Water Resources Assessment for Sustainability and Energy Management

SCOTT A. HEMMERLING, F. RYAN CLARK, AND HARRIS C. BIENN

Produced for and funded by: Louisiana Department of Natural Resources Office of Conservation and the Louisiana Coastal Protection and Restoration Authority

July 13, 2016

ABOUT THE WATER INSTITUTE OF THE GULF

The Water Institute of the Gulf is a not-for-profit, independent research and technical services resource for resilient coasts and sustainable water systems worldwide. The work of the Institute helps ensure livable communities and a thriving economy and environment. For more information, visit www.thewaterinstitute.org.

SUGGESTED CITATION

Hemmerling, S.A., Clark, F.R., & Bienn, H.C. (2016). Water Resources Assessment for Sustainability and Energy Management. The Water Institute of the Gulf. Prepared for and funded by the Louisiana Department of Natural Resources and the Coastal Protection and Restoration Authority. Baton Rouge, LA.

Table of Contents

List of Figures 2
List of Tables 3
List of Acronyms 4
Acknowledgements 5
Executive Summary 6
Introduction 8
Part 1: Framework Development and Selection of Parameters 10
Framework Description 10
Energy Use in the Water Sector 16
Energy for Water Extraction 16
Energy for Water Conveyance from the Source Location to the Supply Area 17
Energy for Water Treatment and Distribution to the End User 17
Energy for Wastewater Treatment 19
Framework Application and Data Inventory 19
Water Budget Components 22
Population Change and Future Projections 27
Population Change 27
Landscape Change and Urbanization 27
Data to Assess Projected Water Demand and Energy Cost 29
Additional Research Needs 29
Localized Impacts 30
Water Quality Constraints and Minimum Ecological Flow 30
Part 2: Initial Application and Testing of Framework 32
Study Area Selection Process 32
Selection of Study Areas 34
Pilot Study Area: Southwest Louisiana 42
Geology of the Southwest Louisiana Study Area 45
Water Balance Results 46
Northwest Louisiana Study Area 64
Geology of the Northwest Louisiana Study Area 67
Water Balance Results 68
Southeast Louisiana Study Area 85
Geology of the Southeast Study Area 88
Water Balance Results 90
Conclusions 107
Water Usage and Sustainability 107
Agriculture and Aquaculture 107
Industry 107
Public Supply 108
Population Change 109
References Cited 110

List of Figures

Figure 1. Water budget framework 12
Figure 2. Locations of Selected Study Areas and their Respective Groundwater Recharge Areas 25
Figure 3: Candidate Study Areas. 33
Figure 4: SWLA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary. 35
Figure 5: NWLA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary. 36
Figure 6: SELA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary. 37
Figure 7: Locations of the three selected study areas. 38
Figure 8: Detail of SWLA study area. 39
Figure 9: Detail of NWLA study area. 40
Figure 10: Detail of SELA study area. 41
Figure 11: SWLA total households by census block group. 43
Figure 12: SWLA domestic water demand. 44
Figure 13: SWLA total water balance by HUC8. 47
Figure 14: SWLA groundwater balance by HUC8. 49
Figure 15: SWLA groundwater use by hydrologic unit. 50
Figure 16: SWLA surface water balance by HUC8. 51
Figure 17: SWLA surface water use by hydrologic unit. 52
Figure 18: SWLA annual drinking water treatment energy used by public water supply systems. 54
Figure 19: SWLA estimated annual energy consumption to withdraw water from domestic wells. 55
Figure 20: SWLA annual wastewater treatment energy consumption by treatment plant size. 56
Figure 21: Portion of each HUC8 with mean annual surface water salinity levels greater than 0.5ppt 58
Figure 22: SWLA waters listed as impaired under Clean Water Act Section 303(d). 60
Figure 23: SWLA projected urban growth (2009-2060). 61
Figure 24: SWLA projected 10-year population change by ZIP code. 63
Figure 25: NWLA total households by HUC8. 65
Figure 26: NWLA estimated annual household demand by HUC8 (2010). 66
Figure 27: NWLA total water balance by HUC8. 69
Figure 28: NWLA groundwater balance by HUC8. 71
Figure 29: NWLA groundwater use by hydrologic unit. 72
Figure 30: NWLA surface water use by hydrologic unit. 74
Figure 31: NWLA surface water use by hydrologic unit. 75
Figure 32: NWLA annual drinking water treatment energy used by public water supply systems. 76
Figure 33: NWLA estimated annual energy consumption to withdraw water from domestic wells. 77
Figure 34: NWLA annual wastewater treatment energy consumption by treatment plant size. 79
Figure 35: NWLA waters listed as impaired under Clean Water Act Section 303(d). 80
Figure 36: NWLA projected urban growth (2009-2060). 82
Figure 37: NWLA projected 10-year population change by ZIP code. 84
Figure 38: SELA total households by HUC8. 86
Figure 39: SELA domestic water demand by HUC8 (2010). 87
Figure 40: Geological architecture of the aquifers in the SELA study area (Tsai, 2013). 88
Figure 41: SELA total water balance by HUC8. 91
Figure 42: SELA groundwater balance by HUC8. 93
Figure 43: SELA groundwater use by hydrologic unit. 94

Figure 44: SELA surface water balance by HUC8. 95
Figure 45: SELA surface water use by hydrologic unit. 96
Figure 46: SELA annual drinking water treatment energy used by public water supply systems. 98
Figure 47: SELA estimated annual energy consumption to withdraw water from domestic wells. 99
Figure 48: SELA annual wastewater treatment energy consumption by treatment plant size. 100
Figure 49: SELA waters listed as impaired under Clean Water Act Section 303(d). 102
Figure 50. SELA projected urban growth (2009-2060). 104
Figure 51: SELA projected 10-year population change by ZIP code. 105

List of Tables

Table 1: Unit electricity consumption for surface freshwater treatment plants 18
Table 2: Unit electricity consumption for wastewater treatment by size of plant 19
Table 3: Data Sources – Delineation of Analytical Water Units 20
Table 4: Data Sources – Water Supply and Demand. 20
Table 5: Alternate recharge methods comparison 23
Table 6: Consumptive use coefficients (derived from Carr et al., 1990; Smith et al., 2011) 26
Table 7: Effects of impervious surface on water balance components (Adapted from Arnold & Gibbons, 1996) 28
Table 8: SWLA population, public and domestic water demand summary 42
Table 9: Hydraulic parameters of the Chicot Aquifer 45
Table 10: Southwest study area summary of overall water balance 48
Table 11: Southwest study area summary of groundwater balance 48
Table 12: Southwest study area summary of surface water balance 52
Table 13: SWLA study area surface water balance, including impacts of coastal salinity on water usability 59
Table 14: SWLA study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability 59
Table 15: SWLA total water balance change under future urbanization scenario. 62
Table 16: SWLA total water balance change under urbanization and population growth scenarios. 62
Table 17: NWLA population, public supply, and domestic well information 64
Table 18: Hydraulic characteristics of the Carrizo-Wilcox Aquifer 67
Table 19: Northwest study area summary of overall water balance 68
Table 20: Northwest study area summary of groundwater balance 70
Table 21: Northwest study area summary of surface water balance 73
Table 22: Northwest study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability 78
Table 23: NWLA total water balance change under future urbanization scenario 81
Table 24: NWLA total water balance change under urbanization and population growth scenarios 83
Table 25: SELA population, public and domestic water demand summary 85
Table 26: Hydraulic characteristics of the Southern Hills Aquifer System 89
Table 27: Southeast study area summary of overall water balance 90
Table 28: Southeast study area summary of groundwater balance 92
Table 29: Southeast study area summary of surface water balance 94
Table 30: SELA study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability. 101
Table 31: SELA total water balance change under future urbanization scenario 103
Table 32: SELA total water balance change under urbanization and population growth scenarios 106

List of Acronyms

Acronym	Term
LED	Louisiana Economic Development
ACS	United States Census Bureau American Community Survey
CAGWCC	Capital Area Ground Water Conservation Commission
ECHO	United States Environmental Protection Agency Enforcement and Compliance History Online database
EIA	United States Energy Information Administration
EMSI	Economic Modeling Specialists International
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
HUC	Hydrologic Unit Code
ICIS	United States Environmental Protection Agency Integrated Compliance Information System
LDNR	Louisiana Department of Natural Resources
LDWF	Louisiana Department of Wildlife and Fisheries
LSU	Louisiana State University
NCDC	National Oceanic and Atmospheric Administration National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NWIS	United States Geological Survey National Water Information System
NWLA	Northwest Louisiana
PCS	United States Environmental Protection Agency Permit Compliance System
POTW	Publicly Owned Treatment Works
PRCP	Precipitation
SELA	Southeast Louisiana
SONRIS	Louisiana Department of Natural Resources Strategic Online Natural Resource Information System
SWLA	Southwest Louisiana
TCT	Technical Coordination Team
TNC	The Nature Conservancy
ULL	University of Louisiana at Lafayette
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

Acknowledgements

The Water Institute of the Gulf (the Institute) convened a Technical Coordination Team (TCT) consisting of subject matter experts who provided direct connectivity between the assessment work for this project and other ongoing water resource assessment efforts. The TCT consisted of outside experts with relevant experience analyzing the relationship of water sustainability issues, management, and economics at both the state and regional level and includes both academic and governmental agency researchers. The authors gratefully acknowledge the following members of the TCT for their assistance and guidance throughout the development of this project:

1. David Borrok, PhD – Director of the School of Geosciences, University of Louisiana at Lafayette;
2. Charles Demas – Former Director, USGS Louisiana Water Science Center (Retired);
3. Gary Hanson – Director of the Red River Watershed Management Institute, LSU Shreveport; and
4. John Lovelace – Assistant Director for Investigations, USGS Lower Mississippi-Gulf Water Science Center.

Each of these individuals provided invaluable insight on water resources planning and management issues in Louisiana. Their knowledge on regional and statewide issues proved vital in the conceptualization and operationalization of the water resources assessment framework.

This project was supported by Louisiana Department of Natural Resources (LDNR) and the Louisiana Coastal Protection and Restoration Authority (CPRA). Gary Snellgrove and Matt Reonas of LDNR and Wes Leblanc of CPRA participated and contributed in several project meetings and provided important feedback through each stage of this research as did Chip Groat and Denise Reed of the Institute.

This report was reviewed by Mead Allison and Denise Reed and edited by Chincie Mouton of the Institute. Brendan Yuill and Kai Midboe of the Institute conducted earlier technical reviews. Louisiana Economic Development (LED) provided population projections. Pierre Sargent of the United States Geological Survey (USGS) provided valuable technical guidance and water usage data.

Executive Summary

Effective water management is dependent on two primary factors; the availability of water and the costs to convert that water into a usable resource. The assessment framework developed here supports the effective management of Louisiana's water resources by conjunctively appraising supply and demand in both ground and surface water units and providing a means to estimate the energy costs associated with water resources use. The framework includes a conceptual water budget that addresses both the total water supply and demand in different areas of the state, a water balance equation that mathematically relates the inputs and outputs of the hydrologic system in these areas, and a method for estimating the energy costs associated with extracting, treating, and conveying this water for public use.

The framework uses published, publicly available data and tools to generate information intended for water resources planning. The use of published information for the estimation of water budget parameters (hydraulic conductivity, e.g.,) reflects the average reported characteristic over the study area, but may not reflect conditions at smaller, local scales due to lateral inhomogeneity. Published values are sometimes not considered as conservative as those that may be more appropriate for water use regulation or for site-specific determinations. Publicly available tools (USGS Groundwater Toolbox, e.g.,) were chosen for this planning-level test approach, but more detailed studies and models may be appropriate to local conditions, and be substituted in the future. The results are reported in the native precision of the tools used. This precision was retained for reporting, but may be overly precise for future applications of the framework. All water supply and usage terms are expressed as annual means, and may not adequately reflect important seasonal trends in water supply and usage, including seasonal shortages and surpluses. This framework and assessment method was tested using example hydrologic units. The hydro units analyzed were determined by the presence of existing water budget issues, such as declining ground water levels, so that they could adequately demonstrate the utility of the framework, and the availability of data for application of the approach. Application of the framework to the three study areas is intended as a proof-of-concept. The three test cases are provided as a validation of the methodology, to illustrate that the framework output correlates in terms of general magnitude with previously identified water supply trends.

The assessment framework was tested in three different areas of the state. These case study locations were selected based on the presence of critical water budget issues. The southwest study area included a portion of the Chicot Aquifer as well as the Bayou Teche and Vermilion River surface watersheds. A large portion of this study area is dependent on rice cultivation and aquaculture, two industries that require large amounts of fresh water. In addition, the study area contains hydrologic units that are within the coastal zone and have the potential to be impacted by shifting salinity zones. The northwest study area includes a portion of the Carrizo-Wilcox Aquifer as well as the Red River, both of which are extensively utilized by industry and public water suppliers. This area is also notable for the development of the Haynesville shale gas over the last decade, an industry that requires large amounts of water. This study area also makes extensive use of both groundwater and surface water and recent years have seen a push to shift the industrial use of water from groundwater to surface water. Lastly, the southeast Louisiana study area includes that portion of the Southern Hills Aquifer System bounded by the Mississippi River on the west and the Tangipahoa River on the east. This area is one of the most urbanized in the state and is home to a number of large, water-reliant industries. The Baton Rouge area, in particular uses a great deal of groundwater to provide drinking water to its residents as well as to provide water for the petrochemical plants and oil refineries sited along the Mississippi River. Each of the study areas presented unique challenges in operationalizing the assessment framework.

The water balance in each hydrologic unit within the study areas showed similar patterns. Due to the total volume of surface water available for use in each of the hydrologic units, the overall water balance remains positive, with inputs exceeding outputs. However, in several hydrologic units across all study areas, groundwater outflow exceeds inflow, resulting in declining groundwater levels. Statewide, the greatest volume of groundwater withdrawal is used for rice irrigation, followed by public supply, and then industry. In terms of surface water withdrawals, power generation and industry are the largest consumers of fresh water. Similar water use patterns were seen in each of the case study areas, having a direct impact on the overall water balance. The water balance in each study area is also impacted by water quality issues. A number of surface water units in each study area have been identified as being impaired, limiting the value of these water for certain uses, such as ecological functioning and drinking water. In addition, the salinity of surface water in the coastal zone as well as human-induced saltwater intrusion into groundwater units have the potential to limit the value of some freshwater units.

The assessment framework was also used to analyze potential shifts in the overall water balance that would result from future population change. Each case study area includes large urban centers that were used to analyze the impacts of future population growth and urban expansion. The potential impacts of increased urbanization, specifically due to the conversion of open space to impermeable surface, include increased runoff, decreased infiltration of fresh water into the confined and unconfined aquifers, and a decrease in evapotranspiration rates. The ultimate effect of these changes on the overall budget is the reduction of groundwater inflow and a corresponding increase in runoff flowing to the surface waters, via either overland flow or through storm water management systems.

While the impacts of the spatial extent of urbanization on the overall budget was, in general, found to be minimal, increasing population levels were found to be much more impactful. Increasing population levels would be expected to have a similar corresponding increase in water consumption. The increased demand for water would be expected to place a greater amount of strain on groundwater resources in areas with sole source aquifers, such as the Chicot and Southern Hills systems.

The current and future availability of adequate fresh water is vital to the well-being of Louisiana’s human and natural populations. This comprehensive water resources assessment framework developed in this study can appraise current and expected future water supply and demand and serve as a planning instrument that can 1) better inform management decisions, and 2) minimize the potential impact of future growth on overall water costs, both social and economic.

Introduction

Ensuring a clean and sustainable supply of fresh water for Louisiana's people, agriculture, and industry, while also conserving energy and containing the energy costs associated with drawing on and delivering that water supply, is one of Louisiana's most serious and vital charges. In addition, with extensive marshes, islands, native prairies, and diverse coastal and interior forests and savannas, Louisiana's waters support an enormous variety of fish and wildlife habitat. The numerous fresh to saline water bodies located throughout Louisiana maintain diverse and highly productive finfish and shellfish resources that support the State's fisheries industry. The availability of adequate fresh water is vital to the well-being of Louisiana's human and natural environments. Projections of future changes in precipitation and temperature, however, suggest that much of the southeastern United States, including Louisiana, can be expected to experience decreasing levels of available annual moisture (Kunkel et al., 2013). Over time, these moisture deficiencies may increase the occurrence of drought conditions in portions of Louisiana and increase competition for water resources among different sectors of the economy. This study aims to appraise current and expected future water supply and demand and to develop a planning instrument that can 1) better inform management decisions, and 2) minimize the potential impact of future growth on overall water supply costs, including for energy use.

> *<u>Sustainability</u>: A balance between use and supply that causes no further impairment to water resources, and maintains or improves the current health of these systems*

This study will also highlight the importance of both groundwater and surface water in the water budget of Louisiana. Many other states utilize surface water as the primary source for drinking water and other fresh water needs. Nationally, surface water supplies roughly 78% of all withdrawals (Maupin et al., 2014). However, U.S. Geological Survey (USGS) data show that Louisiana's public water supply systems draw roughly half of the water provided to consumers from groundwater sources and half from surface water sources while rural homes are supplied almost entirely by groundwater wells (Sargent et al., 2011). In addition, over 70% of the water used for agriculture, including rice cultivation is drawn from groundwater.

To effectively manage Louisiana's water resources, it is necessary to develop an assessment framework that can conjunctively appraise supply and demand in both ground and surface water units across the state. Conjunctive management (use) refers to the coordinated and planned use and management of both surface water and groundwater resources to maximize the availability and reliability of water supplies in a region to meet various management objectives. Surface water and groundwater resources typically differ significantly in their availability, quality, management needs, and development and use costs. Managing both resources together, rather than in isolation, allows water managers to use the advantages of both resources for maximum benefit (California Water Plan Update, 2009). Surface and groundwater interact in complex ways, and these interactions can affect the supply of both. Groundwater contributes a significant amount of water to streams (surface water) as base flow. Conversely, surface water in the recharge zone of an aquifer supplies new water to the aquifer as recharge. If these processes are altered by human activity, climate change, or some other mechanism, the distribution and availability of water in the surface and subsurface may be affected.

