Louisiana Water Resources Research Institute
Annual Technical Report
FY 2015

Introduction

This report presents a description of the activities of the Louisiana Water Resources Research Institute for the period of March 1, 2015 to February 29, 2016 under the direction of Dr. Frank Tsai. 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.

Louisiana has an abundance of water resources, and while reaping their benefits, 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, modeling of atmospheric pollutants deposition to water bodies, and 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 Southern Hills aquifer system, the Chicot aquifer system, and Sparta 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 and salty water in drinking water supplies. 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. A Recent cooperative research project has been conducted with LSU Agricultural Center.

During this reporting period, LWRRI continued its work on the saltwater intrusion issue in the Capital Area groundwater system. The LWRRI director advised state agencies, conducted ongoing research on saltwater encroachment modeling and remediation designs, organized a water symposium, and presented research results at local, regional and national meetings. Details of this activity are presented below in the “Notable Achievements” section of the report.

Research Program Introduction

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 2015 focused on selected research themes developed in conjunction with the advisory board. These themes corresponded to the major water resource areas affecting Louisiana described in the Introduction above. Projects selected were from a range of faculty with different academic backgrounds including hydrologist, environmental engineers and water resource engineers and scientists. Supporting research in these priority areas has increased the visibility of the Institute within the State.

The individual research projects are listed below.

Project 2014LA94B – Tsai, Groundwater recharge estimation under climate change impact for the southern hills aquifer system of southeastern Louisiana and southwestern Mississippi (carry-over project)

Project 2015LA99B – Deng, Development of watershed-based dynamic total maximum daily load for dissolved oxygen in lower Bayou Macon

Project 2015LA100B – Tsai, Long-term groundwater recharge projection of southeastern Louisiana and southwestern Mississippi under climate change

Project 2015LA101B – Zhang, Atmospheric deposition of nitrogen and sulfur to Louisiana water bodies

These projects include two projects that focus on Climate and Hydrologic Processes (Projects 2014LA94B and 2015LA100B), and two projects that focus on Water Quality (Projects 2015LA99B and 2015LA101B).

Groundwater Recharge Estimation under Climate Change Impact for the Southern Hills Aquifer System of Southeastern Louisiana and Southwestern Mississippi

Basic Information

Title:	Groundwater Recharge Estimation under Climate Change Impact for the Southern Hills Aquifer System of Southeastern Louisiana and Southwestern Mississippi
Project Number:	2014LA94B
Start Date:	3/1/2015
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	6th
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Models, Methods
Descriptors:	None
Principal Investigators:	Frank Tsai

Publications

1. Beigi E., and F. T.-C. Tsai, 2014. “GIS-Based Water Budget Framework for High-Resolution Groundwater Recharge Estimation of Large-Scale Humid Regions“. Journal of Hydrologic Engineering, ASCE, 19(8), 05014004, doi:10.1061/(ASCE)HE.1943-5584.0000993.
2. Beigi E. and F. T.-C. Tsai. 2015. “Comparative study of climate-change scenarios on groundwater recharge, southwestern Mississippi and southeastern Louisiana, USA”. Hydrogeology Journal 23(4), 789-806. doi :10.1007/s10040-014-1228-8
3. Beigi E. and F. T.-C. Tsai, 2014 “Hierarchical BMA Analysis of Hydrologic Projections under Climate Modeling and Scenario Uncertainties”, Abstract, 2014 American Geophysical Union Fall Meeting, San Francisco, California, December 2014.
4. Beigi E. and F. T.-C. Tsai, 2014 “Comparative Study of Climate Change on Groundwater Recharge”, Abstract, American Society of Civil Engineers (ASCE), 2014 World Environmental and Water Resources Congress, Portland, Oregon, May 2014.
5. Beigi E. and F. T.-C. Tsai, 2014 “A Water Balance Approach to Estimate Surface Runoff and Potential Groundwater Recharge of Southern Louisiana”, Abstract, US-China International Workshop on Key Processes and Regulation of Wetland Ecosystems.” Louisiana State University, Baton Rouge, LA, November 12, 2014.
6. Beigi E. and F. T.-C. Tsai, 2014 “Impact of Climate Change on Groundwater Recharge of Southern Hills Aquifer System”, 7th Annual Groundwater and Surface Water Resources Symposium, Louisiana Geological Survey (LGS), Baton Rouge, LA, April 18, 2014.
7. Beigi, E. and F. T.-C. Tsai, 2015. “Climate change impacts on surface water and groundwater recharge of southwestern Mississippi and southeastern Louisiana”, 9th Annual Louisiana Groundwater, Water Resources & Environmental Symposia, Baton Rouge, Louisiana, April 16, 2015.

Problem and Research Objectives

Significantly increased emissions of greenhouse gases from anthropogenic activities has caused climate to change. As reported by the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature and the global mean sea level have risen by 0.6±0.2 °C and by 20±5 cm, respectively since the late 19th century. Additionally, the IPCC predicted 2 to 4 °C global temperature increase and 18 to 59 cm sea level rise in the 21st century. The global warming is projected to intensify the global hydrologic cycle, alter precipitation amount, pattern and intensity, increase atmospheric water vapor, evaporation and evapotranspiration, and change groundwater recharge and runoff. Climate variation can impact on availability of groundwater through evapotranspiration and recharge processes. Because precipitation and surface water are the main sources to recharge aquifers, evaluating the impact of climate change on groundwater systems needs reliable estimation of recharge, which is important for assessing drought, water quality, groundwater availability and sustainability. Improving the understanding and modelling of climate changes on groundwater recharge have been highlighted in the last five IPCC reports. Recently, the increasing number of climate change studies with regard to groundwater resources has shown the importance of this subject. Knowledge of groundwater recharge is particularly important to regions where large demands of drinking water supplies rely heavily on groundwater, such as the Southern Hills aquifer system, southwestern Mississippi and southeastern Louisiana, USA. Reliable recharge estimation is important for efficient and sustainable groundwater resource management and for aquifer protection from rapidly expanding urbanization, drought or climate change.

The goal of the project is to develop a GIS-based water budget framework to estimate groundwater recharge under climate change for the area of Southern Hills aquifer system shown in Figure 1. The scope of the project includes collection of various data (e.g., weather data, soil data, land use and land cover data, vegetation data, etc.), development of a hydrologic model for groundwater recharge estimation, and predict recharge changes under various climate change scenarios. To achieve the project goal, we propose the following specific objectives:

Objective 1 Groundwater recharge model development: A GIS-based water budget framework will be developed to estimate high-resolution spatial and temporal groundwater recharge for the study area.

Objective 2 Climate change impact studies: The developed framework will incorporate two climate models and three climate change scenarios to estimate potential recharge and analyze recharge anomalies for the next century.

Methodology

This study assesses the climate change impact on groundwater recharge in humid areas using the water budget method. The HELP3 model (Schroeder et al. 1994), a water budget model, is employed to estimate potential recharge since HELP3 has been widely used to estimate recharge. To investigate the impact of climate change on groundwater recharge for a large-scale humid region, this study develops a water budget framework using HELP3 in conjunction with a geographic information system (GIS). The framework estimates potential recharge under three different emission scenarios (B1, A2 and A1FI) of two global climate models (GCMs), which are the National Center for Atmospheric Research's Parallel Climate Model 1 (PCM) and the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Lab's (GFDL) model (Maurer et al. 2002 and Maurer 2013). The historical condition in 1950-2009 is used as a baseline and is compared to the results of six climate change scenarios for three future periods: 2010-2039, 2040-2069 and 2070-2099.

Principal Findings and Significance

1. Baseline Historical Potential Recharge

The mean annual potential recharge shown in Figure 2 for the area of the Southern Hills aquifer system is considered as the baseline historical recharge for climate change comparisons. The mean annual potential recharge ranges from 0 to 857 mm. The average of the mean annual potential recharges (1950-2009) for the entire area is 227.5 mm. 45.6 % of the subdivisions have mean annual potential recharge above the average. 48.8 % of the subdivisions have mean annual potential recharge lower than 205 mm while 40.7 % have mean annual potential recharge between 205 mm and 410 mm, and 10.45 % have mean annual potential recharge higher than 410 mm. The west of the study area (including the parishes of Adams County, Claiborne County, Jefferson County, Wilkinson County, and West Feliciana) is the recharge zone of the Baton Rouge aquifer system and shows high potential recharge historically. High potential recharge is also demonstrated in the east and central Florida parishes. Low potential recharge is demonstrated in the north and northeast of the study area.

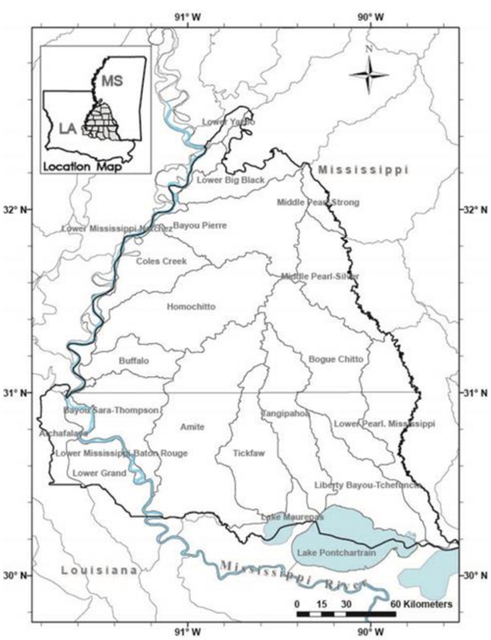

Figure 1: The Southern Hills aquifer system (bounded by a thick black line), covering 24 HUC8 hydrologic units.

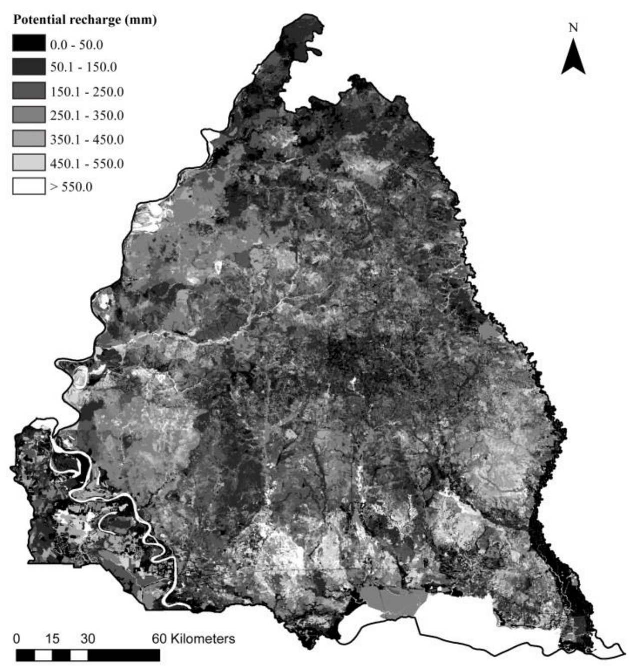

Figure 2: Mean annual potential recharge (mm) for 1950-2009 for the Southern Hills aquifer system.

2. Temporal Results

The changes in temperature and the cumulative changes in precipitation and solar radiation for individual scenarios with respect to the historical baseline (1950-2009) are shown in Figure 3. To calculate the changes for the Southern Hills aquifer system, the area-averaged values of the climate variables of all subdivisions were calculated and subtracted from the mean annual for 1950-2009. Sums of the changes over years show the cumulative changes. If changes in climate variables are negative over time, their cumulative changes will amplify this phenomenon by showing large negative values. For example, a fall of almost 10 m cumulative change in 2099 for GFDLA1F1 shows that the yearly precipitation continuously decreases from 2040 to 2099 with respect to the baseline precipitation. The differences of the cumulative changes between the scenarios become more evident over time. The cumulative changes of solar radiation projected by the PCM and GFDL models are opposite and distinguishable from the beginning of projection. After the mid-century, the cumulative changes of precipitation and the changes of temperature between emission scenarios are distinguishable, which is consistent with the global projections (Cubasch et al. 2001). Scenarios PCMB1, PCMA2, and GFDLB1 project overall precipitation increase while the other three scenarios project overall precipitation decrease for the 21st century. Moreover, scenarios PCMB1, PCMA2, and GFDLB1 project relatively less temperature change than the other three scenarios for the 21st century.

In general, the projections of the PCM and the GFDL models begin to diverge greatly after the mid-century for the study area. This divergence is in harmony with greenhouse forcing associated with the various scenarios and starts at the point at which substantial differences between the projections by these two models begin. These differences stem from the two models' parameterizations, sensitivities and responses to greenhouse gases and other forcings (Cayan et al. 2007).

Figure 4 presents the cumulative changes in potential recharge, runoff and evapotranspiration with respect to the historical baseline scenario for each climate change scenario. It is observed that potential recharge cumulative changes follow the same trend as precipitation cumulative changes, which highlights the fact that the potential recharge in the study area is more sensitive to precipitation than temperature and solar radiation. Scenarios GFDLA2 and GFDLA1FI project significant potential recharge decrease towards the end of the 21st century. On the other hand, scenarios PCMB1 and PCMA2 project the most potential recharge increase for the 21st century. Almost all of the climate change scenarios project runoff decreases for the 21st century except for the GFDLB1. PCMA1FI projects the highest runoff reduction, followed by PCMB1. Although projecting precipitation increase for the 21st century, scenarios PCMB1 and PCMA2 show runoff decrease due to projected high evapotranspiration shown in Figure 4(c). The PCM model projects continuous evapotranspiration increase for the 21st century. However, the GFDL model does not show significant change of evapotranspiration before 2069, but has a wide-ranging evapotranspiration projection in 2070-2099.

3. Spatial Results

Future mean annual potential recharge, runoff, and evapotranspiration with respect to the mean annual from 1950 to 2009 are listed in Table 1. The mean annual potential recharge, runoff, and evapotranspiration in 1950-2009 are 227.5 mm, 362.7 mm and 943.2 mm, respectively. The PCM model projects recharge change from −33.7 % to +19.1 % and the GFDL model projects recharge change from −58.1 % to +7.1 % for the 21st century. In general, the PCM projects more recharge than the GFDL. The potential recharge is likely to increase in 2010-2039 and is likely to decrease in 2070-2099. The mean annual potential recharge in 2070-2099 is projected to decrease from 227.5 to 95.4 mm/year under the most pessimistic scenario (GFDLA1FI), and decrease to 192.5 mm/year under the most optimistic scenario (PCMB1). As a result, the potential recharge to the Southern Hills aquifer system is projected to be reduced in

2070-2099 as the climate change studies have projected for other places (e.g., Serrat-Capdevila et al. 2007).

