Development of Total Maximum Daily Load for Dissolved Oxygen in Nutrient-Enriched Lowland Rivers

Basic Information

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Principal Investigators:	Zhi-Qiang Deng

Publications

1. Zahraeifard, V., Deng, Z., and Malone, R. F. (2014). “Modelling Spatial Variations in Dissolved Oxygen in Fine-Grained Streams under Uncertainty.” Hydrological Processes, DOI: 10.1002/hyp.10144 (in press) (http://onlinelibrary.wiley.com/doi/10.1002/hyp.10144/abstract).
2. Zahraeifard, V. and Deng, Z. “Development of Total Maximum Daily Load for Dissolved Oxygen in Amite River.” World Environmental & Water Resources Congress, June 1 – 5, 2014, Portland, Oregon.

SYNOPSIS

Problem and Research Objectives

Nutrient-enriched lowland rivers in Louisiana are largely impaired due to low dissolved oxygen. In fact, the Louisiana's latest (2010) Integrated Report for water quality assessment indicates that about 45.7% of assessed rivers (155/339) are impaired due to low dissolved oxygen (DO) in terms of supporting fish and wildlife propagation (fishing). The US EPA requires states to develop Total Maximum Daily Load (TMDL) for pollutants causing impairments. While the DO load allocation requires the determination of sediment oxygen demand (SOD), the SOD in the organic-rich fluid mud (fluff) layer, commonly occurring in coastal Louisiana rivers, is rarely taken into account in TMDL development due to the lack of an effective modeling tool. The lack of an effective modeling tool for DO in nutrient-enriched lowland rivers causes high uncertainty in TMDL development and makes it challenging to restore impaired water bodies and thereby to comply with the Federal Clean Water Act. This is a critical regional and state water quality problem needing to be addressed.

The overall goal of this project is to develop an efficient and effective modeling tool for determining spatial and temporal variations in DO in nutrient-enriched lowland rivers and thereby to address the critical regional and state water quality problem. The proposed strategy is to test and demonstrate the new modeling tool for DO in the Lower Amite River and the Lower Tangipahoa River in southeast Louisiana. The Lower Tangipahoa River is on the latest US EPA and LDEQ 303(d) list for not supporting its designated use of fish and wildlife propagation due to low DO. Specific objectives of the project are: (1) to develop and test a new modeling tool, called VART DO-3L, for simulation of spatial and temporal variations in DO in nutrient-enriched lowland rivers. This objective will be addressed by the extension of the PI's VART model; and (2) to identify critical source areas of pollution in the Lower Tangipahoa River watershed, as shown in Figure 1.

Methodology

The objectives are accomplished by executing two tasks: (1) Development of triple-layer model for simulation of instream DO, and (2) construction of Google earth maps showing source locations of DO pollution. The proposed tasks are implemented by combining PI's proven VART model for solute transport in rivers, ArcGIS, Google Earth, and various data.

While this project focuses on the Lower Tangipahoa River and the Lower Amite River watersheds, the methods (particularly the VART DO-3L model) developed in this study can be easily extended to other watersheds in Louisiana and in other low relief regions. Therefore, this project has broader implications for environmental restoration and sustainability in Louisiana and in the nation as well.