This study aims to develop a framework and to test its application in three regions across Louisiana. One key feature of the framework presented here is a conceptual water budget that quantifies the inputs, outputs, water withdrawals, and usage in ground and surface water in hydrologic units across the state. This water budget maintains that the change in water stored in a unit, such as a watershed, is controlled by the rate at which water flows into and out of that unit (Healy et al., 2007). Volumes of water pumped from groundwater and surface water systems must come from some change in the water budget. This change occurs in one or more of the following ways (McKee & Hays, 2002):

1. more water entering the aquifer system (increased recharge),
2. less water leaving the system (decreased discharge), and
3. removal of water stored in the system (water level declines).

The total amount of water entering and leaving the system combined with the total unallocated water (including water shortfalls) must sum to zero, yielding a balanced water budget. When outflow exceeds inflow (withdrawal rates exceed ability of aquifer to replenish itself), then water levels decline as water is removed from storage to balance the water budget (McKee & Hays, 2002). Observed changes in the water budget of an area over time are in the assessment framework to measure the effects of environmental variability and human activities on water resources.

Part 1: Framework Development and Selection of Parameters

To lay a foundation for the appraisal process the Institute reviewed existing water resources assessment frameworks, reports, and other information from Louisiana and other states with regard to their approach, scope, technical content, scientific basis, geospatial/hydrologic scale of analysis, methods of future projection, and other key components. Widely shared features of many of the plans include short term (seasonal and annual) and long term (decadal) planning, planning based on hydrologic units, planning for surface water and groundwater, and developing water allocation strategies only after statewide water resource planning is underway. Some novel features identified in individual plans include critical areas planning, conjunctive management of both surface and ground water, linking water quality and quantity, and planning for conservation and efficiency particularly in states with experienced water shortages. Guidance for linking energy & water supply was gained from a review of California's Water – Energy Relationship (California Energy Commission, 2005). Novel aspects of water planning in Louisiana include the continental-scale Mississippi River, coastal demand for fresh water, and integration of water planning with the Coastal Master Plan.

FRAMEWORK DESCRIPTION

The assessment framework was developed to provide an appraisal of current and expected future water supply and use and to develop a planning instrument that can better inform management decisions and minimize the potential impact of future growth on overall water supply costs, including for energy use. The framework includes a conceptual water budget that can be used to estimate the total water supply and demand in hydrologic units across the state, a water balance equation that mathematically relates the inputs and outputs of the hydrologic system in these areas, and a method for determining the potential impacts of future demand and supply constraints. This framework can be used to assess each of the state's hydrologic units with regard to water supply sustainability for relevant existing and potential uses, including energy conservation. The framework has been constructed to provide uniformity of analysis across hydrologic units using existing data sources. Many elements of the assessment framework can be measured directly using existing data sources or estimated using established techniques. To minimize the impacts of known or expected gaps in information and data, those elements that could not be measured directly were calculated using the water balance equation.

For purposes of constructing the conceptual water budget, water units were categorized as surface water (streams, lakes, and reservoirs), surface alluvial/unconfined groundwater, or confined/deep groundwater storage units. Inputs and outputs for each of these water unit types were identified, and linkages between water units were established in the framework. Water quality, with respect to how it may affect the quantity and availability of a water resource, can also be considered within the framework. A diagram of the conceptual water budget can be seen in Figure 1.

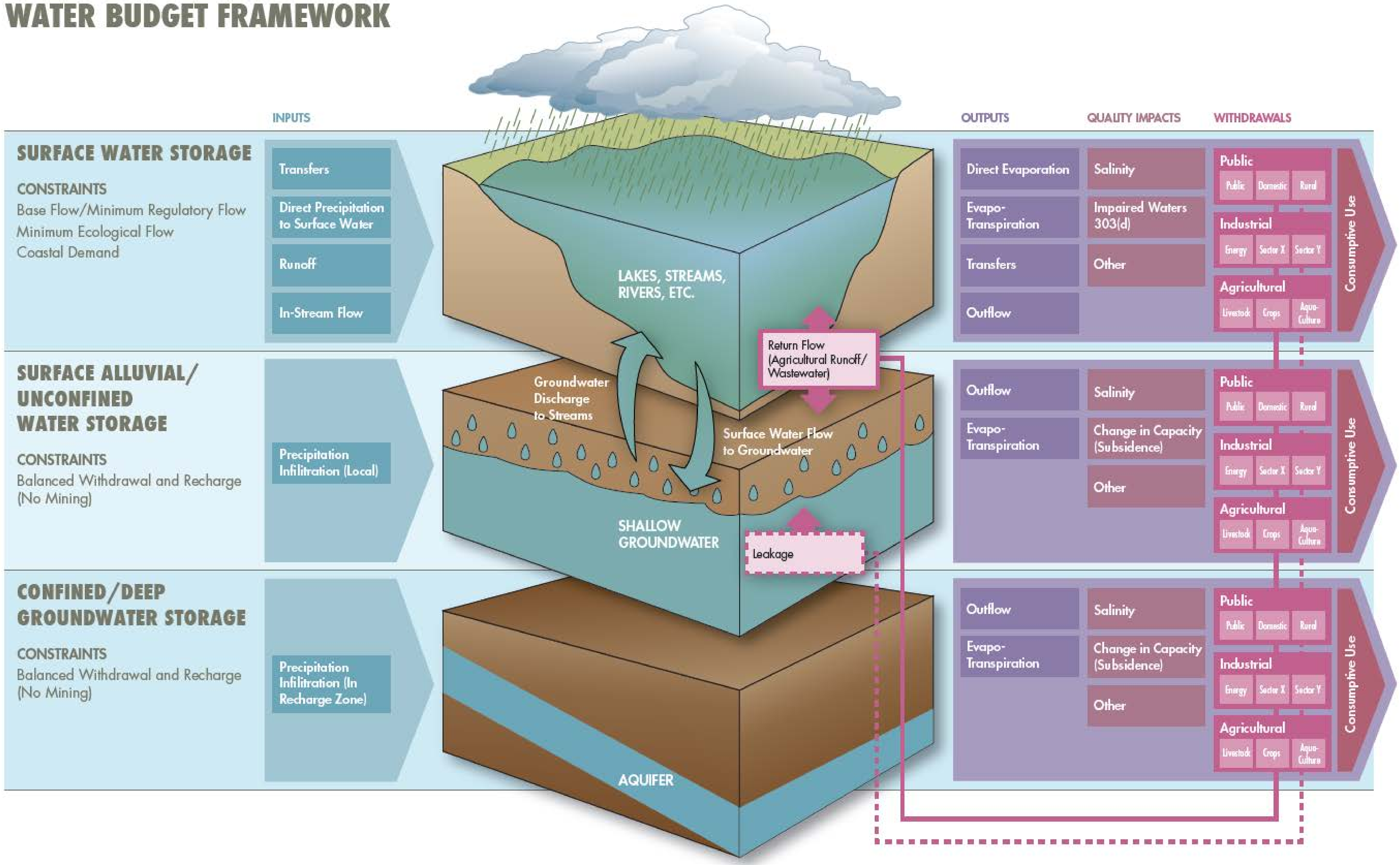
The framework supports calculation of a water budget to appraise sustainability by quantifying the inflows, outflows, and unallocated water for the hydrologic units of interest. The derived water budget maintains that for any given period, the change in the volume of unallocated water within each unit of analysis is balanced by the volume of water that flows into and out of the unit. The change in water volume within an accounting unit can therefore be conceptualized in its simplest form by Equation 1:

$$\boldsymbol{Flow\ In - Flow\ Out = Unallocated\ Water} \qquad \textbf{Equation 1}$$

Unallocated water, as used in this framework, consists of both the amount of water that is not used in the hydrologic unit that is discharged from the terminal node of the system (i.e. flow in exceeds flow out) and water shortfalls (i.e. flow out exceeds flow in). Areas where more water is used than is locally renewed would result in a reduction of unallocated water, or a water shortfall, which may be indicative of unsustainable water withdrawal (Roy et al., 2005). With regard to groundwater, the difference between water demand and the sustainable yield of the aquifer could provide a measure of the supply gaps for each of Louisiana’s aquifers. However, Louisiana has not yet developed groundwater availability models (GAM) to measure sustainable yield in the state’s aquifers (Ecology and Environment, 2011). As a result, the framework has been developed and applied here recognizing that detailed aquifer yield estimations are not available, and it can be used to identify the importance of this data gap relative to others.

Louisiana Water Resources Assessment for Sustainability and Energy Management

WATER BUDGET FRAMEWORK



The inflows and outflows in the framework can be expressed in the form of a generalized water balance equation (Equation 2):

$$\boldsymbol{P + Q_{in}^{tot} = ET + Q_{ua} + Q_{out}^{tot}} \qquad \text{Equation 2}$$

Where,

P is precipitation,
Q_{in}^{tot} is total water flow into the unit,
ET is evapotranspiration (the sum of evaporation from soils, surface-water bodies, and plants),
Q_{ua} is unallocated water, and
Q_{out}^{tot} is total water flow out of the unit.

The individual components of the equation were refined and customized to address the conjunctive management goals of this study. Components of the water budget to be quantified are precipitation, evapotranspiration, streamflow into and out of the hydro unit, groundwater underflow into and out of the hydro unit, surface and groundwater withdrawals, transfers into and out of the basin, and changes in allocation throughout the basin (Healy et al., 2007; Scanlon et al., 2002). Key components and subcomponents of the framework and their inter-relationships are illustrated in Figure 1and can be written as Equation 3 below:

$$\boldsymbol{P + Q_{in}^{sw} + Q_{in}^{gw} = ET^{sw} + ET^{gw} + ET^{uz} + {Q_{ua}}^{sw} + {Q_{ua}}^{gw} + Q_{out}^{sw} + Q_{out}^{gw}} \qquad \text{Equation 3}$$

Where,

P is precipitation,
Q_{in}^{sw} is surface water flow into the unit,
Q_{in}^{gw} is groundwater flow into the unit,
ET^{sw} is evapotranspiration from surface water,
ET^{gw} is evapotranspiration from groundwater,
ET^{uz} is evapotranspiration from the unsaturated zone,
${Q_{ua}}^{sw}$ is unallocated surface water,
${Q_{ua}}^{gw}$ is unallocated groundwater,
Q_{out}^{sw} is total surface water flow out of the unit, and
Q_{out}^{gw} is total groundwater flow out of the unit.

For any location, some of the terms in this equation are likely to be negligible in magnitude and may be ignored (Scanlon et al., 2002). The rainfall and evapotranspiration components of the equation can have significant positive and negative effects on groundwater recharge, defined for this framework as the precipitation within the basin that is not lost to evapotranspiration or runoff. Most groundwater systems receive both localized and diffuse recharge (Reilly et al., 2008). Groundwater storage is divided into three types (surface alluvial, unconfined, and confined). Surface alluvial and unconfined aquifers that contain the water table are generally recharged directly via precipitation that percolates though the unsaturated zone to the water table and from losing streams, lakes, and wetlands (Alley et al., 1999). Confined or deep groundwater, on the other hand, is recharged almost entirely by precipitation in that aquifer's recharge zone (Reilly et al., 2008). For the purposes of this assessment, all surface water storage (in lakes, streams, and reservoirs) is treated as a single variable. The various components of the enhanced water budget equation can be defined as follows (Equations 4-8):

$$\boldsymbol{Q_{in}^{sw} = RO + Q_{in}^{bf} + Q_{in}^{streams} + Q_{in}^{transfers} + Q_{in}^{return\ flow\ ag} + Q_{in}^{return\ flow\ ww}} \quad \text{Equation 4}$$

$$\boldsymbol{Q_{in}^{gw} = Q_{in}^{gw\ surface\ al} + Q_{in}^{gw\ unconf} + Q_{in}^{gw\ conf}} \quad \text{Equation 5}$$

$$\boldsymbol{Q_{ua}{}^{gw} = Q_{ua}{}^{gw\ al} + Q_{ua}{}^{gw\ unconf} + Q_{ua}{}^{gw\ conf}} \quad \text{Equation 6}$$

$$\boldsymbol{Q_{out}^{gw} = (Q_{out}^{gw\ al} + Q_{out}^{gw\ unconf} + Q_{out}^{gw\ conf}) + (WD_{out}^{gw\ al} + WD_{out}^{gw\ unconf} + WD_{out}^{gw\ conf}) + Q_{out}^{bf}}$$

Equation 7

$$\boldsymbol{Q_{out}^{sw} = Q_{out}^{streams} + WD_{out}^{sw}} \quad \text{Equation 8}$$

Where,

Q_{in}^{sw}	is surface water flow into the unit,
RO	is runoff,
Q_{in}^{bf}	is base flow into the unit,
$Q_{in}^{streams}$	is stream flow into the unit,
$Q_{in}^{transfers}$	is water transferred into the unit,
$Q_{in}^{return\ flow\ ag}$	is water returned to the surface water system after being withdrawn for agricultural use, either from surface water or groundwater sources,
$Q_{in}^{return\ flow\ ww}$	is water returned to the surface water system after being withdrawn for industrial, public supply, rural domestic and power supply use, either from surface water or groundwater sources,
Q_{in}^{gw}	is groundwater flow into the unit,
$Q_{in}^{gw\ surface\ al}$	is the surface alluvial component of groundwater flow into the unit,
$Q_{in}^{gw\ unconf}$	is the unconfined component of groundwater flow into the unit,
$Q_{in}^{gw\ conf}$	is the confined component of groundwater flow into the unit,
$Q_{ua}{}^{gw}$	is unallocated groundwater,
$Q_{ua}{}^{gw\ al}$	is unallocated surface alluvial groundwater,
$Q_{ua}{}^{gw\ unconf}$	is unallocated unconfined groundwater,
$Q_{ua}{}^{gw\ conf}$	is unallocated confined groundwater,
Q_{out}^{gw}	is total groundwater flow out of the unit.
$Q_{out}^{gw\ al}$	is the surface alluvial component of groundwater flow out of the unit,
$Q_{out}^{gw\ unconf}$	is the unconfined component of groundwater flow out of the unit,
$Q_{out}^{gw\ conf}$	is the confined component of groundwater flow out of the unit,
$WD_{out}^{gw\ al}$	is the withdrawal of surface alluvial groundwater out of the unit,
$WD_{out}^{gw\ unconf}$	is the withdrawal of unconfined groundwater out of the unit,
$WD_{out}^{gw\ conf}$	is the withdrawal of confined groundwater out of the unit,

Q_{out}^{bf} is base flow out of the unit,
Q_{out}^{sw} is total surface water flow out of the unit,
$Q_{out}^{streams}$ is stream flow out of the unit, and
WD_{out}^{sw} is the withdrawal of surface water out of the unit.

Estimated water withdrawals from both surface water and groundwater sources are broken into various subcomponents in the water budget framework developed here. Quantifying the various outflow components of the water system will allow the framework to estimate impacts that the subcomponents have on the water budget. In this framework, water withdrawals encompass three major water use categories: public use, agricultural use, and industrial use. Each of these categories may include several subcategories that can be combined within the framework. Conveyance losses (leakage from water delivery systems), often unaccounted for in water budget calculations, are treated as withdrawals from the system here. The withdrawal components of the water balance equation can be calculated using the water use subcomponents in Equations 9-12:

$$\boldsymbol{WD_{out}^{gw\,al} = WD_{public}^{gw\,al} + WD_{industrial}^{gw\,al} + WD_{agricultural}^{gw\,al}} \quad \text{Equation 9}$$

$$\boldsymbol{WD_{out}^{gw\,unconf} = WD_{public}^{gw\,unconf} + WD_{industrial}^{gw\,unconf} + WD_{agricultural}^{gw\,unconf}} \quad \text{Equation 10}$$

$$\boldsymbol{WD_{out}^{gw\,conf} = WD_{public}^{gw\,conf} + WD_{industrial}^{gw\,conf} + WD_{agricultural}^{gw\,conf}} \quad \text{Equation 11}$$

$$\boldsymbol{WD_{out}^{sw} = WD_{public}^{sw} + WD_{industrial}^{sw} + WD_{agricultural}^{sw}} \quad \text{Equation 12}$$

Where,
$WD_{out}^{gw\,al}$ is the total withdrawal of surface alluvial groundwater out of the unit,
$WD_{public}^{gw\,al}$ is the withdrawal of surface alluvial groundwater out of the unit for public use,
$WD_{industrial}^{gw\,al}$ is the withdrawal of surface alluvial groundwater out of the unit for industrial use,
$WD_{agricultural}^{gw\,al}$ is the withdrawal of surface alluvial groundwater out of the unit for agricultural use,
$WD_{out}^{gw\,unconf}$ is the total withdrawal of unconfined groundwater out of the unit,
$WD_{public}^{gw\,unconf}$ is the withdrawal of unconfined groundwater out of the unit for public use,
$WD_{industrial}^{gw\,unconf}$ is the withdrawal of unconfined groundwater out of the unit for industrial use,
$WD_{agricultural}^{gw\,unconf}$ is the withdrawal of unconfined groundwater out of the unit for agricultural use,
$WD_{out}^{gw\,conf}$ is the total withdrawal of confined groundwater out of the unit,
$WD_{public}^{gw\,conf}$ is the withdrawal of confined groundwater out of the unit for public use,
$WD_{industrial}^{gw\,conf}$ is the withdrawal of confined groundwater out of the unit for industrial use,
$WD_{agricultural}^{gw\,conf}$ is the withdrawal of confined groundwater out of the unit for agricultural use,
WD_{out}^{sw} is the total withdrawal of surface water out of the unit,
WD_{public}^{sw} is the withdrawal of surface water out of the unit for public use,
$WD_{industrial}^{sw}$ is the withdrawal of surface water out of the unit for industrial use, and
$WD_{agricultural}^{sw}$ is the withdrawal of surface water out of the unit for agricultural use.