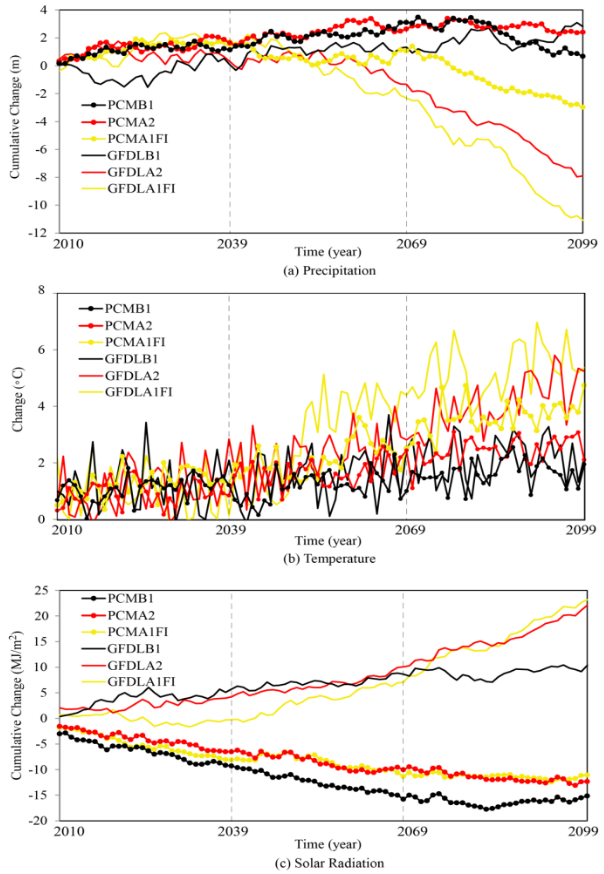

Figure 3: Cumulative changes of (a) precipitation, (b) changes of temperature, and (c) cumulative changes of solar radiation with respect to the historical baseline

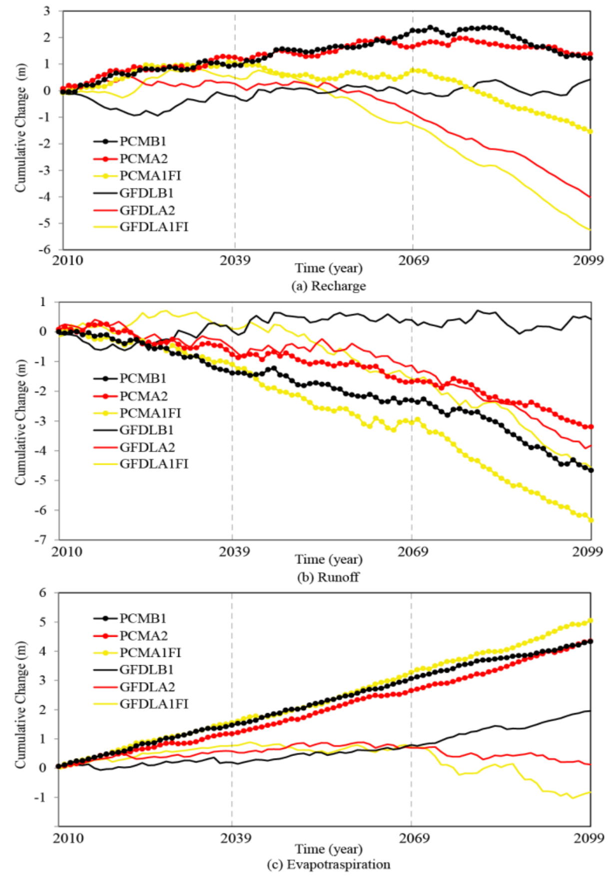

Figure 4: Cumulative changes of (a) potential groundwater recharge, (b) surface runoff, and (c) evapotranspiration with respect to the historical baseline

Table 1: Projected changes in mean annual potential recharge, runoff and evapotranspiration with respect to the mean annual for 1950-2009.

Climate model	Scenario	Potential recharge (%) Mean annual = 227.5 mm			Runoff (%) Mean annual = 362.7 mm			Evapotranspiration (%) Mean annual = 943.2 mm		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
PCM	B1	+14.1	+19.1	−15.4	−12.8	−8.4	−21.6	+5.2	+5.6	+4.5
	A2	+18.4	+5.9	−4.0	−7.0	−8.4	−13.9	+4.1	+5.2	+6.0
	A1FI	+15.4	−4.2	−33.7	−10.1	−18.0	−30.2	+5.5	+6.1	+6.3
GFDL	B1	−3.1	+3.3	+6.0	+0.2	+3.4	+0.2	+0.7	+2.1	+4.1
	A2	+3.9	−16.3	−46.5	−5.1	−5.2	−24.8	+2.1	+0.4	−2.0
	A1FI	+7.1	−25.8	−58.1	+0.9	−15.5	−27.4	+2.7	−0.2	−5.4

Runoff is likely to decrease for the 21st century as projected by the GCMs (Table 1). PCM projects runoff decrease from −7.0 % to −30.2 % while GFDL projects runoff change from +3.4 % to −27.4 %. In general, PCM projects less runoff than GFDL for the 21st century. Evapotranspiration is likely to increase for the 21st century. The PCM projects evapotranspiration increase from 4.1 % to 6.3 % and the GFDL projects evapotranspiration change from −5.4 % to +4.1 %.

In order to understand the range of possible future changes in potential recharge, results from the most optimistic scenario (PCMB1) and the most pessimistic scenario (GFDLA1FI) are investigated. Figure 5 shows the changes in 30-year mean annual potential recharge with respect to the mean annual potential recharge (1950-2009). The PCMB1 projects relatively higher potential recharge increase in southeastern Louisiana than southwestern Mississippi in 2010-2039 and 2040-2069. Recharge is projected to decrease in 2070-2099. The GFDLA1FI also projects more potential recharge in southeastern Louisiana in 2010-2039. Potential recharge is projected to decrease in 2040-2069 by the GFDLA1FI and more severely in 2070-2099. In general, the PCM model projects more potential recharge than that of the GFDL model.

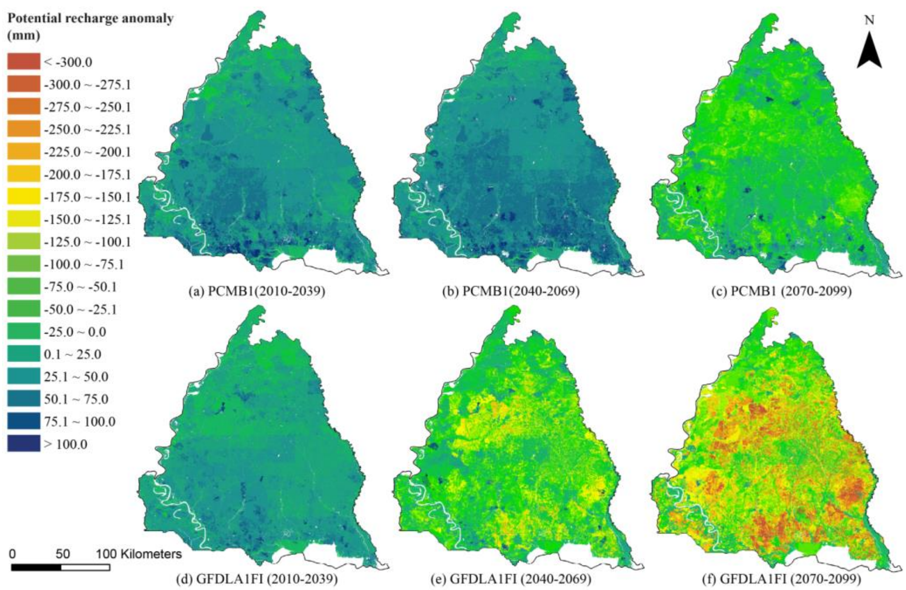

Figure 5: Potential recharge anomaly map for three future periods (2010-2039, 2040-2069, and 2070-2099) for the most optimistic scenario (PCMB1) and the most pessimistic scenario (GFDLA1FI). Each map shows the changes in 30-year mean annual potential recharge with respect to the mean annual potential recharge (1950-2009) in Figure 2.

4. Sensitivity Analyses of Recharge to Climate Change

The sensitivity of potential recharge to climate change was evaluated by using the linear regression method to analyze the relationship between the change in potential recharge and the change in individual climate variables such as precipitation, temperature and solar radiation under different climate change scenarios (Crosbie et al. 2013). The slope (dR/dP) of a linear regression represents the sensitivity of the potential recharge to a climate variable given a climate change scenario; and the intercept represents the sensitivity of the potential recharge to all other variables. A sensitivity analysis was conducted for each subdivision to assess sensitivity variation in space. This study selected GFDLA1FI scenario for the period 2070-2099 since it shows the highest potential recharge change for the study area. As shown in Figure 6, subdivisions with high potential recharge have the lowest slope and intercept while subdivisions with low potential recharge have the highest slope and intercept. As a result, subdivisions with high potential recharge show lower potential recharge sensitivity to precipitation, temperature and solar radiation and vice versa.

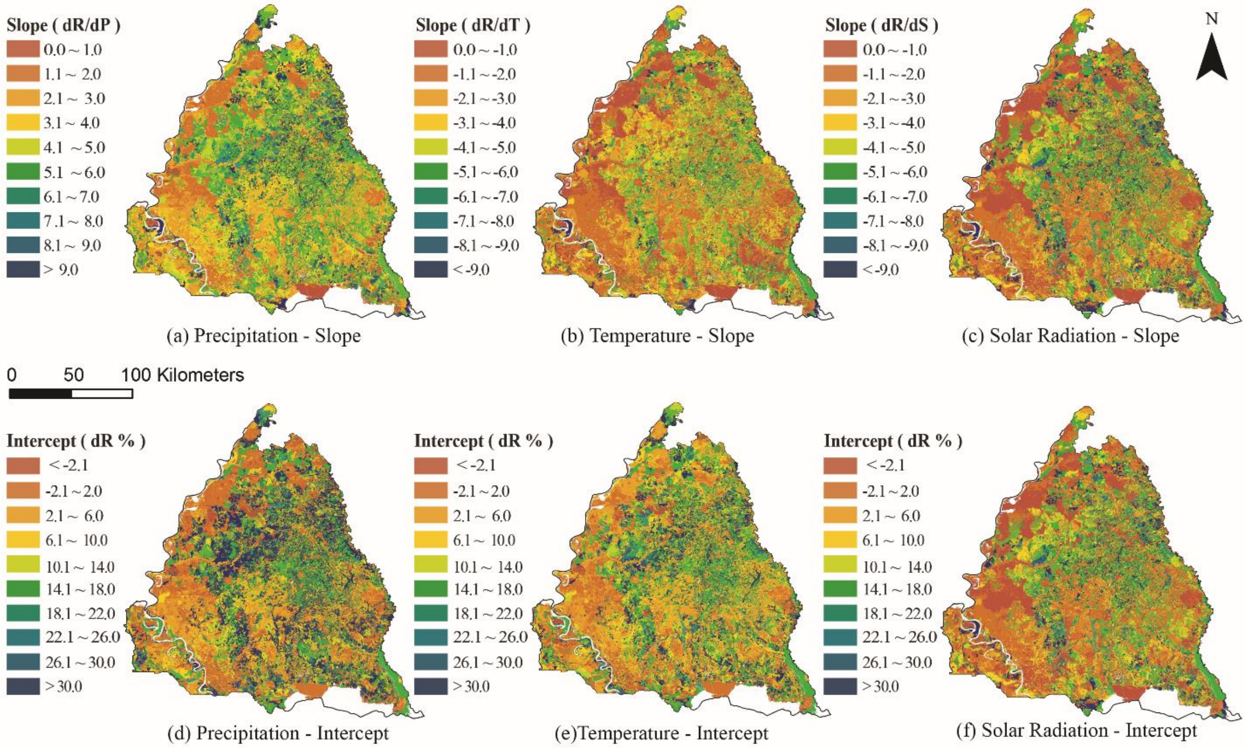

Figure 6: Slopes and intercepts of the relationship between changes in mean annual potential recharge and changes in mean annual precipitation, temperature and solar radiation for GFDLA1FI for 2070-2099.

5. Conclusions

Assessing the impact of climate change on potential groundwater recharge for humid areas can be achieved by the proposed HELP3 model in a GIS-based water budget framework. Intersecting various datasets through the GIS can easily create a great number of subdivisions, which makes the potential recharge estimation virtually infeasible on a single-core computer. The framework includes parallel programming to divide required HELP3 model runs to multiple cores of a supercomputer to significantly reduce computing time. The parallel programming allows the methodology to be applied to century-long potential groundwater recharge, surface runoff and evapotranspiration estimation for the area of the Southern Hills aquifer system, southwestern Mississippi and southeastern Louisiana, under a large number of emission scenarios and GCMs.

Under a wide range of climate change scenarios, it was found that the GFDL climate model projects more intense changes in future precipitation, temperature and solar radiation in the study area than the PCM model for the 21st century. Given these projected climate forcings, potential recharge is likely to increase in 2010-2039 and likely to decrease in 2070-2099 with respect to the estimated historical potential recharge (1950-2009). The study area is projected to have a wide range of future potential recharge. The potential recharge is projected to decrease in 2070-2099 by much as 58.1 % (GFDLA1FI) and to increase by as much as 19.1 % (PCMB1 scenario). Runoff is likely to decrease for the 21st century as projected by the GCMs (Table 1). PCM projects runoff decrease from -7.0 % to -30.2 % while GFDL projects runoff change from +3.4 % to -27.4 %. The PCM projects evapotranspiration increase from 4.1 % to 6.3 % and the GFDL projects evapotranspiration change from −5.4 % to +4.1 %.

It was found that the future potential recharge variation has strong correlation with the precipitation projections. Potential recharge was found to be most sensitive to the changes in future precipitation, followed by solar radiation, and then temperature. Moreover, both GCMs show a consistent result that the A1FI scenario projects the highest recharge sensitivity to the precipitation, temperature and solar radiation, followed by the A2 scenario, and then the B1 scenario. This order follows the increment of the degree of global warming in the emission scenarios. Subdivisions with high potential recharge show lower recharge sensitivity to precipitation, temperature and solar radiation.

The impact of climate change on groundwater recharge in the study area is unclear as it highly depends on selected climate models and scenarios. Using high-responsive and low-responsive climate models in conjunction with low, medium, and high emission scenarios exhibits a broad extent of uncertain future potential recharge projections. The precipitation and temperature uncertainty analyses show that precipitation influences potential recharge more than temperature.

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Information Transfer

The research results were disseminated to the public through the *9th Annual Louisiana Groundwater, Water Resources and Environmental Symposia*, Baton Rouge, Louisiana, April 16, 2015 (http://lwrri.lsu.edu/ninth-annual-louisiana-groundwater-water-resources-and-environmental-symposia/) and PI's research website (https://sites.google.com/site/franktctsai/home/recharge-estimation-for-southern-hills-aquifer-system)

Student Support

Ehsan Beigi, Doctoral Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge.

Long-Term Groundwater Recharge Projection of Southeastern Louisiana and Southwestern Mississippi Under Climate Change

Basic Information

Title:	Long-Term Groundwater Recharge Projection of Southeastern Louisiana and Southwestern Mississippi Under Climate Change
Project Number:	2015LA100B
Start Date:	3/1/2015
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	6th
Research Category:	Ground-water Flow and Transport
Focus Category:	Hydrology, Methods, Models
Descriptors:	None
Principal Investigators:	Frank Tsai

Publications

1. Mani, A., F. T.-C. Tsai, and K. Paudel, 2016. “Mixed integer linear fractional programming for conjunctive use of surface water and groundwater,” Journal of Water Resources Planning and Management. Accepted. doi:10.1061/(ASCE)WR.1943-5452.0000676
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3. Beigi, E., 2015. “Uncertainty Analyses of Climate Change Impact on Hydrologic Projections”, Ph.D. Dissertation, Louisiana State University, Baton Rouge. http://etd.lsu.edu/docs/available/etd-03312015-144718/
4. Mani, A. and F. T.-C. Tsai, 2015. “Conjunctive management of multireservoir network system and groundwater system”, Poster Presentation, 2015 American Geophysical Union Fall Meeting, San Francisco, CA, 14-18 December 2015
5. Mani, A. and Frank T.-C. Tsai, 2015. “Conjunctive management of surface water and groundwater for northern Louisiana”, 9th Annual Louisiana Groundwater, Water Resources & Environmental Symposia, Baton Rouge, Louisiana, April 16, 2015

Problem and Research Objectives

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and the U.S. National Climate Assessment Report have not adequately addressed the issue of uncertainty in assessments and projections of climate change. The need to carefully characterize and quantify uncertainty in climate change projections is essential not only for detection and attribution purposes, but also for effective climate change adaptation and mitigation strategies. The future climate projections from global climate models (GCMs) are an important tool in tracing the impacts of anthropogenic forcings in the Earth's climate. However, these GCM projections are subjected to considerable uncertainties derived from three main sources: model uncertainty, scenario uncertainty and internal variability. Model uncertainty stems from inaccuracies in the climate models due to an imperfect understanding and representation of complex physical, chemical, biological and other processes of climate system. Additionally, model uncertainty arises when different models response differently to the same external forcing due to the differences in model structures (e.g. physical and numerical formulations). Scenario uncertainty occurs because of insufficient knowledge about future greenhouse gases (GHG) emissions and other external forcings that influence the climate system. The internal variability which is the fluctuation of natural processes within the climate system that occurs without external forcing's effect. The outputs from GCMs are used as inputs to hydrological models to investigate the hydrological impacts of climate change for global and regional water resources.