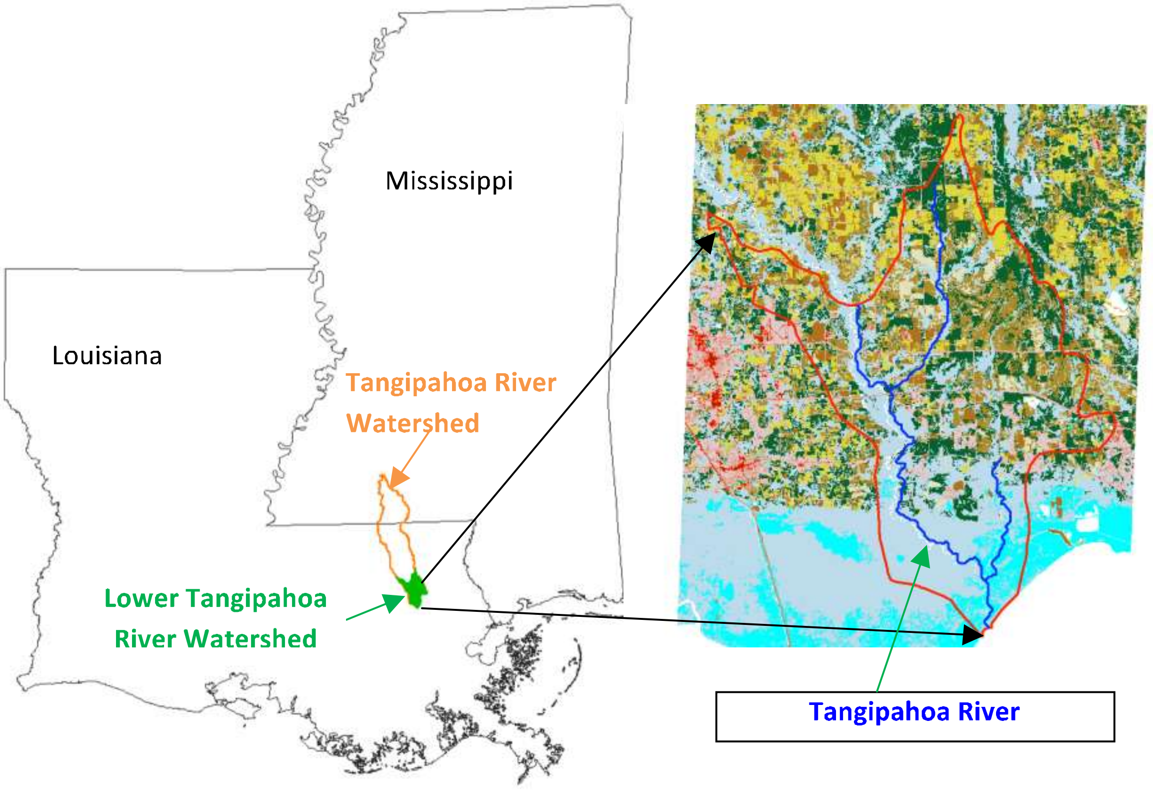


Figure 1. Map for the Tangipahoa River watershed.

PRINCIPAL FINDINGS AND SIGNIFICANCE

1. Mathematical Model for Spatial Variations in DO: VART DO-3L Model

(1) The triple-layer model is described mathematically with the following three equations:

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}=\frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right)+\left(\frac{A_{adv}+A_{dif}}{A}\right)\left(\frac{1}{T_V}\right)(C_F-C)+K_2(C_{sat}-C)-K_D L \qquad (1)$$

$$\frac{\partial C_F}{\partial t}=\frac{1}{T_V}(C-C_F)-D_e\frac{\partial C_s}{\partial z}\bigg|_{z=0}\frac{P_{ws}}{\left(\frac{A_s}{A}\right).A}-R \qquad (2)$$

$$\frac{\partial C_s}{\partial t}=D_e\frac{\partial^2 C_s}{\partial z^2}-\mu_o \qquad (3)$$

where C, C_F, and C_s are DO concentration in water column, in the flocculent layer, and in consolidated stream bed [ML^{-3}], respectively; C_{sat} = saturation concentration of DO; U = average flow velocity [LT^{-1}] along x direction; E_x = longitudinal dispersion coefficient

$[L^2T^{-1}]$; t = traveling time [T]; x = distance in flow direction [L]; z = distance in vertical direction pointing downward [L]; K_D = biochemical oxidation rate of carbonaceous materials $[T^{-1}]$; L = BOD concentration $[ML^{-3}]$ in the water column; K_2 = reaeration coefficient $[T^{-1}]$; A = cross-sectional area of stream channel $[L^2]$; A_{adv} = advection-dominated storage zone (flocculent layer) area $[L^2]$ with the thickness of δ_{adv} [L]; A_{dif} = diffusion-dominated storage zone (stream-bed sediment) area $[L^2]$ with the thickness of δ_{dif} [L]; $A_{\mathrm{s}} = A_{adv} + A_{dif}$, T_V = residence time in storage zones (including A_{adv} and A_{dif}) [T]; D_{e} = effective diffusion coefficient in the bottom sediment layer; P_{ws} = wetted perimeter of stream channel; R = lumped reaction term representing SOD in the flocculent layer; and μ_{o} = lumped reaction term denoting SOD in the bottom sediment. Eqs. (1) - (3) are utilized for simulation of spatial and temporal variations in DO in fine-grained streams, characterized by three layers, including water column, flocculent layer, and consolidated stream bed. Equations (1) – (3) constitute the triple-layer (VART DO-3L) model. The VART DO-3L model provides an efficient and cost effective modeling tool for environmental and water resources management agencies to determine instream DO more accurately due to the incorporation of SOD in the fluff layer commonly occurring in nutrient-enriched lowland rivers and thus reduce the uncertainty in TMDL development and implementation.

(2) The VART DO-3L model was first utilized to simulate vertical DO profiles in the Lower Amite River. Figure 2 shows normalized DO concentration profiles in the overlying water column, the flocculent layer, and diffusive bottom sediment layer at Denham Springs station, Port Vincent station, and a third station in between that is 17 km downstream of Denham Springs station. The overall variation trends in the vertical DO profiles particularly in the bottom sediment layer are similar to those produced by using the concept of diffusive boundary layer above the sediment-water interface. The difference is due to the introduction of advection-dominated storage zone in this study with constant DO concentration throughout the flocculent layer and water column layer.

