

**Louisiana Water Resources Research Institute
Annual Technical Report
FY 2006**

Introduction

This report presents a description of the activities of the Louisiana Water Resources Research Institute for the period of March 1, 2006 to February 28, 2007 under the direction of Dr. John Pardue. The Louisiana Water Resources Research Institute (LWRRI) is unique among academic research institutions in the state because it is federally mandated to perform a statewide function of promoting research, education and services in water resources. The federal mandate recognizes the ubiquitous involvement of water in environmental and societal issues, and the need for a focal point for coordination.

As a member of the National Institutes of Water Resources, LWRRI is one of a network of 54 institutes nationwide initially authorized by Congress in 1964 and has been re-authorized through the Water Resources Research Act of 1984, as amended in 1996 by P.L. 104-147. Under the Act, the institutes are to:

"1) plan, conduct, or otherwise arrange for competent research that fosters, (A) the entry of new research scientists into water resources fields, (B) the training and education of future water scientists, engineers, and technicians, (C) the preliminary exploration of new ideas that address water problems or expand understanding of water and water-related phenomena, and (D) the dissemination of research results to water managers and the public.

2) cooperate closely with other colleges and universities in the State that have demonstrated capabilities for research, information dissemination and graduate training in order to develop a statewide program designed to resolve State and regional water and related land problems. Each institute shall also cooperate closely with other institutes and organizations in the region to increase the effectiveness of the institutes and for the purpose of promoting regional coordination."

The National Water Resources Institutes program establishes a broad mandate to pursue a comprehensive approach to water resource issues that are related to state and regional needs. Louisiana is *the* water state; no other state has so much of its cultural and economic life involved with water resource issues. The oil and gas industry, the chemical industry, port activities, tourism and fisheries are all dependent upon the existence of a deltaic landscape containing major rivers, extensive wetlands, numerous large shallow water bays, and large thick sequences of river sediments all adjacent to the Gulf of Mexico.

History of the Institute

Louisiana has an abundance of water resources, and while reaping their benefits, also faces complex and crucial water problems. Louisiana's present water resources must be effectively managed, and the quality of these resources must be responsibly protected. A fundamental necessity is to assure continued availability and usability of the state's water supply for future generations. Specifically, Louisiana faces five major issues that threaten the quality of the state's water supply, which are also subsets of the southeastern/island region priorities:

Nonpoint sources of pollution are estimated to account for approximately one-half of Louisiana's pollution. Because of the potential impact of this pollution and the need to mitigate its effects while maintaining the state's extensive agricultural base and coastal zones, continued research is needed in the area of nonpoint issues. Louisiana's regulatory agencies are addressing non-point source problems through the development of waste load allocation models or total maximum daily load (TMDL) calculations. There are serious technical issues that still require resolution to insure that progress is made in solving the non-point source problem.

Louisiana's vast *wetlands* make up approximately 40% of the nation's wetlands. These areas are composed of very sensitive and often delicately balanced ecosystems which make them particularly vulnerable to contamination or destruction resulting both from human activities and from natural occurrences. Understanding these threats and finding management alternatives for the state's unique wetland resources are priority issues needing attention.

Water resources planning and management are ever-present dilemmas for Louisiana. Severe flooding of urban and residential areas periodically causes economic loss and human suffering, yet solutions to flooding problems can be problems in themselves. Water supply issues have also recently a focus of concern. Despite the abundance of resources, several aquifers have been in perennial overdraft, including the Chicot aquifer. Louisiana passed its first legislation that restricts groundwater use in the past year. Water resources and environmental issues are intricately interconnected; therefore, changes in one aspect produce a corresponding responsive change in another. Further study is needed to understand these relationships.

Water quality protection, particularly of ground water resources, is an area of concern in Louisiana. Researchers are beginning to see contamination in drinking water supplies that was not present in the past. Delineating aquifer recharge areas, understanding the impacts of industrial activities on water resources, evaluating nonpoint sources of pollution, and exploring protection alternatives are issues at the forefront.

Wastewater management has been a long-standing issue in Louisiana. The problem of wastewater management focuses primarily on rural and agricultural wastewater and the high costs for conventional types of wastewater treatment as found in the petrochemical industry.

The Institute is administratively housed in the College of Engineering and maintains working relationships with several research and teaching units at Louisiana State University. Recent cooperative research projects have been conducted with the Louisiana Geological Survey and the EPA's Hazardous Substance Research Center- South & Southwest.

Research Program

The primary goal of the Institute is to help prepare water professionals and policy makers in the State of Louisiana to meet present and future needs for reliable information concerning national, regional, and state water resources issues. The specific objectives of the Institute are to fund the development of critical water resources technology, to foster the training of students to be water resources scientists and engineers capable of solving present and future water resources problems, to disseminate research results and findings to the general public, and to provide technical assistance to governmental and industrial personnel and the citizens of Louisiana.

The priority research areas for the Institute in FY 2006 focused on selected research themes. Because of the small nature of the projects, it was apparent that a greater impact is possible if a thematic area is chosen to focus several complimentary research groups on a single issue. Several themes were considered. At the State level, greater emphasis was being placed on issues related to the impacts of Hurricanes Katrina and Rita. One area that had not received enough examination was the potential impact of storm surge on shallow aquifers in the state. Saltwater intrusion impacts many Louisiana groundwater sources, particularly shallow coastal aquifers. Projects selected were from a range of faculty with different academic backgrounds including geological scientists, environmental engineers and water resources. Supporting research in this priority area has increased the visibility of the Institute within the State.

The selected research projects are designated as Projects 2005LA38G, 2006LA45B, 2006LA46B, and 2006LA47B, as listed below.

- Project 2005LA38G, Tsai & Singh - Saltwater Intrusion Management with Conjunctive Use of Surface Water and Ground Water.
- Project 2006LA45B, Tsai - A Pilot Study on Modeling and Management of Hurricane- Accelerated Saltwater Encroachment in Coastal Aquifers.
- Project 2006LA46B, Van Biersel & Carlson Assessment of the Impact of Hurricane Katrina's and Rita's storm surges on the Southern Hills Aquifer System in Southern St. Tammany and Tangipahoa Parishes.
- Project 2006LA47B Deng, GIS-Aided Water Quality Monitoring and Assessment System for Lake Pontchartrain.

These projects include two projects that focus on ground water flow and transport and solute transport (2005LA38G & 2006LA45B) and one project that focuses on ground water flow and transport and water supply (2006LA46B). One project (2006LA47B) focuses on water quality issues.

LWRRI researchers have been involved in a range of response activities to the 2005 hurricanes which has substantially increased the Institute's visibility. In addition to our early floodwater research we have conducted studies on sediment, air, microbiological and landfill research that will lead to further peer-reviewed publications on the issues raised by the impacts of the storms. This year, LWRRI joined with the LSU Hurricane Center to conduct the planning meeting for the Louisiana Levee School which would train Levee Board Members from around the state on several issues such as, flood protection policy and administration, flooding processes, non-structural approaches to managing flood risk and flood control, and structural controls. We continue to partner with LSU Hurricane Center and others on planning and evacuation work for the upcoming 2007-2008 Hurricane season.

Saltwater Intrusion Management with Conjunctive Use of Surface Water and Ground Water

Basic Information

Title:	Saltwater Intrusion Management with Conjunctive Use of Surface Water and Ground Water
Project Number:	2005LA38G
Start Date:	9/1/2005
End Date:	8/31/2008
Funding Source:	104G
Congressional District:	Louisiana
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Management and Planning, Solute Transport
Descriptors:	None
Principal Investigators:	Frank Tsai, Vijay P. Singh

Publication

1. Tsai, F. T.-C., Enhancing random heterogeneity representation by mixing the kriging method with the zonation structure, *Water Resources Research*, 42, W08428, doi:10.1029/2005WR004111, 2006.
2. Rahman, A., F. T-C. Tsai, C.D. White, D.A. Carlson, C.S. Willson, Geophysical Data Integration and Stochastic Simulation on Significance Analysis of Ground Water Responses Using ANOVA, submitted to *Hydrological Processes*, 2007
3. Tsai, F. T-C. and X. Li. 2006. A Genetic Algorithm on Conditional Estimation of Distributed Hydraulic Conductivity in Groundwater Inverse Modeling: Indicator Generalized Parameterization and Natural Neighbors, in Abraham, See, Solomatine eds. *Hydroinformatics in practice: computational intelligence and technological developments in water applications*. Springer. (In press)
4. Elrawady, M.H., and F. T-C. Tsai. 2006. Saltwater Intrusion Barrier Development and Management in Coastal Aquifer System. American Institute of Hydrology 25th Anniversary Meeting, Baton Rouge, LA, May 21-24.
5. Li, X., and F. T-C. Tsai. 2006. Aquifer Heterogeneity Estimation and Uncertainty Analysis Using a Multi-Parameterization Method. 4th Annual Groundwater Symposium, ASCE/EWRI World Water & Environmental Resources Congress, Omaha, Nebraska, May 21-25.
6. Rahman, A., F. T-C. Tsai, C. D. White, D. A. Carlson, and C. S. Willson. 2006. Geophysical Data Integration and Conditional Uncertainty Analysis on Hydraulic Conductivity Estimation. 4th Annual Groundwater Symposium, ASCE/EWRI World Water & Environmental Resources Congress, Omaha, Nebraska, May 21-25.
7. Tsai, F. T-C. 2005. Bayesian Model Averaging on Parameterization Non-uniqueness and Conditional Uncertainty Analysis, presented at the American Geophysical Union 2005 Fall Meeting, San Francisco, CA, Dec 5-9.
8. Frank Tsai and Vijay Singh, 2006, Saltwater Intrusion Management with Conjunctive Use of Surface Water and Ground Water, Louisiana Water Resources Research Institute, Louisiana State University, Baton Rouge, Louisiana, 10 pages.
9. Tsai, F. T-C. and X. Li, Maximum Weighted Log-Likelihood Estimation for Hydraulic Conductivity Estimation in Alamitos Gap Area, California, submitted to *Journal of Hydrology*, 2007.
10. Tsai, F. T-C., Data Indicators, Conditional Geostatistical Parameterization, and an Efficient Adjoint State Method in Groundwater Inverse Modeling: A Hydraulic Barrier Case Study, submitted to *Advanced in Water Resources*, 2007.
11. Tsai, F. T-C. and B. Servan-Camas, Saltwater Intrusion Modeling in Heterogeneous Aquifer Using Lattice Boltzmann BGK Model, submitted to *Water Resources Research*, 2007
12. Servan-Camas B. and F. T-C. Tsai, Non-negativity Analysis of the Equilibrium Distribution Functions and Stability in the Lattice Boltzmann Method, submitted to *Journal of Computational Physics*, 2007
13. Rahman, A., F. T-C. Tsai, C. D. White, C.S. Willson, Coupled Semivariogram Uncertainty of Hydrogeological and Geophysical Data on Capture Zone Uncertainty Analysis, submitted to *Journal of Hydrologic Engineering*, ASCE, 2007
14. Elrawady, M.H., and F. T-C. Tsai., Saltwater Intrusion Barrier Development and Management in Coastal Aquifer System in Coastal Environmental and Water Quality, Proceedings of the AIH 24th Anniversary Meeting & International Conference Challenges in Coastal Hydrology and Water Quality, Edited by Y.J. Xu and V.P. Singh, Water Resources Publications, LLC, Highlands Ranch, Colorado, 421-430.

15. Li, X., and F. T-C. Tsai, Aquifer Heterogeneity Estimation and Uncertainty Analysis Using a Multi-Parameterization Method, in Examining the Confluence of Environmental and Water Concerns, Proceedings of the 2006 World Environmental and Water Resources Congress, edited by R. Graham, American Society of Civil Engineers, Reston, VA. CD version.
16. Rahman, A., F. T-C. Tsai, C. D. White, D. A. Carlson, and C. S. Willson, Geophysical Data Integration and Conditional Uncertainty Analysis on Hydraulic Conductivity Estimation, in Examining the Confluence of Environmental and Water Concerns, Proceedings of the 2006 World Environmental and Water Resources Congress, edited by R. Graham, American Society of Civil Engineers, Reston, VA. CD version.
17. Tsai, F. T-C., and X. Li, "Hydraulic Conductivity Estimation using Bayesian Model Averaging and Generalized Parameterization", American Geophysical Union 2006 Fall Meeting, San Francisco, CA, Dec 11-15, 2006. Abstract.
18. Servan-Camas, Borja, and F. T-C. Tsai, "Saltwater Intrusion Simulation in Heterogeneous Aquifer Using Lattice Boltzmann Method", American Geophysical Union 2006 Fall Meeting, San Francisco, CA, Dec 11-15, 2006. Abstract.
19. Tubbs, K., F. T-C. Tsai, C. White, G. Allen, and J. Tohline, "Numerical Investigations of Electrical Resistivity Tomography using Lattice Boltzmann Modeling and Adjoint-State Method", American Geophysical Union 2006 Fall Meeting, San Francisco, CA, Dec 11-15, 2006. Abstract. (Outstanding Student Paper Award)
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21. Servan-Camas, Borja, 2007, MS Thesis, Department of Civil and Environmental Engineering, College of Engineering, Louisiana State University, Baton Rouge, Louisiana, 77 pages.

SYNOPSIS

Title: Saltwater Intrusion Management with Conjunctive Use of Surface Water and Ground Water

Problem and Research Objectives

Saltwater intrusion in coastal aquifers is one of the major issues in coastal water resources management. The encroachment of saltwater from the sea floor is triggered by natural hydrologic processes and human-built environments. Seawater always intrudes geological formations due to the fact that seawater has slightly higher density and much higher dissolved salt concentration than freshwater. However, severe saltwater intrusion is mainly caused by the combination of droughts and excessive groundwater withdrawals. Once saltwater has invaded an aquifer, it could take significant time and cost to regain the virgin aquifer. Effective coastal saltwater intrusion management plans need the better understanding of saltwater intrusion mechanism and development of flow and transport simulation models as a decision-making tool.

In this study, we focus on two research objectives for the saltwater intrusion problem. The first research objective is to simulate saltwater intrusion in coastal aquifers using a lattice Boltzmann method. The saltwater intrusion phenomenon is described by the density-viscosity-dependent groundwater flow and mass transport equations. Our focus is on the understanding of the similarities between the lattice Boltzmann model (LBM) and the macroscopic saltwater intrusion model such that the macroscopic aquifer parameters, e.g., dispersion coefficient and hydraulic conductivity, can be properly represented by the LBM parameters. One of the challenges of using LBM is to cope with the spatial-temporal heterogeneity when particle distribution functions stream to neighboring lattice nodes. We will use the Henry problem to demonstrate the capability of our LBM to solve the saltwater intrusion in the heterogeneous aquifer.

Another challenge in real-world saltwater intrusion problems is the parameter heterogeneity estimation problem when the parameterization method is non-unique and inflexible. Therefore, the second research objective is to develop the maximum weighted log-likelihood estimation (MWLLE) and Bayesian model averaging (BMA) along with the generalized parameterization (GP) method (Tsai and Yeh, 2004; Tsai 2006) to cope with this problem in hydraulic conductive estimation. We will apply the MWLLE and BMA to a real-world case study to estimate the hydraulic conductivity in the Alamitos Gap area, California, where the Alamitos Barrier Project (ABP) has been operated for more than forty years to protect freshwater aquifers from saltwater intrusion.

Methodology

1. Density-Viscosity-Dependent Saltwater Intrusion Model

The groundwater flow equation with changes in water density and viscosity due to the presence of the dissolved salt has been formulated in terms of the freshwater pressure head (Huyakorn et al., 1987; Boufadel et al., 1999; Simpson and Clement, 2003). Using fresh groundwater head in the groundwater flow equation was suggested to improve the numerical efficiency for the case that large static pressures dominate the dynamic pressure differences (Frind, 1982). In this study, we have derived the density-viscosity-dependent groundwater flow equation in terms of fresh groundwater head:

$$\phi S_{sf} \frac{\partial h_f}{\partial t} + n \frac{\partial \phi}{\partial C} \frac{\partial C}{\partial t} = \left[\frac{\partial}{\partial x} \left(\frac{\phi}{\lambda} K_f \frac{\partial h_f}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{\phi}{\lambda} K_f \frac{\partial h_f}{\partial z} \right) + \frac{\partial}{\partial z} \left(\frac{\phi(\phi-1)}{\lambda} K_f \right) \right] + \frac{\rho_{ss}}{\rho_f} Q_{ss} \quad (1)$$

where S_{sf} is the freshwater specific storage, h_f is the fresh groundwater head, n is the porosity, K_f is the freshwater hydraulic conductivity, ρ_{ss} is the water density at the sinks/sources; and Q_{ss} is the flow rate per unit aquifer volume at the sinks/sources. $\phi = \rho/\rho_f$ is the ratio of fluid density to freshwater density. $\lambda = \mu/\mu_f$ is the fluid dynamic viscosity to the freshwater dynamic viscosity.

In general, the dissolved salt is considered as a conservative solute, which usually has very small to zero sorption and chemical reaction in the formation environment. Therefore, the salt transport is described by the advection-dispersion equation (ADE).

$$\frac{\partial nC}{\partial t} + \nabla \cdot (n\mathbf{u}C) = \nabla \cdot (nD\nabla C) + C_{ss} Q_{ss} \quad (2)$$

where \mathbf{u} is the average pore velocity vector, D is the dispersion coefficient; and C_{ss} is the salinity at the sinks/sources. We recognize that the dispersion coefficient depends on both anisotropy and flow velocity (Scheidegger, 1961; Bear, 1972). However, our current focus is on the scalar dispersion coefficient in LBM. Using a constant dispersion coefficient to study the saltwater intrusion will not destroy essential features of the problem (Henry, 1964; Pinder and Cooper, 1970; Lee and Cheng, 1974).