Using a single model likely underestimates prediction uncertainty and tends to statistically biased modeling. Due to inaccuracy of each individual GCM, no single model can be declared as the best model; hence, future projections should exhibit the results of all GCMs. The IPCC suggests using multi-model ensembles for detection and attribution as well as for impact and adaptation studies, and provides recommendations for good practice on assessing and combining multi-model climate projections.

The goal of the project is to analyze climate modeling uncertainty and emission scenario uncertainty in projecting future precipitation and temperature, their impacts on future groundwater recharge, runoff, and evapotranspiration projections, and their uncertainty contributions to total uncertainty for southeastern Louisiana and southwestern Mississippi. The study area is shown in Figure 1.

Methodology

Bayesian model averaging (BMA) (Hoeting et al., 1999) is a robust multi-model method to combine multiple prediction models and conduct uncertainty analysis. BMA has been successfully implemented to provide reliable prediction and to conduct uncertainty analysis in various studies, such as weather forecasting, inverse groundwater modeling, and hydrological prediction. However, the BMA framework does not quantify contributions of individual sources of uncertainty to total prediction uncertainty, whereas addressing this issue is very important for a thorough uncertainty analysis. Li and Tsai (2009) and Tsai (2010) developed a new BMA formulation to discuss individual impacts of two sources of model uncertainty in groundwater prediction and remediation designs. Thereafter, Tsai and Elshall (2014) generalized the formulation and developed a hierarchical Bayesian model averaging (HBMA) method to analyze uncertainty from different types of groundwater model components. HBMA systematically segregates and prioritizes distinct sources of uncertainty in a hierarchical structure known as BMA trees for analyzing model uncertainty and uncertainty propagation for model prediction.

This study adopts the HBMA to analyze climate modeling uncertainty and emission scenario uncertainty in projecting future precipitation and temperature, their impacts on future hydrologic projections, and their uncertainty contributions to total uncertainty. Climate modeling uncertainty includes the use of different GCMs and GCM initial conditions. The emission path uncertainty arises from the assumption of future GHG emissions, atmospheric GHG concentrations and other climate drivers. For the illustration purpose, this study utilizes the precipitation and temperature projections derived by 21 GCMs with different initial conditions and four representative concentration pathways (RCPs) of the Coupled Model Intercomparison Project phase 5 (CMIP5) (Maurer et. al, 2013; USBR 2013). The precipitation and temperature projections are input to a hydrological model, HELP3 (Schroeder et al. 1994), to project future surface runoff, evapotranspiration and groundwater recharge southwestern Mississippi and southeastern Louisiana. Sources of uncertainty that causes climate projection uncertainty can be structured in a hierarchical order, as shown in Figure 2.

Principal Findings and Significance

1. HBMA Analysis of CMIP5 Precipitation and Temperature Projections

In order to improve precipitation and temperature projections for the southwestern Mississippi and southeastern Louisiana, the hierarchical Bayesian model averaging (HBMA) method is implemented to quantify means and variances of precipitation and temperature projections. The posterior model probabilities are assigned to climate models to enhance the effect of climate models with greater performance in terms of simulating monthly precipitation and temperature from 1950-2009. The BMA mean and one standard deviation interval of annual precipitation and temperature predictions from 2010 to 2099 for the study area using the entire 133 climate projections is shown in Figure 3. The predictions are the results of the hierarch model in Figure 2, which take into account uncertainties arising from different GCMs, GCM initial conditions, and emission paths. As shown in Figure 3, the projected mean precipitation indicates a slightly decreasing trend while the projected mean temperature indicate increasing trends throughout 2099. Precipitation projections show higher uncertainty than temperature projections. The projection uncertainty in precipitation shows a constant trend while uncertainty in temperature projection grows continuously after midcentury through the end of the 21 century.

Table 1 shows projection anomalies in mean annual precipitation and temperature for three 30-year periods (2010-2039, 2040-2069, and 2070-2099) with respect to mean annuals of 1950-2009 at different levels of the BAM tree in Figure 2. Projection anomalies using the best and the second best climate models under each emission path (level 3 of Table 1) show that precipitation has diverse projections with no clear trend.

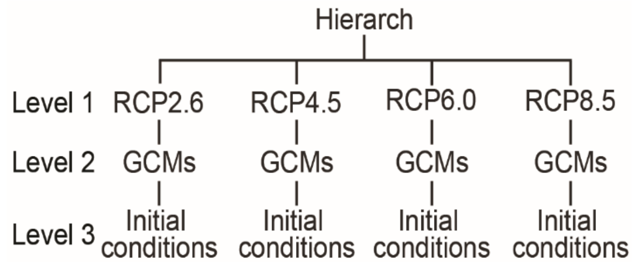

Figure 1: Hierarchical structure of sources of uncertainty for precipitation and temperature projections in the CMIP5 multi-model ensembles.

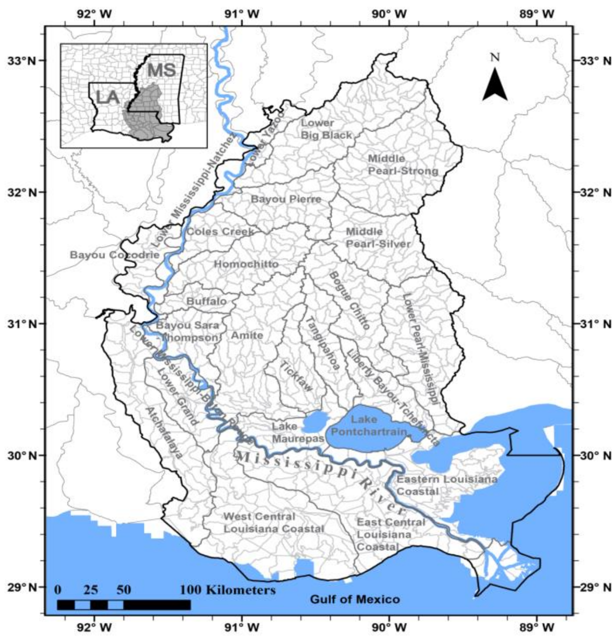

Figure 2: The study area of southwestern Mississippi (MS) and southeastern Louisiana (LA) bounded by thick black line. Dark gray lines represent the boundaries of 8-digit hydrologic units (HUC8) and light gray lines represent the boundaries of 12-digit hydrologic units (HUC12).

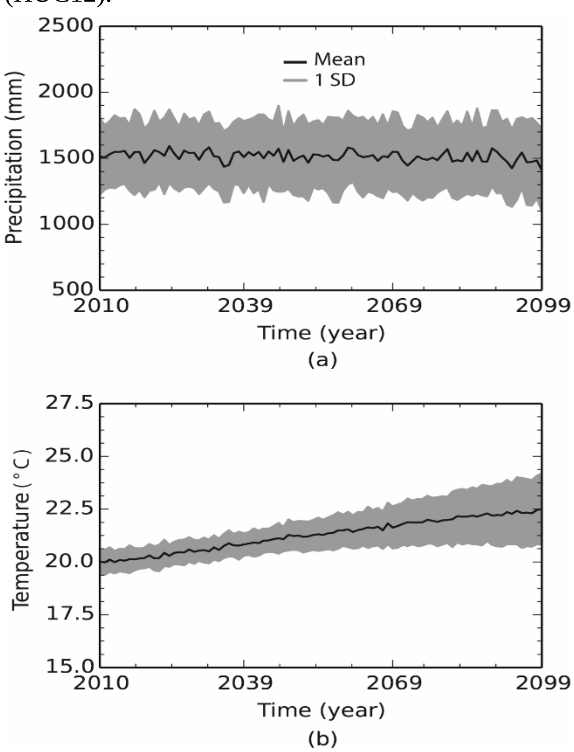

Figure 3: BMA mean and one standard deviation (SD) interval of precipitation and temperature projections for 2010-2099 at the hierarch level using 133 climate models.

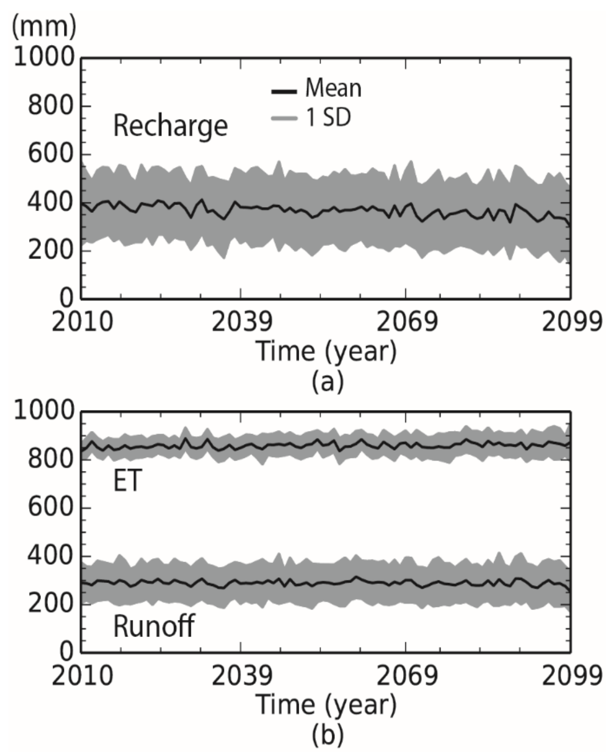

Figure 4: BMA mean and one standard deviation (SD) interval of potential recharge, runoff and ET projections for 2010-2099 at the hierarch level using 133 climate models

Table 1: Projected changes in mean annual precipitation and temperature with respect to mean annuals of 1950-2009. Level 3 lists the best and the second best climate models under each emission path. Level 2 lists the best and the second best GCMs under each emission path.

Level	Climate model	Precipitation (%) Mean annual = 1522.1 mm			Temperature (ºC/year) Mean annual = 18.9 ºC		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
3	rcp26.gfdl-esm2g.1	−1.0	−1.6	−0.8	+0.042	+0.050	+0.048
	rcp26.csiro-mk3-6-0.10	−0.3	+5.1	+5.8	+0.048	+0.068	+0.064
	rcp45.ipsl-cm5a-lr.4	+3.2	−5.7	−12.2	+0.049	+0.090	+0.104
	rcp45.cnrm-cm5.1	+4.8	+4.9	+0.3	+0.039	+0.062	+0.083
	rcp60.gfdl-esm2g.1	+2.5	−2.8	−7.6	+0.043	+0.062	+0.088
	rcp60.miroc-esm-chem.1	−2.1	+0.8	−8.9	+0.045	+0.069	+0.104
	rcp85.ipsl-cm5a-lr.4	−2.6	−8.7	−16.7	+0.056	+0.116	+0.175
	rcp85.cnrm-cm5.1	+5.0	+6.9	+2.0	+0.037	+0.085	+0.136
2	rcp26.csiro-mk3-6-0	+0.5	+5.0	+7.6	+0.044	+0.065	+0.064
	rcp26.canesm2	+0.1	+6.7	+5.1	+0.059	+0.074	+0.072
	rcp45.csiro-mk3-6-0	+1.9	+5.9	+6.5	+0.045	+0.075	+0.094
	rcp45.ipsl-cm5a-lr	+3.1	−4.1	−12.0	+0.052	+0.089	+0.102
	rcp60.gfdl-esm2g	+2.5	−2.8	−7.6	+0.043	+0.062	+0.088
	rcp60.miroc-esm-chem	−2.1	+0.8	−8.9	+0.045	+0.069	+0.104
	rcp85.csiro-mk3-6-0	+1.4	+1.0	−0.9	+0.047	+0.090	+0.155
	rcp85.ipsl-cm5a-lr	−2.1	−8.4	−17.6	+0.059	+0.114	+0.177
1	rcp26	+0.5	+2.3	+3.7	+0.049	+0.065	+0.063
	rcp45	+0.6	+0.1	−0.7	+0.048	+0.076	+0.091
	rcp60	−0.3	−2.1	−6.2	+0.043	+0.067	+0.098
	rcp85	+0.0	−1.4	−5.3	+0.051	+0.098	+0.157
Hierarch	Hierarch	+0.3	−0.1	−1.7	+0.048	+0.080	+0.107

As shown in Table 1, the rcp26.csiro-mk3-6-0.10 model projects highest precipitation increase (+5.8 %) while rcp85.ipsl-cm5a-lr.4 model projects highest precipitation decrease (−16.7 %) in 2070-2099.Temperature is projected to increase continuously for 2010-2099 under all climate models. Similar to projection anomalies at level 3, climate models at level 2 produce wide range of precipitation projections. Projection anomalies at level 1 follow the degree of global warming in the development of future emissions. RCP2.6 is optimistic for precipitation and projects continuous precipitation increase for the next century due to the assumption of strong mitigation, the lowest GHG concentration, and the least warming. RCP4.5 also shows positive for precipitation, but with a decreasing trend over time. RCP6.0 and RCP8.5 project precipitation decrease in 2040-2099. Again, RCP8.5 shows most pessimistic emission path with the least precipitation increase and the highest temperature increase. Conversely, RCP2.6 demonstrates the most optimistic emission path due to projecting highest precipitation increase and the least temperature increase. Using all 133 climate models, the BMA mean precipitation in southwestern Mississippi and southeastern Louisiana is projected to decrease from 1522.1 mm to 1496.1 mm for the next century. Temperature is projected to increase from 18.9 ºC to 22.1 ºC through the end of the next century.

2. HBMA Temporal Analysis of Potential Recharge, Runoff, and Evapotranspiration

Using the entire 133 climate projections, the BMA mean and one standard deviation interval of annual potential recharge, runoff and ET predictions from 2010 to 2099 for the study area is shown in Figure 3. These predictions take into account uncertainties arising from different GCMs, GCM initial conditions, and emission paths. The projections are the results of the hierarch model in Figure 2. The projected mean potential recharge plot indicates a slightly decreasing trend while the projected mean runoff and ET plots indicate constant trends throughout 2099. The coefficient of variation (CV) of projections for each year was calculated by dividing the standard deviation to the mean in Figure 3. The ranges of CV for potential recharge, runoff and ET projections are 31.5 %-54.1 %, 23.3 %-35.6 % and 3.6 %-8.9 %, respectively. The temporal average CV for potential recharge, runoff and ET projections are 40.1 %, 28.6 % and 5.4%, respectively. Again, projected recharge has much higher uncertainty than runoff and ET. High uncertainty in potential recharge projection indicates that potential recharge prediction is more sensitive to climate projections than runoff and ET predictions.

3. Projection Anomalies

Table 2 shows projection anomalies in mean annual potential recharge, runoff and ET for three 30-year periods (2010-2039, 2040-2069, and 2070-2099) with respect to mean annuals of 1950-2009 at different levels of the BAM tree in Figure 2. The estimated mean annual potential recharge, runoff and ET for the study area in 1950-2009 are 337.4 mm, 352.8 mm and 832.9 mm, respectively, which accounts for 22.1 %, 23.1 %, and 54.4 % of the mean annual precipitation in the study area.

Projection anomalies using the best and the second best climate models under each emission path (level 3 of Table 2) show that potential recharge is likely to increase in 2010-2069. There is no clear trend in 2070-2099. The rcp26.csiro-mk3-6-0.10 model projects highest potential recharge increase (+26.9 %) while rcp85.ipsl-cm5a-lr.4 model projects highest potential recharge decrease (−38.9 %) in 2070-2099. Runoff is likely to decrease through 2099 while ET is likely to increase comparing to their mean annual in 1950-2009. ET increase is not significant.