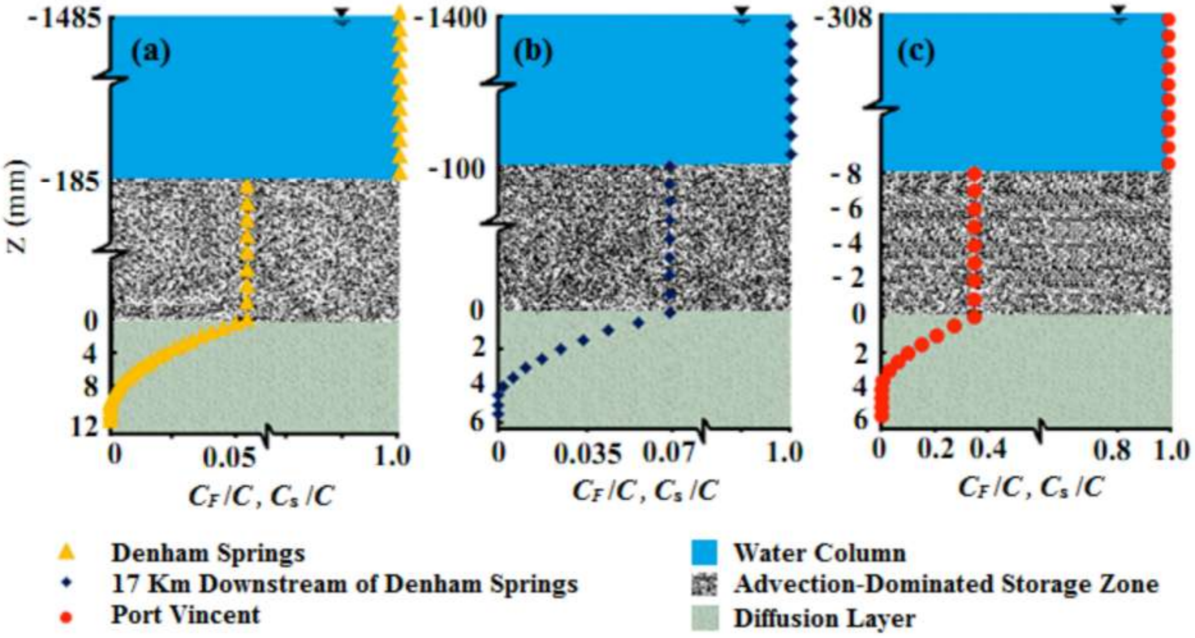


Figure 2. Vertical DO concentration ratio relative to DO concentration in water column at Denham Springs station (a), Port Vincent station (c), and a third station in between (b).

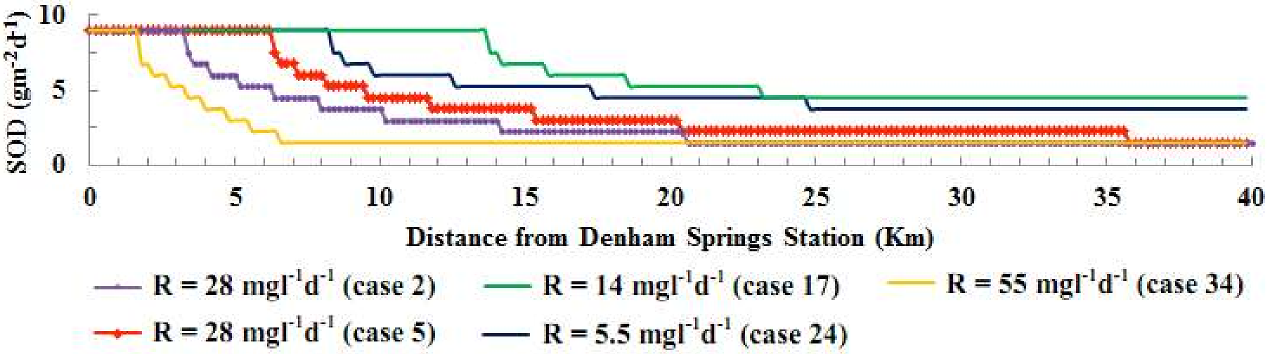


Figure 3. SOD variation along Amite River under different conditions.