ENERGY USE IN THE WATER SECTOR

Effective water management is dependent on two primary factors: the availability of water and the costs to convert that water into a usable resource. In 2010, approximately 8,500 million gallons per day of water were withdrawn from groundwater and surface water sources in Louisiana (Sargent et al., 2011). As water is extracted and utilized, energy costs are embedded into the water use cycle (Bennett et al., 2010). As water is extracted and utilized, energy costs are embedded into the water use cycle. Beginning with a water source, water is extracted and conveyed, moving directly to an end use such as irrigation or to a treatment plant. From there, it is distributed to customers. Once it is used by the end users, water then moves through a wastewater collection system to a treatment plant and is typically discharged back into the environment, not always to the same place from which it was originally extracted. Every step along this cycle involves energy expenditures (Water in the West, 2013). Because the supply and use of water and energy are intricately connected, energy costs should be an essential component of an operational water budget framework.

> *Embedded Energy: The amount of energy used to collect, convey, treat, and distribute a unit of water to end users, and the amount of energy that is used to collect and transport used water for treatment prior to safe discharge of the effluent*

The limits to how much water can be extracted from an aquifer are economic and environmental. When groundwater is extracted faster than it can be replaced by natural processes, the potentiometric surface in the aquifer drops and the distance water must be raised to the surface increases. As lift distance increases, so does the energy required to pump the water. Ultimately, water extraction will cease when the energy costs exceed the value of the water (economic exhaustion), the quality of the water in the aquifer drop below acceptable levels, or the well runs dry (resource exhaustion) (Gleick, 1994). Energy costs must therefore be considered a constraint on both surface water and groundwater withdrawals to a water budget. This research used a water-energy life cycle approach to examine energy for water extraction, energy for water conveyance, energy for water treatment and distribution, and energy for wastewater treatment (Water in the West, 2013). Each of these components of the cycle differentially consumes energy that is ultimately embedded in the cost of the water.

Energy for Water Extraction

The amount of energy required per unit volume will not vary significantly from one geographic area to another, but they will vary significantly between sources of water and the technology used to extract these waters. The extraction of water from surface sources and aquifers require very different amounts of energy to convert that fresh water into a supply.

Surface Water

Surface water comes from precipitation and is captured, stored, and conveyed in natural lakes, streams, bayous, and wetlands as well as anthropogenic reservoirs, canals, and aqueducts. Surface water is, by definition, water that is already a treatable, above-ground water source ready to be conveyed (Navigant

Consulting, Inc., 2006). Typically, it requires little to no energy for surface water to become a supply source (Water in the West, 2013). However, in tidally influenced areas such as Louisiana's coastal zone, a large portion of the surface water along the coast and in lakes and bayous is brackish and unusable as a supply source. The process of desalinating these waters would be extremely energy intensive and costly. Using modern desalination technologies, energy costs would represent more than one-half of the cost of fresh water produced by desalination (Pappas, 2011). As a result, desalination is not used to treat brackish water in Louisiana's coastal areas. Therefore, in this research, high salinity zones defined as surface waters containing an average of greater than 0.5 parts per thousand (ppt) are used to delineate the limits of usable surface water area and excluded from the total water volume calculations. The energy intensity of converting the remaining fresh surface water to a supply is zero.

Groundwater

The amount of energy devoted to groundwater pumping depends on:

- how far the water must be pumped before reaching the surface, which can change seasonally;
- the volume of groundwater pumped; and
- the types of pumping devices water rights holders choose to use (e.g., age, efficiency, fuel type) (Water in the West, 2013).

The amount of energy expended to extract groundwater from individual domestic wells was estimated using data on active water wells obtained from the LDNR's Strategic Online Natural Resource Information System (SONRIS). These data included information on the depth of each well and the water levels. These data were examined, and significant outliers were removed from the dataset. Wells listed as plugged or abandoned were also excluded from this analysis. Assuming that each individual well served a family of four, the total volume of groundwater pumped per household was roughly estimated. Estimated annual energy costs were calculated based upon average domestic water use of 400 gallons per day for a family of four using an electric water pump using 1.6 kWh for each 10 feet of water lift.

Energy for Water Conveyance from the Source Location to the Supply Area

Along with energy employed in water distribution, the energy for water conveyance comprises the greatest source of energy use in the water sector, and managing energy use in water conveyance nationally is directly tied to reducing water loss during conveyance. Conveyance is defined as moving raw water from the source to water treatment or to direct uses in agriculture, energy production, or other uses that do not require water treatment (Water in the West, 2013). Surface water conveyance systems are designed to move water to areas of need away from the location where the water was collected. In completely gravity fed systems, energy costs to convey water to the supply area is assumed to be zero. In systems that are not gravity fed, energy costs are derived from both pumps and generators to convey water to the supply areas. These transfers account for most of the energy embedded in surface water supplies and is largely a product of the distance and elevation over which the water must travel (California Energy Commission, 2005). Other factors include the length and diameter of the water pipes, water flow levels, and power installations at the pumping stations.

Energy for Water Treatment and Distribution to the End User

Electricity use for water treatment systems in Louisiana is not currently measured directly and must therefore be estimated based on national averages (Stillwell et al., 2011). Unit electricity consumption estimates for the treatment of surface water and groundwater were used along with inventories of public water supply systems to estimate electricity consumption for each of the study areas. According the United States Environmental Protection Agency (USEPA), public water systems, whether publically or privately owned, provide water for residential consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of at least 25 people for at least 60 days a year. Data on the population served for each of the public water systems within the study area were extracted from the U.S. Environmental Protection Agency's Enforcement and Compliance History Online (ECHO) database. Spatial locations for each of the systems were estimated using well data and surface water intake data obtained from LDNR. Additional information on the water systems was extracted from the Louisiana Department of Health and Hospitals' Office of Public Health Drinking Water Watch database. These three data sources were used to estimate the total energy needed to extract and treat both groundwater and surface water within each hydrologic unit in the study areas. Once the water is treated, it is pumped into the distribution network. National estimates indicate that public water systems use approximately 1,200 kWh/MM gal to deliver water from treatment plant to end users (California Energy Commission, 2005).

Surface Water Treatment

After being extracted, surface water must be screened, filtered, and treated to remove other dissolved contaminants and biota. The treated water is then distributed to consumers by high pressure pumping. Regardless of size of the treatment plant, the predominant use of electricity in water treatment plants is for pumping the water to the distribution system. This represents about 80-85% of the total electricity consumption for surface water treatment (Water in the West, 2013). Using information on the facility, the population served by that facility, and established unit electricity values (Table 1), the total energy consumed to treat water at treatment plants was estimated across the study areas.

Table 1: Unit electricity consumption for surface freshwater treatment plants

Unit Electricity Consumption for Surface Water Treatment Plants	
Treatment Plant Size	Unit Electricity Consumption
1 MM gal/day (3,785 m^3/d)	1,483 kWh/MM gal (0.392 kWh/m^3)
5 MM gal/day (18,925 m^3/d)	1,418 kWh/MM gal (0.375 kWh/ m^3)
10 MM gal/day (37,850 m^3/d)	1,406 kWh/MM gal (0.371 kWh/ m^3)
20 MM gal/day (75,700 m^3/d)	1,409 kWh/MM gal (0.372 kWh/ m^3)
50 MM gal/day (189,250 m^3/d)	1,408 kWh/MM gal (0.372 kWh/ m^3)
100 MM gal/day (378,500 m^3/d)	1,407 kWh/MM gal (0.372 kWh/ m^3)
Source: Electric Power Research Institute, 2002	

Groundwater

Unit electricity consumption for supply from groundwater is estimated at 1,824 kWh/million gallons (0.482 kWh/m^3), some 30% greater than for surface water (Electric Power Research Institute, 2002). This is independent of the size of the pumping and treatment facility. The predominant consumer of electricity is pumping. About one-third of the electricity is used for well pumping, while most of the balance is used for booster pumping into the distribution system. Less than 0.5% of the electricity is used for chlorination of the water (Electric Power Research Institute, 2002).

Energy for Wastewater Treatment

Approximately 4% of the electricity consumed in the United States goes towards moving and treating water and wastewater (Electric Power Research Institute, 2002). All sectors of the economy have a demand for fresh water to some extent and generate quantities of wastewater that must be treated before it can be released into a surface water unit. Unit electricity requirement values were used to determine the total energy costs of wastewater treatment at all publicly owned treatment works (POTW) located within each hydrologic unit (Table 2). Spatial data for each POTW as well as plant capacity (measured in gallons of water treated per day) were extracted from the ECHO website and used to sum the total wastewater treatment energy costs within each hydrologic unit in the study areas.

Table 2: Unit electricity consumption for wastewater treatment by size of plant

Unit Electricity Consumption for Wastewater Treatment by Size of Plant				
Treatment Plant Size	Unit Electricity Consumption (kWh/MM gal)			
	Trickling Filter	Activated Sludge	Advanced Wastewater Treatment	Advanced Wastewater Treatment Nitrification
1 MM gal/day	1,811	2,236	2,596	2,951
5 MM gal/day	978	1,369	1,573	1,926
10 MM gal/day	852	1,203	1,408	1,791
20 MM gal/day	750	1,114	1,303	1,676
50 MM gal/day	687	1,051	1,216	1,588
100 MM gal/day	673	1,028	1,188	1,558
Source: Electric Power Research Institute, 2002				

FRAMEWORK APPLICATION AND DATA INVENTORY

Data were obtained and analyzed from a wide variety of sources for use in this study. These data were collected by the sourcing agency over varying spatial and temporal scales, as well as on a variety of subject matter. These data can be categorized in two ways: geospatial data used to derive the water unit boundaries (Table 3) and water supply and demand data used to determine the water budget within the derived analytical units (Table 4). The spatial scale of the data ranges from local, discrete points, to parish or regional data, to those datasets with complete statewide coverage. The temporal scale of the data varies as well, ranging from discrete one-time sample points to continuously collected data varying from hourly, daily, monthly, or annual scales, with periods of record extending from days to decades.

Table 3: Data Sources – Delineation of Analytical Water Units

Study Unit Components	Data Source
Surface Water Units	
Hydrologic Unit Code – 8 Digit Cataloguing Unit (HUC8)	USGS National Hydrography Dataset
Hydrologic Unit Code – 12 Digit Subwatershed (HUC12)	USGS National Hydrography Dataset
Groundwater	
Aquifer Group	Louisiana Geological Survey
Recharge Area	Louisiana Geological Survey, Louisiana DEQ
Aquifers and Water Bearing Units	Louisiana DNR Well Data

Table 4: Data Sources – Water Supply and Demand.

Water Budget Component	Method of Analysis	Framework Variable
Precipitation	National Oceanic and Atmospheric Administration National Climatic Data Center (NOAA NCDC) observed daily precipitation data, in inches, retrieved with the USGS Groundwater Toolbox (PRCP dataset)	P
Streamflow	USGS National Water Information System (NWIS) daily mean streamflow data retrieved with the USGS Groundwater Toolbox	Q_{out}^{sw}
Base flow	Average of the six hydrograph-separation methods calculated with the USGS Groundwater Toolbox	Q_{out}^{bf}
Runoff	Streamflow minus base flow, calculated using base flow separation techniques in the USGS Groundwater Toolbox	RO
Recharge	Calculated using the RORA method provided with the USGS Groundwater Toolbox	$Q_{out}^{gw\ al}$
Evapotranspiration, total	Calculation method 1: Precipitation minus streamflow	ET
Evapotranspiration, total (alternate method, not used in budget)	Calculation method 2: From regression model developed by Sanford & Selnick (2012) and NOAA NCDC data retrieved with the USGS Groundwater Toolbox	$ET\ 2$

Water Budget Component	Method of Analysis	Framework Variable
Evapotranspiration, groundwater	Calculated as recharge minus base flow	ET^{gw}
Evapotranspiration, near surface	Calculated as total evapotranspiration (method 1) minus evapotranspiration from the groundwater system	$ET^{uz} + ET^{sw}$
Percent of HUC in high recharge Area	Calculated using areas from Boniol et al., (1988)with ArcGIS (ESRI 2011)	$\% \, SWgwrcg$
Infiltration coefficient	Average of values from Delin & Risser (2007)	INF
Deep Aquifer Recharge from rainfall in recharge zone	Recharge above (Etgw+Qbf) x (%SWgwrcg) x infiltration coefficient (INF)	$Q_{in}^{gw\ unconf}$
Deep Aquifer Recharge from vertical leakage coefficient	L'vovich (1979), and Doll & Fiedler (2008)	$RCvlCoeff$
Percent of HUC not in Chicot high recharge area	Calculated with ArcGIS (ESRI 2011)	$\%swgwvl$
Deep Aquifer Recharge from vertical leakage	Recharge above (Etgw+Qbf) x (%SWgwrvl) x certical leakage coefficient ($RCvlCoeff$)	$Q_{in}^{gw\ surface\ al}$
Surface Water and Groundwater Withdrawals	Values obtained from USGS Water Use in Louisiana (Sargent et al., 2011)	$WD_{out}^{sw}, WD_{out}^{gw}$
Return Flow (leakage and runoff)	WD*Consumptive Use Coefficients obtained from USGS National Water Summary (Carr et al., 1987) and Lawrence Livermore National Laboratory (Smith et al., 2011)	$Q_{in}^{return\ flow}$
Consumptive Use	WD - Qsw in (return flow)	$WD - Q_{in}^{return\ flow}$
Return Flow (wastewater discharge into rivers)	Discharge values obtained from USEPA Permit Compliance System (PCS) and Integrated Compliance Information System (ICIS)	$Q_{in}^{return\ flow\ ww}$

Water Budget Components

The conceptual water budget developed here required the compilation of datasets drawn from a wide variety of sources that quantify water volumes associated with meteorology, surface water, groundwater, and net consumptive demand. The data used to perform the assessment are shown in Table 4 and are summarized below.

Meteorological Inputs

In the majority of basins, precipitation is the main source of renewable water. Some of the precipitation is lost to the atmosphere through direct evaporation or through transpiration by plants. Some is contained in surface water impoundments. The remainder percolates into the ground and is stored as groundwater or is transported as runoff. Precipitation data were retrieved from the NOAA National Climatic Data Center (NCDC) precipitation dataset using the USGS Groundwater Toolbox.

Mean annual evapotranspiration estimates were calculated as the difference of precipitation minus streamflow (Barlow et al., 2015), and verified using a regression model developed by Sanford & Selnick (2012) and NOAA NCDC data retrieved with the Groundwater Toolbox (Barlow et al., 2015).

Surface Water Inflow and Outflow

Selected stream gauges were used to estimate surface water inflow, based on gauge location and sufficient period of record. For this study, hydrograph separation methods were applied to continuous-record streamflow-gaging stations having at least one year of complete streamflow record from January through December (Nelms et al., 2015). Stream gauges were prioritized as having a period of record of at least 10 continuous years, as recent as possible, with at least 15 peaks for hydrograph separation analysis. For optimal performance of the hydrograph separation and recharge calculations, watershed size was kept below 500 square miles, with a few exceptions when optimal stream gauges were not available for a particular HUC8. Stream gage data were retrieved from the USGS NWIS using the tools in the USGS Groundwater Toolbox (Barlow et al., 2015). Contributions from the interaction of groundwater and surface-water within the water unit were incorporated into the surface water flow calculations.

Groundwater Inflow and Outflow

The analysis of groundwater inflow and outflow within the analytical water units utilized data obtained in previous groundwater studies (Clark et al., 2013; Heywood & Griffith, 2013; McKee & Clark, 2003). Where such studies are unavailable, groundwater flows were estimated within each study area using estimates of deep aquifer recharge due to two mechanisms: infiltration of precipitation in the aquifer recharge area and vertical leakage from overlying strata. These flows in and out were used to roughly estimate groundwater components of the budget. As aquifer-specific groundwater availability models or other new data become available, these values can then be substituted into the framework. The USGS Groundwater Toolbox methodology was modified to provide for these processes, and the volumes of water were subtracted from the base flow output of the USGS Groundwater Toolbox. Precipitation infiltration in the recharge area is estimated using the method in Table 4, as the product of the percent of the HUC8 area inside the recharge zone of the aquifer, an average infiltration coefficient for humid subtropical soils (Delin & Risser, 2007), and the base flow. Aquifer recharge from vertical leakage was estimated as the product of the percent of the HUC8 area outside the recharge zone of the aquifer, an average vertical leakage coefficient for humid subtropical soils (L’vovich, 1979, Doll & Fiedler, 2008), and the base flow. This method provided estimates of groundwater recharge that compared well with estimates for the Southern Hills Aquifer System by Beigi & Tsai (2014). An alternate method for comparative analysis, based on local and regional hydraulic conditions using the Darcy Equation (13), performed and compared to the results for the northwest Louisiana (NWLA) study area:

$$\boldsymbol{Q = KA\left(\frac{dh}{dl}\right)} \quad \text{Equation 13}$$

Where,

Q is groundwater flow,
K is hydraulic conductivity,
A is cross-sectional aquifer area, and
dh/dl is hydraulic gradient, estimated using water surface elevation in wells along a transect, where *dh* is the change in water surface elevation, and *dl* is the distance along the transect.

The equation gives daily flow rates. Hydraulic conductivity and cross-sectional aquifer area were referenced from published sources for each aquifer, while hydraulic gradients were determined from potentiometric surface maps and water surface elevation from observation wells. Summaries of these parameters for the three study areas are presented in Table 9, Table 18, and Table 26 later in this document. Annual estimates were developed assuming that the daily rate is constant year-round (Tetra Tech, 2007). A summary of the comparison of this estimation method to other methods for the study areas is shown in Table 5. Future efforts could examine the effects of seasonality, in addition to the current method using annual mean values.