Projection anomalies at level 2 show the same observations as level 1, GCMs produce wide range of potential recharge projection. In general, potential recharge is likely to increase in 2010-2069. Runoff is likely to decrease and ET is likely to slightly increase in the next century.

Projection anomalies at level 1 show consistent results with the development of future emissions. RCP2.6 is positive for potential recharge and projects continuous potential recharge increase for the next century owing to the assumption of strong mitigation, the lowest GHG concentration, and the least warming. RCP4.5 also shows positive for potential recharge, but with a decreasing trend over time. RCP6.0 and RCP8.5 project potential recharge increase in 2010-2069. The decreasing trend indicates lesser potential recharge in 2070-2099 than in 1950-2009. RCP8.5 shows the least potential recharge increase and the highest potential recharge decrease. All emission paths show decreasing runoff and increasing ET in the next century compared to their annual means in 2010-2069.

Using all 133 climate models, the BMA mean potential recharge in southwestern Mississippi and southeastern Louisiana is projected to increase with a decreasing trend for 30-year interval. Runoff is likely to decrease and ET is likely to increase in the next century.

Table 2: Projected changes in mean annual potential recharge, runoff and evapotranspiration (ET) with respect to mean annuals of 1950-2009. Level 3 lists the best and the second best climate models under each emission path. Level 2 lists the best and the second best GCMs under each emission path.

Level	Climate model	Potential recharge (%) Mean annual = 337. 4 mm			Runoff (%) Mean annual = 352.8 mm			ET (%) Mean annual = 832.9 mm		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
3	rcp26.gfdl-esm2g.1	+11.6	+8.9	+13.4	−16.3	−15.8	−14.7	+0.5	+0.3	+0.5
	rcp26.csiro-mk3-6-0.10	+12.7	+22.0	+26.9	−17.8	−10.2	−9.1	+2.1	+4.7	+3.9
	rcp45.ipsl-cm5a-lr.4	+21.5	−2.5	−24.7	−12.2	−21.6	−27.9	+2.8	+0.3	−0.2
	rcp45.cnrm-cm5.1	+27.0	+26.9	+12.4	−14.7	−16.0	−20.7	+4.0	+5.2	+4.6
	rcp60.gfdl-esm2g.1	+18.0	+4.0	−8.9	−12.2	−18.6	−21.3	+2.5	+1.6	−0.1
	rcp60.miroc-esm-chem.1	+4.8	−2.0	−18.4	−19.9	−19.1	−27.0	+2.3	+2.5	+1.9
	rcp85.ipsl-cm5a-lr.4	+1.4	−17.7	−38.9	−20.4	−25.0	−31.9	+3.5	+2.3	−0.4
	rcp85.cnrm-cm5.1	+27.6	+28.2	+8.2	−16.2	−12.2	−20.1	+5.3	+6.4	+9.2
2	rcp26.csiro-mk3-6-0	+18.0	+22.2	+30.0	−16.3	−11.0	−7.8	+2.2	+4.0	+4.2
	rcp26.canesm2	+15.8	+32.7	+28.4	−19.7	−11.5	−12.0	+2.2	+4.0	+3.4
	rcp45.csiro-mk3-6-0	+19.5	+24.6	+25.3	−15.0	−9.3	−8.2	+2.3	+4.7	+5.6
	rcp45.ipsl-cm5a-lr	+21.1	+0.3	−23.2	−13.1	−20.4	−28.5	+2.9	+1.5	−0.1
	rcp60.gfdl-esm2g	+18.0	+4.0	−8.9	−12.2	−18.6	−21.3	+2.5	+1.6	−0.1
	rcp60.miroc-esm-chem	+4.8	−2.0	−18.4	−19.9	−19.1	−27.0	+2.3	+2.5	+1.9
	rcp85.csiro-mk3-6-0	+14.4	+9.0	−2.6	−16.5	−14.9	−17.7	+2.9	+5.0	+8.1
	rcp85.ipsl-cm5a-lr	+3.1	−17.6	−40.7	−19.7	−25.4	−33.4	+3.5	+2.9	−0.6
1	rcp26	+15.3	+17.4	+21.4	−17.4	−14.5	−12.9	+2.0	+3.2	+3.2
	rcp45	+15.2	+11.8	+7.8	−17.4	−17.1	−17.8	+2.3	+3.2	+3.2
	rcp60	+12.2	+4.9	−7.0	−17.6	−19.1	−23.6	+2.1	+2.3	+1.9
	rcp85	+10.7	+3.5	−10.3	−18.3	−18.8	−22.8	+3.4	+4.3	+4.8
Hierarch	Hierarch	+13.4	+9.8	+3.7	−17.7	−17.2	−18.8	+2.6	+3.5	+3.6

4. HBMA Spatial Analysis of Potential Recharge, Runoff, and Evapotranspiration

The BMA means of annual potential recharge, runoff and ET projections for 728 HUC12s in 2010-2039, 2040-2069, and 2070-2099 using 133 climate models are shown in Figure 5. The areal changes for every 30-year period are not distinguishable since the maximum changes of potential recharge, runoff and ET projections are relatively small (56.2 mm, 44.7 mm and 38.6 mm, respectively). High potential recharge rate was estimated at the outcrops of Miocene deposits in southwestern Mississippi, which are the potential recharge zones of the deep sands in southeastern Louisiana. Projection uncertainty increases over time as shown in Figure 6. The BMA standard deviations of projected potential recharge, runoff and ET in 2070-2099 range 4.1-123.2 mm, 1.7-96.7 mm and 7.8-45.6 mm, respectively. The CV of projected potential recharge, runoff and ET in 2070-2099 range 12.3-44.6 %, 8.1-24.2 % and 2.4-6.4 %, respectively. Potential recharge projection has greater uncertainty than runoff projection, followed by ET projection.

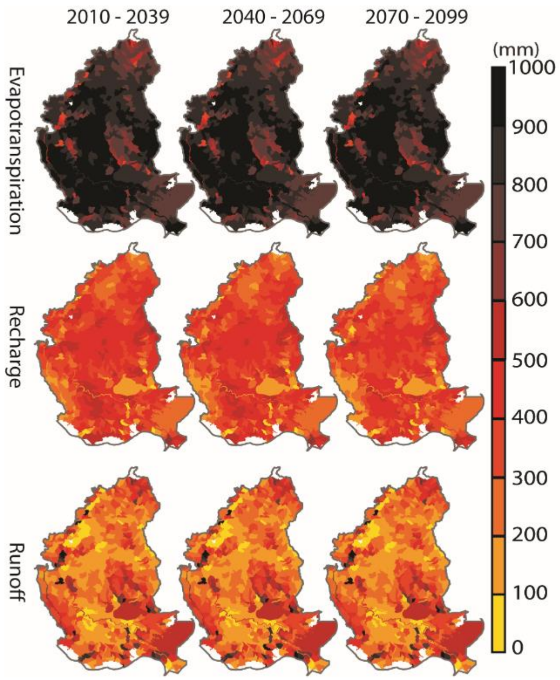

Figure 5: BMA mean of annual potential recharge, runoff and ET projections for 30-year interval at the hierarch level using 133 climate models.

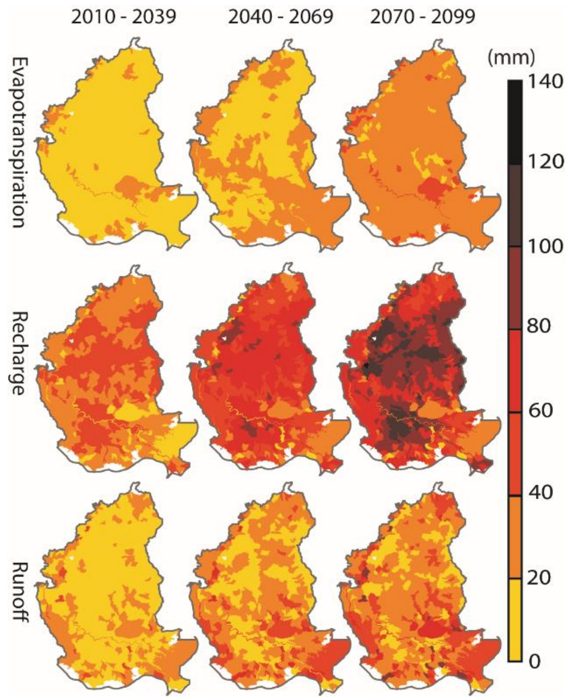

Figure 6: BMA standard deviation of annual potential recharge, runoff and ET projections for 30-year interval at the hierarch level using 133 climate models.

Contributions of individual sources of uncertainty to the total uncertainty of projected potential recharge in 728 HUC12s are shown in Figure 7, which supports that GCM uncertainty is the dominant source of uncertainty in assessing climate change impacts on hydrologic projection. Contribution of emission path uncertainty to the total uncertainty increases every 30-year period since emission paths start to diverge significantly after mid-century, resulting in higher uncertainty in 2070-2099. This indicates that climate models' parameterizations, sensitivities and responses to greenhouse gases and other forcings grow over time and become evident. On the contrary, contribution of GCM initial condition uncertainty to the total uncertainty decreases every 30-year period, indicating that impact of GCM initial conditions on total potential recharge projection uncertainty becomes less important as emission path uncertainty increases towards the end of the century.

Means and standard deviations of uncertainty contributions of the three sources to the total uncertainty of projected potential recharge over 728 HUC12s are shown in Table 3. The small standard deviations indicate variations of uncertainty contributions of individual sources across the HUC12s are small. The mean uncertainty contribution from GCMs dominates and ranges from 62.2% to 77.1%. The GCMs and GCM initial conditions contribute 95.7% of total uncertainty to potential recharge projection in 2010-2039. The GCMs and emission paths contribute 91.6% of total uncertainty in 2070-2099. Although not presented in this study, the contributions of the three sources of uncertainty to the projected runoff and ET are similar to the projected potential recharge in the study area.

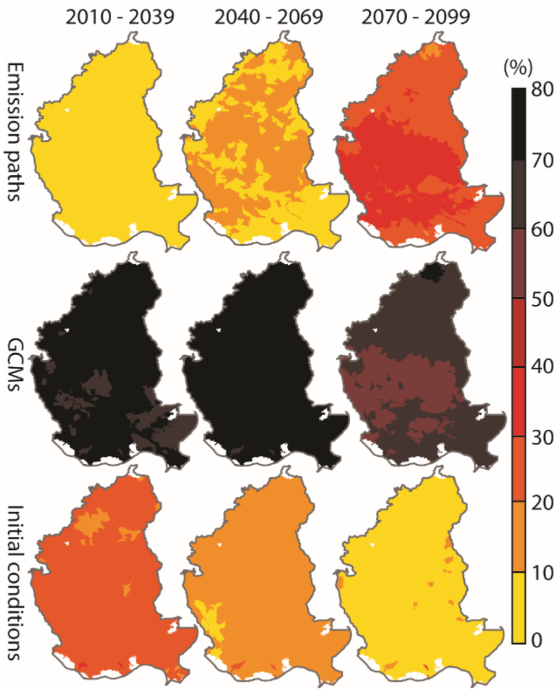

Figure 7: Contributions of individual sources of uncertainty to the total uncertainty of projected potential recharge for 30-year interval.

Table 3: Mean and standard deviation (SD) of contributions of individual sources of uncertainty to the total uncertainty of projected potential recharge over 728 HUC12s.

Uncertainty Source	2010-2039 Mean (%)	2010-2039 SD (%)	2040-2069 Mean (%)	2040-2069 SD (%)	2070-2099 Mean (%)	2070-2099 SD (%)
Emission Path	4.3	1.2	10.0	1.4	29.4	3.6
GCM	72.5	2.1	77.0	2.0	62.2	3.7
GCM Initial Condition	23.2	2.4	13.0	2.0	8.4	1.7

5. Conclusions

The hierarchical Bayesian model averaging (HBMA) method provides an intriguing approach to analyze different types of uncertainties existing in climate projections and consequent impacts on hydrologic projections. Working on the 133 sets of 1/8-degree-BCCA-downscaled daily precipitation and temperature projections of CMIP5, the HBMA is able to display the hierarchical nature of emission scenario uncertainty (emission paths) and climate modeling uncertainty (GCMs and GCM initial conditions) and provide hydrological projection means and variances thought Bayesian model averaging.

Quantifying climate-related hydrologic projection uncertainty is computational demanding and requires parallel computation. This study successfully demonstrates a detailed hydrologic modeling work for southwestern Mississippi and southeastern Louisiana using CPU-based multi-core supercomputers. The modeling complexity includes highly parameterized hydrologic model (2.6 million homogeneous subdivisions for the HELP3 model), 133 sets of daily precipitation and temperature projections, and a century-long simulation.

The GCM posterior model probabilities suggest that GCMs with more initial conditions in the emission paths are usually important, which, however, exhibit more projection uncertainty. The best GCM for southwestern Mississippi and southeastern Louisiana is CSIRO-Mk3.6.0 that uses 10 initial conditions in RCP2.6, RCP4.5, and RCP8.5, and is followed by IPSL-CM5A-LR, CanESM2, and MIROC5 models that use at least 3 initial conditions for projections.

The hydrologic modeling and HBMA results show higher spatial and temporal variability and variance in projected potential recharge than those in projected runoff and evapotranspiration. Evapotranspiration projection exhibits the least uncertainty. In general, future potential recharge in southwestern Mississippi and southeastern Louisiana is likely to increase in next several decades and is not certain about its trend toward the end of the century. Runoff is likely to decrease significantly while evapotranspiration is likely to increase slightly in the next century.

The prevailing GCM uncertainty is the major contributor to the total uncertainty of future hydrologic projections in southwestern Mississippi and southeastern Louisiana. Contributions from emission path uncertainty and GCM initial condition uncertainty compensate each other over time. Contribution from the initial condition uncertainty is noticeable for first several decades and decreases over time toward the end of the century. On the contrary, contribution of the emission path uncertainty is not evident in next decades, but grows after mid-century and becomes significant at the end of the century.

This study does not discuss uncertainty from hydrological models. We acknowledge that uncertainty from hydrologic model is also very important and needs to be considered in the future study.

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Information Transfer

The research results were disseminated to the public through the *9th Annual Louisiana Groundwater, Water Resources and Environmental Symposia*, Baton Rouge, Louisiana, April 16, 2015 (http://lwrri.lsu.edu/ninth-annual-louisiana-groundwater-water-resources-and-environmental-symposia/)

Student Support

Hamid Vahdat Aboueshagh, Ph.D. Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana

An Li, Ph.D. Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana

Amir Mani , Ph.D. Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana

Jina Yin, Ph.D. Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana

Atmospheric deposition of nitrogen and sulfur to Louisiana water bodies

Basic Information

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End Date:	2/29/2016
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Congressional District:	6th
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Principal Investigators:	Hongliang Zhang, Hongliang Zhang

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1. Hongliang Zhang, Hao Guo, 2015. “Atmospheric deposition of nitrogen and sulfur in Louisiana”, The American Geophysical Union 2015 Fall meeting, San Francisco, CA, December 2015.
2. Hao Guo, Fenglin Han, Hongliang Zhang, 2016. “Deposition of nitrogen and sulfur to Louisiana water bodies”, The 10th Annual Louisiana Groundwater, Surface Water and Water Resources Symposium, Baton Rouge, LA, March 2016.

