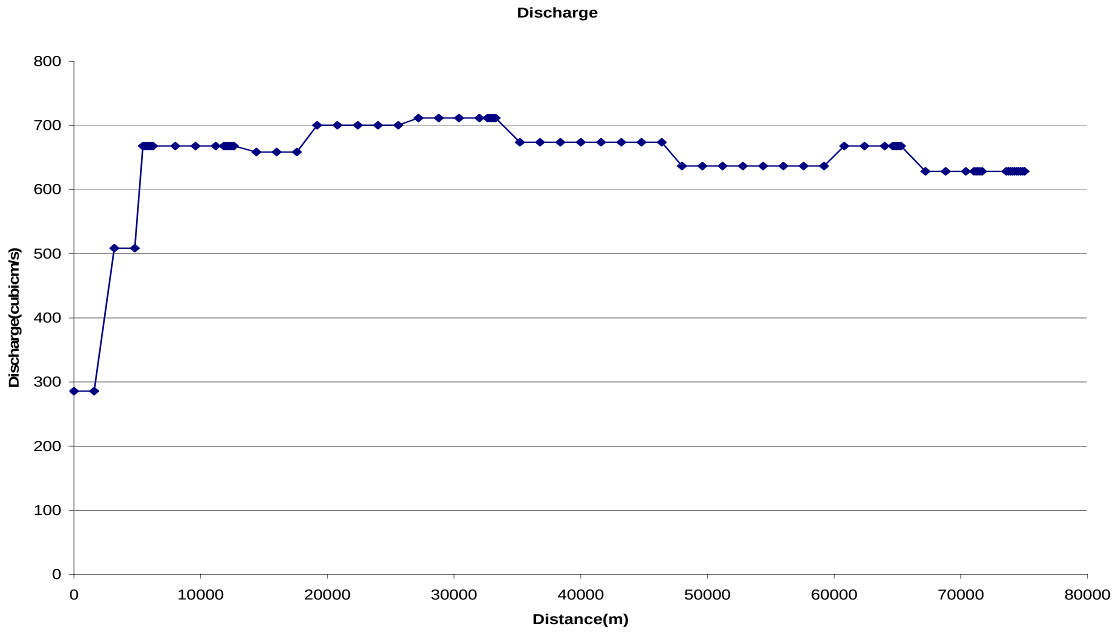

Figure 3: Steady flow discharges with the various inflows and outflows

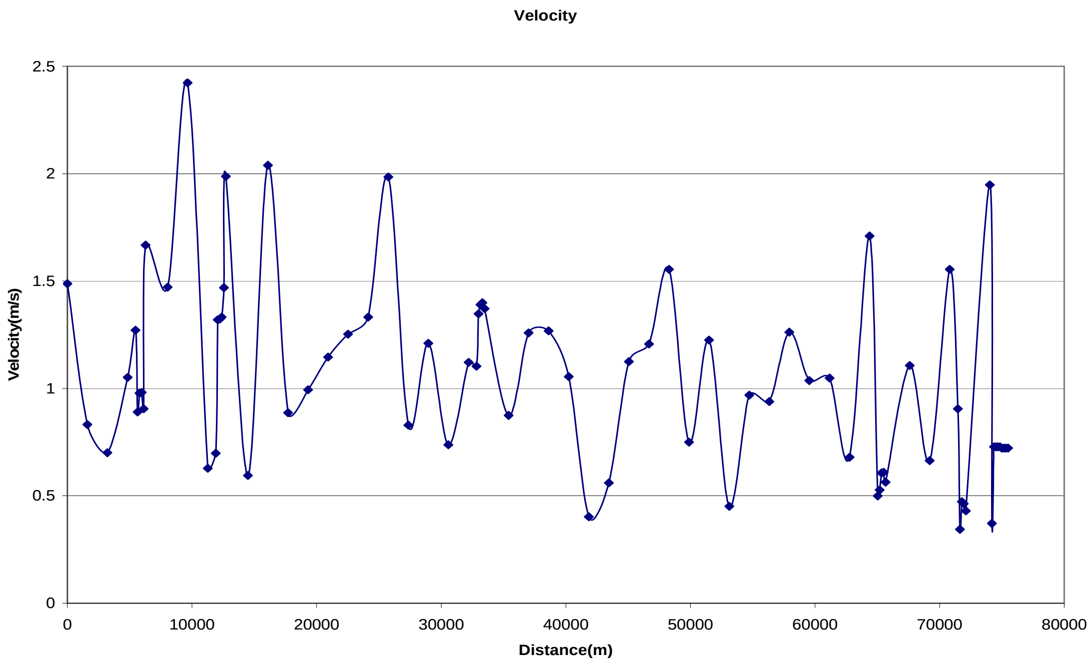

Figure 4: Velocity variations along the Amite River

(4) The 1-D model predicts a maximum sediment concentration of 114 mg/L and the average concentration of 25 mg/L, ranging from 3 mg/l to 114 mg/l in the Amite River, as shown in Figure 5.