2. Lattice Boltzmann Model (LBM)

The discrete lattice Boltzmann model with the Bhatnagar-Gross-Krook (BGK) collision model has been introduced by Bhatnagar et al. (1954):

$$f_i' - f_i = -\frac{1}{\tau} (f_i - f_i^{eq}) + \frac{F}{N} \Delta t \quad (3)$$

where $f_i' = f(\mathbf{x} + \mathbf{c}_i \Delta t, t + \Delta t)$, $i = 1, 2, \dots, N$ are the particle distribution functions after the collision step; i represents the discretized direction; N is the number of lattice directions; $f_i(\mathbf{x}, t)$ are the particle distribution functions after the streaming step; f_i^{eq} are the equilibrium distribution functions (EDFs); τ is the relaxation parameter; F is the forcing term that represents the sinks/sources in the macroscopic equation, which is invariant of lattice directions; and Δt is the lattice time step. The lattice speed is defined as $c = \Delta x / \Delta t$, where Δx is the lattice spacing. To solve the ADE (Eq.(2)), D2Q9 EDFs are used (Chen and Doolen, 1998). Using LBM to solve the density-viscosity-dependent groundwater flow equation (Eq.(1)) has lesser numerical instability than in the ADE because the groundwater flow equation principally is a diffusion equation. Therefore, D2Q5 EDFs are sufficient for solving the groundwater flow equation with less computation demand. To cope with the density-viscosity variation in space and time and hydraulic conductivity heterogeneity, in each lattice time step we need to modify the speed of sound in the EDFs in order to take into consideration the heterogeneity effect when the particle distribution functions stream to their neighboring lattice nodes. We have found the equivalent squared speed of sound along each lattice direction to cope with the heterogeneity problem. The new EDFs for each lattice direction can be obtained.

3. The Maximum Weighted Log-Likelihood Estimation (MWLLE)

To increase flexibility of a conditional parameterization method in hydraulic conductivity estimation, Tsai and Yeh (2004) and Tsai (2006) have developed a generalized parameterization (GP) method, which is able to conditionally estimate a non-smooth random field. However, due to limited data, there may be many zonation structures and interpolation methods that are equally important according to the measured data. Combinations of these zonation and interpolation methods will result in many possible GP methods, which should be taken into consideration simultaneously in the aquifer parameter estimation and groundwater modeling. To estimate the data weighting coefficients, β (Tsai 2006), among the multiple GP methods, this study proposes the weighted log-likelihood (WLL), which combines the log-likelihood functions through the weight of each GP method:

$$\ln L_w(\beta | \mathbf{u}^{obs}) = \sum_{i=1}^M W_i \ln L(\beta | \mathbf{u}^{obs}, \theta^{(i)}) \quad (4)$$

where $\ln L_w(\beta | \mathbf{u}^{obs})$ is the weighted log-likelihood function of the data weighting coefficients given groundwater head observations \mathbf{u}^{obs} ; $\ln L(\beta | \mathbf{u}^{obs}, \theta^{(i)})$ is the log-likelihood function of the data weighted coefficients given groundwater head observations and a GP method $\theta^{(i)}$; W_i is the GP method weight, which relates to the selected GP methods and data; and M is the number of the selected GP methods. The sum of the weights is $\sum_{i=1}^M W_i = 1$.

The parsimony principle for the GP weight leads us to consider the posterior probability of a GP method conditioned on the observed groundwater head data, i.e., $W_i = \Pr(\theta^{(i)} | \mathbf{u}^{obs})$, which can be calculated in terms of the Akaike information criterion (AIC), Bayesian information criterion (BIC), Kashyap information criterion (KIC), etc. We consider the BIC in this study. The traditional Bayesian weights, especially in the real-world case study, tends to single out the best GP method and overkill other good GP methods because the GP method weights exponentially decrease with $\frac{1}{2} \Delta \text{BIC}^{(i)}$, where $\Delta \text{BIC}^{(i)} = \text{BIC}^{(i)} - \text{BIC}_{\min}$ and BIC_{\min} is the minimum BIC value among the GP methods, the traditional. A straightforward way to overcome this problem is to consider a scaled likelihood function for $\Pr(\mathbf{u}^{obs} | \beta, \theta^{(i)})$ such that a scaled Bayesian information criterion (SBIC) is resulted

$$\text{SBIC}^{(i)} = \alpha \text{BIC}^{(i)} \quad (5)$$

where α is a scaling factor. We choose $\alpha = 3/\sqrt{L}$, where L is the number of head observations. Therefore, the GP weights are determined by the following

$$W_i = \exp\left(-\frac{3}{2\sqrt{L}} \Delta \text{BIC}^{(i)}\right) / \sum_{i=1}^M \exp\left(-\frac{3}{2\sqrt{L}} \Delta \text{BIC}^{(i)}\right) \quad (6)$$

Substituting Eq.(6) into Eq.(4), the MWLLE becomes

$$\min_{0 \leq \beta \leq 1} -\ln L_w(\beta | \mathbf{u}^{obs}) = -\sum_{i=1}^M \exp\left(-\frac{3}{2\sqrt{L}} \Delta \text{BIC}^{(i)}\right) \ln L(\beta | \mathbf{u}^{obs}, \theta^{(i)}) / \sum_{i=1}^M \exp\left(-\frac{3}{2\sqrt{L}} \Delta \text{BIC}^{(i)}\right) \quad (7)$$

Once the optimal data weighting coefficients are obtained, the GP weights are also determined. Through the Bayesian model averaging (BMA) (Draper, 1995; Hoeting et al., 1999), the conditional mean and conditional covariance of the estimated hydraulic conductivity using multiple GP methods can be obtained via the BMA approach:

$$\mathbb{E}[\boldsymbol{\pi} | \boldsymbol{\pi}^{data}] = \bar{\boldsymbol{\pi}}_{GP} = \sum_{i=1}^M W_i \boldsymbol{\pi}_{GP}^{(i)} \quad (8)$$

$$\text{Cov}[\boldsymbol{\pi} | \boldsymbol{\pi}^{data}] = \sum_{i=1}^M W_i \left[\text{Cov}_{GP}^{(i)} + (\boldsymbol{\pi}_{GP}^{(i)} - \bar{\boldsymbol{\pi}}_{GP})(\boldsymbol{\pi}_{GP}^{(i)} - \bar{\boldsymbol{\pi}}_{GP})^T \right] \quad (9)$$

where $\boldsymbol{\pi}$ is the log hydraulic conductivity value. The first term in the right side of Eq.(9) is the within-GP covariance and the second term represents the between-GP covariance. The conditional estimation $\boldsymbol{\pi}_{GP}^{(i)}$ and conditional covariance $\text{Cov}_{GP}^{(i)}$ for each GP method have been derived by Tsai (2006).

Principal Findings and Significance

1. Saltwater Intrusion Modeling Using Lattice Boltzmann Method

1.1 The Henry Problem

The Henry problem (Henry, 1964) is one of the benchmark problems for validating the density-dependent groundwater flow and mass transport models, especially for the saltwater intrusion problem in coastal aquifers. The parameter values for the Henry problem are listed in Table 1.

Table 1: Parameter Values for the Henry Problem.

Parameters	Value
D : dispersion coefficient, [m ² /sec]	1.886×10^{-5}
K_f : freshwater hydraulic conductivity, [m/sec]	0.01
Q_{in} : inflow flux, [m ³ /sec-m]	6.6×10^{-5}
n : porosity, [-]	0.35
ρ_f : freshwater density, [kg/m ³]	1000
ρ_s : seawater density, [kg/m ³]	1025
C_s : seawater concentration, [kg/m ³]	35

Considering the constant concentration of salt at the seaside, Figure 1(a) shows the LBM results of the Henry problem against the Henry analytical solution revisited by Segol (1994). The 50% isochlor is almost exactly on the analytical solution. Although not shown here, the 25%, 50% and 75% isochlors agree with the Henry analytical solution revisited by Simpson and Clement (2004).

In Figure 1b, the flow field and the fresh groundwater head distribution demonstrate the seawater circulation from the sea floor (Cooper, 1964). The saltwater circulation is characterized by the interface of zero horizontal velocity (solid line) in Figure 1b. The area below the interface represents the landward flow zone, where the water is coming into the aquifer from the seaside. The area above the interface represents the seaward flow zone, where the water flows out of the aquifer. The outflow region at the seaside boundary is $1 \leq z \leq 0.43$. It is noted in Figure 1b that the fresh groundwater equipotential lines are not perpendicular to the top and bottom no-flow boundaries because of the density variation. The salt groundwater equipotential lines are orthogonal to the impermeable boundaries.

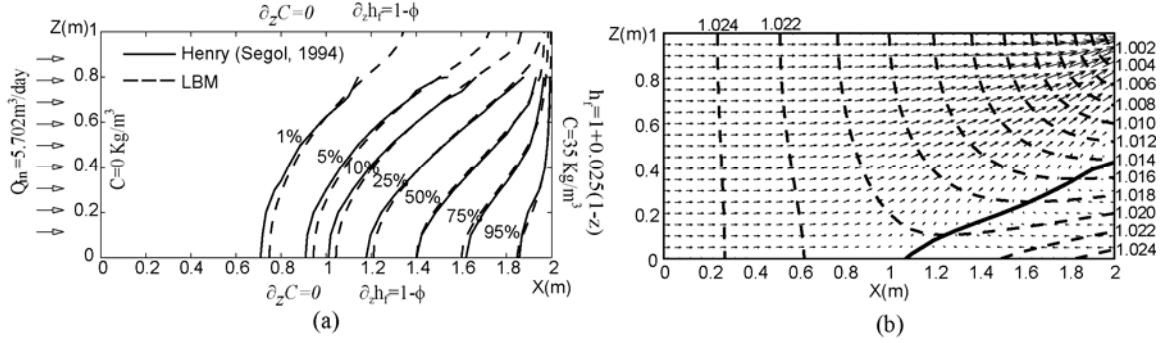


Figure 1: (a) The isochlor distribution. (b) The fresh groundwater head distribution and flow field.

1.2 Saltwater Intrusion in Heterogeneous Aquifer

Based on our literature review, we don't find any studies using the lattice Boltzmann method to simulate saltwater intrusion in the heterogeneous hydraulic conductivity (K) field. To demonstrate our LBM capability of handling the heterogeneity problem, we consider one correlated K field and one uncorrelated K fields as shown in Figure 2 to test the LBM. The mean of $\log_{10}K$ is -2. The unconditional standard deviation is 0.5m/s. The integral scale along x direction is 0.5 m and along z direction is 0.1m for correlated K. The uncorrelated K field has zero integral scale.

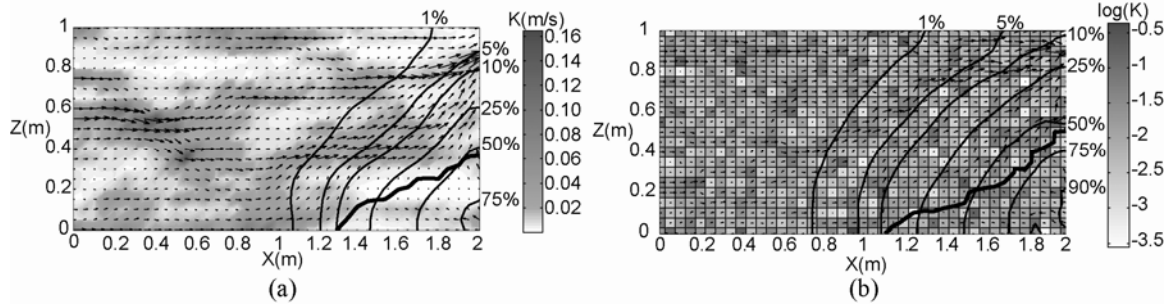


Figure 2: The isochlor distribution and flow field with (a) the correlated heterogeneous K field and (b) the uncorrelated heterogeneous K field.

The parameter values in Table 1 are also used for the heterogeneous K case. We consider the mixed Neumann-Cauchy boundary condition at the seaside. Less saltwater intrusion is observed in Figure 2a in comparison with the homogeneous case. High flow velocities are also observed at the high K areas. The isochlors in Figure 2b are very close to those for the homogeneous aquifer (not shown here). This indicates that completely random heterogeneity does not significantly change the scale of the saltwater intrusion from that predicted using the mean K value. However, the correlated K field has a significant impact on the saltwater intrusion result, which is quite different from that obtained by the mean K field.

2. Case Study: Alamitos Barrier Project, Southern California

Long-term overproduction of groundwater from the Coastal Plain aquifer in Southern California has significantly lowered the groundwater surface below sea level in extensive areas. The landward gradient from the ocean to these human-built pumping depressions has developed a condition wherein seawater has intruded into the aquifer system which is in hydraulic continuity with Pacific Ocean (Callison et al., 1991). One of the saltwater intrusion remediation actions has

been taken to protect aquifers from saltwater intrusion is the development of regional-scale freshwater barriers, which create local hydraulic ridges along the coastal line via injecting freshwater into aquifers through a series of freshwater injection wells. The Alamitos Barrier Project (ABP) is one of three major freshwater barriers in Southern California, which was constructed in 1964 and has been operated since 1966 to protect the groundwater supplies of the central basin of Los Angeles County and southwest portion of the Coastal Plain area in Orange County from the intrusion of seawater through the Alamitos gap area (Callison et al., 1991).

Groundwater flow simulation is important in order to improve the performance of the barrier operations and better the groundwater management in the Alamitos Gap area, which has 5 major aquifers, R, C, B, A, and I zones overlaying each other in this order. In collaboration with Los Angeles County Department of Public Works (LACDPW), the groundwater model is developed using the 566 groundwater head observation data from 56 head observation wells in the Alamitos Gap area and injection record for 37 injection wells from 1992 to 2002. Location of the groundwater head boreholes and injection wells are shown in Figure 3a. Figure 3a also shows the complexity of I zone. Several places in I zone are missing or merging with other aquifers. The missing and merging areas are interpreted from the log data (Callison et al., 1991). The 148 logs shown in Figure 3b determine the top and bottom elevations of I zone and hydraulic conductivity values at the log sites (Callison et al., 1991). The Seal Beach Fault forms a substantial barrier to the movement of groundwater into or out of the Central Basin for I zone. However, groundwater in I zone does flow in and out of the Central Basin through the erosion gaps in the Recent aquifer (Callison et al., 1991).

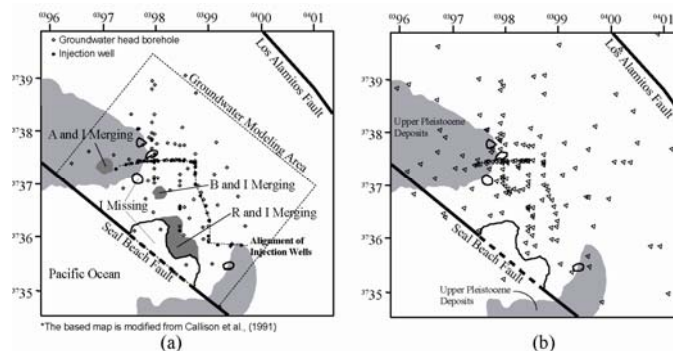


Figure 3: (a) The study area (I zone) in the Alamitos Gap area. (b) The log sites where top and bottom elevations and hydraulic conductivity values are available in I zone.

2.1 Groundwater Modeling and Parameterization

We adopt MODFLOW-2000 (Harbaugh et al., 2000) for groundwater flow simulation from July 1992 to July 2002 in I zone. Currently, we don't consider saltwater transport in this study. The hydraulic conductivity is considered to be log-normally distributed. The time-varied constant-head boundary conditions are given to the boundaries of the study area as well as the aquifer mergent areas. The 148 hydraulic conductivity values (Figure 3b) show a secondary-order stationary K field. An exponential semivariogram model $\gamma(d) = 0.3257(1 - \text{Exp}(-d/649.7134))$ is obtained, where d is the distance lag. We choose Voronoi tessellation (VT) as the zonation method (Tsai et al., 2003) and choose three interpolation methods, the natural neighbor interpolation (NN) method (Sibson, 1981; Tsai et al., 2005), inverse distance squared interpolation (ID) method (Watson and Philip, 1985; Gotway et al., 1996, and ordinary kriging

(OK) methods (Olea, 1999). Combination of the zonation and interpolation methods results in three GP methods, NN-VT, ID-VT, and OK-VT.

2.2 Data Weighting Coefficient Identification in MWLLE

The three GP methods (NN-VT, ID-VT, and OK-VT) are considered in MWLLE. The individual zonation and interpolation methods are not considered in MWLLE because they are a subset of the GP methods. The groundwater head variances are estimated as the mean of the groundwater head variances from the zonation and interpolation methods. Three GP methods use the same data weighting coefficients in this study. We use the combination of a gradient-based method and a local search method to identify the optimal data weighting coefficients. We adopt a BFGS solver (Byrd et al., 1994) to solve MWLLE. The local search method is used to improve the BFGS solution on one data weighting coefficient at a time. Moreover, the adjoint-state method was used to calculate the gradients and tremendously reduces the computation time. In each optimization step, we only need to run three times the groundwater flow equation and three times the adjoint-state equation due to three GP methods.

The optimal data weighting coefficient values and their locations over the study area for the unscaled case ($\alpha = 1$) and scaled case $\alpha = 3/\sqrt{566}$ show no distinct pattern for the distribution of the weighting coefficient values in both cases. However, some areas do show clustering weighting coefficients with value close to 1 or close to zero. The GP method shows its advantage to produce a non-smooth distribution of hydraulic conductivity. Almost one third of the β values are 0 in both cases, which will make the estimated hydraulic conductivity distribution preserve the feature of zonation distribution.