Problem and Research Objectives

Sulfur and nitrogen contained air pollutants are directly emitted from anthropogenic and biogenic sources or secondarily formed through complex reactions using the atmosphere as a potent oxidizing medium. The result of atmospheric processes is the existence of sulfur and nitrogen pollutants in gas phase, aerosol phase, and aqueous phase. The ultimate methods that remove sulfur and nitrogen species from atmosphere are wet deposition and dry deposition. Although deposition of these pollutants reduces their concentrations in atmosphere, it leads to increase of sulfur and nitrogen fluxes to the surface. Atmospheric deposition of sulfur and nitrogen can lead to acidification of surface water bodies (lakes, rivers, and coasts) (Heard et al., 2014) and subsequent damage to aquatic ecosystems as well as damage to forests and vegetation (Benedict et al., 2013; Bytnerowicz et al., 2007; Vinebrooke et al., 2014) since major of sulfur and nitrogen species are in acidic forms. Also, as an essential nutrient element for all living, deposition of nitrogen originated from anthropogenic sources causes nutrient imbalances of ecosystems, contributing to long-term eutrophication, increase of weedy plant species, and loss of native species. (BergstrÖM and Jansson, 2006).

Efforts have been made to understand and control atmospheric deposition of sulfur and nitrogen in US and worldwide. The National Atmospheric Deposition Program (NADP) (Lamb and Bowersox, 2000) was initiated in 1977 to measure atmospheric deposition and the Clean Air Status and Trends Network (CASTNET) (Baumgardner et al., 2002) was established in 1991 to assess the trends in acidic deposition. Total sulfur deposition in East US declined 46% and nitrogen deposition decreased by 26% from 1990 through 2009 (MACTEC Engineering and Consulting, 2011).

Louisiana has abundant water resources with approximately 11% of the total surface area is composed of water bodies. The state has more than 40,000 miles of rivers, streams and bayous, and 400 miles of coastline. Almost every aspect of economy in Louisiana can be tied to the development and utilization of water resources. Thus, it is important to protect water resources from excessive atmospheric deposition of sulfur and nitrogen. However, there are only two sites in NADP and no sites in CASTNET located in Louisiana. Thus, the information can be obtained from the observation systems for understanding the deposition of sulfur and nitrogen and the adverse effects in Louisiana is limited. For example, during the past 30 years, wet deposition of nitrogen and sulfur in Louisiana has decreasing trends based on observation data at the Southeast

Research Station, LA through NADP. Critical information for designing effective control measures to further reduce the deposition fluxes of sulfur and nitrogen, such as the forms in which they are deposited, the contributions of different source sectors or regions, and the spatial patterns, is missing. Sulfur is mostly emitted as SO_2 from combustion sources and oxidized to sulfate in the atmosphere. Nitrogen is emitted as oxides (NOx) or ammonia (NH_3), and can exist in various forms including nitric acid in gas phase and nitrate and ammonium in aerosol phase. Understanding of the forms will be helpful to estimate the effects on water bodies. Due to the complex reactions of sulfur and nitrogen, they can be transported for long distances, thus, it is not only the local emission sectors but also the surrounding regions that contribute to sulfur and nitrogen depositions in Louisiana.

Thus, the objective of this project is to 1) understand the forms and quantities of sulfur and nitrogen deposition from wet and dry processes in Louisiana; 2) show the spatial and temporal variations of sulfur and nitrogen fluxes; and 3) quantify the contributions to sulfur and nitrogen deposition from different source sectors or source regions.

Methodology

The EPA Community Multiscale Air Quality (CMAQ) modeling system will be used in this study. It is a third generation air quality model that is designed for applications regulatory and policy analysis to understanding the complex interactions of atmospheric chemistry and physics (Byun and Schere, 2006). CMAQ is a community model with highly transparent code and modular configuration that facilitates the extensibility through community development by researchers worldwide. Nested domains are usually used for regional air pollution simulation. For this project, three nested domains are used. The outer domain, 36km, covers the East US, including the areas that may affect air pollution in Louisiana. 12km domain includes Louisiana and surrounding states, and 4km domain covers most part of Louisiana with the center on Baton Rouge and New Orleans. 36km domain uses typical boundary conditions and it provides boundary conditions for 12km domain while 12km domain provides boundary conditions for 4km domain. The inputs include emissions and meteorology.

After the platform is built, the first round of simulations will be conducted. And the model performance will be evaluated before interpolating the results and conducting source apportionment studies. Several datasets will be used in validating meteorological variables, air pollutants concentrations, and deposition fluxes. After the model performance is validated, the results will be analyzed to show the forms, amounts, and distribution of sulfur and nitrogen fluxes. Sulfur has the forms of sulfur dioxide, sulfuric acid, and sulfate. Nitrogen occurs in different forms including nitrogen oxides, nitric acid, nitrate, ammonia, and ammonium. Comparison of the fluxes in different forms will inform us their relative importance. The comparison between fluxes caused by dry deposition and wet deposition also show which one is more important. Based on the results, the total amounts that sulfur and nitrogen are deposited to land and waterbodies are calculated.

To quantify the contributions from different source sectors and regions, a source-oriented version of CMAQ is established based on reactive tracer method. The CMAQ model will track all species containing sulfur and nitrogen through emission, transport, reaction, and deposition.

Principal Findings and Significance

1. Platform and model performance

In this study, the modeling platform in Louisiana was established and was applied for August 2011. The model was validated. The predicted temperature, relative humidity, rain (precipitation), wind speed and wind direction were compared with observation data from the National Climate Data Center (NCDC). A total of 41 meteorological stations with hourly observations are located in the 4km resolution domain. The observations from these stations were compared with the WRF predictions at the grid cells where the stations are located. Statistical matrix was calculated to evaluate the domain-wide performance of WRF, including mean observation (OBS), mean prediction (PRE), mean bias (MB), mean fractional bias (MFB), mean normalized gross error (MBGE), and root mean square error (RMSE). The results are presented in Table 1. MFB is normalized by average of observation and model which gives equal weight to underestimations and overestimations. The precipitation gave the most biased prediction based on the MFB value due to small amount of rainfall in August 2011, the data was prescreened and a small sample space retained. However, other meteorological parameters can be considered well predicted from the model.

Table 1. Validation of meteorology simulation results

	OBS	PRE	MB	MFB	MNGE	RMSE
Temperature (˚C)	28.93	28.84	-0.092	-1.70E-03	0.069	2.56
Relative Humidity (%)	68.31	72.36	4.05	0.061	0.19	14.32
Rain (Harris et al.)	3.66	2.04	-1.62	-0.69	2.50	6.20
Wind speed (m/s)	2.89	3.87	0.98	0.25	1.06	2.79
Wind direction (˚)	209.98	209.04	-0.94	-0.064	1.07	120.85

Table 2 shows the model performance on NH_4^+, NO_3- and SO_4^{2-} fluxes in August 2011. The simulation under-predicted the three aerosols NH_4^+, NO_3^- and SO_4^{2-} with MFB values of -75%, 0.77% and -44%, respectively. The flux of NO_3^- was well predicted while NH_4^+ had larger uncertainty. SO_4^{2-} flux was also under-predicted. Biases in WRF model estimated precipitation translated into biases in the CMAQ model predictions. Overall, the model results can be used for understanding the forms and sources of sulfur and nitrogen deposition.

Table 2. Validation of simulation results of deposition fluxes

	Southeast Research Station		
	NH_4^+	NO_3^-	SO_4^{2-}
Mean OBS ($\times10^{-4}$ kg/ha)	13.48	38.99	28.01
Mean PRE ($\times10^{-4}$ kg/ha)	5.20	35.20	15.97
MB ($\times10^{-4}$ kg/ha)	-8.3	-3.79	-12.04
MNB	-0.54	0.012	-0.36
NMB	-0.61	-0.097	-0.43
MFB	-0.75	7.7E-03	-0.44

2. Forms of sulfur and nitrogen deposition

The depositions of different forms of sulfur in both wet and dry conditions in Louisiana are shown in Figure 1. There are 3 forms of sulfur: SO_2, H_2SO_4 and aerosol phase (ASO_4). The sulfate (ASO_4) is the dominant contributor in both dry and wet depositions of sulfur and SO_2 deposition is important in dry deposition. As the major contributor of total sulfur deposition, the deposition of ASO_4 ranges from 0-1 kg/ha in dry condition and 0-2 kg/ha in wet condition. Compared with dry deposition, which is major wind driven motion, wet deposition is the process which can provide a liquid environment for reaction between soluble compounds like rainfall and fog (Hodas et al., 2014).

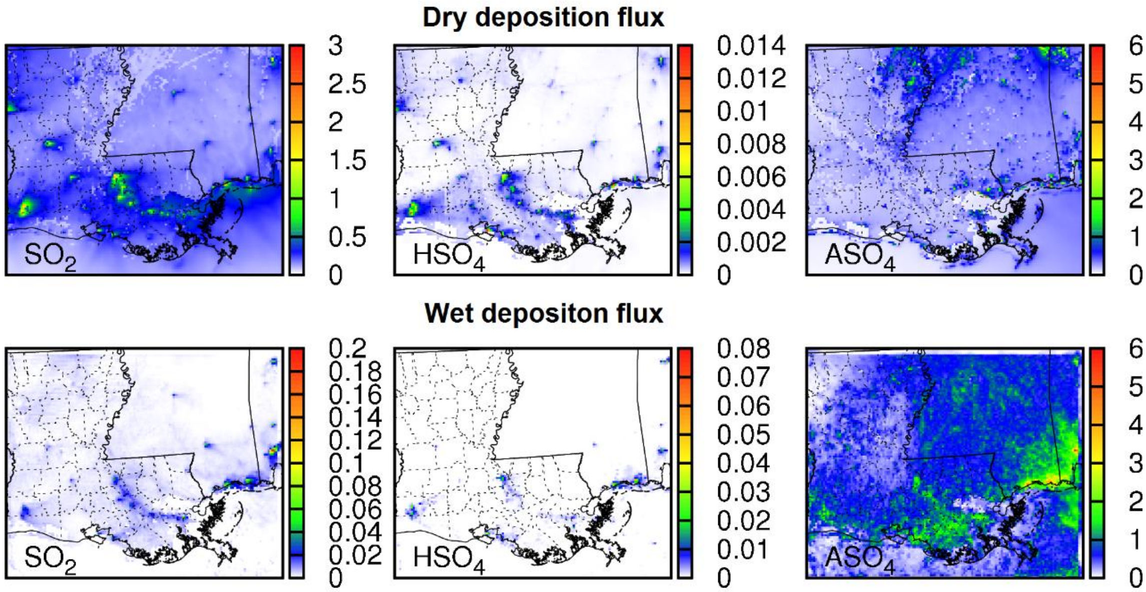

Figure 1. Dry and wet deposition of different forms of sulfur (Unit: kg/ha)

SO_2 deposition is deceased from 0.5-1.5 kg/ha in dry deposition to 0-0.04 kg/ha wet deposition since SO_2 can be easily converted to sulfate in liquid phase through acidification process and increased wet depositions of H_2SO_4 and ASO_4 (Nguyen et al., 2014). Also, H_2SO_4 and SO_2 depositions were significantly higher at central and Southwest Louisiana as there are many industrial emission sources here and they are the major sources of sulfur in atmosphere.

The depositions of different forms of nitrogen in both wet and dry conditions are shown in Figures 2 and 3. There are 9 forms of nitrogen species: NO, NO_2, NO_3, HNO_3, HONO, N_2O_5, PAN, NH_3 and aerosol phase nitrate (ANO_3). The deposition of NH_3 and NO_2 are two major issues of nitrogen dry deposition. NO_2 deposition varies from 0.5 to 3 kg/ha over Louisiana. The fact that distribution of NO_2 deposition on map is along with the highway and concentrated on urban areas like Baton Rouge or New Orleans attracts our attention. Generally, the major sources of NOx are vehicle emissions, so the large amount of NO_2 deposition is highly correlated to the population density and vehicle quantity (Zhao et al., 2013). The deposition of NH_3 acts differently from NO_2. The extreme high deposition of NH_3 is observed at central Louisiana near Baton Rouge and the deposition is almost 10 kg/ha in Figure 2. This area has ammonia plant in operation and their emissions may be the reason of high values of dry NH_3 deposition.

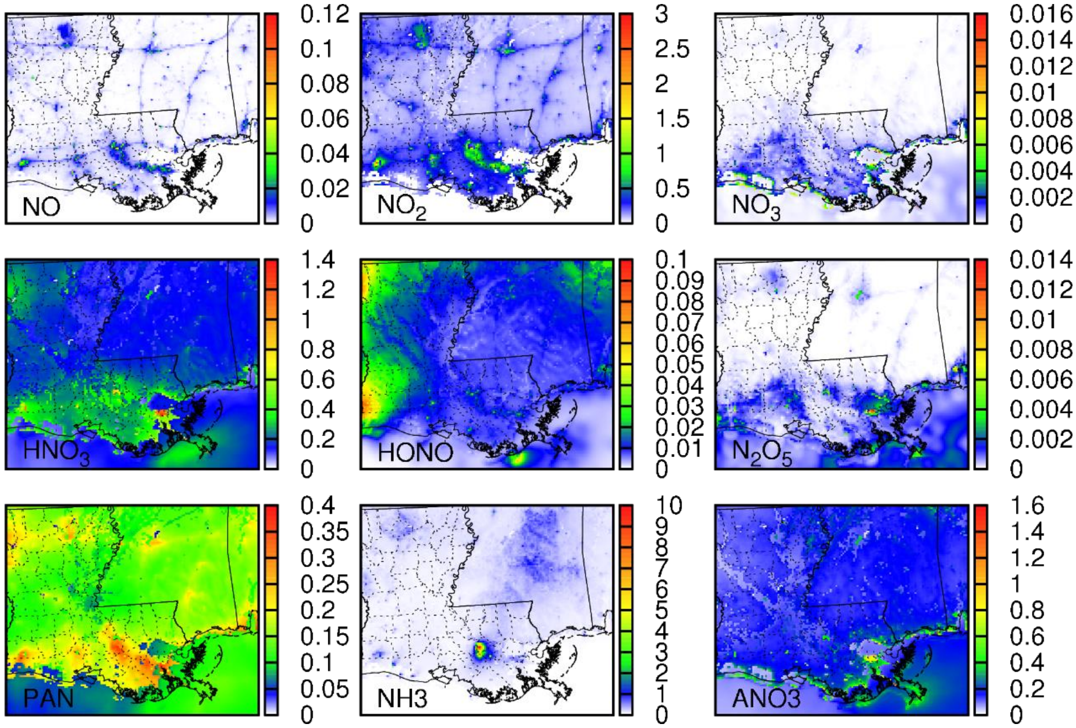

Figure 2. Dry deposition of different forms of Nitrogen (Unit: kg/ha)

In wet deposition as shown in Figure 3, nitrogen is generally at aerosol form (ANO_3: 0.2-0.6 kg/ha) or gas phase nitrate acid form (HNO_3: 0-0.8 kg/ha). The wet depositions of other forms of nitrogen form are very low (less than 0.01 kg/ha). This phenomenon indicates that chemical reactions happening in the atmosphere quickly convert other types of nitrogen to the nitrate/nitrate acid. The potential relationship between the wet deposition of nitrate/nitrate acid and land-sea breeze circulation (Vieira-Filho et al., 2015) can be detected in Figure 3. The simulation results show that wet deposition occurs more close to the seashore. Same as dry deposition, the extreme high value of nitrate acid wet deposition is observed near New Orleans. As there are many chemical industries near New Orleans at the bank of Mississippi River and nitrogen can related to thousands of chemical industrial process, industry probably is the source of nitrogen in atmosphere (Liu et al., 2013).