Table 5: Alternate recharge methods comparison

Aquifer	Recharge from vertical leakage (acre-feet/year)	Recharge from infiltration in recharge zone (acre-feet/year)	Total Recharge (acre-feet/year)	Alternate Result (acre-feet/year)	Alternate Result method
Chicot	106,113	210,404	316,517	359,963	Darcy
Carrizo-Wilcox	84,924	269,614	354,537	n/a	n/a
Southern Hills	44,136	499,742	543,878	883,688	Beigi & Tsai, 2014

Groundwater – Surface Water Interaction

Separation of streamflow hydrographs into baseflow and surface runoff components was used to estimate the groundwater discharge (baseflow) and surface runoff components of streamflow and to estimate rates of groundwater recharge. This also helps to quantify the groundwater components of basin-scale hydrologic budgets (Barlow et al., 2015; Sloto & Crouse, 1996). The USGS Groundwater Toolbox employed in this study uses the average of six hydrograph-separation methods to determine the groundwater discharge and surface runoff components of streamflow – the Base-Flow Index (BFI;

Standard and Modified), HYSEP (Fixed Interval, Sliding Interval, and Local Minimum), and PART methods—and the RORA recession-curve displacement method and associated RECESS program to estimate groundwater recharge from streamflow data (Barlow et al., 2015). Confined aquifer recharge was calculated using a modification of the RORA method provided in the USGS Groundwater Toolbox. A portion of the recharge calculated by the RORA method was estimated to enter confined aquifer storage via the infiltration of rainfall in the high recharge zone of the aquifer (Figure 2), or by vertical leakage from overlying water bearing units. Confined aquifer recharge from rainfall infiltration in the high recharge zone was calculated using the percent of area of each HUC8 in the high recharge zone of the aquifer derived from the Recharge Potential of Louisiana Aquifers dataset (Boniol et al., 1988) and the total base flow value. Confined aquifer recharge within areas of each HUC8 not in the high recharge areas defined in Boniol et al. (1988) was calculated as leakage from overlying water bearing units. It was calculated using the percent of area of each HUC8 not in the high recharge zone of the aquifer derived from the Recharge Potential of Louisiana Aquifers dataset (Boniol et al., 1988) and the total base flow value.

Water Transfers

Transferred water is water originating outside the water unit that is discharged or conveyed into the unit. Within this water budget, transferred water consists of two components: wastewater discharge and inter-unit water transfers. Wastewater discharge includes treated wastewater from municipal sewer systems, and effluent from other uses, that is discharged into a nearby surface water body from which it was not initially withdrawn. Best estimates were made on a case-by-case basis to determine the appropriate transfer terms for the source hydro units for wastewater return flows. Inter-unit water transfers generally involve the transfers between one river basin and an adjacent river basin to meet the public, agricultural, and/or industrial needs of the receiving basin.

Withdrawals

Withdrawals is the water diverted or withdrawn from a surface water or groundwater source and conveyed to a place of use (Molina-Rivera & Gomez-Gomez, 2008). In this framework, withdrawal encompasses three major water use categories: public use, agricultural use, and industrial use. Conveyance losses, though generally considered to be an unaccounted use, are treated as withdrawals here. In many cases, conveyance losses serve as transfers between hydro units, depending on the locations of the withdrawal and leakage areas (e.g., water withdrawn from a deep aquifer could be conveyed across a surface alluvial aquifer, and the conveyance loss of the deep aquifer water could serve to recharge the surface alluvial aquifer).

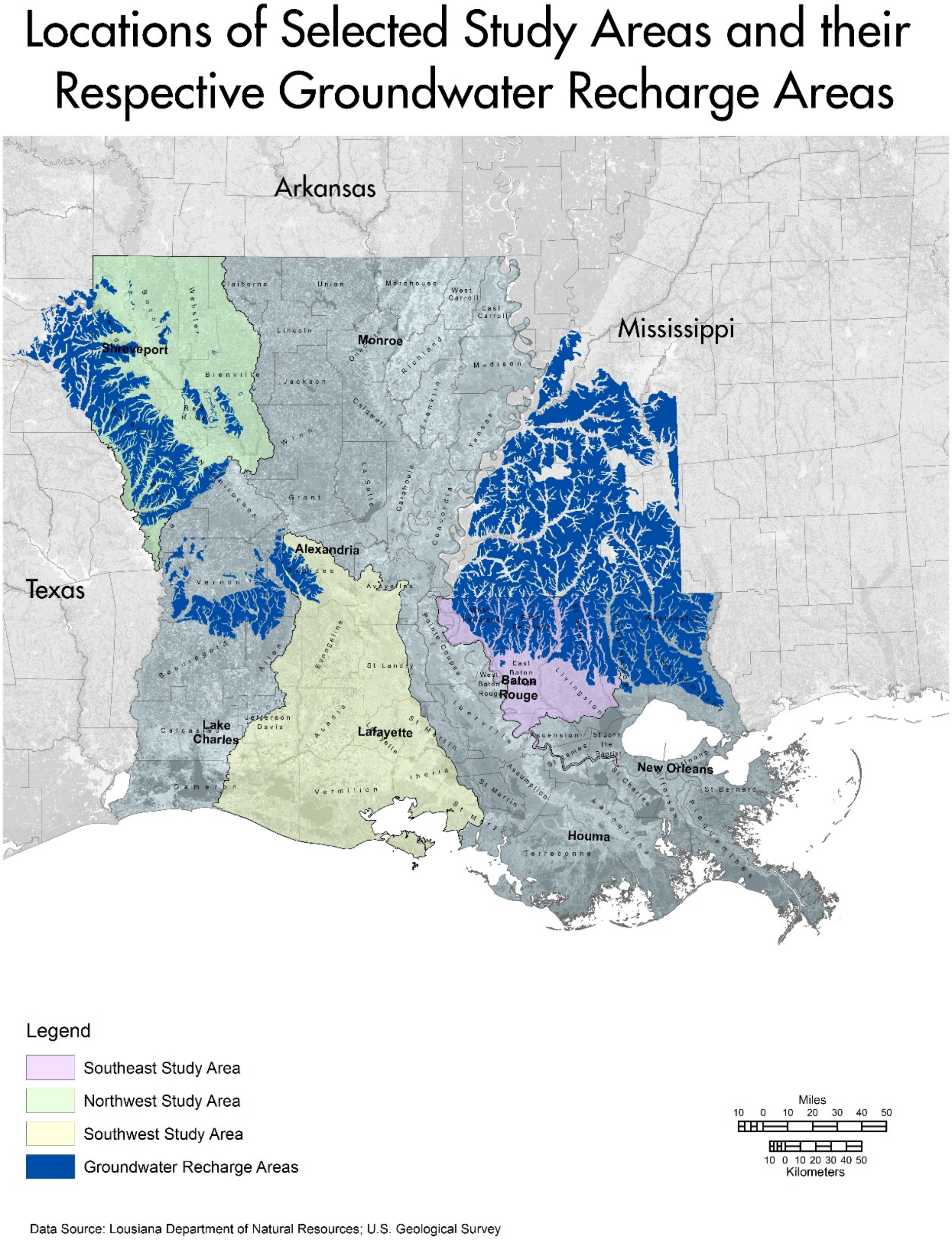


Figure 2. Locations of Selected Study Areas and their Respective Groundwater Recharge Areas

The availability and use of surface and groundwater varies spatially across the state. Total withdrawals are driven largely by economic demand. The USGS has identified seven water use sectors in the state that nest within the three major water use categories identified in the assessment framework, each with a distinctive spatial distribution: Public Supply and Rural Domestic, Industrial Use and Power Generation, and Livestock, Rice Irrigation, General Irrigation, and Aquaculture. Unless otherwise stated, all water use data in this analysis come from the USGS Water Use in Louisiana reports (Sargent et al., 2011). The USGS, in cooperation with the Louisiana Department of Transportation and Development, has collected and published water withdrawal and use information every five years since 1960. Starting in 2012, the USGS, in cooperation with the Louisiana Department of Natural Resources, began estimating water withdrawals in Louisiana on an annual basis.

Consumptive Use and Conveyance Losses

The USGS water use reports do not describe the disposition (fate) of the water that has been used by various sectors of the economy. Water can be consumed or evaporated from a water use sector after it is withdrawn. The majority of this consumed or evaporated water is not assumed to be reintroduced to the surface waters in any particular geographic location and is classified as conveyance loss in the water budget framework (Smith et al., 2011). Consumptive use coefficients were used to determine the amount of water consumed and the amount of return flow for each water use sector. Statewide coefficients for Louisiana have been determined by the Lawrence Livermore National Laboratory and the USGS for each withdrawal sector (Table 6). Consumptive water use (in Mgal/d) was calculated using Equation 14 (Molina-Rivera & Gomez-Gomez, 2008):

$$Consumptive\ Use = Withdrawals * Consumptive\ Use\ Coefficient \qquad \text{Equation 14}$$

The value obtained here will give the amount of water consumed. The remaining withdrawn water, which is not consumed, will be the amount of water returned to the environment via return flows

Table 6: Consumptive use coefficients (derived from Carr et al., 1990; Smith et al., 2011)

Category	Consumptive Use Coefficient
Aquaculture	25.18%
General Irrigation	69.70%
Industry	15.15%
Livestock	57.50%
Power Generation	22.22%
Public Supply	28.00%
Rice Irrigation	64.43%
Rural Domestic	28.00%

POPULATION CHANGE AND FUTURE PROJECTIONS

The water budget framework developed and operationalized here provides a snapshot view of water supply and demand based upon past (last 50 years) hydrologic and climatological conditions and is dependent upon current landscape morphology patterns. Future population changes and subsequent landscape modifications will alter the water budget outputs in numerous ways, on both the supply and demand side of the equation. The finite levels of renewable fresh water makes it a critical natural resource to examine in the context of population growth. As population grows, the average amount of renewable fresh water available to each person declines. When certain ratios of human population to renewable fresh water supplies are exceeded water stress and scarcity becomes inevitable (Gardner-Outlaw & Engelman, 1997).

Population Change

Any future projections of changing water demand should begin with population growth. As population grows, demand for fresh water is also expected to increase. This study assumes that current trends in population, economy, and technology continue and that changes in population are proportional to changes in demand across public supply, rural domestic, and commercial water supply systems. Population projections were obtained from Economic Modeling Specialists International (EMSI) demographics, a Census-based dataset containing population counts and projections for ZIP codes by age, gender, and race/ethnicity. These data were derived from the U.S. Census Bureau's Population Estimates Program. EMSI projected these data forward using the sum of least squares and fit the data to a curve to avoid dramatic jumps from the base year to the first projected year. These data include 10-year ZIP code level population change estimates, which were used to estimate increases in public water supply consumption within the water balance assessment framework. Changes were estimated in both surface water and groundwater levels. An assumption was made that any increase in population would be served by existing facilities. In other words, the projections assumed that no new facilities would be constructed. The water balance was then recalculated using the increased consumption to estimate the projected supply gap resulting from these increases.

Landscape Change and Urbanization

While changes in population levels will have direct impacts on the water usage of the region, this population growth has a spatial component as well. In Louisiana, population growth has involved an outward spread of development from urbanized areas along with changes in both land use and land cover. This conversion of land from undeveloped to developed has occurred around the edges of larger population centers and within commuting distance of these areas (Karstensen & Sayler, 2009). Research has shown that the consumption of land resources needed to support population growth generally increases at a faster rate than the population itself (Faulkner, 2004).

Land use and land cover change has an impact on the water budget. Conversion of wetlands, native forests, and grasslands to agricultural use is the largest land use change in the United States (Healy et al., 2007). In coastal Louisiana, however, the leading land-cover conversion was wetland to water. The loss of herbaceous and woody wetlands as a result of complex and often interactive natural and human-induced processes has the potential to impact the water budget in various ways (Couvillion et al., 2011; Karstensen & Sayler, 2009). Replacement of native vegetation with agricultural crops and conversion to open water lead to changes in patterns of infiltration, evapotranspiration, and ground-water recharge.

Urbanization accounts for the second largest change in land use. Urbanization is a process that involves an increase in human habitation linked with increased per capita energy and resource consumption, and extensive landscape modification (Faulkner, 2004). Urbanization impacts the hydrology of basins because of its creation of impervious surfaces, removal of vegetation, and changes in the consumptive use of water (DeWalle et al., 2000). The development of urban land has several implications for the availability of water. When an area is developed or urbanized, it is changed from a more natural condition to a developed condition. This process necessarily increases the amount of impervious surface, which directly affects the amount of water available to both groundwater and surface water (Table 7). As impervious surface area increases, less precipitation is lost to evapotranspiration. Similarly, less water is able to infiltrate into both shallow and deep groundwater. Much of this water is instead diverted to runoff, which ultimately ends up in surface water via direct runoff into the waterways or via discharge from storm water management systems. Urban features such as buildings, paved roads, and parking lots are impermeable and tend to increase surface runoff of precipitation and reduce infiltration. Runoff from these features may be channeled through storm sewers to streams, leading to increased streamflow and flooding in the worst situations. Lowered infiltration reduces groundwater recharge and lowers the water table, which threatens water supplies and reduces groundwater contribution to streamflow (Arnold & Gibbons, 1996).

Table 7: Effects of impervious surface on water balance components (Adapted from Arnold & Gibbons, 1996)

Ground Cover	Evapotranspiration	Runoff	Shallow Infiltration	Deep Infiltration
Natural Ground Cover	40%	10%	25%	25%
10-20% Impervious Surface	38%	20%	21%	21%
35-50% Impervious Surface	35%	30%	20%	15%
75-100% Impervious Surface	30%	55%	10%	5%

To best estimate changes in the supply of fresh water resulting from population growth and urbanization, this study looked at projections of urban growth and dispersion of populations. This research utilized the SLEUTH (Slope, Land Use, Excluded, Urban, Transportation, and Hillshade) model and has been calibrated using historical data. SLEUTH incorporates four growth rules (i.e., Spontaneous Growth, New Spreading Centers, Edge Growth, and Road-Influenced Growth) to model the rate and pattern of urbanization. The model simulates outward growth of existing urban areas and growth along transportation corridors and new centers of urbanization. Parameter coefficient values range between 1 and 100. The model produces one urban growth cycle per year. For each growth cycle, a GIF image is produced showing the probability of undeveloped land converting to urban land for each 60-meter pixel (Belyea & Terando, 2013). The SLEUTH output were summarized for each HUC8 and the total percentage of area that converted to urban land was calculated. These data were used to estimate the changes in evapotranspiration, runoff, shallow groundwater infiltration, and deep groundwater infiltration, as per Table 7.

Data to Assess Projected Water Demand and Energy Cost

Water demand projections and energy cost data were gathered as input for projecting future water demand and energy costs. Water use for domestic purposes ranks behind only industry and power generation in total statewide withdrawals from surface and groundwater (Sargent et al., 2011). Domestic water demand can be estimated a function of household size and total population. To estimate current water usage, demographic data from the 2010 Census and recent American Community Survey (ACS) releases were used to determine the average household size, family size, and household income by census block. Total water usage was estimated based upon the total number of families within each census block and a water usage coefficient based upon per family estimates. Energy costs were estimated based upon well depth, metered rates and, in the case of rural domestic water sources, average domestic well power usage and current cost of electricity as reported by the Energy Information Administration (EIA).

Potential increases in the domestic water usage are assumed to be largely driven by changing demand due to population and electricity production increases (Roy et al., 2005). EMSI data projects population growth on an annual basis on a 10-year time horizon. Future domestic water use were estimated by multiplying the projected population by the water usage coefficient. Per capita water usage is not expected to change in these estimates. If necessary, population estimates beyond the 10-year time horizon were calculated using the EMSI growth rates. Additional scenarios can be run calculating estimates both higher and lower than current projected population trends.

A number of assumptions were necessary to project other future water uses. The same growth rate calculated for domestic usage would apply to commercial facilities. Growth in industrial and agricultural production would be offset by increased water efficiency resulting in no change over the time horizon (Medalie & Horn, 2010; Roy et al., 2005). Forecasts for electrical generation are calculated by the EIA at the census division scale. Any water analysis units within the census division that had any form of power generation was given the forecast percent increase of the census division (Roy et al., 2005). Units that have no generation at present were not allocated any new generation. While these assumptions were used to project future demand, the water budget framework developed in this study can be adapted to include other scenarios of change.

ADDITIONAL RESEARCH NEEDS

The framework developed here was constructed to provide uniformity of analysis across hydrologic units using existing data sources or established techniques to establish estimates where data were unavailable. The framework uses published, publicly available data and tools to generate information intended for water resources planning. The use of published information for the estimation of water budget parameters (hydraulic conductivity, e.g.,) reflects the average reported characteristic over the study area, but may not reflect conditions at smaller, local scales due to lateral inhomogeneity. Published values are sometimes not considered as conservative as those that may be more appropriate for water use regulation or for site-specific determinations.

The framework was designed to be modular in nature, with the capability for components and tools to be replaced as more accurate or site-specific tools or data become available. Publicly available tools (USGS Groundwater Toolbox, e.g.,) were chosen for this planning-level test approach, but more detailed studies and models may be more appropriate to local conditions, and could be substituted in future assessments. The results are reported in the native precision of the tools used. This precision was retained for reporting, but may be overly precise for future applications of the framework. Within this assessment, all water supply and usage terms are expressed as annual means, and may not adequately reflect important seasonal trends in water supply and usage, including seasonal shortages and surpluses. To minimize the impacts of known or expected gaps in information and data, those elements that could not be measured directly were calculated using the water balance equation. Some components of the framework, particularly those that are highly localized, such as water withdrawal-induced subsidence, water quality constraints, and ecological needs for water, require more in-depth study to determine their full impacts on the water budget and sustainability.

Localized Impacts

The assessment framework relies on historical averages to estimate inputs to surface water and groundwater storage. Outputs from the system, particularly the anthropogenic withdrawals, generally respond to current and seasonal weather conditions. For example, a portion of the 2.1 acre-feet of water per acre of rice cultivated would be provided by precipitation with the remainder drawn from either ground or surface water sources using irrigation systems. In general, the difference in acre-feet of water pumped from one year to another reflects the differences in rainfall between the two years. However, if this precipitation occurs subsequent to the field being pumped to capacity, nearly all of the rainfall would run out through field overflows (Saichuk et al., 2004). To accurately capture seasonal and annual fluctuations in the water balance, a finer grained analysis is needed. Incorporating additional data on the water needs of rice and other individual crop types into the water balance would allow the assessment to more accurately model the water use at a more localized level.