For the unscaled case in Table 2, the small difference between the maximum BIC=3764.75 at ID-VT and the minimum BIC=3755.39 at NN-VT results in the dominant GP weight $W_{NN-VT} = 89.0\%$ for NN-VT. Even though the BIC of the OK-VT method is very close to that of the NN-VT method, the GP weight for OK-VT is only 1.2%. Again, using unscaled BIC may overkill good parameterization methods. For example, both ID-VT and OK-VT have small conditional uncertainty and misfit values with respect to NN-VT, but their weights to the hydraulic conductivity estimation are extremely small, which is not logically reasonable.

The scaled case in Table 2 has similar fitting residuals, where NN-VT has the minimum BIC=3756.95 and ID-VT has the maximum BIC=3759.73. The misfit values and the conditional uncertainty in both cases are close to each other. With the scaling factor value $\alpha = 3/\sqrt{566}$, the reasonable GP weights are obtained around one-third for each GP method. The misfit values for MWLLE are obtained using the weighted hydraulic conductivity distribution, which in both cases are very close to NN-VT, the best GP method in this study. The conditional uncertainty for MWLLE in the scaled case is smaller than that in the unscaled case because the ID-VT and OK-VT have smaller conditional uncertainty and similar weights to the NN-VT. Nevertheless, the NN-VT has the height weight 35.70%.

Table 2: Identification Results of the Unscaled and Scaled Cases.

	NN-VT	ID-VT	OK-VT	MWLLE
$\alpha = 1$ (unscaled)				

BIC	3755.39	3764.75	3759.72	
Δ BIC	0	9.36	4.33	
W_i	89.0%	0.8%	1.2%	
tr(Cov), uncertainty $\alpha = 3/\sqrt{566}$ (scaled)	2013	1794	1823	1997
SBIC	3756.95	3759.73	3757.67	
Δ SBIC	0	2.78	0.71	
W_i	35.70%	30.06%	34.24%	
tr(Cov), uncertainty	2016	1806	1818	1903

2.3 Hydraulic Conductivity Estimation and Uncertainty

The weighted conditional hydraulic conductivity estimations obtained by MWLLE are shown in Figure 4. Although the reasonable GP weights are calculated in the scaled case, the difference between the hydraulic conductivity distributions obtained by the unscaled and scaled cases is visually insignificant. This is expected because the similar hydraulic conductivity distributions obtained by individual GP methods will give similar hydraulic conductivity distributions under different GP weights. However, the significance of the GP weights will be revealed on the conditional covariances and estimation uncertainty in MWLLE, which will distinguish the conditional simulation (CS) results in the groundwater modeling when different GP weights are considered.

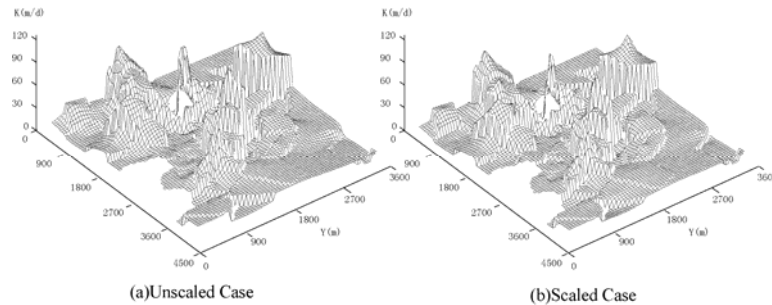


Figure 4: The estimated hydraulic conductivity distributions by MWLLE for (a) the unscaled case and (b) the scaled case.

Using the Bayesian model averaging (BMA) for the scaled case, the within-GP variance (Figure 5a), between-GP variance (Figure 5b), and the total variance (Figure 5c) are obtained for conditional simulation on hydraulic conductivity. The between-GP variance is much smaller than the within-GP variance in this case because the similar hydraulic conduction distributions are obtained by the three GP methods.

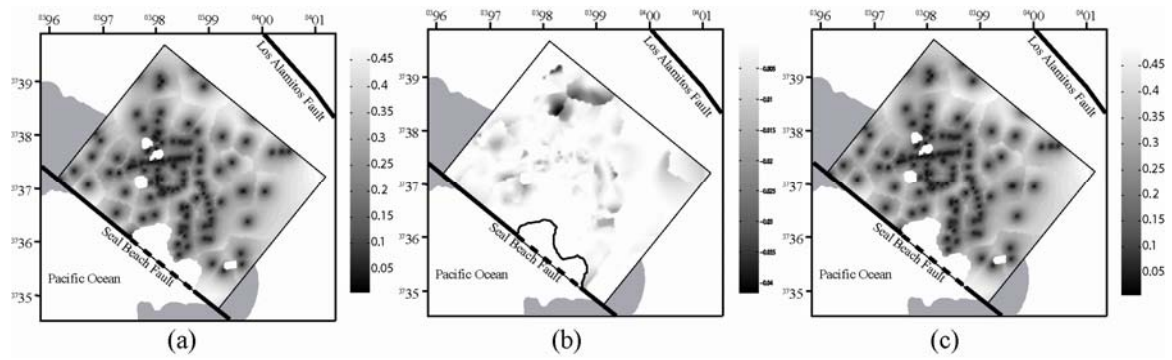


Figure 5: Conditional variance distributions (a) within-GP variance, (b) between-GP variance, and (c) total variance.

A Pilot Study on Modeling and Management of Hurricane-Accelerated Saltwater Encroachment in Coastal Aquifers

Basic Information

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SYNOPSIS

Title: A Pilot Study on Modeling and Management of Hurricane-Accelerated Saltwater Encroachment in Coastal Aquifers

Problem and Research Objectives

This research studies the potential saltwater intrusion acceleration in East Baton Rouge (EBR) Parish relating to potential groundwater rise at south of the Baton Rouge Fault due to hurricane-induced sea level rise. In EBR, there are fourteen freshwater aquifers, which are composed of sediment from very fine to coarse sand and pea- to cobble-size gravel (Meyer and Turcan, 1955, p. 21-47). Thirteen of the aquifers were originally named according to their general depth in the Baton Rouge industrial district (Meyer and Turcan, 1955, p. 12-13). Most of the aquifers have been reported the saltwater intrusion problem for more than fifty years due to excessive groundwater withdrawal. In this study, we focus on the "1,500-foot" sand aquifer, which is a major source of drink water for the Capital Area (East Baton Rouge, West Baton Rouge, East Feliciana, West Feliciana, and Pointe Coupee Parishes). Groundwater withdrawal from the "1,500-foot" sand began in 1927 (Torak and Whiteman, 1982, Table 4). In 2001, the groundwater was withdrawn with 14.5 Mgal/d in EBR (Don Dial, Capital Area Ground Water Conservation Commission (CAGWCC), written communication 2002 cited in Griffith and Lovelace, 2003). From 1940 to 2001 water levels has declined about 160 ft at well EB-168, located near the pumping center southeast of the industrial district in Baton Rouge.

The Baton Rouge Fault represents an important hydrogeologic feature. Due to the throw-down at the south side of the fault, the "1,500-foot" sand (north) connects to the "1,200-foot" sand (south). Recent studies show that the Baton Rouge Fault acts as a leaky barrier, which does not completely block the saltwater encroachment from the south side of the fault. The large cone of depression in the northern area of the fault has induced saltwater encroachment across the fault toward the pumping centers in the "1,500-foot" sand, which previously contained freshwater. Tomaszewski (1996, p. 9) showed that saltwater was present in the "1,500-foot" sand north of the fault around an area of 3.88km² in the vicinity of the Acadian Thruway in Baton Rouge. To better understand the saltwater intrusion problem around the fault, the research overriding objective aims to develop a saltwater intrusion model for the "1,500-foot" sand in East Baton Rouge Parish. We will test different levels of groundwater head rise at the south of the Baton Rouge Fault to simulate the potential sea level rise from Gulf of Mexico.

Methodology

1. Data Collection for "1,500-Foot" Sand Groundwater Flow Model Development

The study area shown in Figure 1 extends about 300 km² and includes the major part of the Baton Rouge metropolitan area. To develop the regional groundwater model, we have collected 706 groundwater observation records from 18 observation wells (see Figure 1a) for the period from January 1990 to December 2004 (15 years) through the USGS National Water Information System website. These 18 head observation wells are all in the "1,500-foot" sand of Baton Rouge Area [12115BR] north of the fault. The well EB-780A was used to determine the groundwater head in the "1,200-foot" sand for the southern boundary condition. The monthly pumping data from the 16 production wells (see Figure 1b) was provided by the CAGWCC.

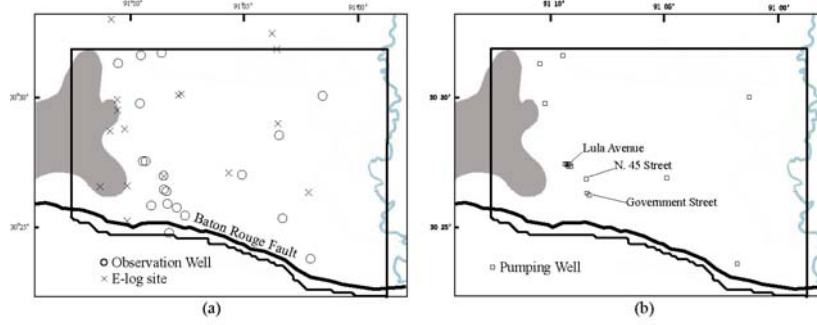


Figure 1: The study area. (a) The location of groundwater head observation wells and E-log wells. (b) The location of production wells.

We also obtained electrical resistivity data from 21 E-log wells (see Figure 1a) from USGS Water Resources Division in Louisiana. We analyzed the 21 resistivity readings and obtained the thickness of the “1,500-foot” sand as well as the average formation resistivity (R_0). The 21 thickness data were used to construct the aquifer structure. Moreover, we used the Archie’s law to interpret the formation factor ($F = R_0/R_w$) into the porosity (Archie 1942):

$$R_0 = a\Phi^{-m}R_w \quad (1)$$

where Φ is the sand porosity. The two parameters a and m are the pore geometry coefficient and the cementation factor, respectively. Typically, the pore geometry coefficient a varies between 0.62 and 2.45, and the value of cementation factor m has a range between 1.08 and 2.15 depending on the formation type (Asquith and Gibson 1982). Once the porosity was estimated, we used the Kozeny-Carmen equation (Carmen 1956) to estimate pointwise hydraulic conductivity, which relates to the formation factor:

$$K = \frac{\gamma_w}{180\mu_w} \frac{(R_0/R_w)^{-1/m} a^{3/m}}{\left((R_0/R_w)^{1/m} - a^{1/m}\right)^2} d_e^2 \quad (2)$$

The groundwater temperature in the “1,500-foot” sand was reported as $30^\circ C$. The formation water resistivity was assumed to be $R_w = 12.7$ ohm-m. The water specific weight $\gamma_w = 9.771$ KN/m³ and the dynamic viscosity $\mu_w = 7.97 \times 10^{-4}$ N.s/m² were used in this study. The average effective particle diameter $d_e = 0.22$ mm was calculated from the USGS sieve analysis data (Meyer and Turcan, 1955, page 40).

In this study, we developed a two-dimensional groundwater flow model using MODFLOW. In the next section, we estimated the pore geometry coefficient and the cementation factor in the Archie law. We also estimated storage coefficient (storativity) and hydraulic characteristic (HC) of the horizontal flow barrier (the fault). The hydraulic characteristic represents the hydraulic conductivity per unit width of the Baton Rouge Fault.

2. Groundwater Model Development

2.1 Parameter Estimation

In this study, we considered three interpolation methods (natural neighbor interpolation method (NN), inverse distance method (ID), and ordinary kriging method (OK)) as the initial step to depict hydraulic conductivity (K) heterogeneity based on the 21 pointwise K values at the E-log

sites. Given an interpolation method, Table 1 lists the estimated parameters through the inverse method.

Table 1: The Estimated Parameter Values.

Interpolation Method	Pore Geometry (a)	Cementation Factor (m)	Specific Storage (S _s)	Fault Hydraulic Characteristic (HC)	Fitting Residual $\sum_j (h_j - h_j^{obs})^2$
NN	0.81926	2.0433	2.24E-05	0.0006920	2065.03
ID	0.81819	2.0391	2.13E-05	0.0001921	1378.05
OK	0.79657	2.0790	2.26E-05	0.0006736	1898.79
Average	0.81134	2.0538	2.21E-05	0.0005191	

The ID method has the best fit to the groundwater head observations with the fitting residual 1378.05. The identified parameter (a , m , S_s , and HC) values using three different interpolation methods are close to each other. We used the averaged identified parameter values in Table 1 to further the identification of hydraulic conductivity using the generalized parameterization (GP) method in section 2.3.

2.2 Bayesian Model Averaging on Hydraulic Conductivity Estimation

This study adopted the Bayesian model averaging (BMA) method (Draper, 1995; Hoeting et al., 1999) to consider multiple parameterization methods. Let a set of parameterization methods $\Theta = \{\theta^{(p)}; p=1, 2, \dots\}$ be considered to describe the hydraulic conductivity heterogeneity for the region. BMA provides a way to consider multiple parameterization methods through a weighted average of the conditional inferential distribution. Here, the “model” is referred to the parameterization method. If Δ is a predicted quantity (scalar or vector) of interest, e.g., hydraulic conductivity, given available data \mathbf{D} , e.g., observed groundwater heads, the conditional inferential distribution $\Pr(\Delta | \mathbf{D})$ given by BMA is

$$\Pr(\Delta | \mathbf{D}) = \sum_p \Pr(\Delta | \mathbf{D}, \theta^{(p)}) \Pr(\theta^{(p)} | \mathbf{D}) \quad (3)$$

where $\Pr(\Delta | \mathbf{D}, \theta^{(p)})$ represents the conditional probability of the predicted quantity given the data and a parameterization method. $\Pr(\theta^{(p)} | \mathbf{D})$ is the posterior probability of a parameterization method given the data. Consider the equal prior probability to all of the selected parameterization methods. According to the Bayes rule, $\Pr(\theta^{(p)} | \mathbf{D})$ is

$$\Pr(\theta^{(p)} | \mathbf{D}) = \Pr(\mathbf{D} | \theta^{(p)}) / \sum_j \Pr(\mathbf{D} | \theta^{(j)}) \quad (4)$$

where $\Pr(\mathbf{D} | \theta^{(p)})$ is the likelihood of the parameterization method. The conditional probability of the predicted quantity $\Pr(\Delta | \mathbf{D}, \theta^{(p)})$ is approximated to $\Pr(\Delta | \mathbf{D}, \theta^{(p)}, \hat{\boldsymbol{\beta}}^{(p)})$, where $\hat{\boldsymbol{\beta}}^{(p)}$ is the maximum likelihood estimation (MLE) of the parameters $\boldsymbol{\beta}^{(p)}$ embedded in the parameterization method $\theta^{(p)}$ (Draper, 1995). The conditional expectation of the predicted quantity is:

$$\mathbb{E}[\Delta | \mathbf{D}] = \sum_p \mathbb{E}[\Delta | \mathbf{D}, \theta^{(p)}] \Pr(\theta^{(p)} | \mathbf{D}) \quad (5)$$

The conditional covariance of the predicted quantity is:

$$\begin{aligned} \text{Cov}[\Delta | \mathbf{D}] &= \sum_p \text{Cov}[\Delta | \mathbf{D}, \theta^{(p)}] \Pr(\theta^{(p)} | \mathbf{D}) \\ &+ \sum_p \left(\mathbb{E}[\Delta | \mathbf{D}, \theta^{(p)}] - \mathbb{E}[\Delta | \mathbf{D}] \right) \left(\mathbb{E}[\Delta | \mathbf{D}, \theta^{(p)}] - \mathbb{E}[\Delta | \mathbf{D}] \right)^T \Pr(\theta^{(p)} | \mathbf{D}) \end{aligned} \quad (6)$$

The first term at the right side of Eq.(6) represents the within-parameterization covariance for individual parameterization methods. The second term represents the between-parameterization covariance.

2.3 Generalized Parameterization for Hydraulic Conductivity Estimation

This study adopted the generalized parameterization method (Tsai and Yeh, 2004; Tsai, 2006) to overcome the inflexibility problem in the traditional parameterization method:

$$\pi_{GP}(\mathbf{x}_0 | \mathbf{x}^{data}) = \sum_{\substack{j=1 \\ j \neq k(\mathbf{x}_0)}}^m \phi_j \left(\pi_j - \pi_{k(\mathbf{x}_0)} \right) \beta_j + \pi_{k(\mathbf{x}_0)} \quad (7)$$

where π_{GP} is an estimator for the hydraulic conductivity field. We considered $\pi = \ln K$, the logarithmic value of hydraulic conductivity. $\beta_m = \{\beta_j, j=1, 2, \dots, m\}$ are the data weighting coefficients of the m sample sites, which values are bounded between 0 and 1. The Voronoi tessellation (VT) was used as a zonation method in Eq. (7). Readers are referred to Tsai (2006) for detailed explanation on Eq. (7) and the GP method. The conditional covariance using GP for a pair of two locations \mathbf{x}_p and \mathbf{x}_q is (Tsai, 2006):

$$\begin{aligned} \text{Cov}_{GP}[\mathbf{x}_p, \mathbf{x}_q | \mathbf{x}^{data}] &= \sum_{\substack{i=1 \\ i \neq k(\mathbf{x}_p)}}^m \sum_{\substack{j=1 \\ j \neq k(\mathbf{x}_q)}}^m \beta_i^p \beta_j^q \phi_i^p \phi_j^q R(\mathbf{x}_i, \mathbf{x}_j) - \sum_{\substack{i=1 \\ i \neq k(\mathbf{x}_p)}}^m \beta_i^p \phi_i^p R(\mathbf{x}_i, \mathbf{x}_q) \\ &- \sum_{\substack{j=1 \\ j \neq k(\mathbf{x}_q)}}^m \beta_j^q \phi_j^q R(\mathbf{x}_p, \mathbf{x}_j) + R(\mathbf{x}_p, \mathbf{x}_q) \end{aligned} \quad (8)$$

where $R(\square)$ is the function of the semivariograms.