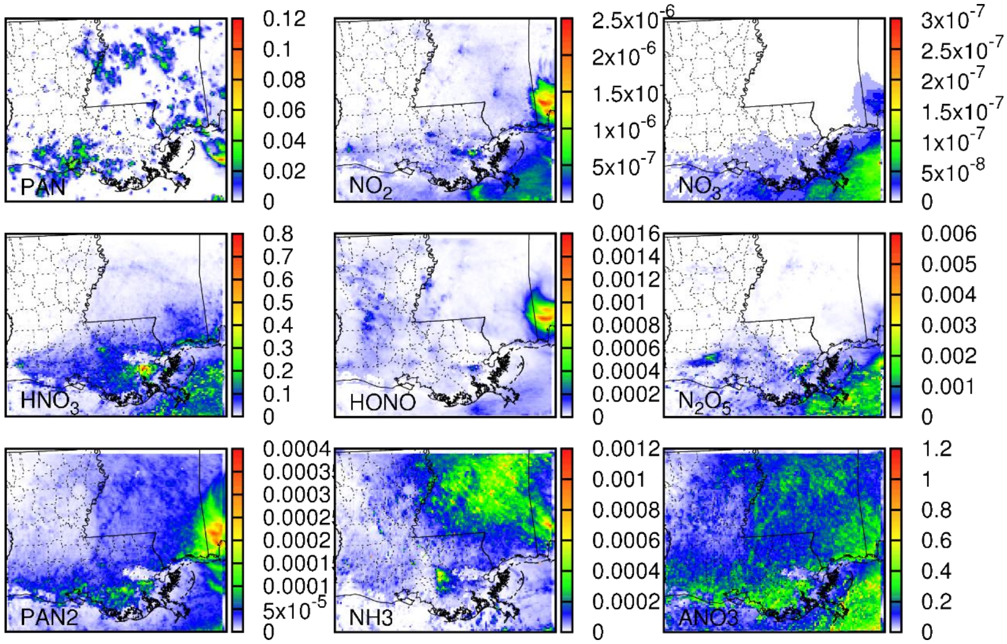

Figure 3. Wet deposition of different forms of Nitrogen (Unit: kg/ha)

3. Source apportionment of sulfur and nitrogen deposition

To better understand the sources of sulfur and nitrogen deposition and provide necessary information for design of effective control strategies, the source apportionment method was used in our project to determine the contribution of each source type to the total sulfur and nitrogen depositions. As Figure 4 shows, industry, electric generating utilities (Egu), and upwind are the top three contributors to total sulfur deposition while deposition of other source types are less than 0.1 kg/ha. Generally, the emissions of power plants and chemical industry should be the main sources of sulfur in atmosphere (Mudd, 2012). The sulfur deposition of Egu and industry can reach 1.6 kg/ha and 1 kg/ha, respectively. It is constant with source apportionment simulation results of as the deposition. Also, the high values of upwind deposition of 0.5-1 kg/ha indicate a significant sulfur transfer from adjunct states like Alabama and Mississippi.

Similar to sulfur deposition; the source apportionment method is also used in study the source of nitrogen deposition in order to identify nitrogen deposition sources and mechanism (Thompson et al., 2015). In Figure 5, on road vehicles, industry and other sources not explicitly tracked contribute high deposition values to the nitrogen deposition than other source types. Different from sulfur, the nitrogen from upwind is less important, which indicates local sources should be the main target for nitrogen reduction. The source apportionment results demonstrate that vehicles and industry emission of NOx or ammonia can be the main sources of nitrogen in atmosphere. Especially, the area near the highway road and bank of Mississippi River from Baton

Rouge to New Orleans, where vehicles and industry aggregate, are suffering worse nitrogen deposition and damage to water bodies. However, the other type shows a high nitrogen deposition near the Gulf of Mexico. This phenomenon probably relate to the land-sea breeze circulation.

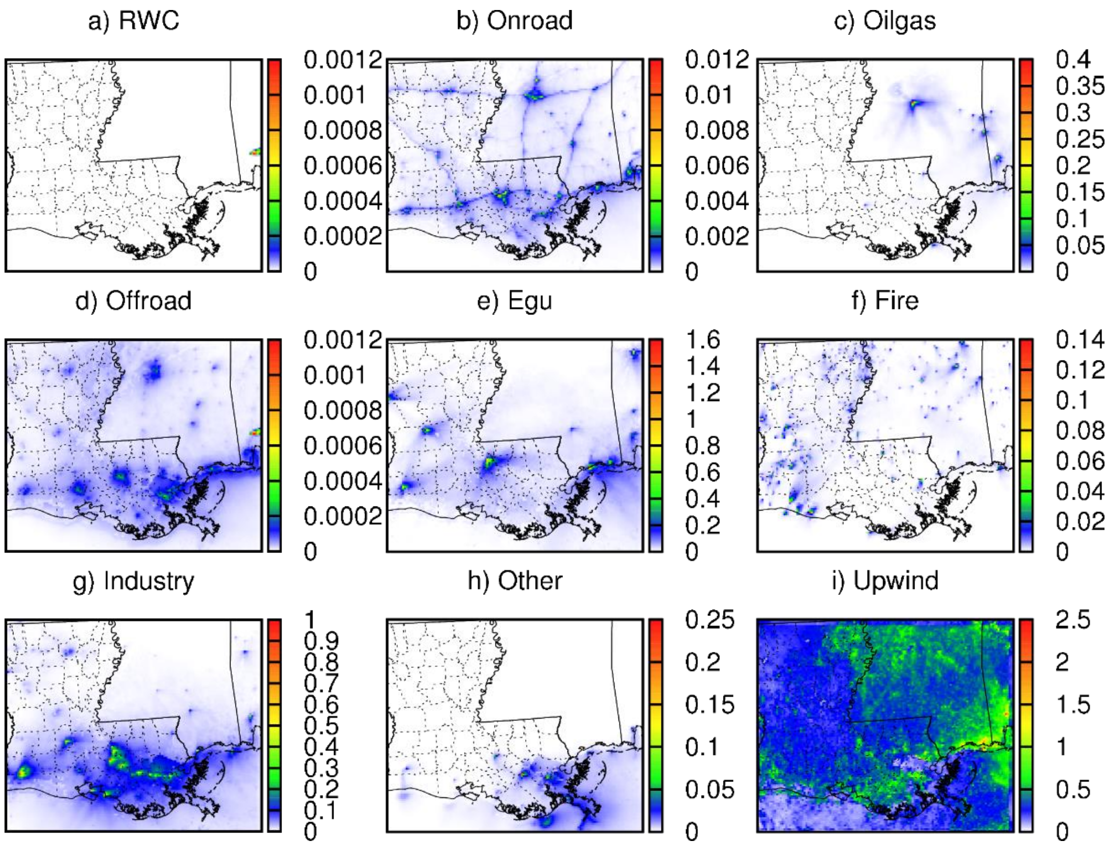

Figure 4. Source apportionment of sulfur deposition (Unit: kg/ha)

4. Conclusion

Deposition of sulfur and nitrogen is simulated using WRF and CMAQ model system and the major sources were identified using the source apportionment method for the state of Louisiana in August 2011. The model performance was validated using meteorological observation and deposition fluxes. Aerosol phase sulfate (ASO_4) is the dominant contributor to wet deposition of sulfur while SO_2 deposition is important in dry deposition. Nitrogen deposition is mainly in forms of NO_2, HNO_3, NH_3, particulate nitrate (ANO3). Egu, industry and upwind sources are important to sulfur deposition. Upwind sources also contribute significantly to sulfur. On-road vehicles, industry, and other type are important to nitrogen deposition 5.

This study offers us a comprehensive view of mechanism of nitrogen and sulfur deposition and identify the sources to help make effective control strategies towards controlling nitrogen and sulfur deposition. In future, the effects of climate change on the deposition with changing climate and increasing emission from industries should be investigated.

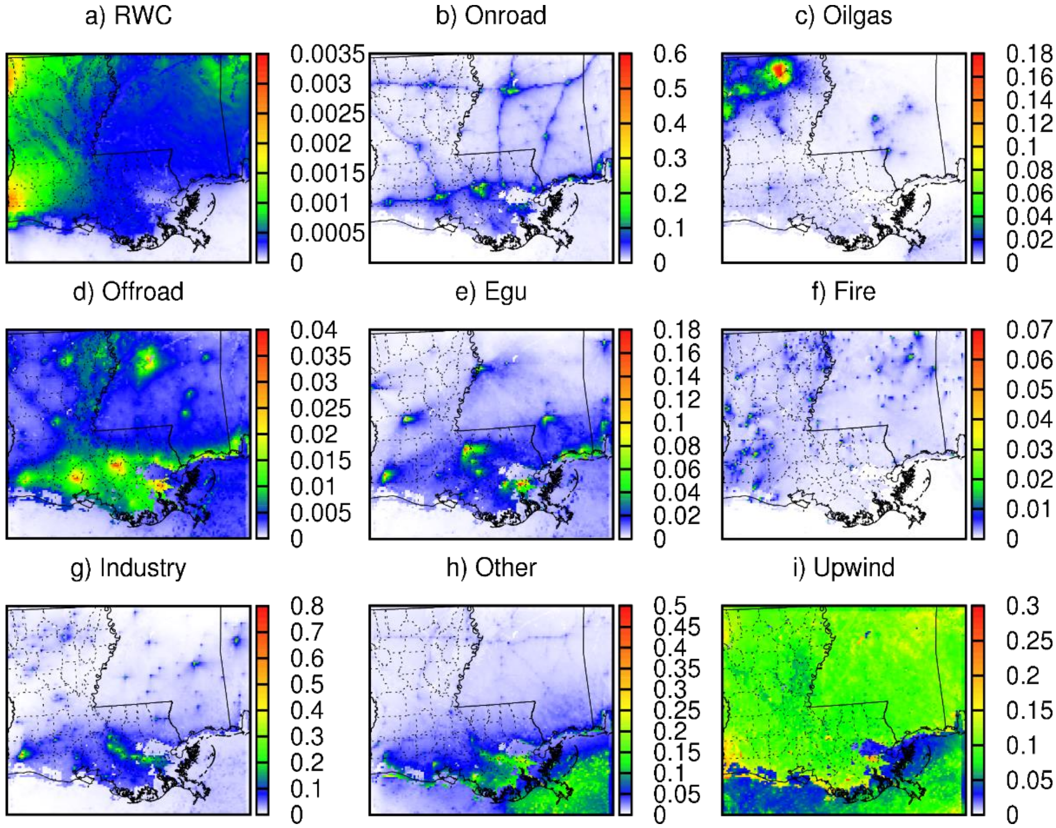

Figure 5. Source apportionment of Nitrogen deposition (Unit: kg/ha)

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Information Transfer

The research results were disseminated to the public through the American Geophysical Union 2015 Fall meeting and the 10th Annual Louisiana Groundwater, Surface Water and Water Resources Symposium.

Student and Postdoc Support

Hao Guo, Doctoral Student, Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge

Development of watershed-based dynamic total maximum daily load for dissolved oxygen in loiwer Bayou Macon

Basic Information

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End Date:	2/29/2016
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Focus Category:	Models, Non Point Pollution, Water Quality
Descriptors:	None
Principal Investigators:	Zhi-Qiang Deng

Publications

1. Tong, Y. and Deng, Z. (2015). “Moment-Based Method for Identification of Pollution Source in Rivers.” ASCE Journal of Environmental Engineering, 141 (10), 04015026, DOI: 10.1061/(ASCE)EE.1943-7870.0000683.
2. Noori, R., Deng, Z., Kiaghadi, A., Kachoosangid, F.T. (2016). “How Reliable Are ANN, ANFIS, and SVM Techniques for Predicting Longitudinal Dispersion Coefficient in Natural Rivers?” Journal of Hydraulic Engineering, 142 (1), 04015039, DOI: 10.1061/(ASCE)HY.1943-7900.0001062.
3. Deng, Z., 2016. “Chapter 63: Water Quality.” In Vijay P. Singh (ed.), Handbook of Applied Hydrology, McGraw-Hill Education, Second Edition, Boston, MA, ISBN-13: 978-0071835091.

Problem and Research Objectives

Low Dissolved Oxygen (DO) was identified in the latest (2014) Louisiana Water Quality Integrated Report (305(b)/303(d)) as the most cited suspected causes of water quality impairment in Louisiana and in the Gulf of Mexico region as well. This is particularly true in agricultural watersheds, such as the Bayou Macon watershed (Figure 1). Since DO is the water quality indicator commonly used to determine support of the FWP (fish and wildlife propagation) use, low DO as the most cited suspected causes of water quality impairment in Louisiana and in the Gulf of Mexico region means that meeting the FWP use is a critical regional and state water quality problem to address. While extensive efforts have been made to address the low DO problem through the development and implementation of Total Maximum Daily Load (TMDL), there was no significant improving trend in FWP (fish and wildlife propagation) use in the past 15 years (2000 - 2014). The PI's research group found that land use and land cover change may significantly increase loading of DO-consuming materials and thereby cause DO impairment in river systems. Since the land use and land cover change is a dynamic process, the source of DO impairment should also be dynamic. It means that a static TMDL or a fixed percentage (typically 10 – 20%) of margin of safety for TMDL is unable to maintain water quality in the long run in terms of the designated uses. This is exactly what happened in Louisiana and in the Gulf of Mexico region as well. Therefore, the development of dynamic TMDL is an essential and specific regional and state water quality problem needing to be addressed.

The overall goal of this project is to develop a new approach, called dynamic TMDL development and implementation, to the restoration of water quality and the sustainability of designated uses of Louisiana water bodies, addressing the critical regional and state water quality problem.

Methodology

The proposed strategy is to test and demonstrate the new TMDL approach by developing dynamic TMDL for DO in the Lower Bayou Macon (subsegment LA081001_00) that is impaired due to low dissolved oxygen. The research methods involved (1) identification of critical source areas for DO impairment using a watershed modeling tool and ArcGIS, (2) development of dynamic TMDL, and (3) LID-based sustainable implementation of DO TMDL. While this project focuses on the Lower Bayou Macon, the methods developed in this study can be easily extended to other watersheds in Louisiana. Therefore, this project has broader implications for environmental restoration and sustainability in Louisiana and in the nation as well.

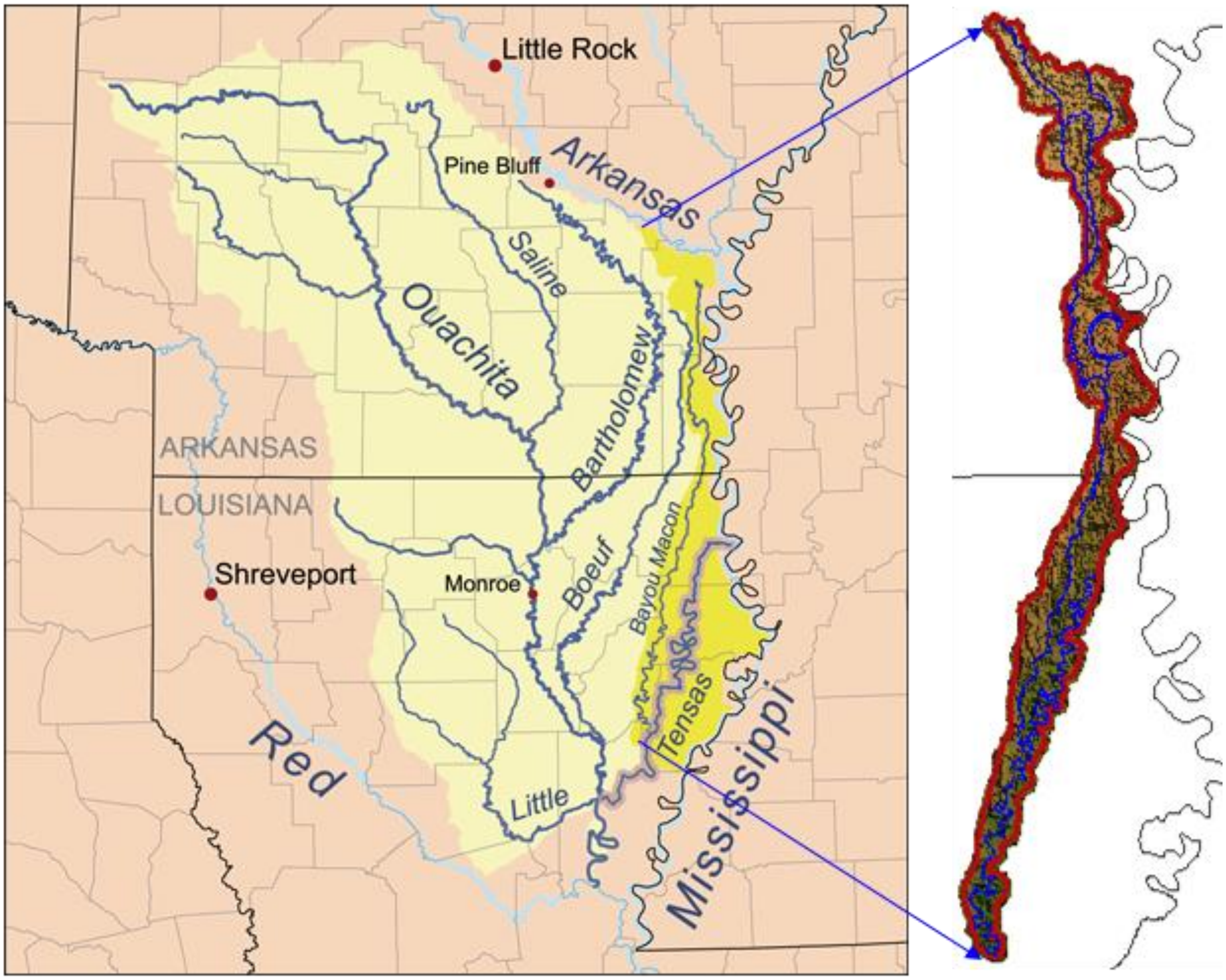

Figure 1. Study area map (left) showing the Bayou Macon watershed (right) across the Louisiana-Arkansas border.