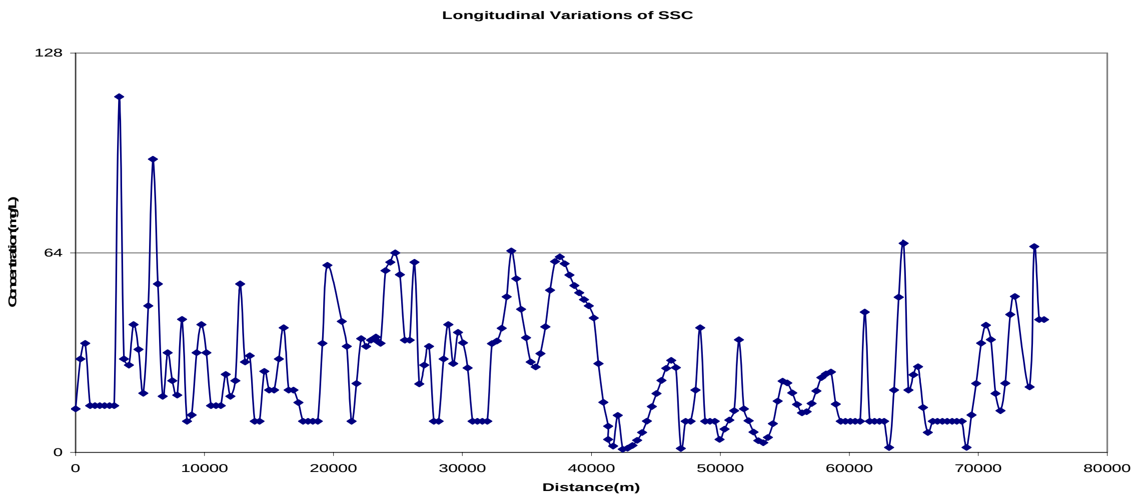

Figure 5: Longitudinal Variations of suspended sediment concentration (SSC) along the Amite River

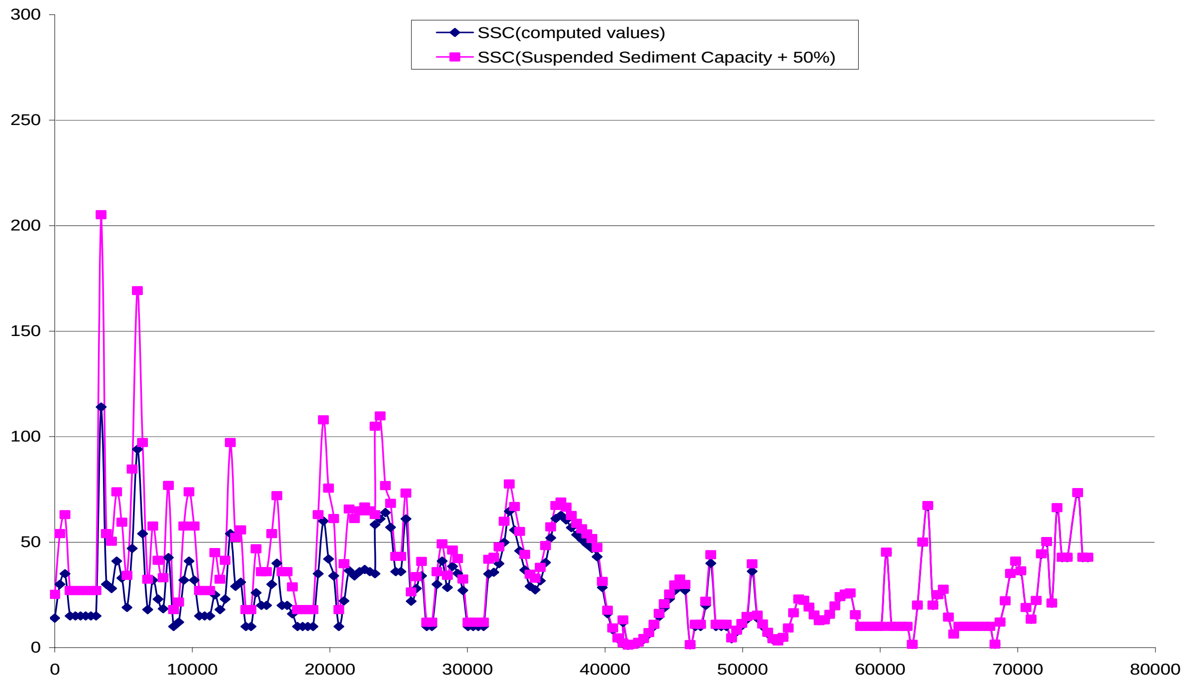

Figure 6: Sensitivity analysis for sediment carrying capacity

(5) Based on the EPA's and LDEQ's water quality standard of 50 NTU, the calculated sediment TMDL for the Amite River is 4665.235 tons/day. The daily reduction in this case

is found to be approximately 220 tons. The TMDL accounted not only for waste load allocation, but also for margin of safety (MOS) and future growth.

(6) Unsteady flow is found to have a significant effect on TMDL calculations. Event based rainfalls produce unsteady flows in the river and a higher erosion rate and thereby sediment concentration in the river, resulting in a higher TMDL for the Amite River. The TMDL value for unsteady flow is found to be 5418.357 tons/day. The median daily reduction is found to be 2653.29 tons/day for the Amite River.

(7) Results of sensitivity analysis show that the most sensitive parameter in the model is the suspended sediment carrying capacity, as shown in Figure 6. Other model parameters such as constant α, settling velocity and dispersion coefficient are also found to have effect on resuspension and on suspended sediment concentration.

(8) Sediment criteria for the Amite River can be met by adopting best management practices such as terraces on the steep slopes, creation of buffer zones along the river. Results indicate that the new model can be an effective tool for sediment TMDL calculations.

This research provided critical insights into the land use, water quality, and sediment TMDLs of the Amite River Basin. The results obtained from this research contribute to developing second phase sediment TMDL development for the Amite River and assessing the feasibility of the Amite River ecosystem restoration. This project produced one Master thesis entitled “SEDIMENT TMDL CALCULATIONS FOR AMITE RIVER” and led to the graduation of one Master’s student. Furthermore, the project and its results will be introduced in several civil engineering courses (CE 3200 and CE 7255) at LSU, immediately benefiting both graduate and undergraduate students in learning how science applications solve real world problems related to coastal restoration in Louisiana.

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