(3) The VART DO-3L model was utilized to simulate longitudinal SOD (Sediment Oxygen Demand) variations. Figure 3 shows simulated SOD variations along the Lower Amite River under five different cases. While a constant *R* value was adopted in the simulation for each case, the *R* value may actually vary along the river due to the change in the composition of sediment particle size and organic content in the sediment. Therefore, the actual variation in SOD along the river may be a combination of the cases. The upper reach close to the Denham Springs may have a relatively low *R* value like Case 24 while the lower reach close to the Port Vincent may have a high *R* value like Case 34. Anyway, it is the SOD that causes gradual reduction in DO from the upstream Denham Springs station (DO = 7.9 mg/l) to the downstream Port Vincent station (DO ≈ 3 mg/l).

(4) The VART DO-3L model was also used to simulate longitudinal DO variations. Figure 4 shows the DO reduction along the Amite River due to the SOD. The daily averaged DO data observed at Denham Springs and Port Vincent stations are also included. It can be seen from Figure 4 that the DO drops rapidly in the upper 10 km and then declines slowly in the lower portion of the river. The slow reduction in DO in the lower reach may be due to the low DO in water column and low DO concentration gradient across the sediment–water interface. Another mechanism possibly responsible for the slow reduction in DO is the increased reaeration at water surface, balancing the DO reduction due to SOD. Figure 4 indicates that the simulation errors vary in the range of +20% to −35% while the simulated DO level fits the observed one almost perfectly in panels (b) and (d).

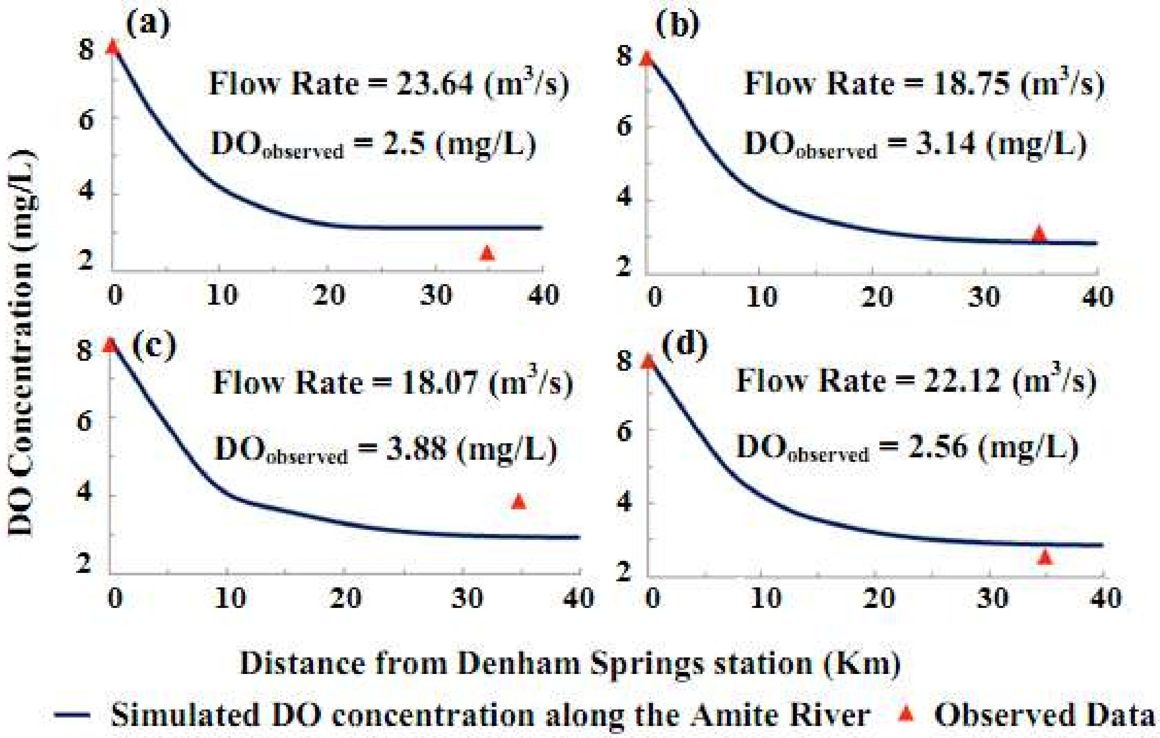


Figure 4. Longitudinal variations in DO along Amite River.

2. Identification of Critical Source Areas of Nonpoint Source Pollution in the Lower Tangipahoa River

(1) The variation in dissolved oxygen (DO) along the Tangipahoa River is mapped using ArcGIS and Google Earth to identify major source areas of DO-consuming contaminants, as shown in Figure 5. The map indicates that the DO level drops significantly downstream of the Chappepeela Creek confluence and particularly the Washley Creek confluence (not shown on the map, http://itouchmap.com/?d=558193&s=LA&f=stream), implying that the Chappepeela Creek watershed and particularly the Washley Creek watershed are potentially the major source areas of DO pollution to the Lower Tangipahoa River. The Chappepeela Creek and the Washley Creek collect runoff from dairy farms. The Runoff from dairy farms carries animal waste into the creeks, resulting in high bacteria counts and low dissolved oxygen concentrations.