Principal Findings and Significance

1. **Watershed modeling for identification of critical river reaches and pollution sources for DO impairment**

   (1) A HSPF-based watershed model has been presented for computation of flow and dissolved oxygen levels in the Bayou Macon Watershed. Figure 2 below indicate that the model-simulated flow fit observed one reasonably well (correlation coefficient = 0.68 and mean error = 8.28%). The practical significance of this model is that it provides an important modeling tool for governmental agencies like Louisiana Department of Environmental Quality to develop and implement TMDLs for the Bayou Macon Watershed and for restoration of impaired water bodies in the watershed.

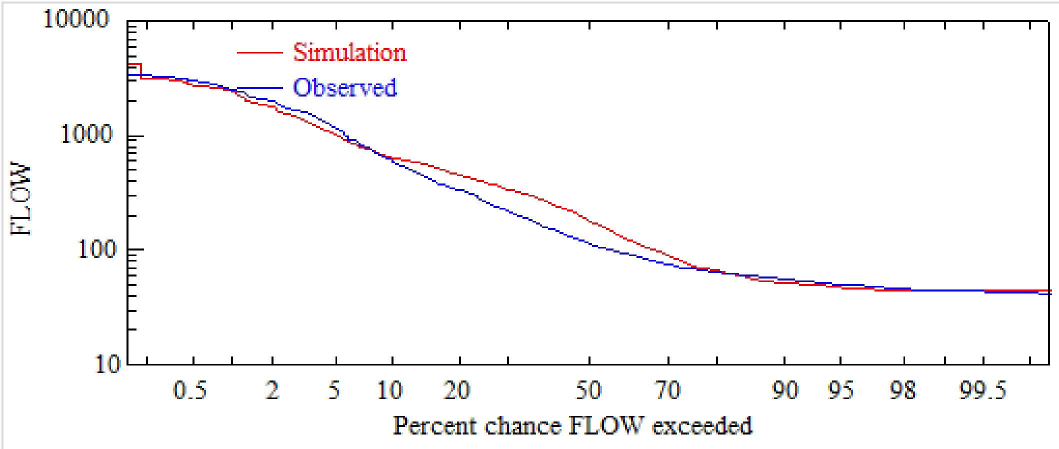

Figure 2. Comparison between simulated and observed flow (in ft^3/s) duration curves for the Bayou Macon (station 07369680)

(2) The validated HSPF model was utilized to simulate the variation of dissolved oxygen (DO) level in the Bayou Macon. Figure 3 shows DO concentration variations in the Bayou Macon at Delhi. It can be seen from Figure 3 that the watershed model is capable of simulate DO concentrations in the Lower Bayou Macon. Panels (a), (b), and (c) show when and where DO impairments occurred. The graphs clearly indicate that Bayou Macon was impaired due to low DO especially in summer during which DO levels were below 5mg/L line which is the numeric criterion for DO. Low flow discharges in summer would deteriorate the water quality condition and the solubility of DO in water is decreased due to high water temperature. It can be also seen from the graphs show that DO impairment in downstream portion of the Bayou Macon is more serious as compared with those in Reach 22 (upstream) and 25 (downstream). The significance of this result is that the watershed model could be employed to identify the **critical reaches** which experienced DO impairment and provide suggestions for TMDL implementation.

(3) The validated HSPF model was also employed to simulate the variation of BOD (Biochemical Oxygen Demand) level in the Bayou Macon. The BOD loading from the watershed was identified by the Louisiana Department of Environmental Quality as the primary source of the DO impairment to the Bayou Macon. Figure 4 below indicates that the model-simulated BOD levels fit observed one reasonably well with the mean error for validation period being 9.7 percent, providing a scientific basis for implementation of Best Management Practices for pollution load reduction.

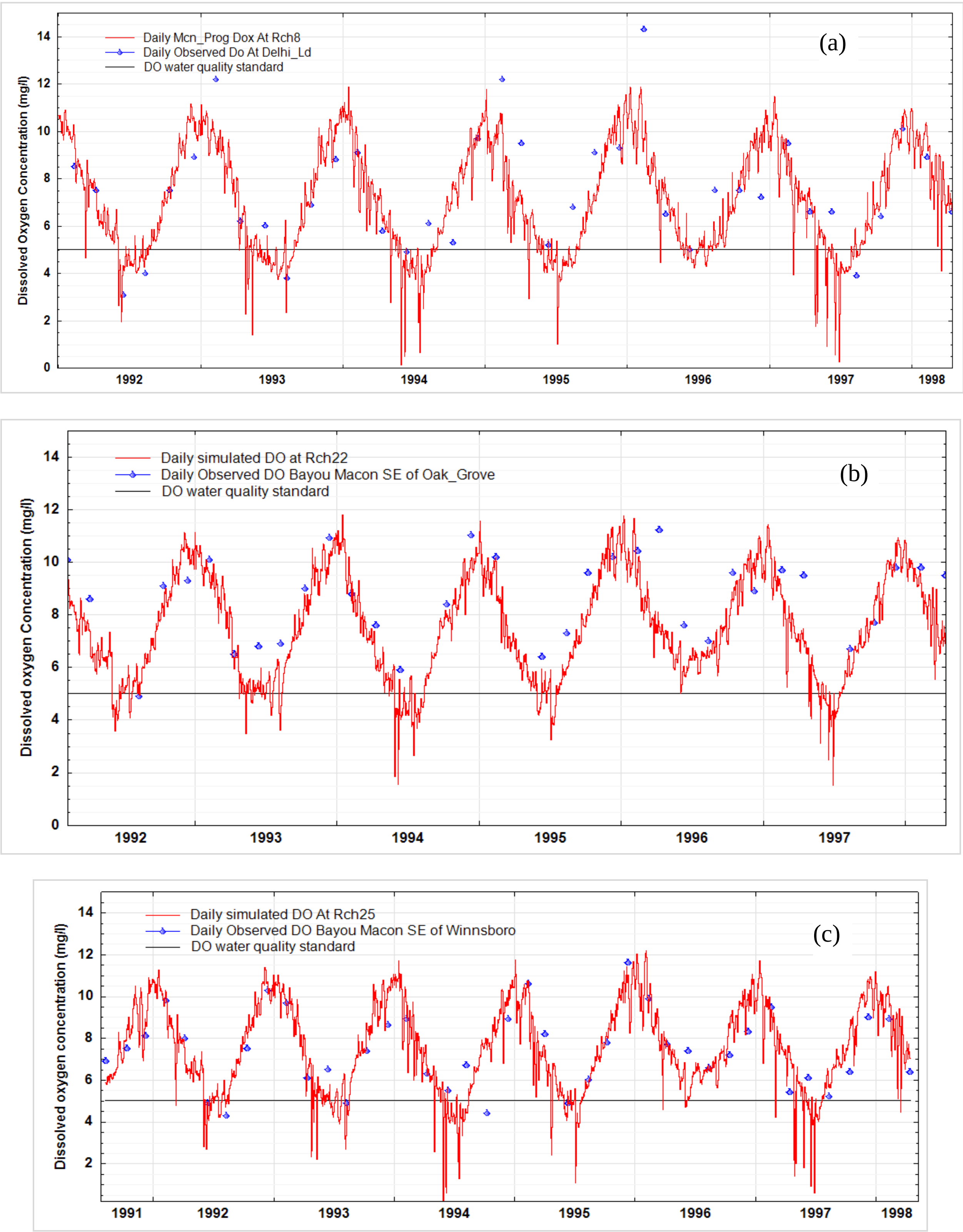

Figure 3. Comparison between simulated and observed DO concentrations in the Bayou Macon at Stations 7370000 (a), 0329 (b), and 0330.

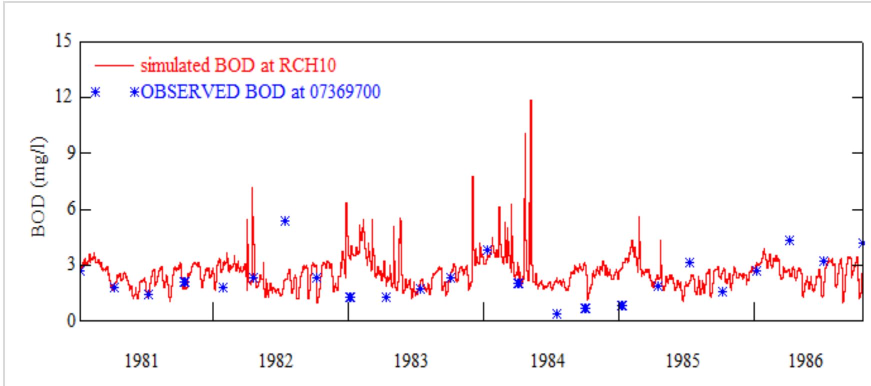

Figure 4. Comparison of Simulated and observed BOD concentrations in the Bayou Macon

2. Identification of Critical Source Areas along in the Bayou Macon Watershed

Critical source areas (CSAs) are defined as the areas (catchments or sub-basins) producing disproportionately high pollutant loadings and have been widely recognized as priority areas for nonpoint source pollution control. The identification and evaluation of CSAs at the watershed scale allows state and federal programs to implement soil and water conservation measures where they are needed most. To that end, the Bayou Macon watershed was delineated into 29 catchments or sub-basins, as shown in Figure 5. Based on the catchments, we have identified CSAs in terms of low DO and high BOD loading areas. Figure 6 shows the CSAs in terms of low DO levels while Figure 7 maps the CSAs in terms of BOD sources. It can be seen from the two figures that results from both figures are consistent and both figures indicate that Catchments 1, 15, 2 and 10 are the CSAs for DO in terms of low DO levels and high BOD loadings.

The significance of this result is that BMPs (Best Management Practices) should be implemented in the CSAs to restore the water quality in the watershed.

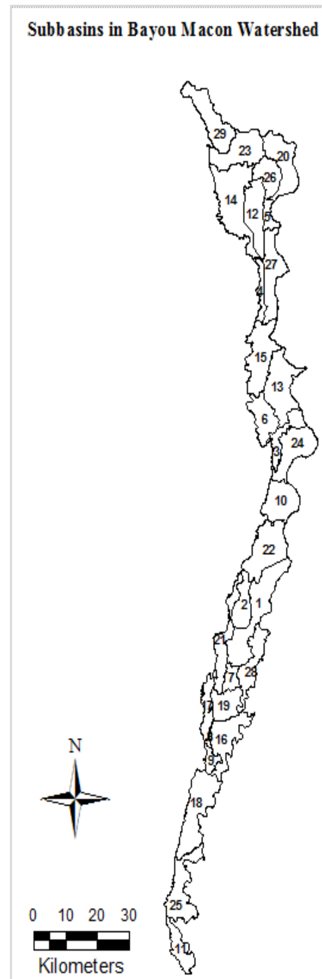

Figure 5. Catchments in Bayou Macon watershed

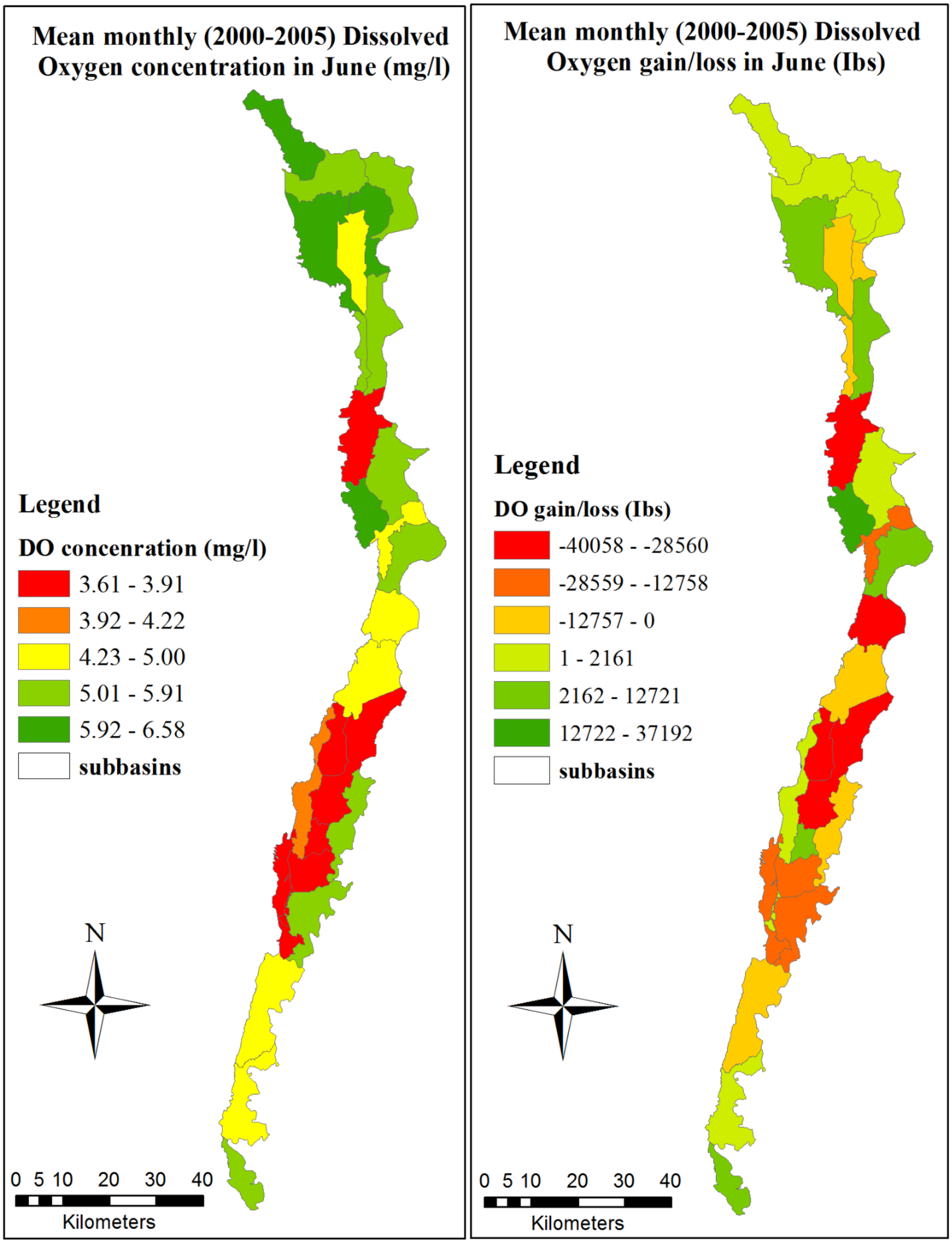

Figure 6. Critical catchments (subbasins) based on average DO concentration (mg/l) and DO gain/loss (Ibs) in June