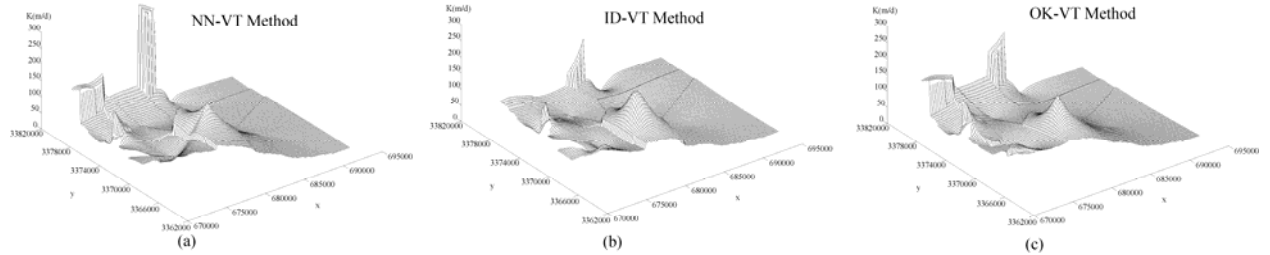


Figure 2: The identified hydraulic conductivity distributions using three GP methods (a) NN-VT, (b) ID-VT, and (c) OK-VT.

The optimal data weighting coefficients in each method were identified through the inverse method. Figure 2 shows and identified hydraulic conductivity distributions using three GP methods.

A scale factor $\alpha = 3/\sqrt{706}$ was considered in the BMA in order to avoid overkilling good interpolation methods (Tsai and Li, 2007) when we combined the three K distributions in Figure 2. The scaled Bayesian information criterion (SBIC) was used as the multiplication of the scale factor and BIC to calculate the posterior probabilities (Eq.(4)). The groundwater head variance

σ_h^2 was estimated from the fitting residuals based on the four parameterization methods (NN, ID, OK, and VT). Table 2 lists the identified results using the optimal data weighting coefficients.

Table 2: The GP and BMA Results.

GP methods	NN-VT	ID-VT	OK-VT	BMA
$Q = \sum_j [(h_j - h_j^{obs}) / \sigma_h]^2$	481.64	438.76	464.97	441.21
SBIC	310.84	306	308.96	
Δ SBIC	4.84	0	2.96	
Posterior Probability, $\Pr(\theta^{(p)} \mathbf{D})$	6.75%	75.96%	17.29%	
tr(Cov)	5344.5	5574.2	5172.7	5666.6

The ID-VT method has the lowest weighted fitting residual, $Q = 438.76$. Using the BMA, we have $\Delta = \pi^{data} = \ln K^{data}$ and $\mathbf{D} = \mathbf{h}^{obs}$. We found that ID-VT has the highest posterior probability 75.96% according to Eq.(4). NN-VT is relatively insignificant to the hydraulic conductivity estimation due to the low posterior probability. Using Eq.(5), BMA obtains the hydraulic conductivity distribution shown in Figure 3(a). The groundwater head distribution for April 2001 is shown in Figure 3(b) using the K distribution in Figure 3(a).

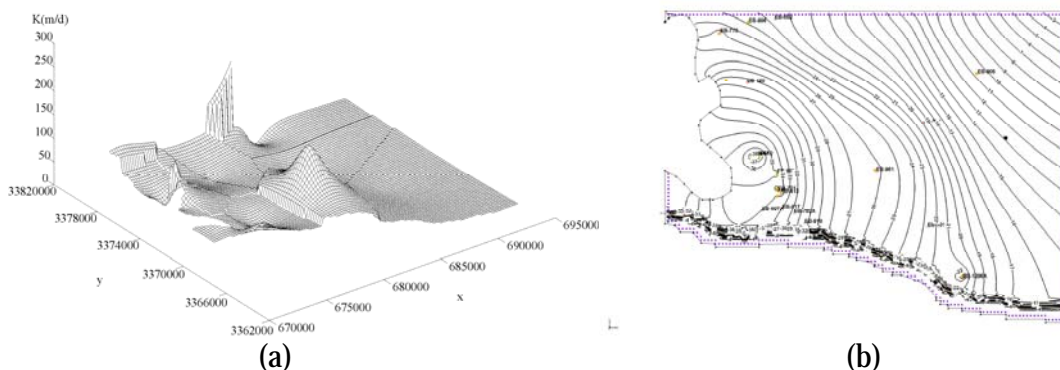


Figure 3: (a) The hydraulic conductivity distribution using BMA. (b) The groundwater head distribution for April 2001.

The uncertainty of the estimated hydraulic conductivity was calculated based on the trace of the conditional covariance matrix using Eq.(8). Table 2 shows that OK-VT has the lowest estimation uncertainty. However, the estimation uncertainties from the three GP methods and the BMP method are close to each other. The conditional variances of the hydraulic conductivity using Eq.(6) are shown in Figure 4. The within-variance is much higher than the between-variance.

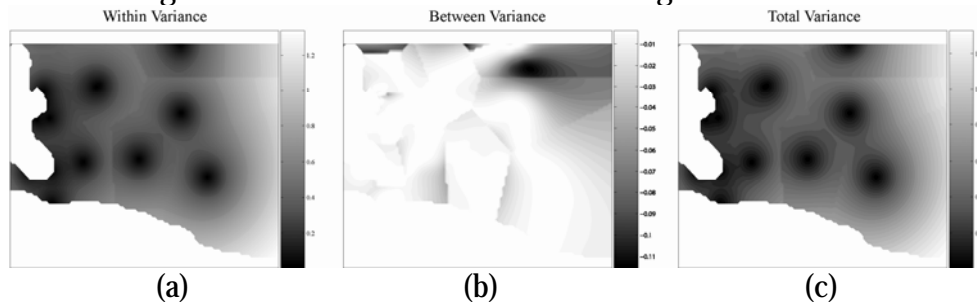


Figure 4: The conditional variance distributions for (a) the within-variance, (b) the between variance, and (c) the total variance.

2.4 Hydraulic Characteristic (HC) Estimation of Baton Rouge Fault

Another approach to estimate the hydraulic characteristic (HC) of the Baton Rouge Fault is to consider the influence of the groundwater heads at EB-917 on those at EB-780A through the fault. EB-780A and EB-917 are separated by the Baton Rouge Fault with a distance of 2,003 meters shown in Figure 5(a). Again, EB-780A screens the "1,200-foot" sand aquifer and EB-917 screens the "1,500-foot" sand. These two sands are partially connected at the fault plane. We considered a one-dimensional groundwater flow problem as shown in Figure 5(a), where we set EB-917 as a time-varied constant head boundary condition. We gave a no-flow boundary at the other end, which is far from the EB-780A and has no effect on the identification result. We identified the HC value of the fault to be $0.000155 \text{ day}^{-1}$. The calculated groundwater heads against the observed heads at EB-780A are shown in Figure 5(b). This HC value is close to that identified by the ID method and is in the same order of the magnitude to the average HC in Table 1. It is noted that due to lack of data a homogenous HC throughout the fault was considered in the groundwater model.

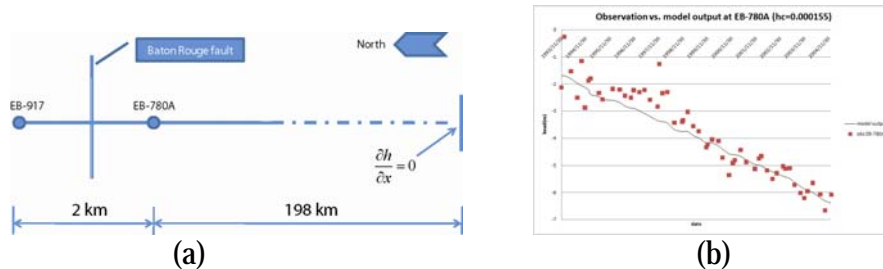


Figure 5: (a) The one-dimensional groundwater model. (b) The calculated vs. and observed groundwater head data at EB-780A.

Principal Findings and Significance

1. The Connector Well, EB-1293

The groundwater model also incorporated the effect of the connector well, EB-1293. The connector well was operated in 1998 as an initial test of a recharge barrier to mitigate saltwater encroachment in the "1,500-foot" sand. CAGWCC installed EB-1293 between the municipal supply wells on Government Street and the freshwater-saltwater interface in the "1,500-foot" sand. The connector well, EB-1293, connects the "800-foot" and "1,500-foot" sands such that "800-foot" sand recharges groundwater into "1,500-foot" with a recharge rate around 500 gallons per minute (CAGWCC Newsletter, January 2002). The groundwater model is able to investigate the effectiveness of the connector well on raising the potentiometric surface around EB-1293 and deflect the advance of the saltwater away from the municipal supply wells at the Government Street.

In the first step, we used EB-1293 groundwater data from USGS as a time-varied constant head boundary condition in the model. Figure 6(a) shows a significant over-predicted groundwater head in EB-917 after the connector well head was added to the model. We suspected that the real EB-1293 groundwater data might not be as high as reported. Instead, we considered EB-1293 as a recharge well with a constant recharge rate $2200 \text{ m}^3/\text{d}$. In Figure 6(b), the model results show no significant differences between the calculated and observed head data in EB-917. Again, a

constant drift (around 7 meters) between the calculated and observed groundwater heads at EB-1293 shown in Figure 6(c) implies that a systematic recording error or a datum error might occur in the EB-1293 data. Nevertheless, the groundwater flow model shows that the connector well does raise the groundwater head around it. In the next section, we demonstrate the potential that the connector well is able to mitigate saltwater intrusion in the “1,500-foot” sand.

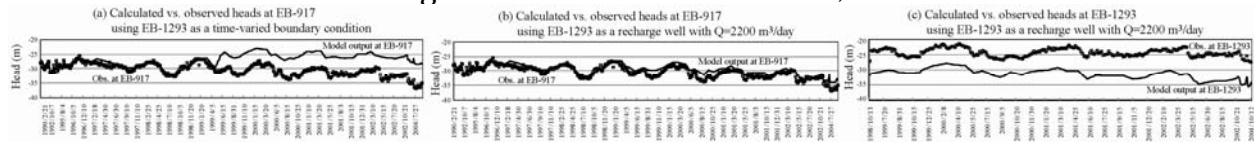


Figure 6: (a) Calculated vs. observed heads at EB-917 using EB-1293 as a time-varied head boundary condition. (b) Calculated vs. observed heads at EB-917 using EB-1293 as a recharge well with 2200 m³/day recharge rate. (c) Calculated vs. observed heads at EB-1293 using EB-1293 as a recharge well with 2200 m³/day recharge rate.

2. Saltwater Intrusion Simulation for 90 Years

At this point, a calibrated groundwater flow model has been completed. In the next step, we want to simulate saltwater intrusion based on the 15-year simulated groundwater heads between year 1990 and 2004 in order to understand the basic mechanism how saltwater intrudes the “1,500-foot” sand. We didn’t calibrate the transport model, but assumed the porosity to be 0.3, longitudinal dispersivity to be 75 m, and the ratio of transverse to longitudinal dispersivities to be 0.1 in the transport model. We used MT3DMS to simulate the saltwater intrusion. We recognized the density effect on the groundwater flow and will consider using SEAWAT in the future study.

The initial salt concentration at January 1990 was assumed to be clean in the northern area of the fault and 1000 ppm (parts per million) of salinity in the southern region of the fault. Figure 7(a) shows the initial salt concentration distribution. We repeated the 15-year groundwater heads six times in order to simulate a 90-year saltwater intrusion. From the simulation results in Figure 7(b)-(g), we observe the following points:

- (1) The saltwater has strong lateral transport along the Baton Rouge Fault once it crosses the fault due to the huge cone of depression formed by the production wells at Lula Avenue.
- (2) The salt dispersion width at the region east of EB-918 is around 850 meters from the fault and is almost unchanged after 30 years simulation. This also implies the strong lateral transport along the fault and weak dispersion northward in this region.
- (3) The salt accumulates at two spots. One spot is at 600 meters the southeast of EB-807A. From this spot, a higher salt concentration migrates clockwise across EB-807A toward Lula Avenue pumping center. The other spot is at 2200 meters southwest of EB-807A.
- (4) The 100 ppm isochlor (the front line) migrates to a production well adjacent to the observation well EB-1295A within 45 years.
- (5) The 100 ppm isochlor first touches down EB-918 and few years later it touches EB-807A. Due to the clockwise movement of the salt along the fault from the east, the concentrations in EB-807A and EB-918 are similar.
- (6) The 100 ppm isochlor touches EB-917 and EB-792A almost at the same time. The simulation results show that the concentrations in EB-917 and EB-792A are similar due to the clockwise movement of the salt along the fault.
- (7) After 90 years, the 100 ppm isochlor reaches the Lula Avenue pumping center.

(8) Figure 7(e) shows a salt movement toward the Government Street pumping center within 60 years. As shown in Figure 7 (f) and (g), the connector well does push the saltwater away from south of the Government Street pumping center.

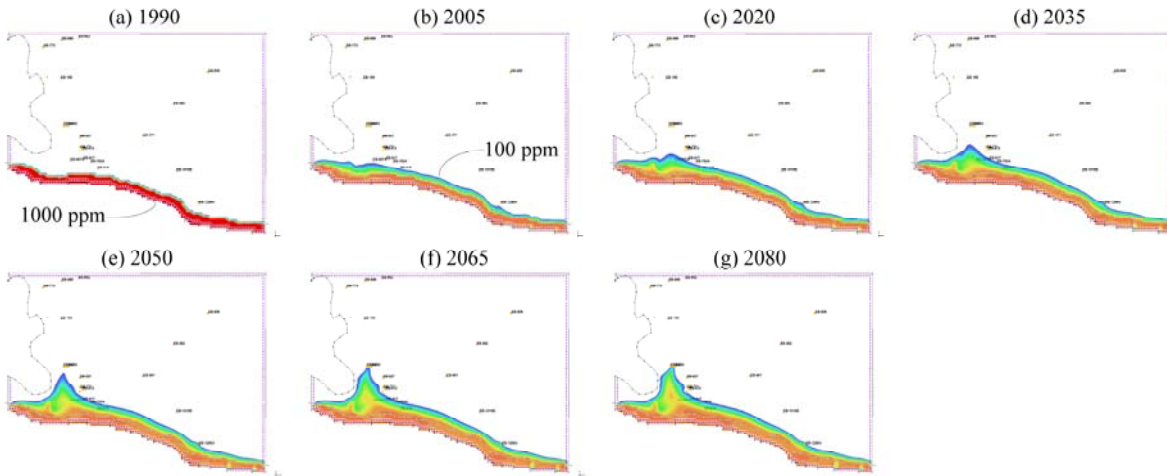


Figure 7: The 90-year saltwater intrusion simulation results.

In summary, although the saltwater intrusion is close to the Government Street pumping center, the simulation results show that saltwater will reach the Lula Avenue pumping center before it reaches Government Street. More observation wells are suggested at the west of EB-807A to monitor the saltwater mitigation.

3. Saltwater Intrusion Enhancement with Groundwater Rise at South of the Fault

To simulate the hurricane-induced groundwater rise at south of the fault, we artificially raised the groundwater head at the south boundary with additional 2, 4, and 6 meters high and rerun the 90-year saltwater intrusion model. We simulated the worst-case scenarios that the raised heads would stay for 90 years.

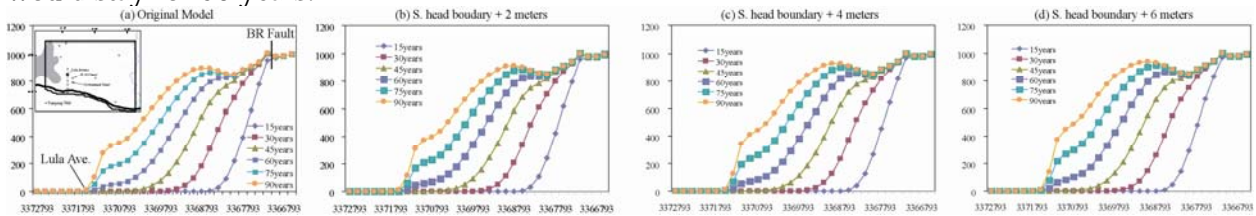


Figure 8: Breakthrough curves for different south groundwater head boundary conditions.

Figure 8 shows the saltwater encroachment along a vertical line (see Figure 8a) through the Lula Avenue pumping center. Figure 9 compares the breakthrough curves at 15 and 90 years. We conclude that the breakthrough curves are not significantly changed for the first 15 years when groundwater heads were raised. However, additional intrusion of salt concentration is observed after 30 years. Nevertheless, the arrival time of saltwater to Lula Avenue does not change significantly even though the groundwater head increases south of the fault.