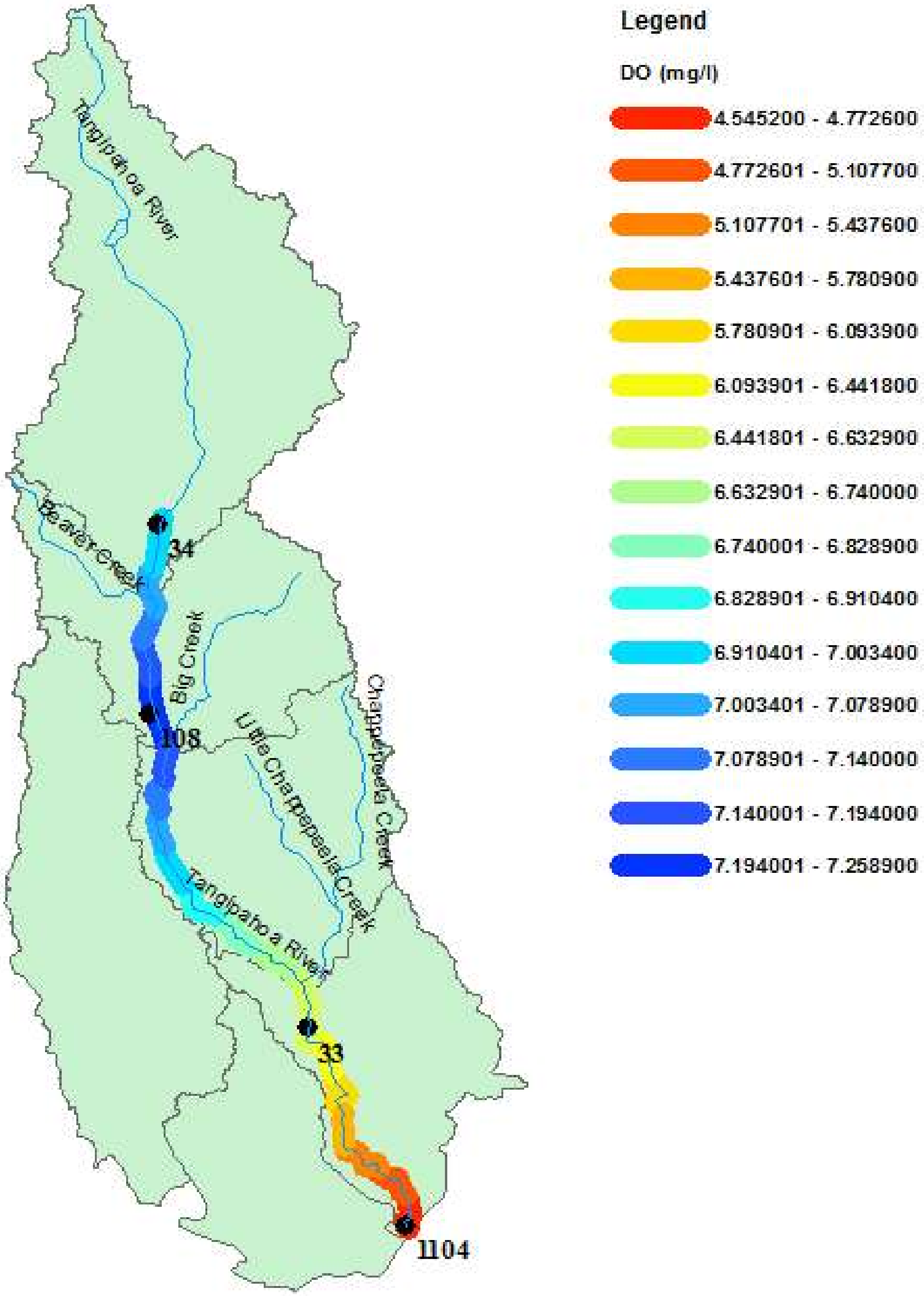
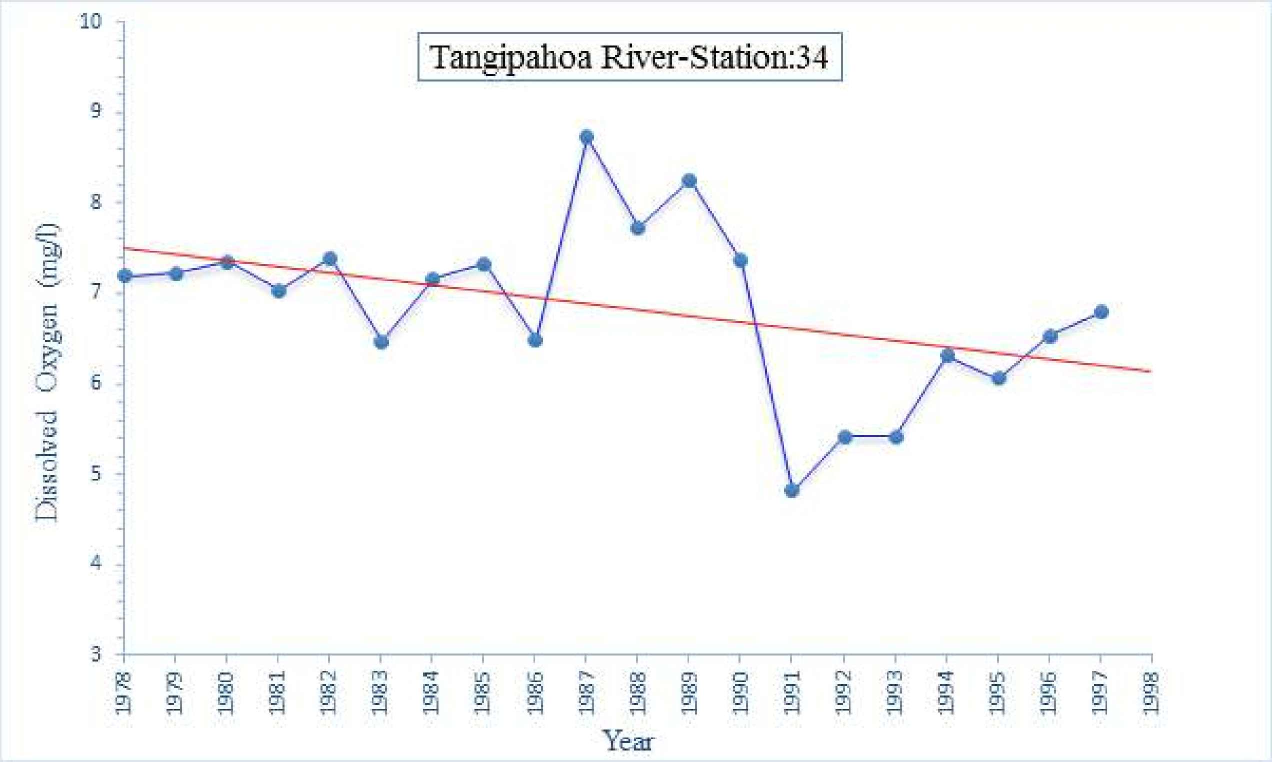