While the framework does allow for the development and testing of scenarios of climate change and fluctuating weather conditions, more research is needed on the societal responses to these changes. For example, during times of drought, the salt content of surface waters adjacent to the Gulf of Mexico often becomes too high for irrigating rice. When this occurs, growers have responded in various ways, including activating old groundwater wells, pumping more water than usual, limiting rice acreage, and recycling existing water supplies and wastewater (Branch, 2004). Each of these responses would impact the water budget in unique ways. Additionally, increased pumping could potentially increase the salinity of water pumped from the aquifers, leading to a reduction of usable water. Additional research on the societal responses to changing water conditions would provide valuable information that would allow the assessment framework to more accurately model future changes in water demand and usage.

Water Quality Constraints and Minimum Ecological Flow

Additional data on the impacts of freshwater inflow on habitat suitability for key fish and wildlife species is needed to establish minimum ecological flow levels in the water budget. This would provide valuable information on the amount of water needed to maintain ecosystem functionality. The Louisiana Department of Environmental Quality (LDEQ) has established water quality standards to assess the viability of surface wasters to support fish and wildlife propagation. The main criterion used by LDEQ to monitor impairment is dissolved oxygen (DO). In freshwater units, DO levels below 5 mg/L are considered impaired and not capable of supporting fish and wildlife propagation while levels below 4 mg/L are considered impaired in estuaries. According to LDEQ standards, six surface water body segments, totaling approximately 238 river miles, and one freshwater lake encompassing 370 acres, are listed as impaired within the Mermentau Headwaters hydrologic unit, for example. The level of impairment is variable however. The waters are unable to be used for both public drinking water and for wildlife and fisheries propagation. However, they are still of high enough quality to be used for agriculture. However, the removal of water from waterways with DO impairment would further deteriorate the waterway. To compound this issue, decreasing water flow increases the possibility of creating DO issues which may in turn result in conditions favorable for the methylation of mercury, which could impact the aquatic food chain. Additional research on individual water bodies is needed to fully assess the quality impacts of impaired waters on the water budget.

While these general guidelines do provide a useful metric that can be used to assess the health of water bodies, and enable the removal of volumes of water from the budget when those water are no longer suitable for particular uses, they do not provide a full assessment of habitat suitability for fish and wildlife species. The impacts of water budget changes on ecological functioning and habitat suitability varies from one species to another. For example, green-winged teal, the most abundant waterfowl species in coastal Louisiana, requires very shallow fresh or brackish water with 25% to 65% vegetation coverage (Leberg, 2015). Conversely, red swamp and southern white river crayfishes require low water or dry conditions during the summer and deeper water conditions during the fall, winter, and spring (Romaire, 2014). For the water assessment framework to fully incorporate such factors as minimum ecological flow, additional research is needed on the impacts of water supply on the variables that impact habitat suitability.

Part 2: Initial Application and Testing of Framework

This framework and assessment method was tested using example hydrologic units. The hydro units analyzed were determined by the presence of existing water budget issues, such as declining ground water levels, so that they could adequately demonstrate the utility of the framework, and the availability of data for application of the approach. Application of the framework to the three study areas is intended as a proof-of-concept. The three test cases are provided as a validation of the methodology, to illustrate that the framework output correlates in terms of general magnitude with previously identified water supply trends.

STUDY AREA SELECTION PROCESS

The availability of accurate groundwater availability models, and the determination of sustainable yield, determined the ability to quantitatively assess groundwater resources availability. While these models are not available for water resources in the State, other datasets and methods are available which allow for a planning-level analysis of surface and groundwater resources. Candidate study areas were evaluated through examination of this information and consultation with experts. The selection of the units for analysis considered whether the geographic extents of the units are demand-driven or location-driven. Areas selected for analysis included entire hydrologic units as well as partial units. This was determined by considering the spatial extent of water bearing surface and groundwater units, as well as the spatial distribution of water demand and other factors. Additional factors influencing the selection of study areas for this analysis were the availability of data and analytical tools, known data gaps, and identified issues of water availability or water budget imbalance. The following geographic divisions of the State were considered as candidates for analysis, and are shown in Figure 2:

1. Atchafalaya River Basin
2. East Chicot Aquifer Area
3. West Chicot Aquifer Area
4. West Southern Hills Aquifer Area (Baton Rouge)
5. East Southern Hills Aquifer Area (Florida Parishes)
6. Mississippi River Delta Plain (down river of Baton Rouge)
7. Sparta Aquifer Area (Including Red River segment)
8. Mississippi River Alluvial Aquifer (upriver of the Delta Plain, including Red River segment)
9. Carrizo-Wilcox (Including Red River segment)

Geospatial data from various State and Federal agencies was used to derive the candidate analytical hydrologic units (Table 3). The surface water-groundwater system is defined by the principal aquifer in each individual study area as well as the network of rivers, streams, ponds, and wetlands that overlie and are in hydrological connection with these aquifers (Barlow & Dickerman, 2001). The analytical boundaries of the subunits within the study areas were derived from the USGS 8-digit (HUC8) cataloguing units.

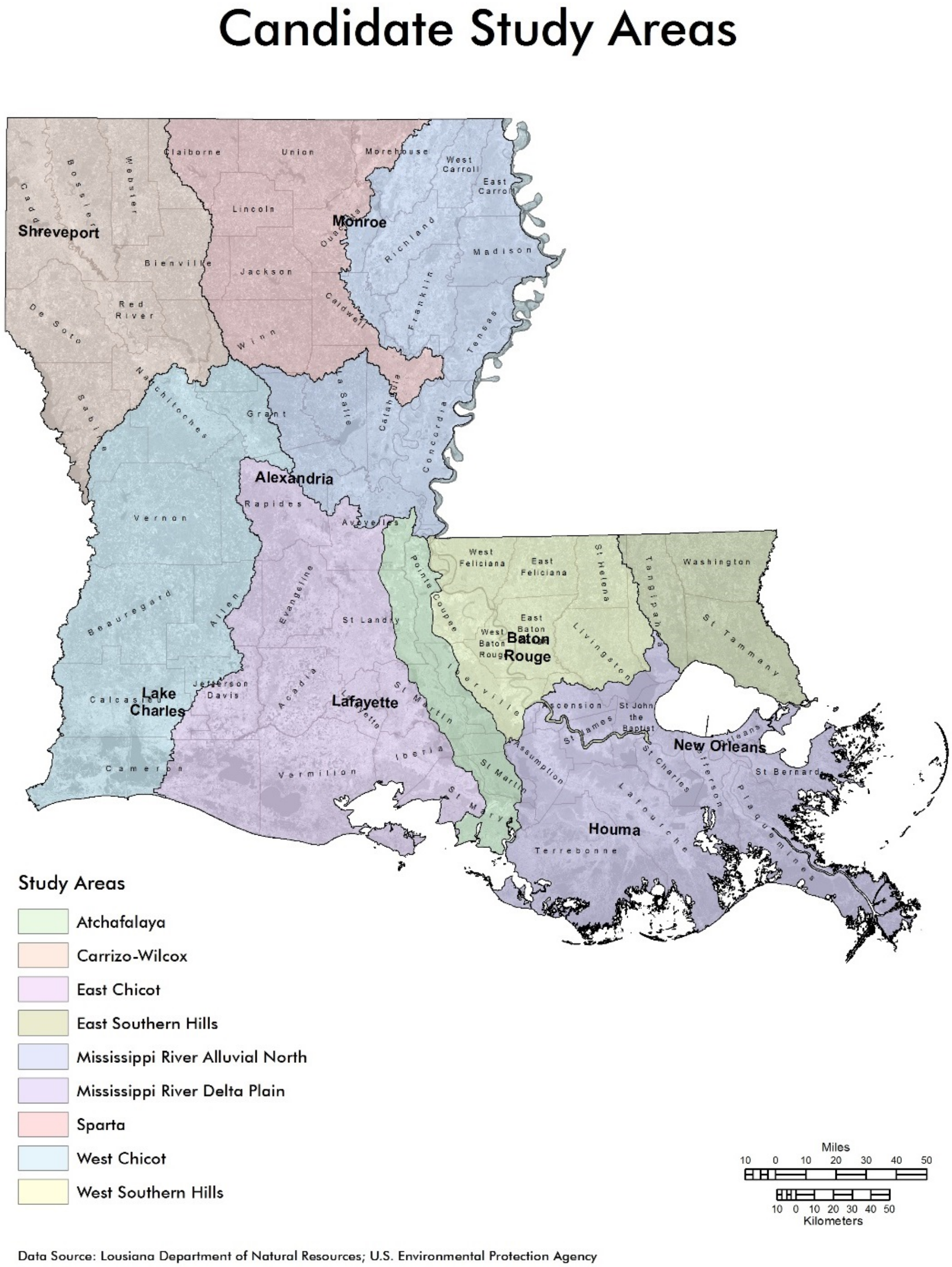


Figure 3: Candidate Study Areas.

Selection of Study Areas

One area was selected from the candidate exercise to serve as a pilot study area to enable testing of the approach, and the framework was then applied to two subsequent selected study areas. One location in Southwest Louisiana (SWLA), which includes surface and groundwater units that correspond to the East Chicot Aquifer Area (Figure 2), was selected for initial focus. Several factors were considered in the selection of the SWLA Study Area. The Calcasieu, Vermillion, Lafourche, and Mermentau basins are good choices for surface water units because they interact with the Chicot Aquifer, and encompass the important demand center of Lafayette. There is also a good mix of demand uses, including agriculture (significant rice production), livestock, industry, public supply, rural domestic, and coastal demand (the minimum flow to the coastal area necessary to sustain coastal ecosystems). This area is also interesting because of the fresh water input to Grand Lake and other coastal lakes and the risk of storm penetration and its effects. The process used to determine the extent of the study area is depicted in Figure 3. The extents of groundwater units in the area (the Chicot and Mississippi River Alluvial Aquifer) were geospatially analyzed in combination with the overlying surface water basins (Hydrologic Unit 8-Digit Code, or HUC8). These surface water units included the Bayou Teche, Vermillion River, Mermentau Headwaters, and Mermentau River basins. A boundary for the proposed study area was extracted using a combination of the surface and groundwater units. It contains portions of Acadia, Allen, Calcasieu, Cameron, Iberia, Jefferson Davis, Lafayette, St. Landry, St. Martin, and Vermillion Parishes.

Once the methodology was established for the delineation of the SWLA study area, it was applied to two other identified study areas, in NWLA and southeastern (SELA) Louisiana, based on the availability of data and analytical tools, known data gaps, and identified issues of water availability or water budget imbalance. The NWLA study area delineation process is illustrated in Figure 4. The surface water units included in the area include Bayou Pierre, Black Lake Bayou, Bodcau Bayou, Caddo Lake, Cross Bayou, Loggy Bayou, McKinney-Poster Bayous, Middle Red-Coushatta River, Middle Sabine, Red Chute, Saline Bayou, and Toledo Bend Reservoir. Groundwater units in the study area include the Carrizo-Wilcox, Cockfield, Red River Alluvial, Sparta, and Upland Terrace Aquifers. It includes portions of Bienville, Bossier, Caddo, De Soto, Natchitoches, Red River, Sabine, and Webster Parishes.

The SELA study area delineation process is illustrated in Figure 5. The surface water units included in the area include Amite River, Bayou Sara-Thompson Creek, Lower Grand, Lower Mississippi River-Baton Rouge, and Tickfaw River. Groundwater units in the study area include the Mississippi River Alluvial and Southern Hills Aquifer systems. It includes portions of Ascension, East Baton Rouge, East Feliciana, Livingston, Pointe Coupee, St. Helena, Tangipahoa, West Baton Rouge, and West Feliciana Parishes. It is bounded by a hydraulic divide roughly at I-55, and south to Baton Rouge Fault.

The three study areas selected represent three geographically diverse areas of the state, with differing water supply, water use, population, and other factors that affect the overall water budget of the state of Louisiana. Locations of the three study areas are shown in Figure 6, while detail maps of the study areas themselves are provided in Figure 7 through Figure 9.

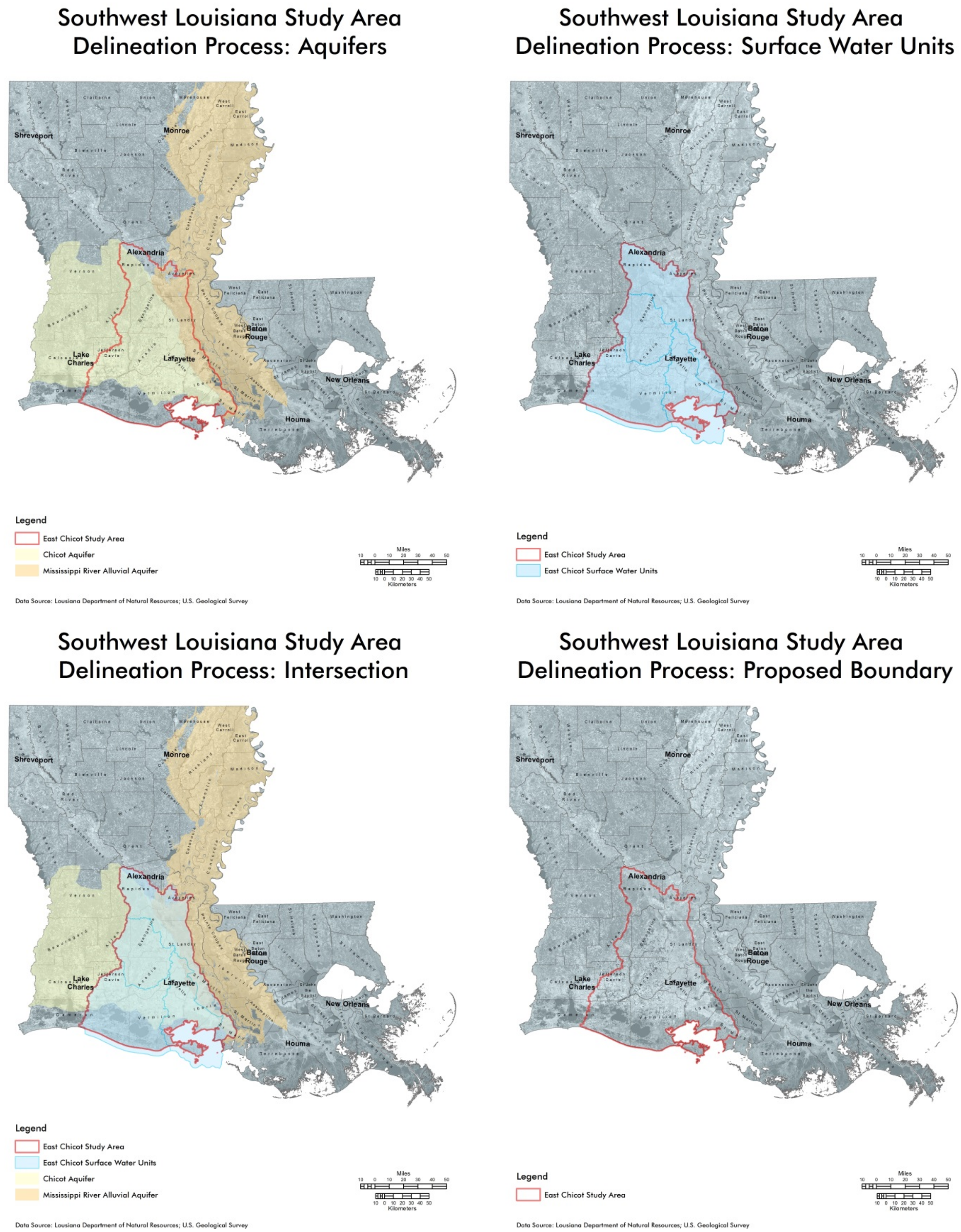


Figure 4: SWLA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary.

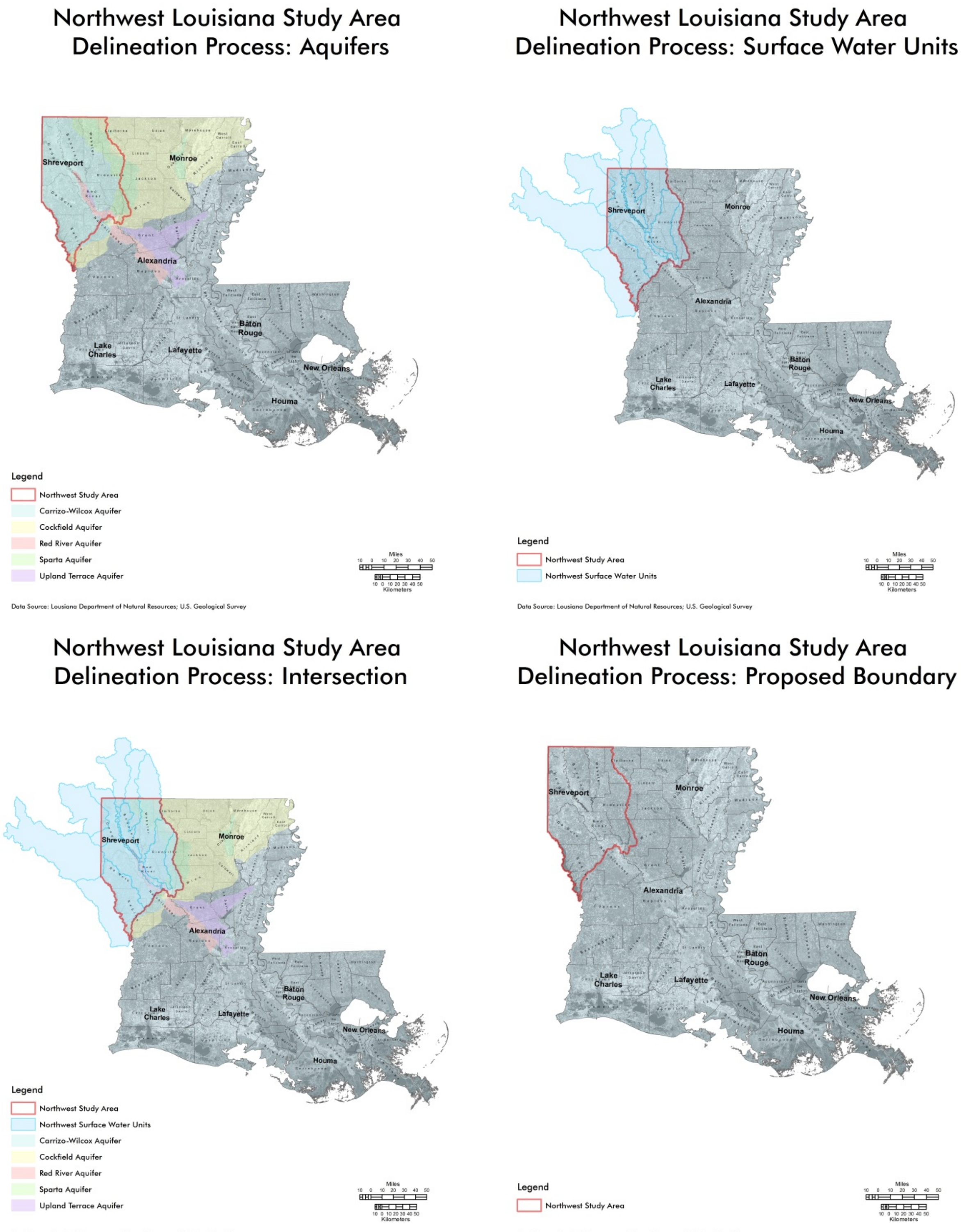


Figure 5: NWLA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary.