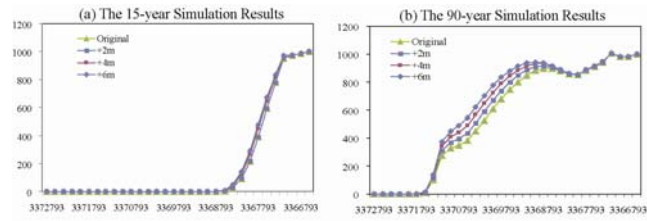


Figure 9: Breakthrough curve comparisons for different south groundwater head boundary conditions at (a) 15 years and (b) 90 years.

Assessment of the Impact of Hurricane Katrina's and Rita's storm surges on the Southern Hills Aquifer System in Southern St. Tammany and Tangipahoa Parishes

Basic Information

Title:	Assessment of the Impact of Hurricane Katrina's and Rita's storm surges on the Southern Hills Aquifer System in Southern St. Tammany and Tangipahoa Parishes
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Principal Investigators:	Thomas P Van Biersel, Douglas alan Carlson, Loyd Riley Milner

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2. Carlson D., T. Van Biersel and L.R. Milner, under revision, Aquifer purging results for a well impacted by a storm surge from a hurricane, submitted to Ground Water.
3. Van Biersel T., D. Carlson and L.R. Milner, 2007, Impact of Storm Surges on the Groundwater Resources of Southern St. Tammany Parish one-year after Hurricanes Katrina and Rita, Transaction of the Baton Rouge Geological Society's 1st Annual Louisiana Groundwater Symposium vol. 1, p. 108-114.

Title: Assessment of the impact of hurricane Katrina's and Rita's storm surges on the Southern Hills Aquifer System in southern St. Tammany and Tangipahoa Parishes

PROBLEM AND RESEARCH OBJECTIVES

On August 29th and again on September 21st, 2005, the shoreline communities located on the north shore of Lake Pontchartrain, an estuarine lake connected to the Gulf of Mexico, were flooded by hurricane storm surges (Fig. 1). The surges displaced the saline water from the lake onto the surrounding coastal lowland. Many of structures lining the shoreline were damaged or destroyed by the surging waters. Of those, many of the residences and businesses obtained their drinking water from adjacent water wells drilled in shallow aquifers. The shallow aquifers (<500-feet deep) along the north shore of Lake Pontchartrain (Fig. 2) are predominantly used by older residential water wells. The shallow aquifer is identified by Griffin (2003) as being part of the Norco Aquifer (aka Upland Terrace Aquifer), which is hydraulically connected with the deeper Gonzales-New Orleans Aquifer, and Upper Ponchatoula Aquifer (Nyman and Fayard, 1978). Although few new wells have been completed in the Norco Aquifer, the other two deeper aquifers are regularly used for domestic water supply. In addition, a review of drillers' well logs from the Louisiana Department of Transportation and Development (DOTD) shows that the surficial clay protecting the shallow aquifer is thinnest/non-existent in the vicinity of Bayou Lacombe. The storm surge at Bayou Lacombe was observed to be ≤ 5 feet above ground, and extended ~ 2 miles inland. Near Slidell, the surge was >10 feet, and extended in excess of 3 miles inland.

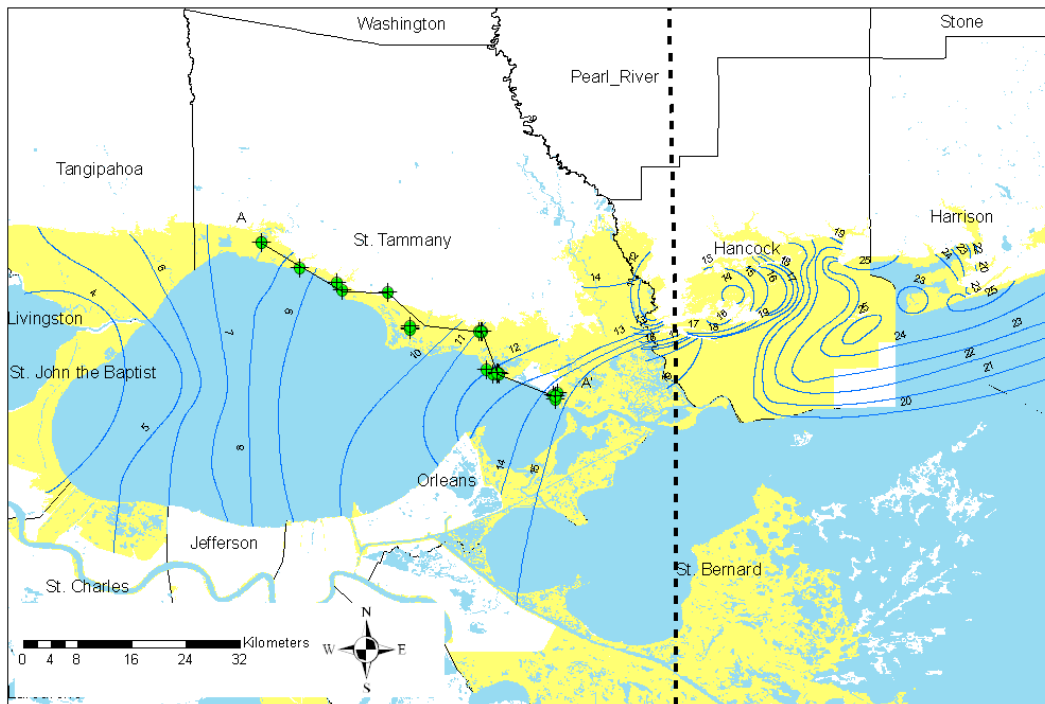


Figure 1: Extent of flooding (shaded in yellow with blue elevation contours) caused by the storm surge of Hurricane Katrina (data source: Federal Emergency Management Agency (FEMA))

2006; Anderson and Brakenridge 2005; and Carroll et al. 2005). The bold dashed line represents the path of Hurricane Katrina (modified from Van Biersel et al, 2007a)

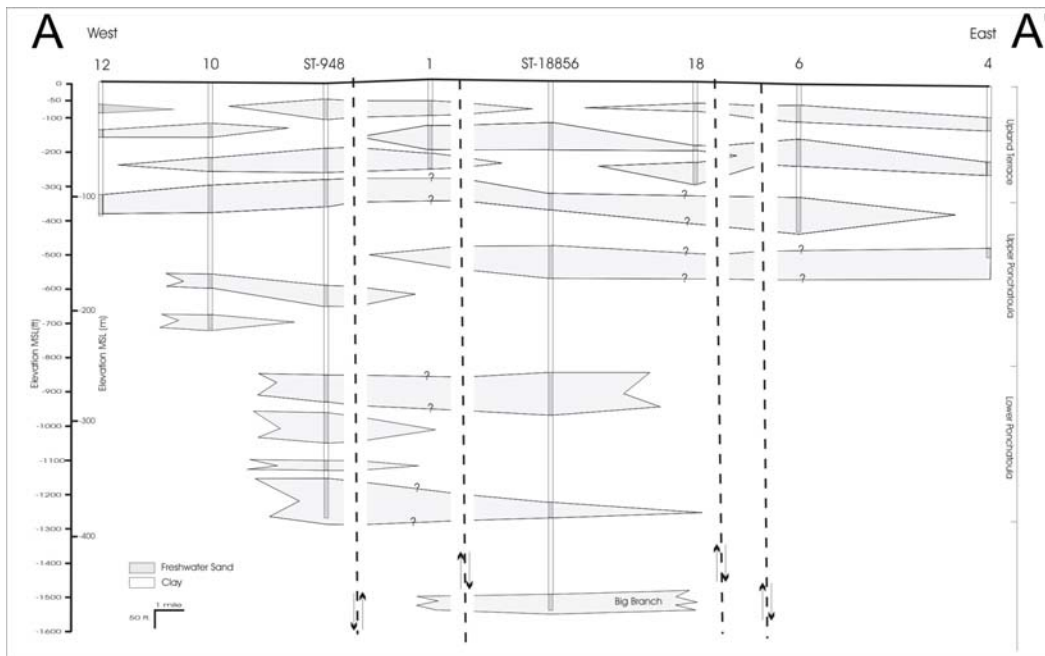


Figure 2: Geologic cross-section of the aquifers along the north shore of Lake Pontchartrain. The cross-section locator is located on Fig. 1 (modified from: Van Biersel et al, 2007b).

As the buildings were damaged or destroyed, so were the associated plumbing, pumps and well housings and casings. These wells became open conduits between the surging lake water of non-drinking water quality and the subsurface aquifer. Saline lake water and surface contaminants were introduced into the aquifer, impacting an important source of drinking water supply. The goal of this research is to assess the short- and long-term implications of hurricane Katrina's and Rita's storm surges on the shallow aquifer system along the north shore of Lake Pontchartrain.

Groundwater sampling and field observations conducted in September and October, 2005 by the PI and CoPIs, in collaboration with the Louisiana Dept. of Environmental Quality (DEQ) and the U.S. Geological Survey (USGS), have shown that surge water has entered the aquifer through water wells damaged during the storm (Van Biersel et al, 2006). Analyses of the groundwater show decreased Ca/Mg ratio from a pre-Katrina value of ~3.8 (average historical value for the Upper Ponchatoula aquifer in St. Tammany parish) to a post-Katrina value of ~1.3 (wells sampled). In addition, chloride concentrations increased from a pre-Katrina of ~8.4 mg/L (average historical value for the Upper Ponchatoula aquifer in St. Tammany parish) to a post-Katrina value up to 6,449 mg/L (wells sampled). The low Ca/Mg ratios and elevated chloride concentrations are indicative of saltwater intrusion. In addition, most wells were contaminated by coliform bacteria, including, in some cases, *Enterococcus* and *Escherichia coli* (*E. coli*).

Bacterial contamination is a greater risk to public health than the presence of elevated seawater constituents, such as chloride. Chloride does have a U.S. Environmental Protection Agency (EPA) National Secondary Drinking Water Standard (non-enforceable nuisance guidelines) of 250 mg/L. However, elevated chloride concentration can be detected by well owners relatively easily by taste. This does provide an early detection mechanism for identifying

a change in water quality. The presence of waterborne bacteria can only be found by testing the water for specific microorganisms. In Louisiana, public water supply systems are regularly tested by the Louisiana Department of Health and Hospitals (DHH); however, private residence wells are not. It is the responsibility of the well owners to test his/her water supply routinely. However, after Katrina, 263 residences and/or businesses submitted water samples to the DHH for bacterial analysis. Fecal coliforms/*E Coli* was present in 2.3% of the samples, and total coliforms in 28.9% of the samples (DHH, 2006).

In addition, the lake water that stagnated for an extended period of time in the areas affected by the two storm surges, overtime, is percolating downward through the subsoil in the form of a saltwater-rich pulse. Overtime, this pulse is diluted with the addition of fresh rainwater to the substrate, and may reach the shallowest aquifer system (Fig. 2), resulting in additional degradation of the water supply for residential wells.

The primary scope of this project was to determine the extent, both aerially and vertically, of contamination in the aquifers affected by the storm surge along the north shore of Lake Pontchartrain in St. Tammany and Tangipahoa Parishes. This is done by sampling water wells, interviewing well owners, combining information gathered by several agencies after the storm, and performing geophysical surveys. Sixteen water wells were monitored for the duration of the study, to determine if bacterial contamination will be a recurring issue for the water wells affected by the storm. The objectives of this study were as follows: (1) to determine the aerial extent of aquifer contamination by lake water along the north shore of Lake Pontchartrain; (2) to determine the vertical extent of storm water migration in areas where the surficial clay is thin or absent; and (3) to determine whether there will be a recurrence of bacterial contamination in the water wells overtime.

METHODOLOGY

The researchers collected geohydrological data from Louisiana Geological Survey (LGS), USGS and DOTD, storm surge data from the Dartmouth University Flood Observatory, the University of Maryland global Land Cover Facility, the USGS and FEMA, geophysical soundings, and groundwater samples. In addition, DHH provided bacteriological data.

Geophysical soundings were collected, using the LGS's Super MiniRes Earth Resistivity (ER) meter. The ER method was selected in this case because it uses an electrical pulse to measure the resistance of the earth material(s) between electrode arrays. The method is neither intrusive nor destructive, and can be used repeatedly at the same location without requiring additional markings. The data was modeled to determine the geological make-up of the subsurface and salinity of the interstitial water. ER soundings were performed at the Fairview Riverside State Park and Fontainebleau State Park. No suitable location was found at Big Branch Marsh National Wildlife Refuge. ER was used in areas of the study where the shallow aquifer is within ~200 feet of the surface, and had been submerged during the storm surge. The selection of data collection sites for ER soundings was made based upon access availability, and the lack of human interferences (e.g. overhead or buried electrical wires, pipelines, cables, etc). The geophysical data was downloaded into a personal computer, and plotted in profiles to verify that a sufficient depth had been reached, and/or to determine if saltwater had been encountered. The analysis of the modeled ER data, in corroboration with groundwater samples and available geologic logs (driller's logs were available at the DOTD) had the advantage of providing data on both the geology of the aquifer and the salinity of the groundwater.

Groundwater samples were collected by the PIs after obtaining permission from the property owners. The water wells were purged for approximately 20 minutes prior to collection of an unpreserved 250-mL bottle for anions, and a field-filtered and HNO₃-preserved 250-mL bottle for cations. A 100-mL water sample was passed through a 0.45µ membrane filter. The filter was then be placed in a Petri dish with m-ColiBlue 24 broth media and placed in the portable incubator. The total coliform analysis (and *E Coli*) was quantified at LGS’s lab. The water was field-tested using LGS’s portable meters for specific conductance (e.g. salinity), temperature and pH. The sample bottles were stored and cooled to 4°C in the field, and transferred to a refrigerator in the lab. The water samples were analyzed in the lab, using LGS’s spectrophotometer for anions (Cl, B, F, SO₄, PO₃, CO₃ and NO₃). Furthermore, the water samples was tested using Prof. Gambrell of the LSU Dept. of Wetland Biochemistry’s Varian (model MPX) Inductively Coupled Plasma – Optical Emission Spectrometer (ICP-OES) for cations of interest (e.g. Al, As, Bo, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, Rb, Si, Sr, Zn).

PRINCIPAL FINDINGS AND SIGNIFICANCE

The groundwater sampling results indicate that water wells recovered to pre-Katrina status relatively quickly under normal use. Most wells were sampled after a water well contractor had rehabilitated the well (e.g. plumbing repair, pump repair/replacement, flushing and chlorination). Tests showed little or no significant changes, which cannot be explained by seasonal variation during the testing period. Of the 25 wells sampled (Table 1), only three wells (#4, #8 and #14) had results which included the impacted water in the casing, as indicated by changes in the specific conductance (SC) recorded in the field (Fig. 3).

Table 1: Summary of well construction information

Well #	Depth (m)	Screen Interval (m)	Aquifer Code	Casing Diam. (cm)	Pump Type	Vented (Y/N)	Surge Depth (m)	# of Smpls	Location	Comments
1	79	70-79	112UPTC	10	Sub.	yes	0	1	Mandeville	Not flooded
2	178	172-178	112PNCLU	5	Jet	no	1.5	1	Lacombe	
3			112PNCLU	5	Jet	no	1.5	15	Lacombe	
4	152	146-152	112PNCLU	10	Sub.	yes	4.0	20	Slidell	not rehabilitated
5	82	76-82	112UPTC	5	Jet	no	4.0	15	Slidell	
6	61		112UPTC	5	none	yes	3.0	15	Slidell	Flowing artesian
7	131	125-131	112PNCLU	10	Sub.	yes	3.0	14	Slidell	no longer vented
8	116	110-116	112UPTC	5	Jet	no	3.0	4	Slidell	
9	83	80-83	112UPTC	5	Jet	no	0.3	15	Slidell	
10				5	Jet	no	1.8	1	Madisonville	
11	122	116-122	112PNCLU	10	Sub.	no	1.5	1	Madisonville	
12	119	110-119	112PNCLU	15	Drive	yes	0.9	1	Madisonville	
13	119	113-119	112UPTC	5	Jet	no	3.4	15	Slidell	
14	140	134-140	112PNCLU	10	Sub.	yes	3.0	24	Slidell	no longer vented
15	162	155-162	112PNCLU	10	Sub.	yes	4.0	12	Slidell	
16	81		112UPTC	8	Jet	no	4.0	14	Slidell	
17	84	78-84	112UPTC	5	Jet	no	0.3	14	Slidell	
18	90	87-90	112UPTC	5	Jet	no	0.3	14	Slidell	has filter
19	184		112PNCLU	10	Sub.	yes	1.5	14	Lacombe	
20			112PNCLU	5	Jet	no	1.5	13	Lacombe	
21	91		112PNCLU	10	Sub.	no	1.8	14	Mandeville	

22	134	125-134	112PNCLU	10	Jet	yes	1.5	14	Mandeville	Flowing artesian
23	107		112UPTC	5	Jet	no	3.0	1	Slidell	
24			112UPTC	5	Jet	No	3.0	1	Slidell	
25	512		120ABIT	15	none	Yes	<0.3	2	Mandeville	Flowing artesian

Note: modified from Van Biersel et al, 2007a

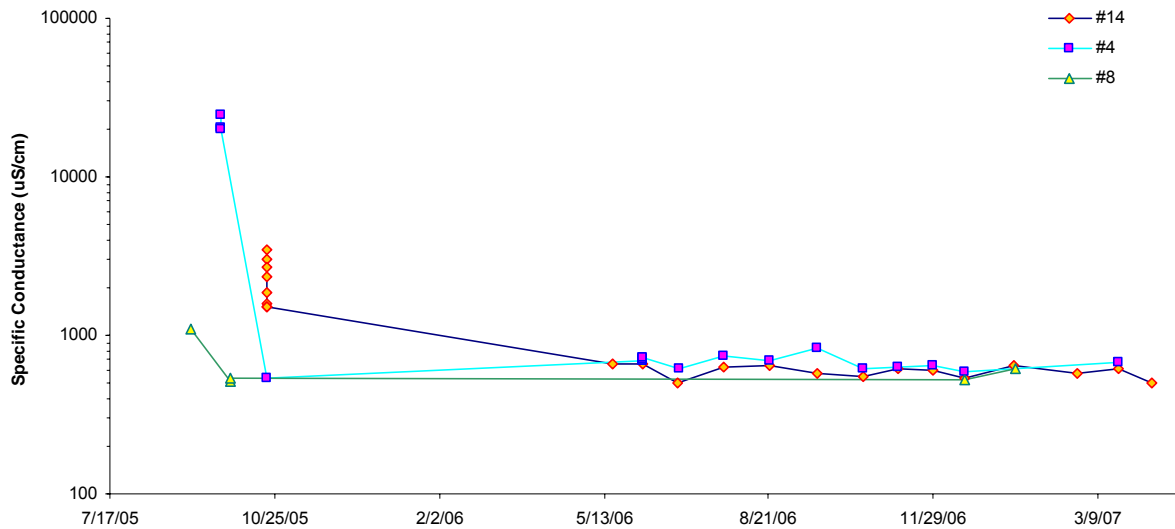


Figure 3: Specific conductance results for the three wells (#4, #8 and #14) whose impacted casing water was tested (modified from Van Biersel et al, 2007a)

Parameters indicative of seawater intrusion, including the calcium (Ca) – magnesium (Mg) ratio, as well as sodium (Na), chloride (Cl), silica (Si) and boron (Bo) concentrations, show the same trend overtime as the SC (Fig. 4). Statistical comparison of the results (Van Biersel et al, 2006; and Van Biersel et al, 2007b) indicated that samples collected after the storm surge exhibit a small to significant deviation from pre-hurricane values. This is particularly true for SC, Si, the Cl/Si ratio, and, to a lesser extent, of Ca.