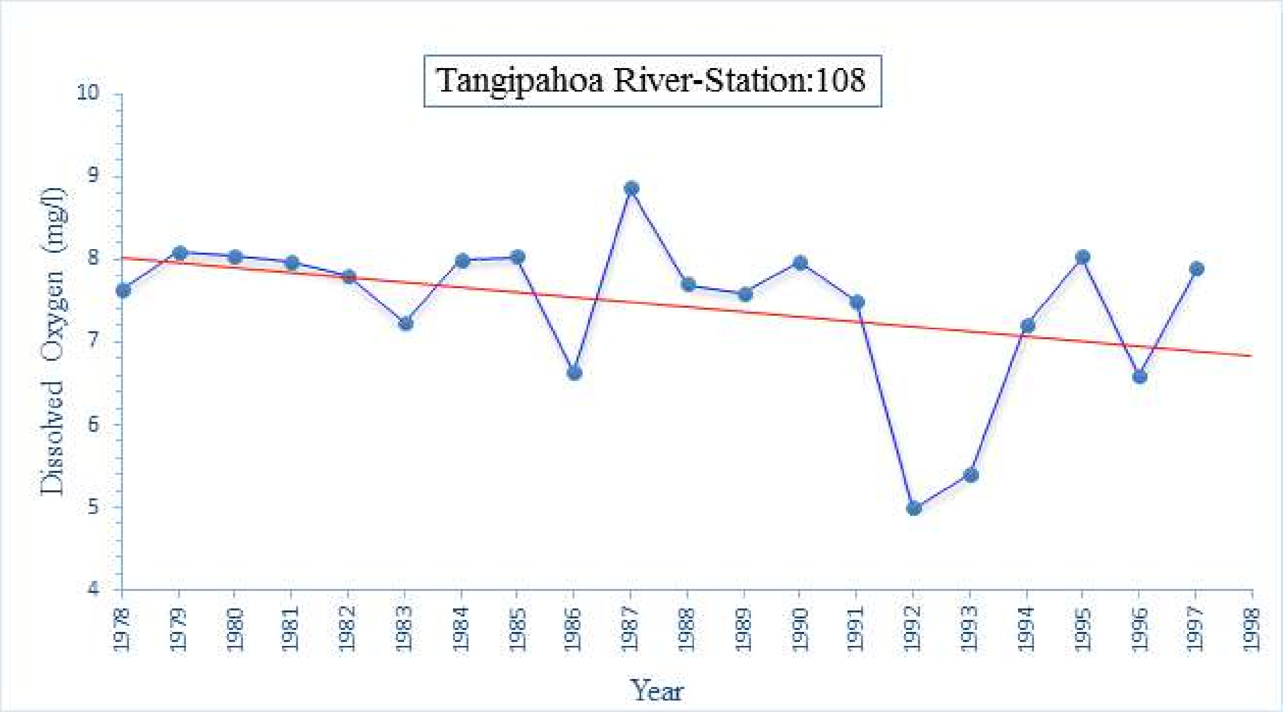