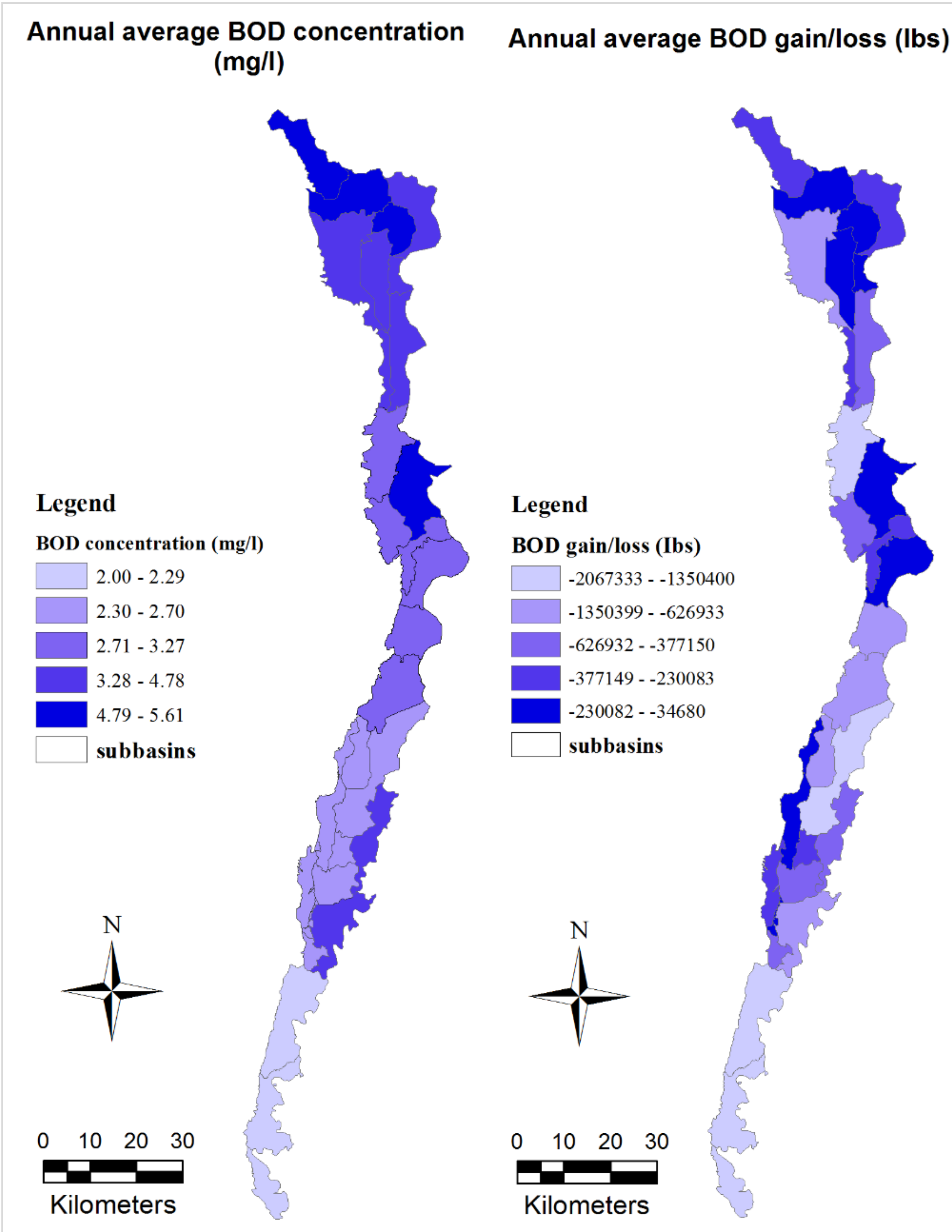

Figure 7. Critical catchments (subbasins) based on annual average of BOD concentration (mg/l) and BOD gain/loss (lbs)

3. Development of Dynamic TMDL for the Bayou Macon

By employing and analyzing crop-specific land cover data layers that are annually created for United States (https://nassgeodata.gmu.edu/CropScape) we were able to detect the changes in land-use in the last decade. These high resolution datasets are available for the Lower Bayou Macon watershed from 2004 to 2015 while the data are available from 1999 for the upper part of the watershed. It was found that the grass/pasture and forest acreages have decreased by 99% and 93%, respectively, while agriculture and urban areas have increased by 14% and 300%, respectively, from 2004 to 2015. Two scenarios were examined to assess the impact of land-use change on water quality. Scenario 1 reflects the land-use condition in 2015. Scenario 2 is set to consider future growth in the agricultural area. Specifically, Scenario 2 involves a 5% increment in the agricultural area that was about 82% of the original land-use in 2004.

Table 1: Seasonal analysis of land-use change impact on DO

scenario	season	River Reach 8			River Reach 22			River Reach 25		
		Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
base scenario	Winter	9.40	6.88	4.73	9.65	7.66	6.51	9.54	6.97	4.50
	Spring	5.93	3.07	0.61	6.40	4.33	2.64	6.32	3.38	0.67
	Summer	5.74	3.94	1.63	6.64	5.01	3.36	6.72	4.41	1.89
	Fall	9.96	7.24	4.58	10.04	7.91	5.81	10.15	7.31	4.50
Scenario 1	Winter	9.30	6.62	4.30	9.63	7.53	6.28	9.53	6.67	3.93
	Spring	5.92	2.76	0.18	6.37	4.13	2.31	6.30	3.06	0.23
	Summer	5.73	3.77	1.14	6.67	4.95	3.29	6.76	4.25	1.44
	Fall	9.96	7.04	4.18	10.03	7.81	5.67	10.06	7.07	4.08
Scenario 2	Winter	9.30	6.51	4.13	9.63	7.48	6.18	9.53	6.56	3.71
	Spring	5.91	2.65	0.09	6.36	4.08	2.20	6.30	2.95	0.14
	Summer	5.72	3.71	0.95	6.66	4.93	3.25	6.76	4.19	1.26
	Autumn	9.96	6.96	4.02	10.03	7.78	5.62	10.02	6.98	3.92

HSPF simulated DO levels for each scenarios are summarized on a seasonal basis in 1. The table shows that DO decreased in Scenarios 1 and 2 with the highest change occurring in spring as compared with the base scenario. Reach 25, which is located downstream, experienced greater changes in DO under first and second scenarios, as compared to Reaches 22 and 8. Maximum, average and minimum seasonal DO reductions in Reach 25 would be 0.09, 0.33 and 0.56 mg/l under Scenario 1 and 0.12, 0.43 and 0.79 mg/l under Scenario 2 condition. Since DO simulations based on 2015 land-use and land-cover data (Scenario1) led to lower DO concentrations, load reduction is needed in order to meet the DO water quality standard. Calculated TMDLs for Bayou Macon under Scenario 1 condition are listed in Table 2.

Table 2. DO TMDL for Bayou Macon under Scenario 1 Condition

	High flow (0-10)	Moist condition (10-40)	Mid-range flows (40-60)	Dry condition (60-90)	Low flows (90-100)
Existing load (lbs/day)	147785.2	32282.0	11229.8	4443.4	1998.3
Target load(lbs/day)	78172.5	21059.8	7325.2	3464.6	1418.6
Load reduction (%)	-89.05	-53.29	-53.30	-28.25	-40.86

It can be seen by comparing Tables 1 and 2 that the load reduction in high flow period is highly affected by land-use/land-cover change while the impact of land-use/land-cover change on TMDL is much smaller for other conditions. Load reductions under Scenario 2 condition are almost the same as those of Scenario 1 except the high flow during which the load reduction is 97 percent under Scenario 2.

4. Implementation of Dynamic TMDL for the Bayou Macon

In order to implement the dynamic TMDL, a number of BMPs/LIDs (Dry well, infiltration basin, infiltration trench, rain barrel, rain garden, bioretention, roof garden sand filter, storage tank, vegetated swale and wetlands) were analyzed. It was found from our model simulation results for BMPs/LIDs that a constructed wetland was the best LID for improving DO concentration. The critical catchment (subbasin #1) was chosen for building a constructed wetland with the area of 4.6 km^2. The simulation result from HSPF model shows that average DO concentration level was increased from 6.8 to 7.3 mg/l, as indicated in Figure 8. The modeling result also indicates that constructed wetland is effective particularly in improving extremely low DO in the summer season (increased from 0.3 to 3.3 mg/l).

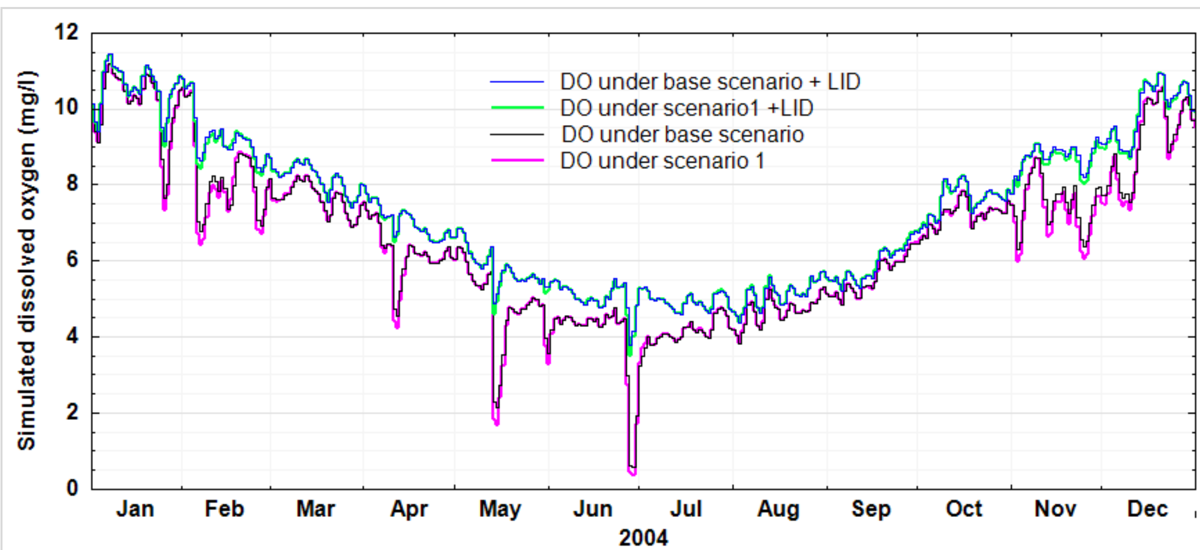

Figure 8. LID implementation results on DO concentration in subbasin 1

INFORMATION TRANSFER

The findings and particularly the critical source areas and dynamic TMDL, identified in this project, will be transferred to the Louisiana Department of Environmental Quality for DO TMDL development and implementation and thereby for the restoration of the impaired Bayou Macon.

STUDENT SUPPORT

Name of supported graduate student: Maryam Roostaee (Female)
Degree Program: Ph.D. in Water Resources
Department: LSU Department of Civil and Environmental Engineering

Information Transfer Program Introduction

None.

USGS Summer Intern Program

None.

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

Notable Awards and Achievements

Of note in FY2015 was LWRRI's participation in response to the saltwater intrusion in the aquifer system underneath the Capital City. Details are presented below.

LWRRI research develops innovative tools for saltwater intrusion modeling:

Dr. Frank Tsai, Professor of Water Resources Engineering in the Department of Civil & Environmental Engineering, Louisiana State University, has developed innovative tools to utilize State's well log database for visualizing and understanding saltwater intrusion in groundwater systems. Tsai and his research group are the only group that uniquely reconstructs the aquifer system underneath East and West Baton Rouge Parishes to better understand saltwater intrusion passing through a geological fault. Tsai's research, conducted in collaboration with the Capital Area Ground Water Conservation Commission (CAGWCC) of Louisiana, is a major achievement in managing groundwater resources for Louisiana. His work has been included in the Commission Brochure (http://www.cagwcc.com/site2015/forms/Brochure_16.pdf). His research results can be found in https://sites.google.com/site/franktctsai/.

Moreover, Dr. Frank Tsai's group is maintaining the Louisiana Well Log Portal (https://sites.google.com/site/louisianawelllogportal/), a well log information website, for education and decision-making. More than 300 CEE undergraduate students were trained to analyze electrical logs and drillers' logs through course projects. Students learnt documenting well log data into Excel spreadsheets, making Google Earth kml files, and displacing well log data to Google Earth. The students' data were eventually deposited to the Portal after quality control. State agencies, the public, and private sectors have been using the Portal to understand Louisiana's geology and groundwater resources. The Portal has been visited by more than 3,000 times and more than 10 countries.

Other Awards and Achievements:

• Received researching funding from Louisiana Board of Regents and CAGWCC.

• Organized the 9th Annual Louisiana Groundwater, Water Resources, and Environmental Symposia, Louisiana State University, Baton Rouge, Louisiana, April 16, 2015

• Assisted in organizing 2016 UCOWR/NIWR Conference, Pensacola Beach, FL, June 21-21, 2016

• Received recognition (Editors' Choice article for 2015) on a paper of studying groundwater flow near Napoleonville Dome, which is partially funded by the Director's 104G grant.

Jamshidzadeh, Z, F. T.-C. Tsai, H. Ghasemzadeh, S. A. Mirbagheri, M. T. Barzi, and J. S. Hanor, 2015. "Dispersive thermohaline convection near salt domes: a case at Napoleonville Dome, southeast Louisiana, USA", Hydrogeology Journal 23, 983-998. doi:10.1007/s10040-015-1251-4 (Editors' Choice article for 2015)

Publications from Prior Years

1. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Chitsazan, N., H.V. Pham, F.T.-C. Tsai, 2015. “Bayesian Chance-Constrained Hydraulic Barrier Design under Geological Structure Uncertainty”, Groundwater 53(6), 908-919. doi: 10.1111/gwat.12304
2. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Elshall, A.S., H.V. Pham, F.T.-C. Tsai, L. Yan, and M. Ye, 2015. “Parallel Inverse Modeling and Uncertainty Quantification for Computationally Demanding Groundwater Flow Models Using Covariance Matrix Adaptation”, Journal of Hydrologic Engineering, 20(8). doi: 10.1061/(ASCE)HE.1943-5584.0001126
3. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Jamshidzadeh, Z, F. T.-C. Tsai, H. Ghasemzadeh, S. A. Mirbagheri, M. T. Barzi, and J. S. Hanor, 2015. “Dispersive thermohaline convection near salt domes: a case at Napoleonville Dome, southeast Louisiana, USA”, Hydrogeology Journal 23, 983-998. doi:10.1007/s10040-015-1251-4 (Editors’ Choice article for 2015)
4. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Chitsazan, N., A.A. Nadiri, and F. T.-C. Tsai, 2015. “Prediction and Structural Uncertainty Analyses of Artificial Neural Networks Using Hierarchical Bayesian Model Averaging”, Journal of Hydrology 528, 52-62. doi:10.1016/j.jhydrol.2015.06.007
5. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Chitsazan, N. and F. T.-C. Tsai, 2015. “Uncertainty segregation and comparative evaluation in groundwater remediation designs: A chance-constrained hierarchical Bayesian model averaging approach”, Journal of Water Resources Planning and Management 141(3), 04014061. doi:10.1061/(ASCE)WR.1943-5452.0000461
6. 2010LA76G ("Hierarchical Multimodel Saltwater Intrusion Remediation and Sampling Designs: A BMA Tree Approach") - Articles in Refereed Scientific Journals - Chitsazan, N. and F. T.-C. Tsai, 2015. “A Hierarchical Bayesian Model Averaging Framework for Groundwater Prediction under Uncertainty”, Groundwater 53(2), 305-316. doi:10.1111/gwat.12207