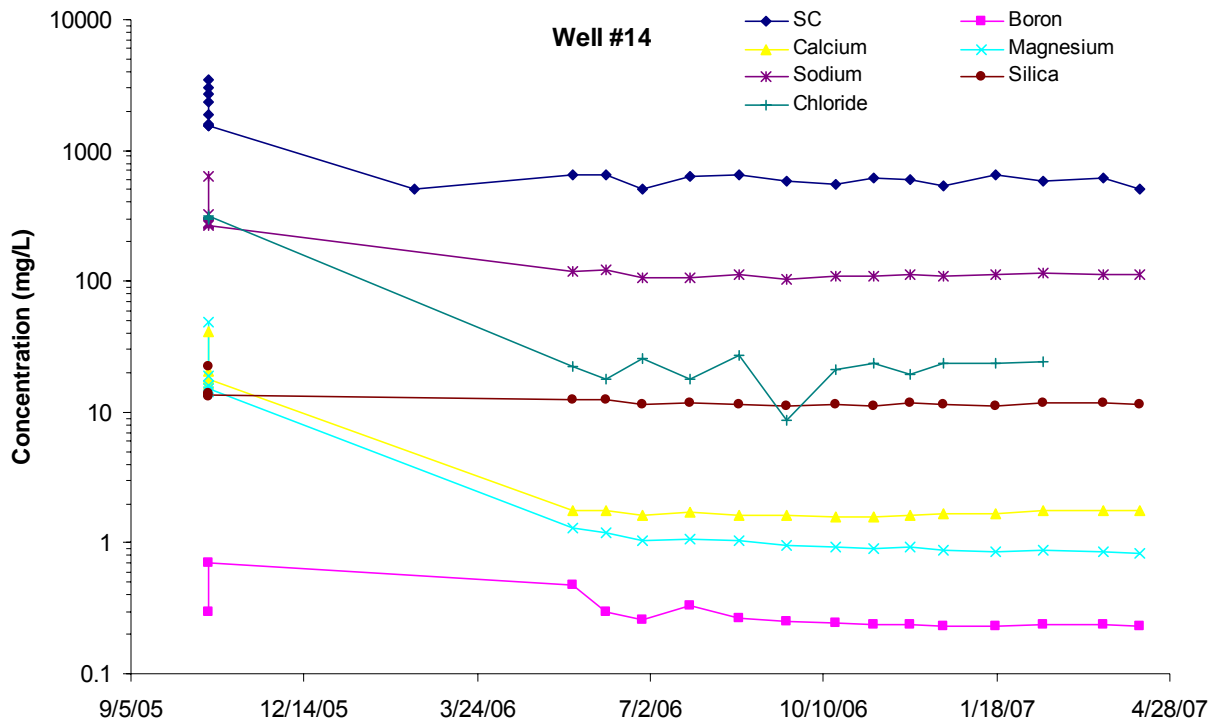


Figure 4: Cations measured in well #14 exhibiting substantial variation as a result of the storm surge

Bacterial testing of the groundwater samples (Fig. 5 and 6) indicates that most water wells remain free of total coliform and E coli bacteria after the rehabilitation of the well, with the exception of six wells. Three wells (#5, #20 and #21) had detectable concentration which could be related to likely field contamination from airborne particulates (e.g. dusty conditions caused by construction equipment) at the time of sampling. One well (#4) was not rehabilitated (e.g. chlorinated), and showed that total coliform was detected in 40% of the samples collected. Two wells (#7 and #15) had repeated total coliform bacteria detected in the samples; although both wells had been rehabilitated more than once. It should be noted that well #4, #7, #14 and #15 (Table 1) have a 10 cm (4") inner diameter casing (e.g. riser) equipped with submersible pumps, and a vented well cap (wells #7 and #14 were modified after the storm to remove the vents).

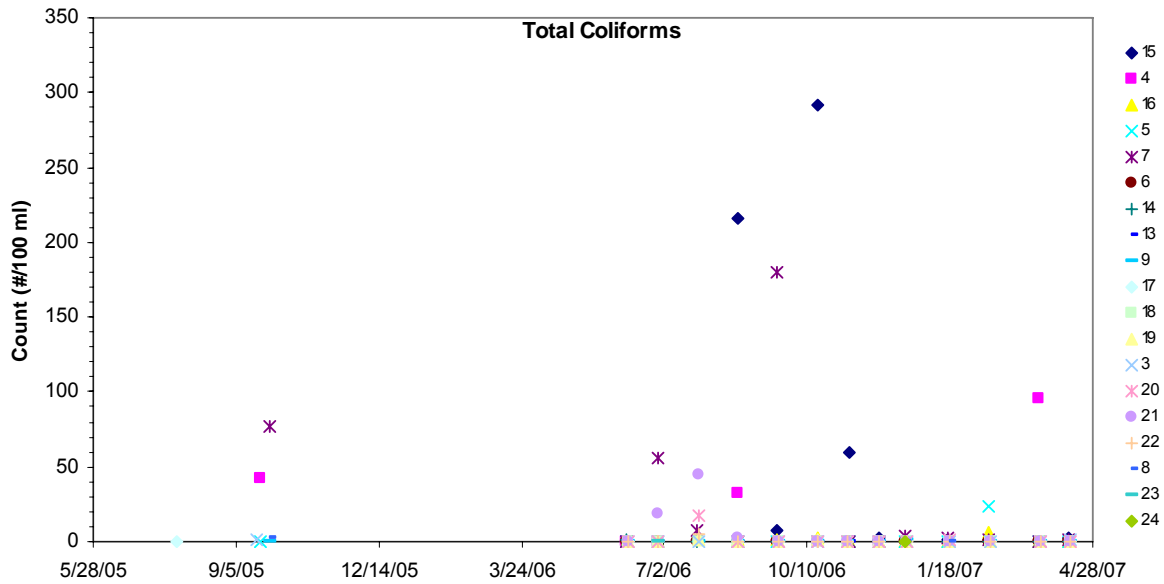


Figure 5: Result of total coliforms count. The 2005 data is the Most Probable Number (MPN) value; thereafter it is the Membrane Filter (MF) value.

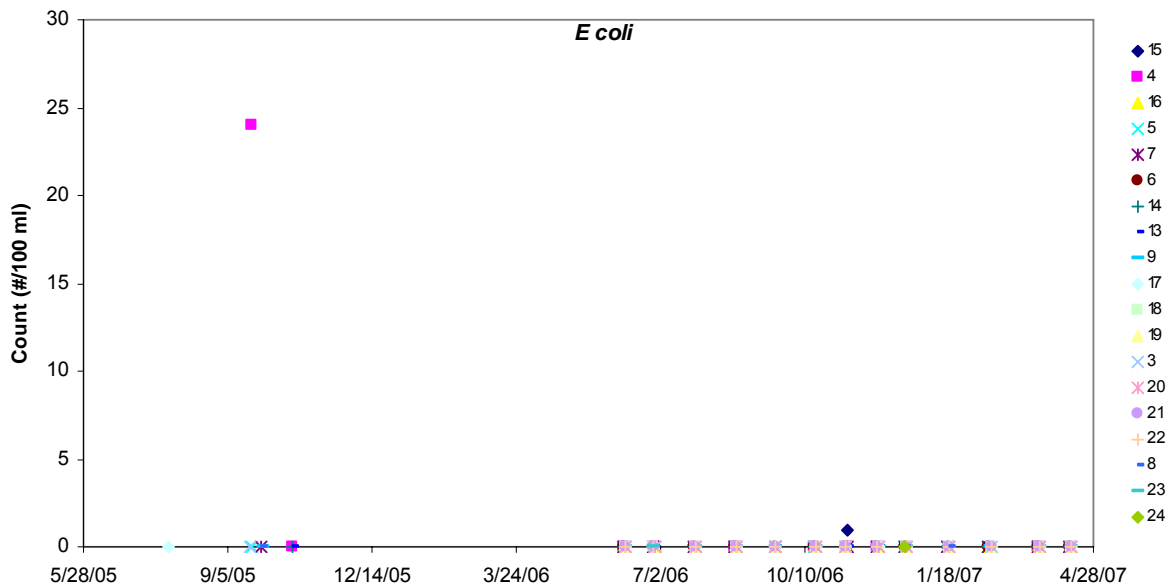


Figure 6: Result of E coli count. The 2005 data is the Most Probable Number (MPN) value; thereafter it is the Membrane Filter (MF) value.

The geophysical surveying included measuring the apparent resistivity of the geological material and interstitial fluid (e.g. groundwater) with depth [e.g. A-spacing (Fig. 7) represents approximately two times (2X) the measurement's depth]. Seven vertical profiles were collected at Fontainebleau State Park (Mandeville, LA), including three replicate profiles (total of 10 profiles), and three at Fairview Riverside State Park (Madisonville, LA). The profiles show an

initial decrease in apparent resistivity (e.g. increased conductivity, potentially due to the presence of electrolytes such as chloride) followed generally by an increase in apparent resistivity. This indicates that an unsaturated zone is present. Profile FSP-1 (Fig. 7) exhibits a significant increase in apparent resistivity (with depth) which is related to the transition from a clay to a sand layer at depth (based on a nearby water well driller's log, there is a sand layer at a depth of 4 m, extending to a depth of 12 m). The results for the three sites (Fig. 7) with surveys repeated approximately seven months apart, suggest that apparent resistivity profiles exhibit decreasing conductivity (e.g. freshening of the interstitial fluid) with time. This occurred at two out of three locations where profiles were repeated. The presence of sand at FSP-1 may explain why resistivity values are fairly consistent over the survey time period. The pulse of saltwater may have already traveled downward beyond the maximum depth achieved (in this case ~25 m). The other two repeated profiles (FSP-6 and FSP-7) appear to have a finer-grained (more clay/silt) lithology, which may have delayed the movement of saltwater downward. This resulted in the larger difference between the profiles (blue diamonds versus magenta squares on Fig. 7).

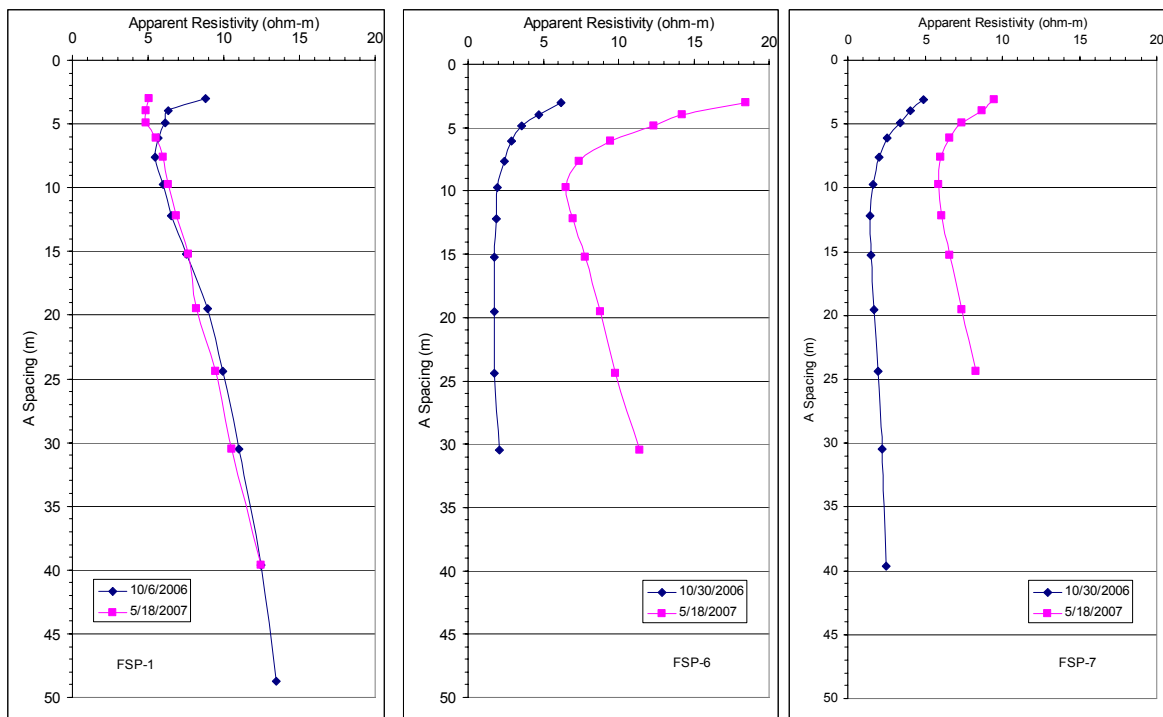


Figure 7: Apparent resistivity profiles repeated at Fontainebleau State Park

In conclusion, based on the results of this study, it can be stated that there appears to be no long term effect of the storm surge flooding on the aquifers screened by the wells tested. However, there appear to be some concerns regarding the wellhead protection of vented-well casings, and the need for these wells to be repeatedly treated to prevent residual bacterial contamination.

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GIS-Aided Water Quality Monitoring and Assessment System for Lake Pontchartrain

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Principal Investigators:	Zhi-Qiang Deng

Publication

1. Deng, Z.-Q., de Lima, J. L. M. P., de Lima, M. I. P., and Singh, V. P. (2006). A fractional dispersion model for overland solute transport. *Water Resources Research*, 42(3), W03416, doi:10.1029/2005WR004146.
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4. Patil, A. A. and Z. Deng (2007). Impact of Land Use/Land Cover Change on Lake Pontchartrain Water Quality. Submitted to the *Journal of Environmental Quality (JEQ)*.

GIS-Aided Water Quality Monitoring and Assessment System for Lake Pontchartrain

Problem and Research Objectives

The pumping of New Orleans floodwaters from Hurricanes Katrina and Rita into Lake Pontchartrain has raised serious environmental concerns regarding adverse impacts of the contaminated floodwaters and sediments on the water quality of the receiving lake. Although water quality sampling programs have been initiated by Federal and State agencies for Lake Pontchartrain, no existing efforts can effectively predict temporal and spatial variations of the pumped contaminants in the lake. This information is crucial to guiding water and sediment quality sampling and to assessing short-term and long-term environmental impacts of the pumped floodwaters and sediments on Lake Pontchartrain.

The goal of this project is to develop a GIS-aided water quality monitoring and assessment system for Lake Pontchartrain. The system can be employed (1) to simulate temporal and spatial variations of water temperature and dissolved oxygen in the lake, (2) to provide guidance to water quality and sediment sampling in the lake, (3) to visualize modeling results, and (4) to provide necessary scientific information for assessment of short-term and long-term environmental impacts of the pumped New Orleans floodwaters on Lake Pontchartrain. To achieve the primary goal of this project, the research is split into six specific objectives: (1) Modeling of New Orleans floodwater plume trajectory and sediment deposition in Lake Pontchartrain, (2) Water and sediment quality sampling, (3) Development of multi-layered water quality database, (4) Development of lake temperature model, (5) Development of dissolved oxygen model, (6) Integration of numerical models and GIS interface.