Figure 5. Map of Tangipahoa River watershed showing longitudinal DO variation along the Tangipahoa River and the critical source areas of DO-consuming contaminants in the Tangipahoa River subwatersheds.

(2) Figure 6 shows temporal variations in DO at four sampling stations, including 34, 108, 33, and 1104, along the Tangipahoa River. It can be seen from the four graphs that DO level exhibits a clear decreasing trend over the past decades at all the four stations. There was a significant drop in DO at the three upstream stations (including 34, 108, and 33) in

1991 - 1993. The implementation of Total Maximum Daily Load for DO has resulted in the improvement in the DO level at the three stations. However, the DO level at the downstream station 1104 remains lower than the minimum DO level of 5.0 mg/L required for maintaining aquatic life. The extremely low DO level at Station 1104 and in the lower portion of the river reach is attributed to the high BOD inputs from the Chappepeela Creek and the Washley Creek watersheds. The results are consistent with those from Figure 5. The last graph for Station 1104 in Figure 6 indicates again that the Chappepeela Creek and the Washley Creek watersheds are the major source areas of DO pollution to the Lower Tangipahoa River. TMDL implementation efforts for the Tangipahoa River should focus on the restoration of the Chappepeela Creek and the Washley Creek watersheds by implementing low impact development practices for dairy farms in the watersheds.