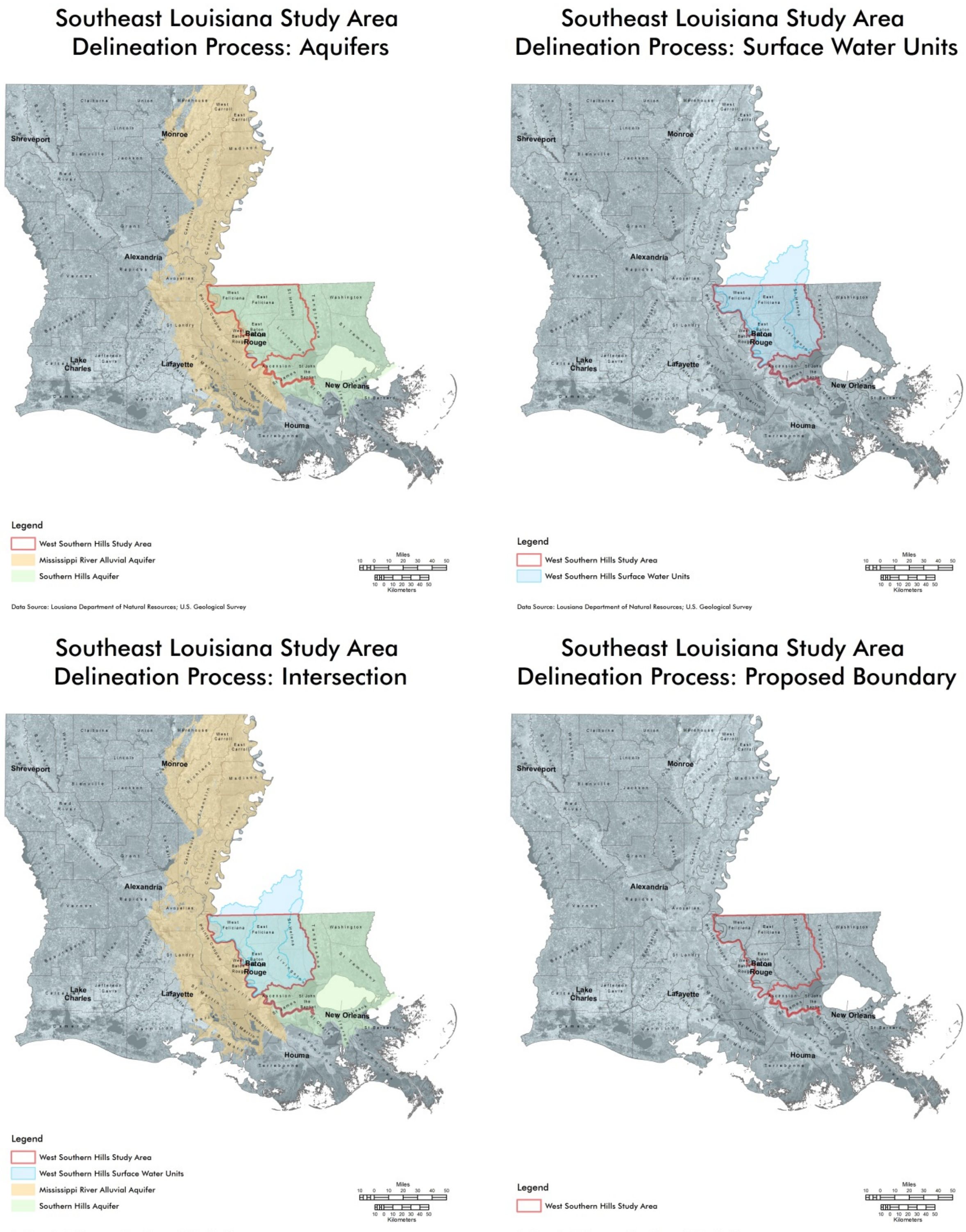


Figure 6: SELA study area delineation process, showing aquifers, surface water units, their overlapping areas, and the proposed study area boundary.

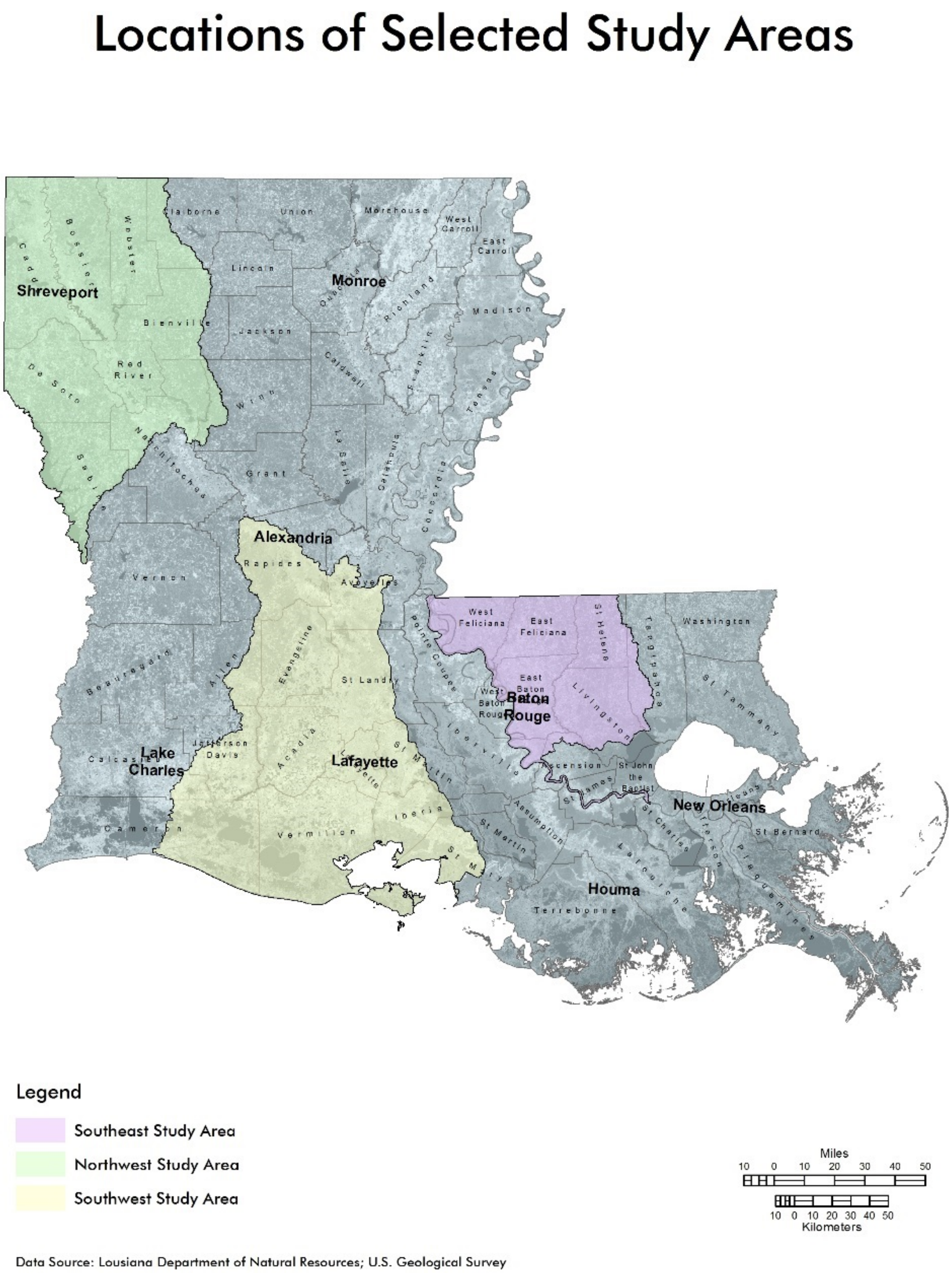


Figure 7: Locations of the three selected study areas.

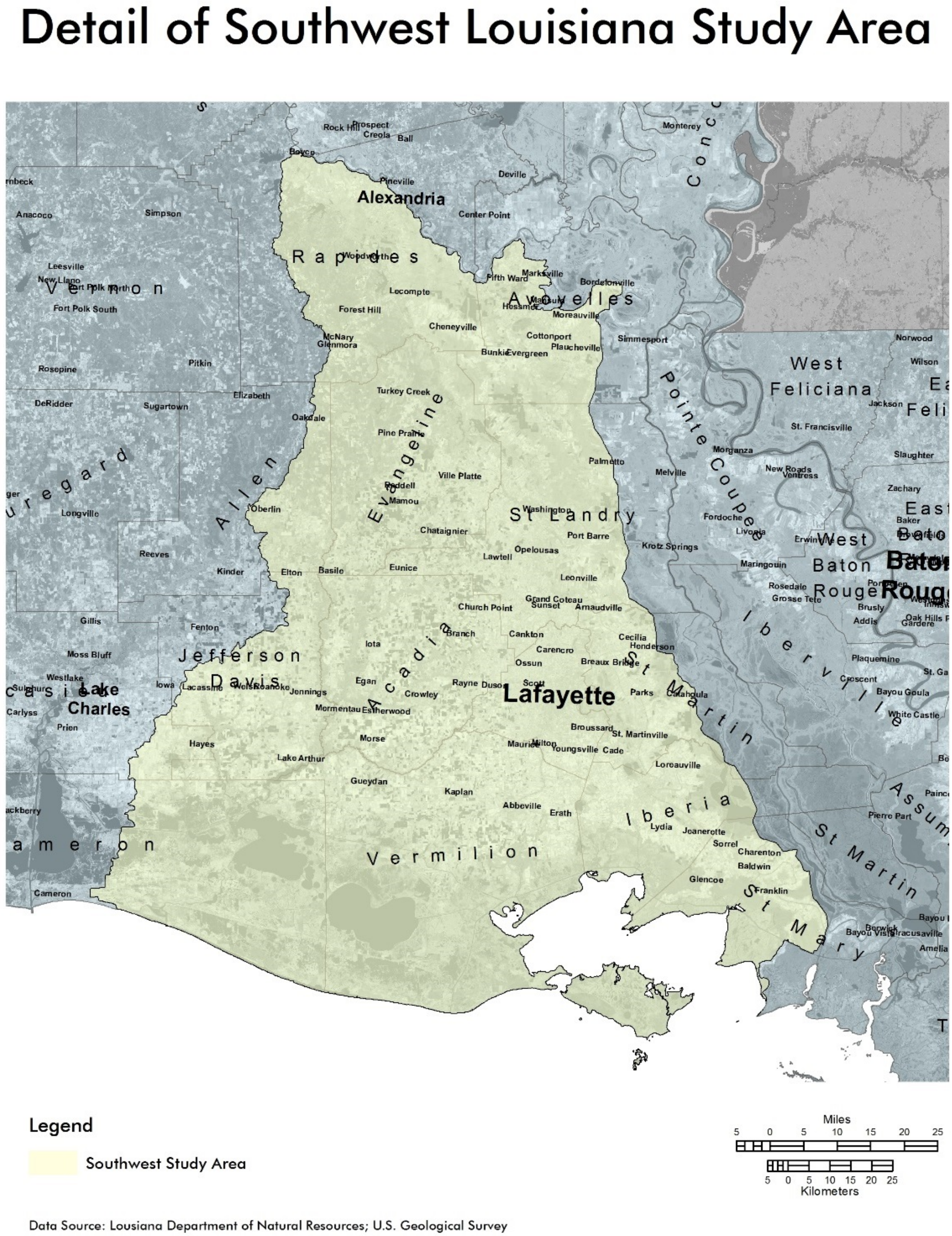
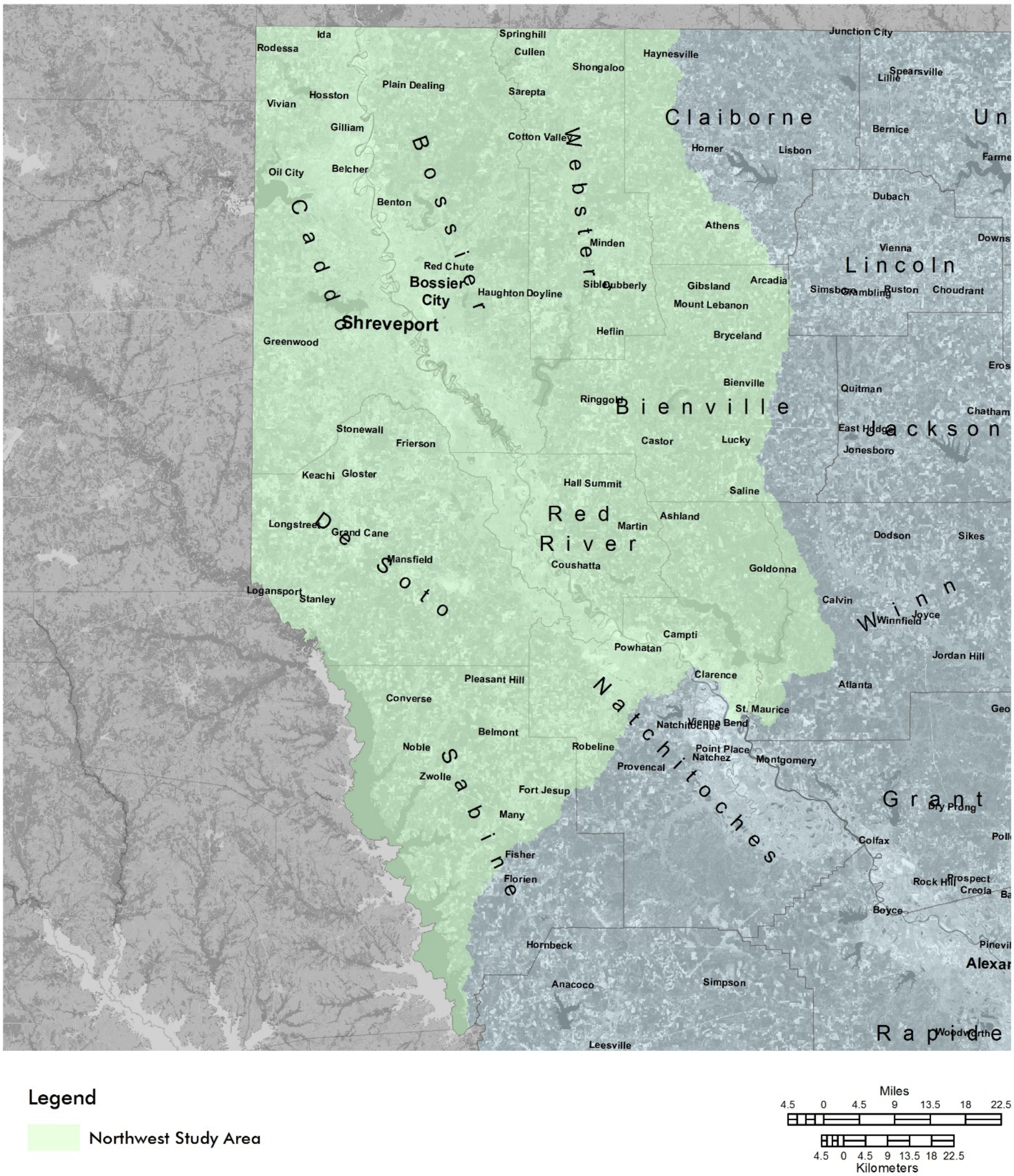


Figure 8: Detail of SWLA study area.

Detail of Northwest Louisiana Study Area



Data Source: Lousiana Department of Natural Resources; U.S. Geological Survey

Figure 9: Detail of NWLA study area.