Methodology

The three-dimensional Hydrodynamic-Eutrophication Model (HEM-3D), also referred to as the Environmental Fluid Dynamics Computer Code (EFDC), is used to simulate flow circulation. The hydrodynamic model of HEM-3D is based on continuity, momentum, salt balance and heat balance equations, with hydrostatic and Boussinesq approximations (Hamrick, 1992). For turbulent closure, the second moment turbulence model developed by Mellor and Yamada (1982) and modified by Galperin et al. (1988) is used. The model includes a wetting and drying scheme, and uses orthogonal curvilinear of Cartesian horizontal coordinates with stretched sigma vertical coordinate. Detailed description of the model, including the governing equations and numerical solution method, can be founded in Hamrick (1992, 1996), Park et al. (1995), Ji et al., 2001, and Park et al., 2005. The modeling domain includes the entire Lake Pontchartrain system. The Surface-Water Modeling System (SMS) software is employed for generation of the model grid with a varying-grid size of 200 – 900 m, as shown in Figure 1. The driving forces for lake circulation include winds and tidal wave propagation through Rigolets Pass and Inner Harbor Navigation Canal (IHNC). Harmonic constants for M2, S2, K1, O1 and P1 tidal constituents are measured at USGS New Canal by NOAA. Surface elevations for Rigolets Pass and IHNC are very similar in terms of tidal phase and amplitude (Chilmakuri, 2005). The depth averaged 2-D sediment transport module of EFDC is used to determine distributions of contaminated sediments from the floodwaters pumped from New Orleans. Five outfalls located along south shorelines of Lake Pontchartrain, as shown in Figure 1, are taken into account. The flow rate for each outfall was

determined using total floodwaters volume (8.86 billion cfs) pumped from New Orleans to the lake from 9/7/2005 to 9/16/2005 after Hurricane Katrina. A sediment concentration of 100 mg/l is utilized in a boundary condition at the outfalls. Sediments pumped into the lake were mainly silt and clay. Settling velocity used in this model is determined as 1.e-5 m/sec.

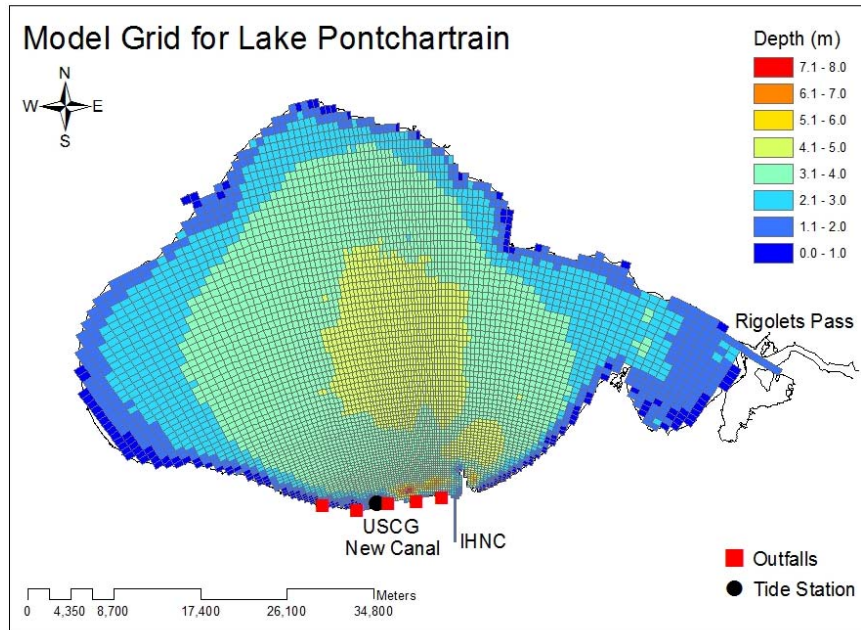


Figure 1: Model grid and water depth of Lake Pontchartrain

To determine temporal and spatial variations in monthly mean dissolved oxygen (DO) the water depth is divided into three sigma-layers and HEM-3D is used. Temperature modeling was performed by considering daily averaged heat exchange between water surface and atmosphere (Edinger et al. 1974). All data, including wind, water and air temperature, dew point temperature, etc., required to estimate the heat exchange are collected from NOAA. Initial and boundary values for DO modeling were collected and analyzed from previous studies and measurements conducted by USGS. In addition, spatially varying sediment oxygen demand (SOD) was applied to consider the effect of contaminated bottom sediments from New Orleans stormwaters. The simulation is conducted for the period of April 1st - October 31st, 2006

Principal Findings and Significance

1. **Lake Circulation:** Figures 2a and 2b show current distribution produced by spring tide and southeasterly wind (dominant wind), respectively. Generally, currents generated by tides are much weaker than those by winds and the effect of tidal currents is limited to tidal entrances. Flow patterns in shallow area along shorelines are controlled by wind direction while flow in the center of Lake Pontchartrain is determined by wind set up, resulting in two large eddies, as shown in Figure 2b. The flow velocity is very small in the center parts of the eddies. Low velocity may facilitate the formation of stratification and thereby hypoxic condition in the bottom layer of water column. In addition to the dominant wind, flow circulation computations are also conducted for other wind directions (N, NE, E, S, SW, W, NW). The

simulation results are similar. The results are saved in the GIS database developed in this study.

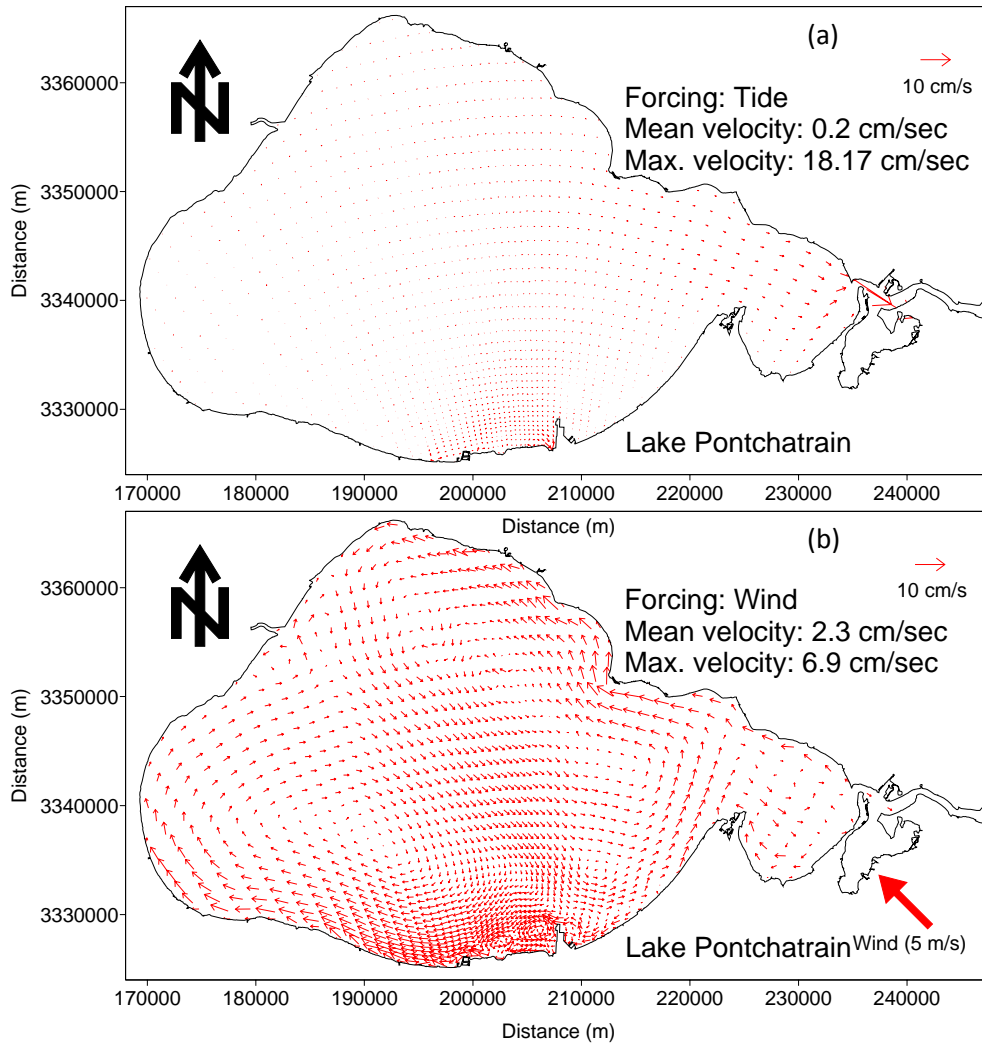


Figure 2: Comparison of velocity distributions produced by tidal forcing (through Rigolets Pass and IHNC) and wind (southeasterly wind) forcing

- Contaminated Sediment Distribution:** Figure 3 (a) and (b) show distributions of the contaminated sediments pumped from New Orleans floodwaters under southeasterly and northerly winds. The distributions of the sediments are mainly determined by flow patterns. For southeasterly wind, the sediments are distributed along the south shoreline of the lake and the dispersion of sediments to the center of the lake is limited, as shown in Figure 3 (a). For northerly wind, the sediment plume spread toward the center of the lake but sediment concentration decrease rapidly before the plume reaches the center, as shown in Figure 3 (b). Under the forcing of other wind directions the sediment plumes are limited in the area close to the south shoreline. It means that the contaminated sediments from New Orleans floodwaters are mainly distributed in a belt area along the south shoreline of the lake. Computation results for sediment distributions are saved in the GIS database.

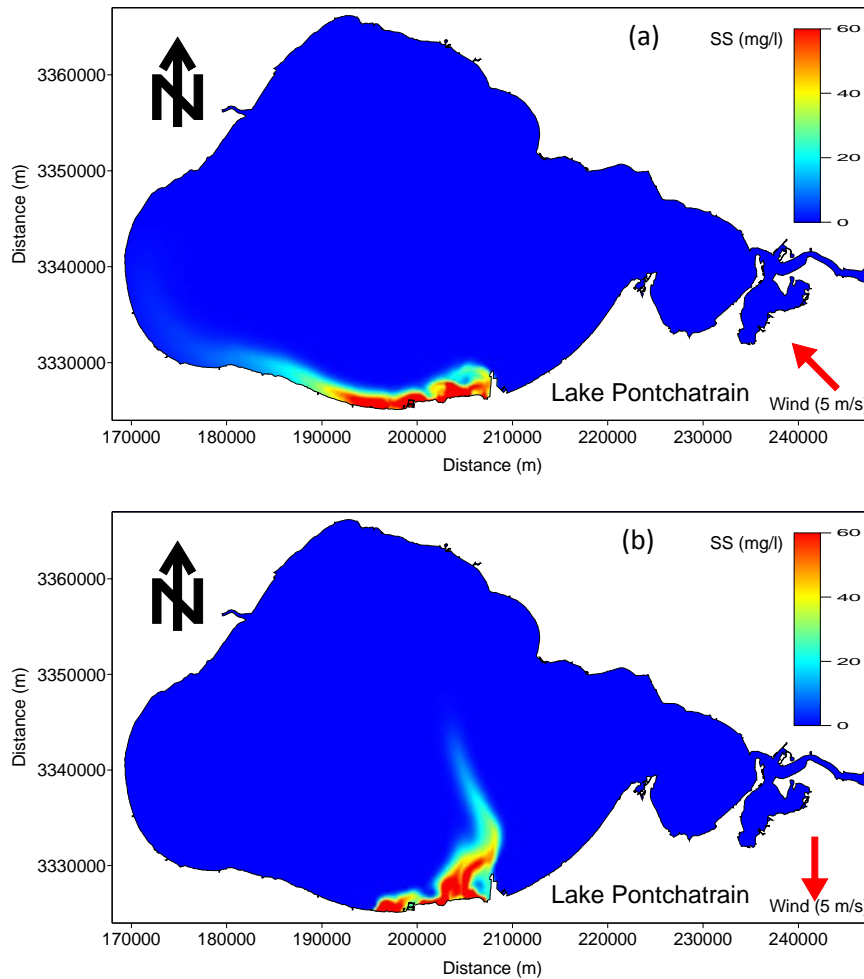


Figure 3: Sediment distributions due to southeasterly (a) and northerly (b) wind.

- Spatial and Temporal Variations in DO:** The simulated temporal and spatial variations in monthly mean dissolved oxygen (DO) for the period from April 1st - October 31st are shown in Figure 5. Figure 4 indicates the simulated distribution of sediment oxygen demand (SOD) in the lake. The figure clearly shows that the contaminated sediments from New Orleans floodwaters cause high SOD in the area close to the outfalls along the south shoreline. Figures (5a) – (5d) demonstrate the temporal variation of DO in the lake due to the combined effect of the contaminated sediments and stratification. DO concentrations in surface layer from April - August were higher than 7 mg/l. However, bottom DO concentration decreased from April to August. The decrease in DO concentration at bottom of the lake is highly related to the formation of stratification and the contaminated sediments. Strong stratification prevents high DO surface water from mixing with low DO bottom water. The low DO zone was formed in the deep water area in the south east part of the lake.

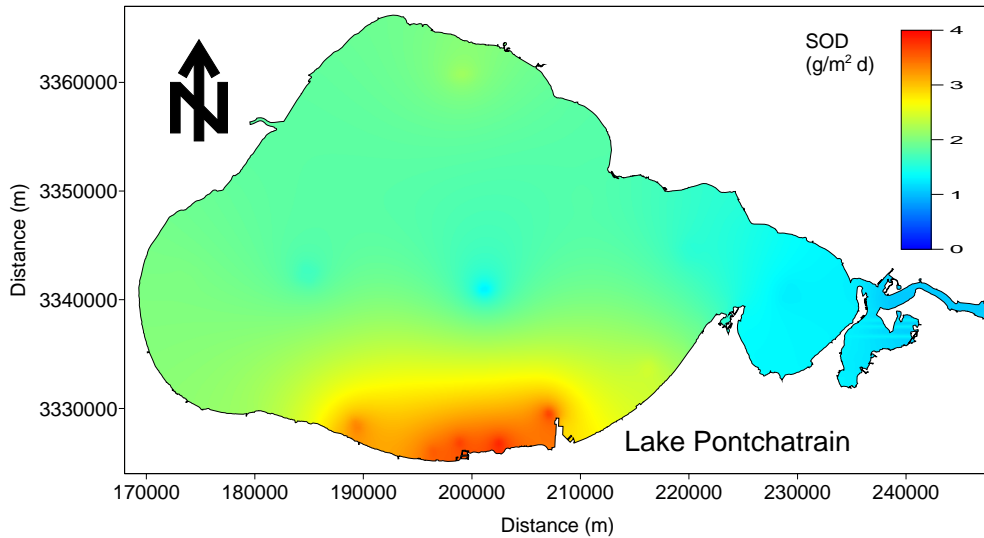


Figure 4: Spatial distribution of Sediment Oxygen Demand (SOD) used for the DO-Model

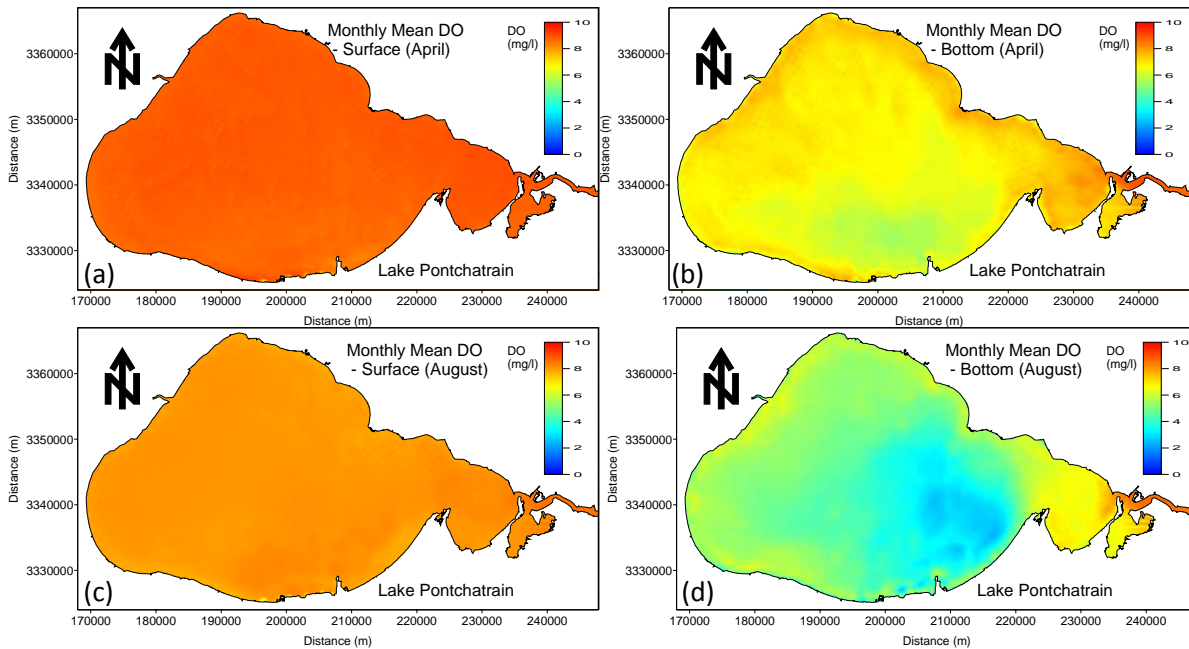


Figure 5: Monthly mean surface and bottom DO distributions in April and August.

- 4. Recommended Water Quality Monitoring Stations:** The computation results of lake circulation, sediment plume development, DO distribution in the lake and current sampling locations are used to identify the most efficient water quality monitoring stations for the Lake Pontchartrain. The current sampling stations by US EPA are concentrated in few areas of the lake and thus they do not sufficiently give the spatial variation in water quality parameters in the lake. In addition to the existing 39 water quality stations, twelve new sampling stations

are recommended based on the above analyses. These sampling stations were selected in such a way that the new stations along with existing stations cover the low bottom dissolved oxygen zone and the sediment plume trajectories obtained by sediment plume modeling. The recommended sampling stations will cover the areas where water quality varies significantly. This will be very helpful for decision makers to implement the water quality monitoring program for lake Pontchartrain. The recommended sampling stations can be seen by clicking “Recommended Stations” button in “Lake Pontchartrain Water Quality Modeling Toolbar” in the following GIS-Aided Water Quality Monitoring and Assessment System developed in this study for Lake Pontchartrain.