Tangipahoa River-Station:108
Dissolved Oxygen (mg/l)
10
9
8
7
6
5
4
1978
1979
1980
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1984
1985
1986
1987
1988
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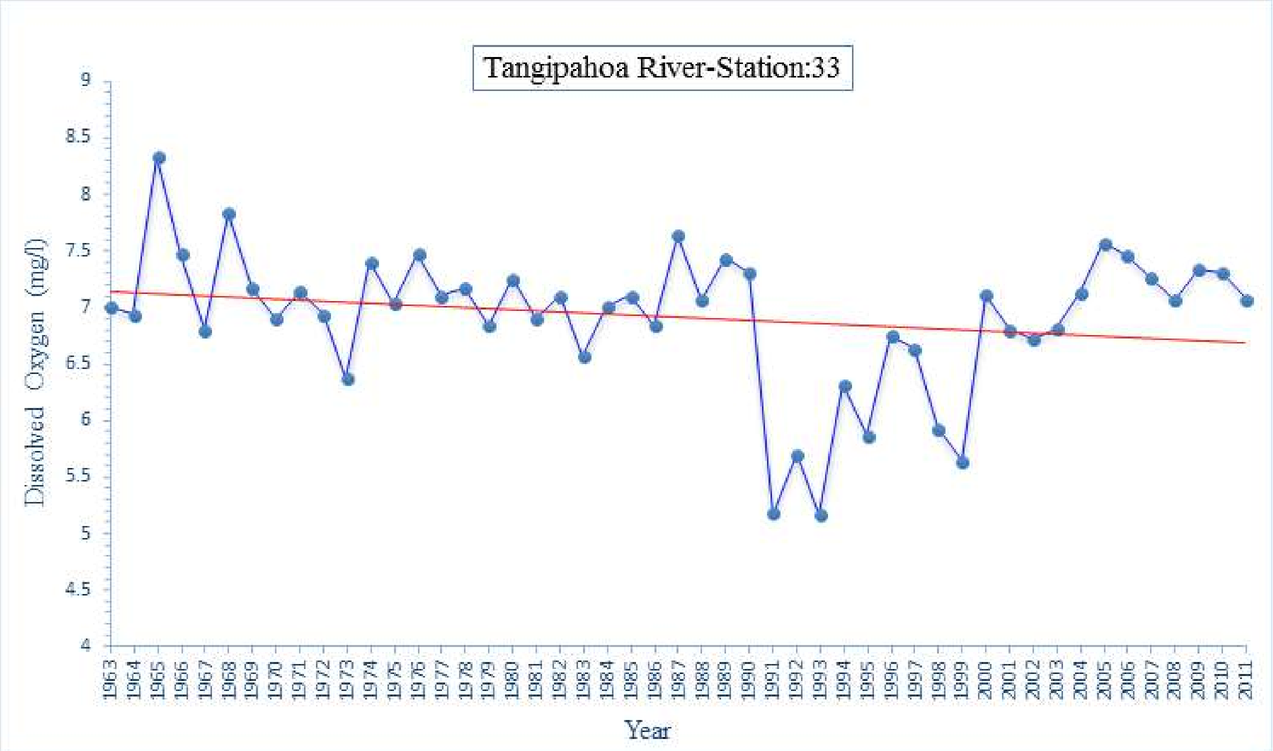
Tangipahoa River-Station:33
Dissolved Oxygen (mg/l)
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
1963
1964
1965
1966
1967
1968
1969
1970
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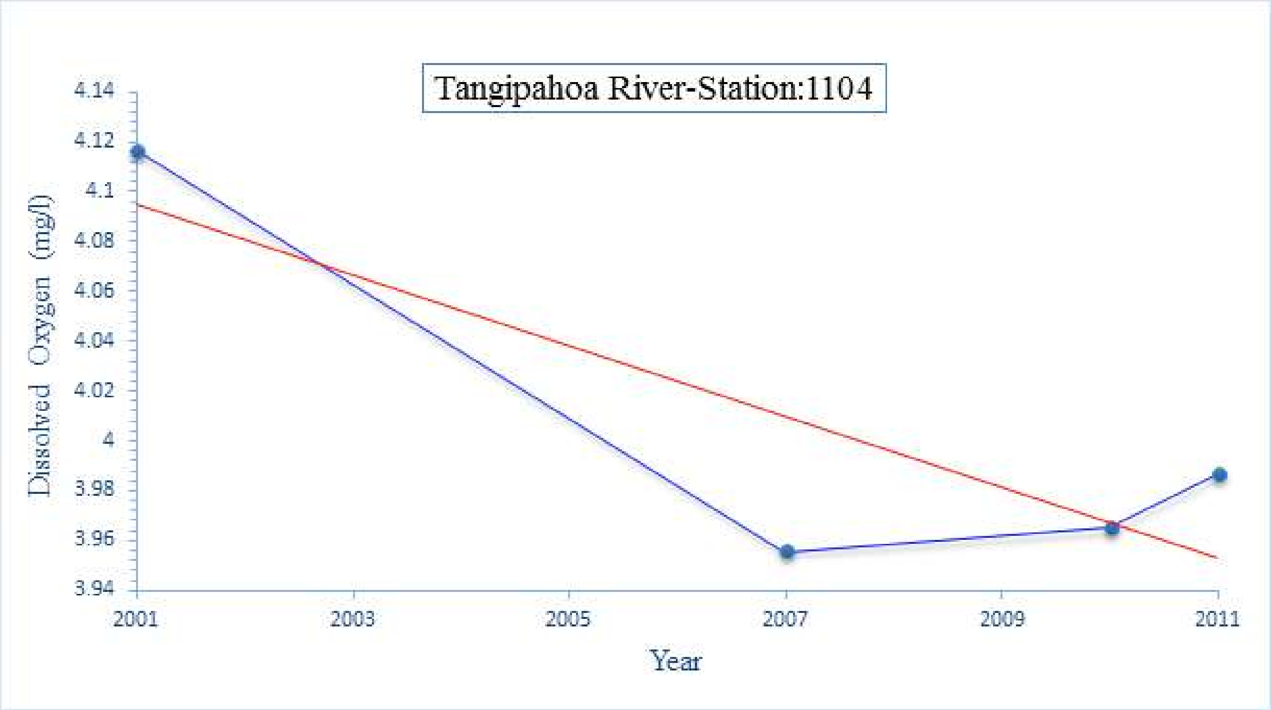

Figure 6. Temporal variations in DO at four monitoring stations, including 34, 108, 33, and 1104, along the Tangipahoa River.

INFORMATION TRANSFER

The findings and the VART DO-3L model developed in this project for simulation of spatial-temporal DO variations and identification of contaminant source areas will be transferred to the Louisiana Department of Environmental Quality for pollutant TMDL development and implementation and thereby for the restoration of the nutrient-enriched lowland rivers.