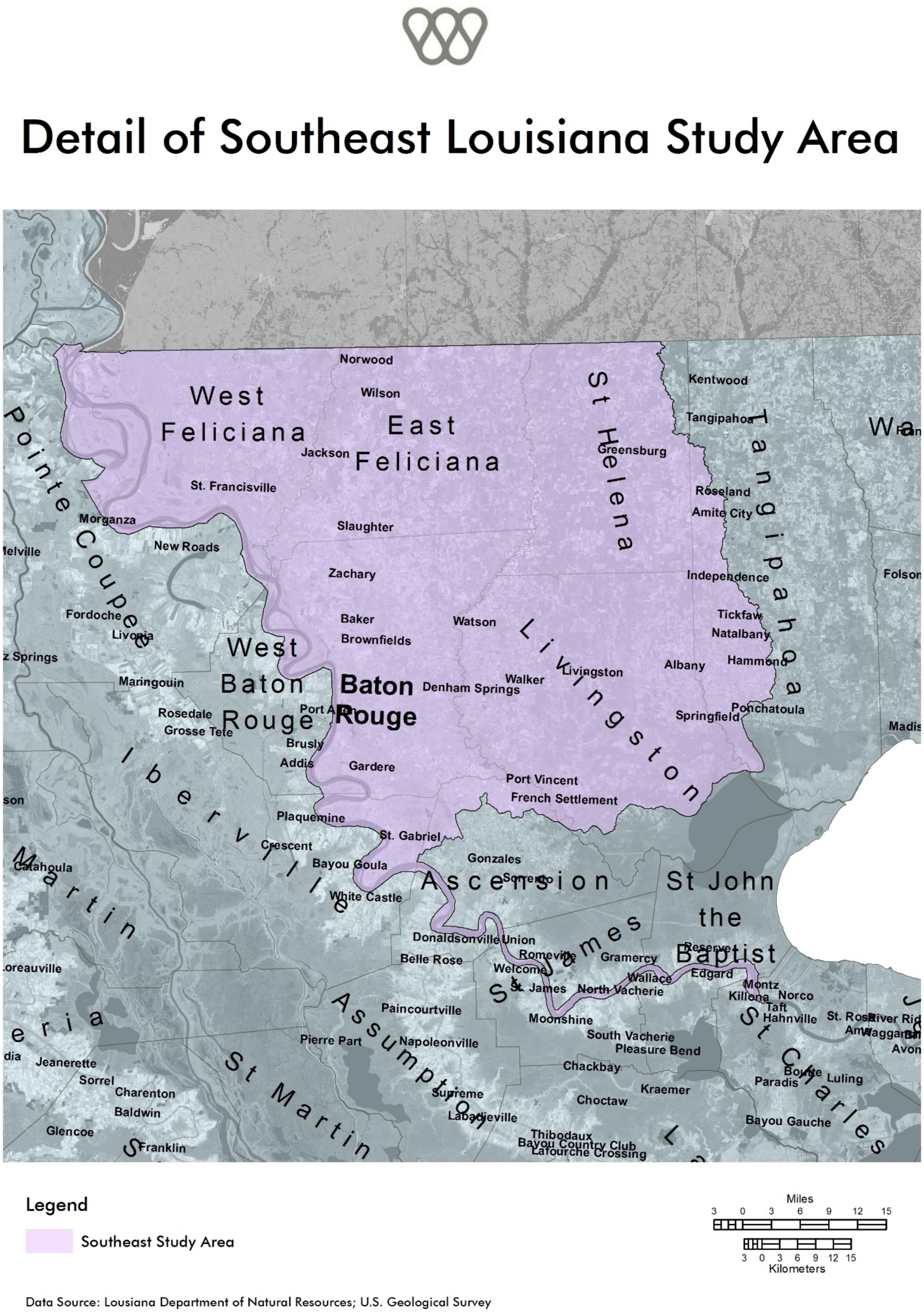


Figure 10: Detail of SELA study area.

Pilot Study Area: Southwest Louisiana

The SWLA study area includes portions of the Chicot Aquifer as well as the Bayou Teche and Vermilion River surface water basins. The Vermilion hydrologic unit is the most populous in the study area, followed by the Bayou Teche unit (Table 8). These units, which contain the cities of Lafayette and Alexandria, respectively, rely heavily on public supply wells, although there are a large number of individual groundwater wells throughout the area (Figure 10). Although water usage throughout the study area is dominated by rice irrigation and aquaculture, the demand for public water is an important draw on the region's water resources (Figure 11). Since the communities that rely on this aquifer have no reliable alternatives of fresh water to groundwater sources readily available, the USEPA has classified the Chicot Aquifer as a sole-source aquifer for much of the southwestern Louisiana area. Groundwater withdrawals from the aquifer system have caused water levels to decline in the region, raising concerns about water availability and quality. According to Borrok & Broussard (2016), the drawdown of the potentiometric surface from pumping due to rice irrigation and industrial needs, largely in Jefferson Davis and Acadia, and Calcasieu Parishes, has altered the groundwater flow patterns in the region, causing groundwater to flow toward these agricultural and industrial centers. Recent estimates of the water supply gap suggest that the Chicot aquifer is being over-drafted by about 1,070 acre-feet per day (Borrok & Broussard, 2016). Farmers and residents in the region are becoming increasingly concerned that water levels in the Chicot Aquifer system may decline below the pump intakes in their wells, leaving them without water, or that increasing drawdown will lead to increasing saltwater encroachment. In areas of the aquifer along the freshwater-saltwater interface, high-capacity wells pumping from the freshwater portion of the aquifer have been shown to draw salt water from the lower parts of the aquifer (Lovelace et al., 2004).

Table 8: SWLA population, public and domestic water demand summary

Hydrologic Unit	Number of Households	Estimated Freshwater Demand (acre-feet/year)	Number of Public Supply Systems	Population Served	Number of Domestic Water Wells
Bayou Teche	81,241	36,401	56	199,533	2,107
Vermilion	135,446	60,688	112	446,824	9,428
Mermentau Headwaters	46,004	20,612	30	124,201	2,209
Mermentau	21,704	9,725	16	44,294	4,271

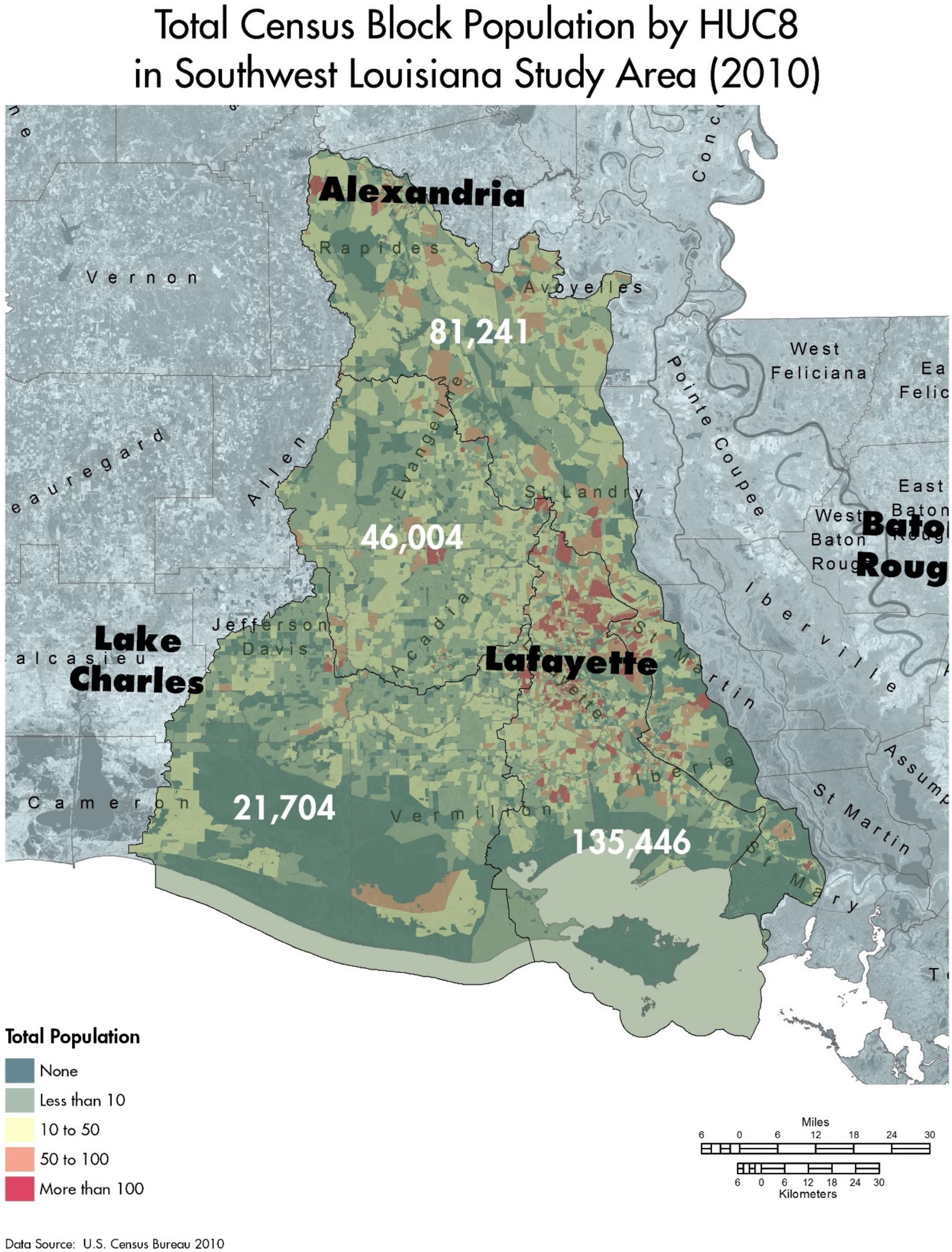


Figure 11: SWLA total households by census block group.

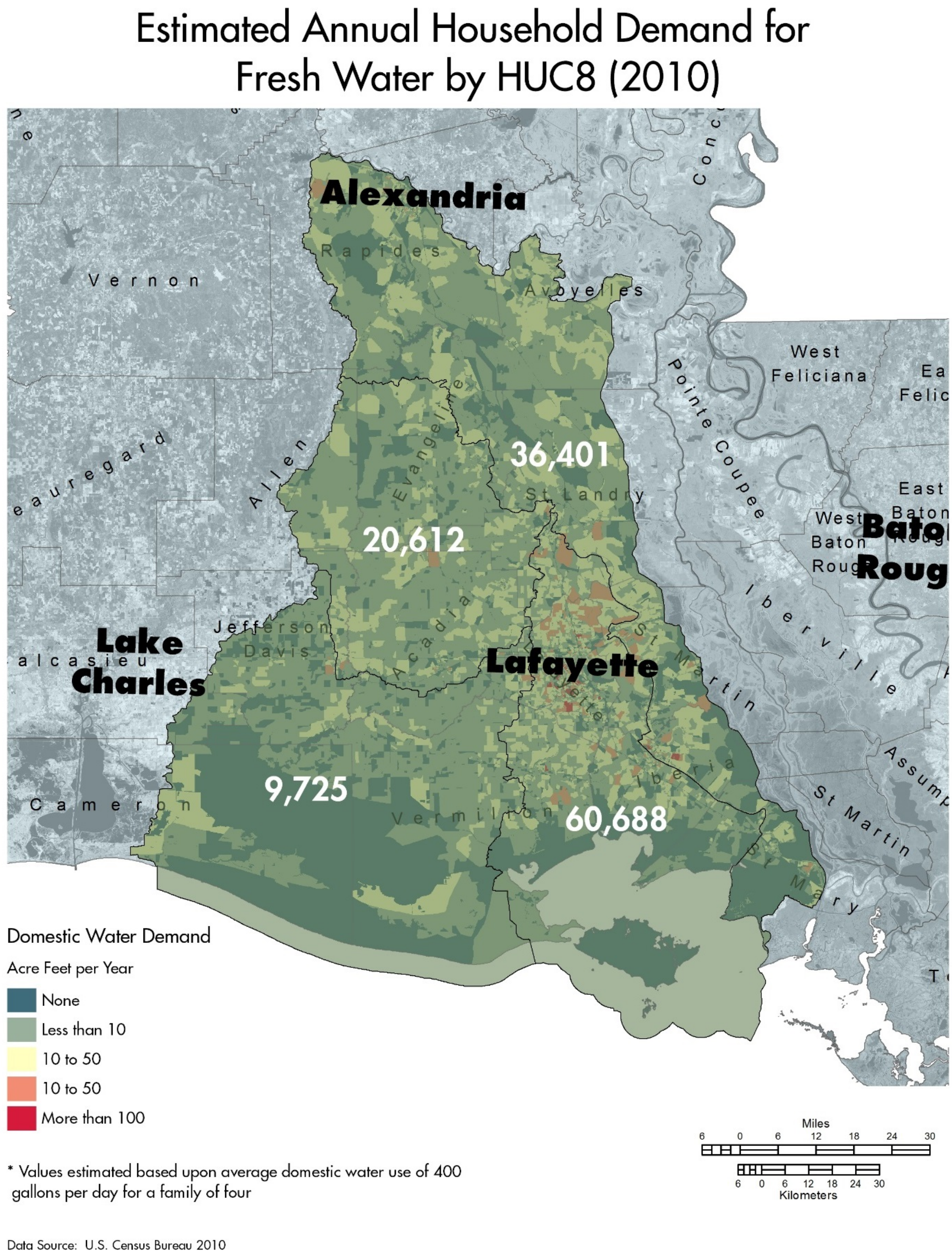


Figure 12: SWLA domestic water demand.

GEOLOGY OF THE SOUTHWEST LOUISIANA STUDY AREA

The main feature of the subsurface geology of the SWLA study area is the Chicot Aquifer system (LDEQ, 2008). It consists of fining upward sequences of gravels, sands, silts, and clays of the Pleistocene Prairie and terrace deposits of southwestern Louisiana. The medium to coarse-grained sand and gravel aquifer unit dips and thickens toward the Gulf, and thickens toward the east where it is overlain by Quaternary alluvium of the Atchafalaya and Mississippi Rivers. The aquifers are confined, have a finer texture, and are increasingly subdivided by silts and clays southward from the northern limit of the outcrop area in southern Vernon and Rapides parishes (LDEQ, 2008). Within the study area, the Chicot is divided into the "upper sand" (in hydraulic connection to the Atchafalaya sand, Abbeville sand, and "200-foot" sand) and the "lower sand" ("700-foot" sand). The "500-foot" sand is largely isolated except where it merges with the "700-foot" sand north of Calcasieu Parish. Fresh water in the Chicot and other southwestern Louisiana aquifers is separated from fresh water in southeast Louisiana by a saltwater ridge in the subsurface along the Mississippi River valley. Salt water occurs within the Chicot along the coast and in isolated bodies north of the coast (LDEQ, 2008).

Recharge to the Chicot occurs primarily through the direct infiltration of rainfall in the interstream, upland outcrop-subcrop areas. Recharge also occurs by water movement from the Atchafalaya alluvium, downward infiltration through the clays south of the primary recharge outcrop area, upward movement from the underlying Evangeline Aquifer, and inflow from the Vermilion and Calcasieu Rivers (LDEQ, 2008). Water movement is generally toward the pumping centers at Lake Charles and Eunice. However, there is little movement of water from the west because of pumping in the Orange, Texas area. A summary of hydraulic parameters for the aquifer is presented in Table 9. The hydraulic conductivity varies between 40-220 feet/day (LDEQ, 2008). An average value of 130 feet/day was used for this study (Boniol, 1988).

Table 9: Hydraulic parameters of the Chicot Aquifer

Aquifer Unit	Min Thickness (ft)	Max Thickness (ft)	Mean Thickness (ft)	Thickness Source	Hydraulic Conductivity (ft/day)	Hydraulic Conductivity Source
Chicot	100	600	350	Nyman et al., 1990	130	Boniol, 1989

The maximum depths of occurrence of fresh water in the Chicot range from 100 feet above sea level, to 1,000 feet below sea level. The range of thickness of the freshwater interval in the Chicot is 50 to 1,050 feet (LDEQ, 2008). An average thickness of 350 feet was used for this study (Nyman et al., 1990). The depths of the Chicot wells that were monitored in conjunction with the Aquifer Sampling and Assessment (ASSET) Program range from 66 to 697 feet (LDEQ, 2008).

The Mermentau River Basin is located in the southwestern part of Louisiana and comprises a drainage area of approximately 6,730 square miles (Mermentau Basin, 2005). This basin, located between the Teche-Vermilion and Calcasieu river basins, begins just north of Oakdale and Ville Platte, and extends south to the Gulf of Mexico. The lower portion of the basin is bounded on the west by Highway 27, and on the east by the Freshwater Bayou Canal. The basin contains highly productive agricultural lands and a variety of natural environments. The natural hydrology of the basin is affected by the operation of five U.S. Army Corps of Engineers navigation locks and control structures, which control the impoundment of winter runoff for irrigation use in the summertime. This helps maintain a freshwater reservoir for agricultural use while preserving the basin's sensitive environments from the detrimental effects of saltwater intrusion from the Gulf (US Army Corps of Engineers, n.d.).

The Vermilion-Teche basin's drainage area covers approximately 4,047 square miles. Land cover types within the basin range from the upland pine forests, northwest of Alexandria, to agriculture lands consisting primarily of corn and soybeans, in its northern portion, and rice and sugarcane in its central and southern portion (Baker, 1988). The coastal zone is mostly freshwater marsh from Bayou Cypremort eastward to Bayou Sale. Intermediate and brackish marsh occupy the entire coastal zone west of Bayou Cypremort with small areas of salt marsh (Baker, 1988). Bayou Teche and the Vermillion River were historically supplied with fresh water from the Atchafalaya River via Bayou Courtableu. A system of flood protection levees, constructed by the U.S. Army Corps of Engineers to parallel the Atchafalaya River after the major flood of 1927, severed this connection. Water from the Atchafalaya River is currently diverted into the Vermilion-Teche River Basin through the Bayou Teche water project. Authorized by the Flood Control Act of 1966, this structure allows the diversion of supplemental fresh water from the Atchafalaya River upstream of Krotz Springs to the head of Bayou Teche at Port Barre. The supplemental fresh water is distributed among Bayou Teche, the Vermilion River, and the west side borrow pit along the Atchafalaya basin protection levee for municipal, industrial, irrigation, and water-quality control uses (Lester et al., 2005).

The Vermillion River Basin covers approximately 1,836 square miles and the Bayou Teche Basin covers approximately 2,211 square miles. The hydrology of the Vermilion River is affected by the geographic features of the basin, the diversion of water from other river basins into the river, the physical characteristics and configuration of drainage channels, and the actions of tides and winds. The river is a coastal stream that flows through the relict deltaic deposits of the Atchafalaya and Red Rivers. Interest in the hydrology of the Vermilion River stems partially from the prevalent use of the streamflow as a water resource and the inadequacy of the river to provide that resource. Water availability for rice irrigation and the dilution of effluents are the major concerns in the Vermilion River basin (Baker, 1988).