5. Operational Manual of the GIS-Aided Water Quality Monitoring and Assessment System for Lake Pontchartrain

- 1) Open the ArcGIS application by clicking the ArcGIS icon in the “Start>All Programs>ArcGIS>ArcMap”.
- 2) Locate the project file “C:\Pontchartrain GIS \pont.mxd” to open it.
- 3) The open GIS project will display ten basic lake Pontchartrain GIS layers including the Sediment Concentration, bottom Dissolved Oxygen Concentration, Sediment Plume trajectory under dominant wind condition (SSC under Wind SE), Landsat TM Satellite Imagery, Water Quality Stations (with link), Streams, Pontchartrain basin boundary, Hydrodynamic link, recent land use (1992) and lake Pontchartrain basin boundary. (Figure 6).
- 4) There are fifteen more GIS layers saved in “C:\Pontchartrain GIS \GIS layers”. These layers are the mean dissolved oxygen in month of April, May, June, and September and the sediment plume trajectory under different wind conditions which can be viewed as per the requirement.
- 5) This geo-database has been customized to perform user specific functions for the lake Pontchartrain. The figure 7 shows the customized toolbar “*Lake Pontchartrain Water Quality Modeling Tool*” to conduct the project specific task. There are seven functions included in this tool.
 - a. To add a new layer for the geo-database in “C:\Pontchartrain GIS \GIS layers”.
 - b. To add the urban outfall from New Orleans metropolitan area.
 - c. To add the contoured bathymetry of the Lake Pontchartrain.
 - d. This button adds the current water quality monitoring stations identified by the USEPA.
 - e. This button will display the recommended sampling stations based on the above analysis.
 - f. This button will import any new layer to the ArcMap.
 - g. This will give the output in the JPEG format saved in location C:\Pontchartrain GIS \Output\pont_output.jpg”.

- 6) To view the hydrodynamic modeling results, select the “Hydrodynamic Link” Layer. Click the Hyperlink button shown in the red box of figure 6. An adobe file will open which shows the hydrodynamic profile under various wind direction was investigated all are categorically saved. This is a set of twelve figures in each simulation showing the instantaneous wind direction.

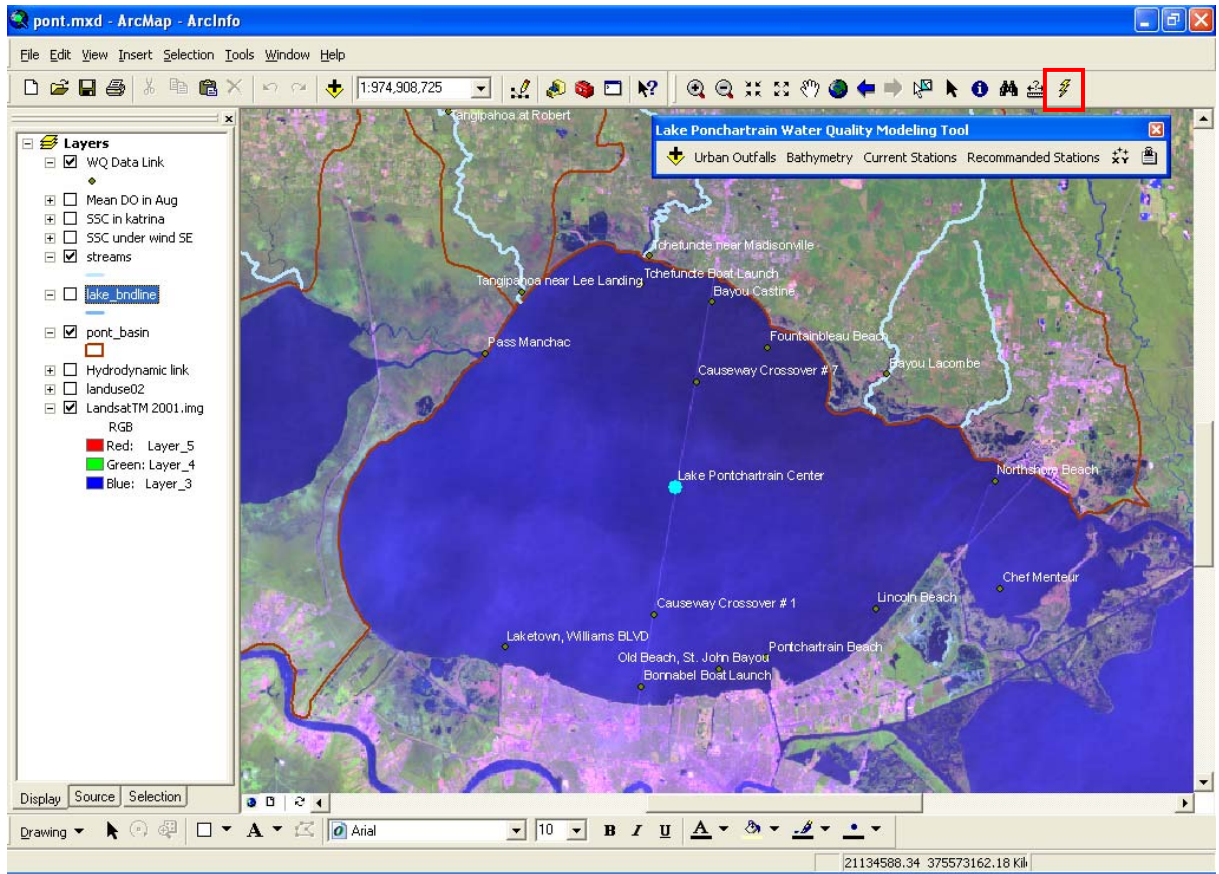


Figure 6: Lake Pontchartrain Base Layers

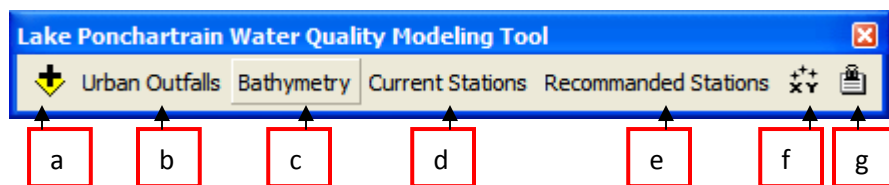


Figure 7: Lake Pontchartrain Water Quality Modeling tool

The GIS-Aided Water Quality Monitoring and Assessment System developed in this project for Lake Pontchartrain will improve water quality monitoring and provide an efficient tool for water quality assessment and restoration of Lake Pontchartrain. This project also leads to the publication of two journal papers and two conference papers. Furthermore, the project and

its results will be introduced in some civil and environmental engineering courses at LSU, immediately benefiting both graduate and undergraduate students in learning how science applications solve real world problems related to coastal restoration in Louisiana.

Reference

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Information Transfer Program

One of the Institute's objectives is to make research results available to the general public and to interested researchers and institutions through publications and other information transfer activities. Although the information transfer component of the budget of Section 104 funds is relatively small (10%), LWRRI attempts to meet this goal in many ways which include actively participating in conferences and workshops, distributing summaries and other Institute information to the public and governmental agencies, maintaining internet access and web sites, and maintaining a library of water research materials. The Institute requests that its investigators participate in reporting and information transfer activities such as publications in professional journals, workshops, and seminars.

The Institute's information transfer program is a subset of its administration program. Assisting with LWRRI's information transfer activities are two undergraduate student workers, a program coordinator (part-time LWRRI support), and one research associate (half-time LWRRI support). Two research associates are also available to assist in information transfer activities of the Institute. The Director, Dr. John Pardue, attends the annual National Institutes of Water Resources meetings in Washington, D.C., to discuss Institute and Program activities.

Further assisting in information transfer, the Engineering Incubation Research Center (EIRC) has given LWRRI access to image processing, GIS, and computing systems. This access provides the Institute with the necessary tools to transfer information in visual graphic format, utilize Internet resources, and develop state-of-the-art presentations. Because of the Institute's expanding development, more emphasis is being placed on updating the public and other organizations about activities and objectives using electronic media and presentation tools.

The Institute's staff continues to maintain emphasis on acquainting Louisiana's research community with the research-funding opportunities through the U.S. Geological Survey Section 104 research program. 104 G program announcements, Mississippi SE-TAC RFPs, and Section 104 RFPs were widely distributed (250+ email addresses, 248 regular mail addresses, and 163 email addresses on the user-subscribed list, totaling 661) to Louisiana colleges and universities and to research organizations throughout the state. In addition, public announcements were made at professional and faculty meetings to encourage wide participation in the program. We send out notifications of meeting and events for the American Water Resources Association, The Capital Area Ground Water Conservation Committee, and the Louisiana Rural Water Association.

Research grants FY 2006-07 technical transfer. Project 2006LA46B, Van Biersel & Carlson - publication of a report of investigation in the Louisiana Geological Survey is planned for late 2007 or early 2008. In addition, presentations of the findings are planned for one or two conferences. Project 2006LA47B, Deng - The GIS-Aided Water Quality Monitoring and Assessment System developed in this project will be transferred to the Louisiana Department of Environmental Quality and Lake Pontchartrain Basin Foundation for improving water quality sampling and lake restoration and management.

Collaboration with major university research initiatives. LWRRI have collaborated extensively with other campus research centers during this cycle. These have led to other funded centers and center proposals. Through these activities we have continued to leverage our resources by collaborating with other faculty. These collaborations include a Biotechnology Center (funding from Governor's Biotechnology initiative) within HSRC (use of molecular techniques for microbial community structure

analysis), the Heath Excellence Fund Public Health Effects of Hurricanes center (chemical transport following a major hurricane), and the LSU Hurricane Center (Louisiana Levee School initiative with LA DNR & LA DOTD).

In addition, our organization is contacted regularly with various questions for the public and/or private sector concerning water issues; we try to connect these people with the proper experts within our organization and the broader academic community. We have built a comprehensive web portal LAWATER.com in conjunction with the LWRRI web site to help facilitate this effort.

LAWATER and electronic publication project. Two outreach projects that we would particularly like to highlight is the development of the LAWATER web portal for Louisiana water issues (www.lawater.lsu.edu) and the digital document library within LWRRI. The web portal LAWATER was designed as a comprehensive collection of web-based information on water issues within Louisiana. It captures information not only from the Institute but collects the rich content developed by USGS, EPA, DEQ, FEMA and others into one location. The portal is divided into several sections emphasizing 4 major issues: water quality, water supply, hazards and flooding and coastal restoration. While only in existence a little over two years, the web portal is being utilized in Louisiana's water community. In addition to LAWATER, we have been active archiving our past research products. LWRRI is one of the oldest research institutes on campus (founded in 1964). The collection of research products funded by the Institute date is in paper versions that are vulnerable to age and not accessible to the public. We have been scanning all of the documents produced by the institute into electronic archived versions for preservation and for any interested researchers to access (<http://www.lwrri.lsu.edu/dwaterlibrary.htm>).

Under the direction of our director, the Institute has developed a branding symbol for all of the information transfer activities and publications and is reconstituting the newsletter. Our annual report is housed at the Louisiana State Archives, Hill Memorial Library at LSU, and is available online at the Institute's web site.

In response to the focused RFP for the 2006-2007 solicitations, we received 4 new proposals and funded 3 of those after advisory board review. The theme, selected in consultation with faculty and advisory board members, is focused on resiliency of community water supplies in Louisiana's coastal zone, storm surge in the Louisiana coastal zone, adaptive management of Louisiana's water resources, total maximum daily load (TMDL) calculations in Louisiana water bodies, and scale-dependent behavior of hydrologic and water quality parameters. Also 2 proposals were submitted to the 104G program; one was chosen for funding and it focused on groundwater flow and transport.

NIWR-USGS Student Internship Program

The Louisiana Water Resources Research Institute did not have any students in the formal NIWR-USGS Intern Program during this reporting period. The Institute maintains both formal and informal relationships with the Baton Rouge office through part time employment of students not in the intern program, and the USGS District Chief serves on the Institute Advisory Board.

Student Support

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	1	0	0	0	1
Masters	1	1	0	0	2
Ph.D.	6	4	0	0	10
Post-Doc.	1	0	0	0	1
Total	9	5	0	0	14

Notable Awards and Achievements

Notable Awards and Achievements

External Activities. LWRRI has been involved in several external activities directed at improving the Institute's presence.

- LWRRI has been active with NIWR in the yearly efforts to maintain the 104 funding within USGS's budget. Under the current administration, the President's budget has allocated no funding for the water institute's program. Every year, however, the Institutes' have been able to restore funding by working with their congressional delegations. We have been active informing the Louisiana delegation about the benefits of the program and we have obtained legislative support for our efforts. This culminated in the passage of the Water Resources Research Act Amendments of 2004 (S. 1017) in the Senate in Fall, 2005. The bill was cosponsored by Senator Vitter and it continues the state's institutes program for the next 5 years and plans to double the funds allocated to each institute. Both Sen. Vitter and Landrieu signed the recent Dear Colleague letter supporting restoration of funding to the program.
- The Director, Dr. John Pardue, was invited by the LSU Hurricane Center to participate and lead a breakout group in the preliminary program development for the Louisiana Levee School. In addition, LWRRI provided administrative support for the coordination and production of the two-day LA Levee School Planning meeting. LWRRI will continue to work with the LSU Hurricane Center on this important effort to establish a world class Center of Excellence for flood protection and coastal restoration. Follow on funding for the LA Levee School is expected from LA DNR & LA DOTD to put the program into action for the 2007-08 cycle.
- Follow-on funding for project 2006LA47B was garnered by Dr. Zhiqiang Deng.
Title: Characterization of Nitrogen Retention in Louisiana Coastal Rivers (under review)
PI: Zhiqiang Deng
Agency: Louisiana Sea Grant
Program: Louisiana Sea Grant College
Program Duration: 02/2008 01/2010
Amount: \$139,495

- The Director, John Pardue, has led the formation of a Coastal and Ecological Engineering degree program at LSU. The letter of intent was submitted this cycle and a proposal is in preparation
- Dr. Pardue was named one of LSU's Distinguished Faculty members in 2006-2007 for his contributions in research, teaching and service.

Dr. Pardue's funded grants as a result of his work in the water resources area:

1. Assessment & Remediation of public health impacts due to Hurricanes and major flooding events Louisiana Millennium Health Excellence Fund; 2001-2007. I. Van Heerden, PI; Pardue and Reible, water modeling group, \$120,000.
2. Molecular methods in Environmental Engineering Governor's Biotech Initiative.
3. SGER: Hydrological, Chemical and Microbial Data Related to the Hurricane Katrina Flooding in New Orleans, LA. National Science Foundation, SUGR , C. Willson, J. Pardue, W. Moe and R. Dokka, 35K, 2005-2007.
4. Phytoremediation of wetlands and CDFs Hazardous Substance Research Center S/SW; 2001 2007. J. Pardue. \$354,649.

Participation in Learned Societies/Professional Associations: Dr. John H. Pardue

Chemical and Microbiological Characteristics of Katrina Floodwater and Sediments. Extreme Water Events in Maryland, University of Maryland-College Park, October 27, 2006 (Invited).

Katrina and the Environment: risks of living in an urban environment (below sea level), Louisiana Materials and Emerging Technologies Conference, dinner talk, LSU, Baton Rouge, LA, October 23rd, 2006 (Invited).

Impact of post-Katrina cleanup operations on air quality, ACS National Meeting, San Francisco, CA (with R. Ravikrishna, S. Mbuligwe, H-W. Lee, K.T. Valsaraj). Co-organizer of session with George Cobb, Texas Tech Univ., Sept. 10-14, 2006.

Chemical and Microbiological Characteristics of New Orleans Floodwater and Sediments. ACS National Meeting, San Francisco, CA (with W. Moe, LJ Thibodeaux, K.T. Valsaraj). Co-organizer of session with George Cobb, Texas Tech Univ., Sept. 10-14, 2006.

Chaired session on Hurricane Katrina at the International conference on Coastal Hydrology and Water Quality, American Institute of Hydrology conference in Baton Rouge, LA. May 23rd, 2006.

Environmental Impacts of Hurricane Katrina. Presentation to US-Japan cooperative science program on wind and seismic hazards. (at LSU) May 20th, 2006.

Molecular Characterization of microbial communities in the pitting corrosion parts (FeS) and the undersurface soils of a crude oil storage tank. American Ecological Engineering Society Conference (Berkeley, California). 6th annual conference, Efficient Sustainability in a Dry Land. (Han-Woong Lee presenting). April 13-14, 2006.

Co-treatability of 1,1,2,2-tetrachloroethane and trichloroethylene in engineered wetland soils,. American Ecological Engineering Society Conference (Berkeley, California). 6th annual conference, Efficient Sustainability in a Dry Land. (Stephen Mbuligwe presenting). April 13-14, 2006.

Impact of *Typha latifolia* roots on the degradation of hexachlorobenzene at nitrate-reducing, iron-reducing, and sulfate reducing conditions. Presentation at 16th Annual AEHS Meeting and West Coast conference on Soils, Sediments and Water. San Diego. Xingmao Ma presenting. March 13-16, 2006.

Publications from Prior Projects

1. 2006LA-ADMIN ("Program Administration Project") - Water Resources Research Institute Reports - John H. Pardue, 2006, Louisiana Water Resources Research Institute Annual Technical Report FY 2005-2006, Louisiana Water Resources Research Institute, Louisiana State University, Baton Rouge, Louisiana, 47 pages.