Water Balance Results

Overall, the water budget shows a surplus of total water resources (including surface and groundwater) of 8,838,203 acre-feet/year, or about 45.4% of the total water input to the study area (Table 10). Excesses were calculated using Equation 3 in all four watersheds – Bayou Teche, Vermillion, Mermentau Headwaters, and Mermentau (Figure 12). Due to the magnitudes of the surface and groundwater supply differences (surface water supply in the SWLA study area is 45 times greater than the groundwater supply), the overall surplus shown is dominated by the surplus of surface water. This surplus of surface water is considered an upper bound, as minimum in-stream and coastal ecological flows were not calculated as part of this effort. These minimum ecological flows would put constraints on the amount of usable water in the study area, and require further study to quantify.

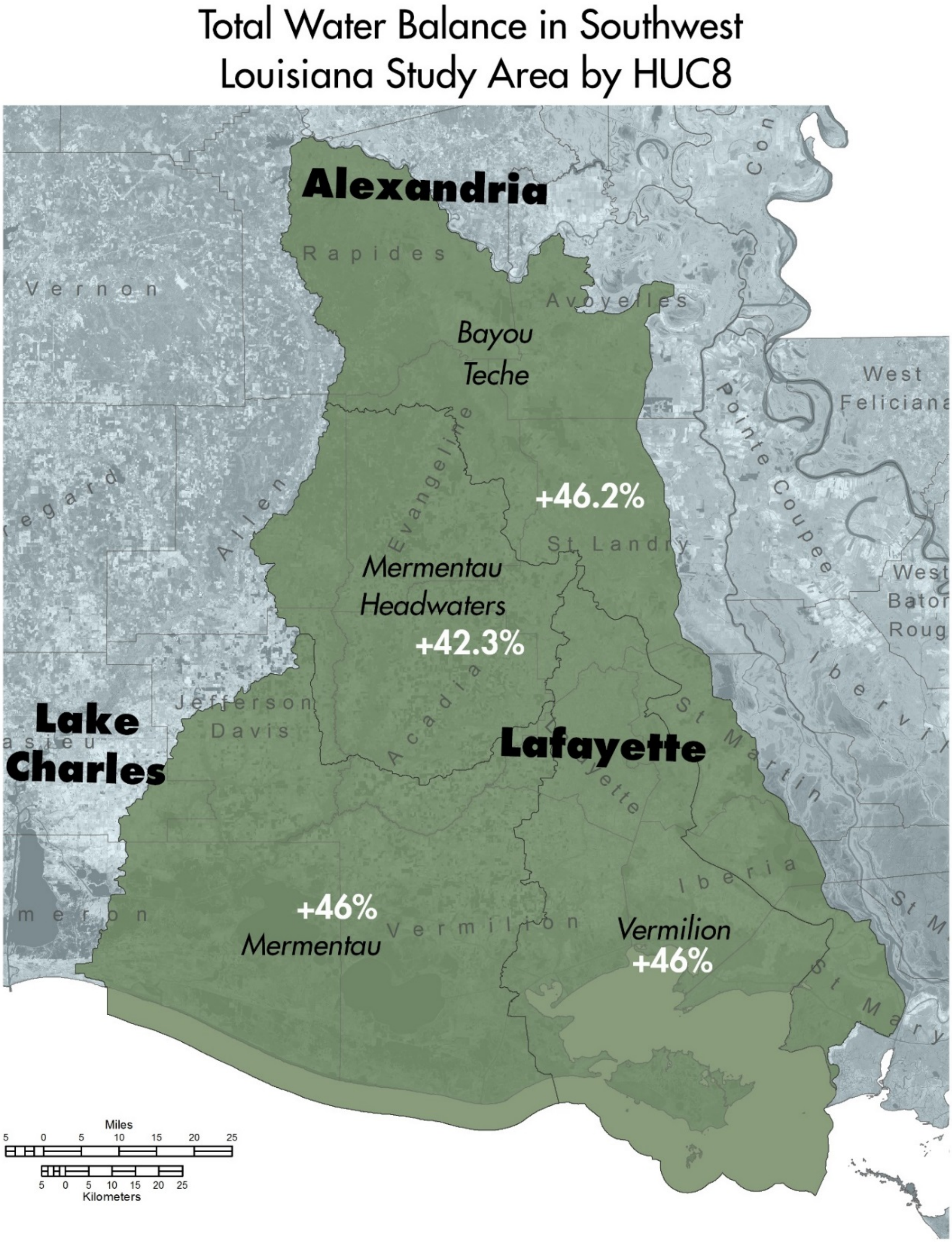


Figure 13: SWLA total water balance by HUC8.

In terms of groundwater resources in the Chicot Aquifer within the study area, there is a calculated deficiency of 561,304 acre-feet/year, or -132.8% of the annual groundwater available in the study area portion of the Chicot Aquifer (Figure 13). The groundwater balance is negative for all four watersheds in the SWLA study area, indicating more use than supply. The imbalance of supply and demand varies from -40.5% (Bayou Teche) to -469.5% (Mermentau Headwaters) (Table 11). Rice production has a significant effect on groundwater resources throughout the study area, and in the Mermentau and Mermentau Headwaters watersheds in particular. Rice production in Mermentau Headwaters and Mermentau watersheds account for 64.4% and 91.1% of the total groundwater deficiencies in those watersheds, respectively (Figure 14). Aquaculture uses groundwater resources in all four watersheds, especially Bayou Teche and Mermentau Headwaters. Usage for public water supply dominates groundwater use in the Vermillion watershed.

Table 10: Southwest study area summary of overall water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Bayou Teche	5,639,321	3,034,498	2,604,823	+46.2%
Vermilion	4,385,187	2,367,734	2,017,454	+46.0%
Mermentau Headwaters	3,409,647	1,967,600	1,442,046	+42.3%
Mermentau	6,031,189	3,257,310	2,773,880	+46.0%
Total	**19,465,344**	**10,627,142**	**8,838,203**	**+45.4%**

Table 11: Southwest study area summary of groundwater balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Bayou Teche	165,649	232,765	-67,116	-40.5%
Vermilion	80,339	168,973	-88,633	-110.3%
Mermentau Headwaters	58,731	334,444	-275,714	-469.5%
Mermentau	117,894	247,736	-129,841	-110.1%
Total	**422,613**	**983,918**	**-561,304**	**-132.8%**

Groundwater Balance in Southwest Louisiana Study Area by HUC8

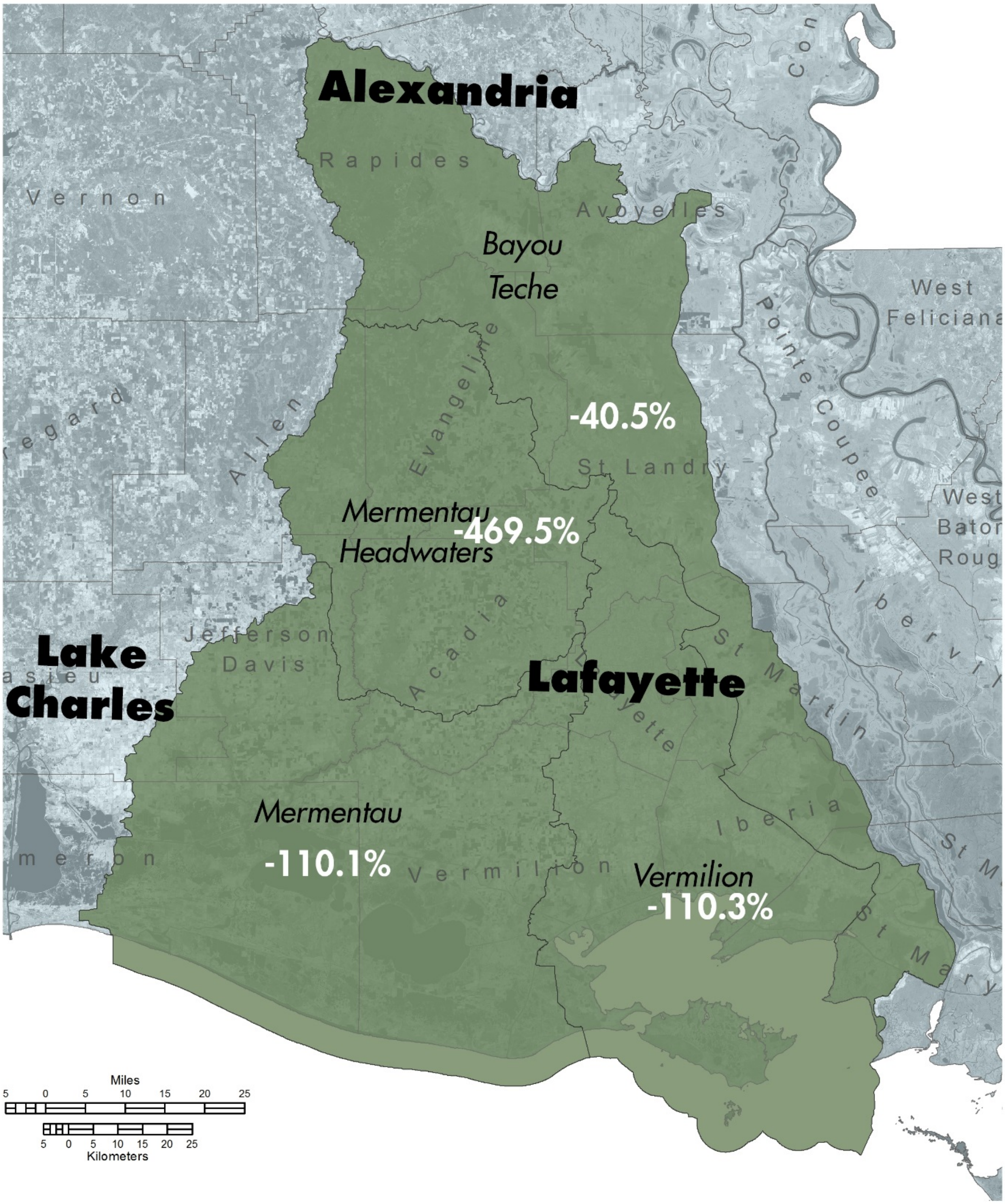


Figure 14: SWLA groundwater balance by HUC8.

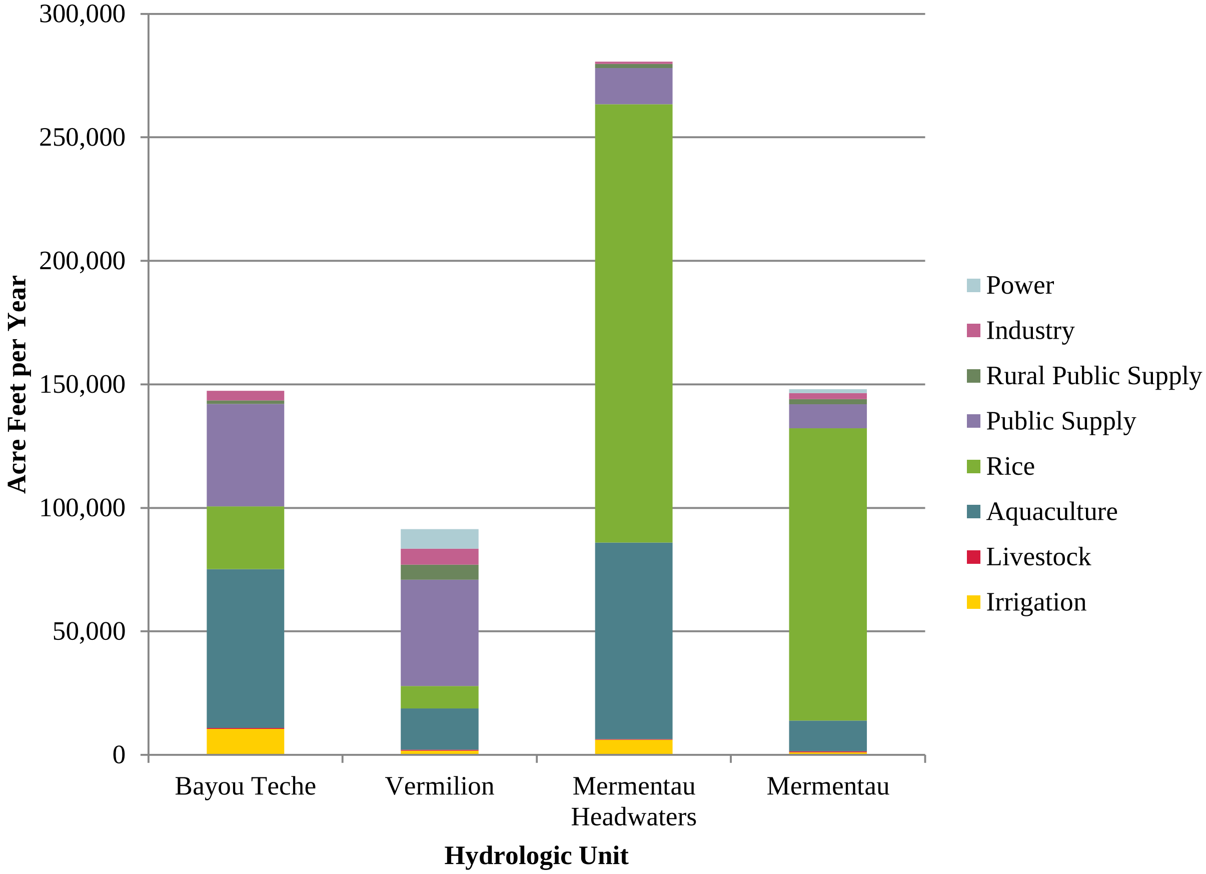


Figure 15: SWLA groundwater use by hydrologic unit.

Supplies of surface water resources in the four watersheds show a surplus of 9,399,507 acre-feet/year (Table 12), or 49.4% of the surface water in the study area remains available (Figure 15). Withdrawals of surface water in Bayou Teche and Vermillion watersheds are dominated by power generation, and account for 72.6% of all surface water use in those two watersheds (Figure 16). Twenty percent of that water withdrawn for power generation is consumptively used, while the remaining 80% is returned to surface water via return flows. After consideration of these return flows, only 14.3% of the surface water supply is consumptively used by power generation. By contrast, rice production, which accounts for the majority of surface water use in Mermentau and Mermentau Headwaters watersheds, and is second to power generation in Bayou Teche and Vermillion watersheds in terms of surface water use, is highly consumptive, consuming nearly 65% of the water withdrawn.

Surface Water Balance in Southwest Louisiana Study Area by HUC8

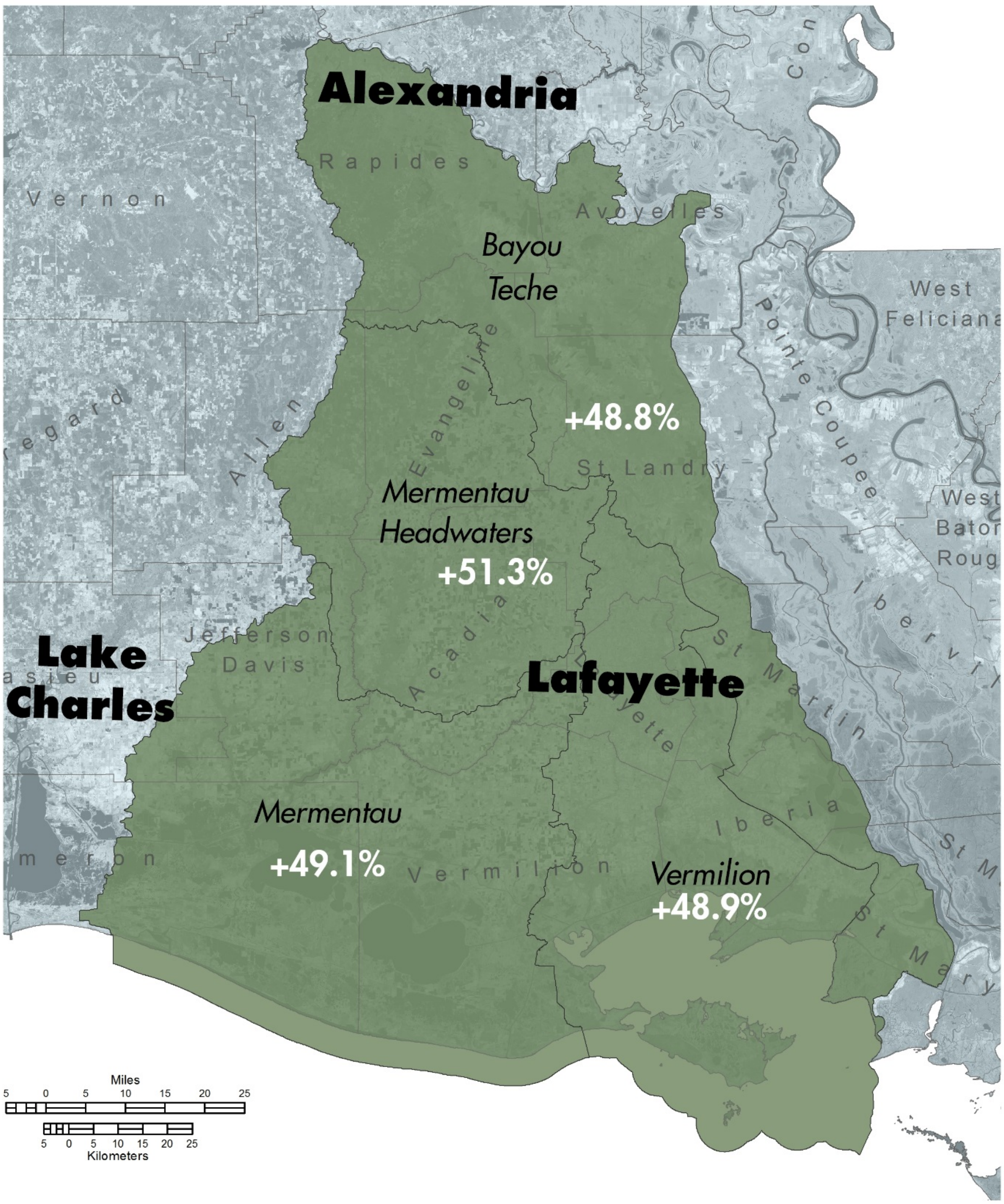


Figure 16: SWLA surface water balance by HUC8.

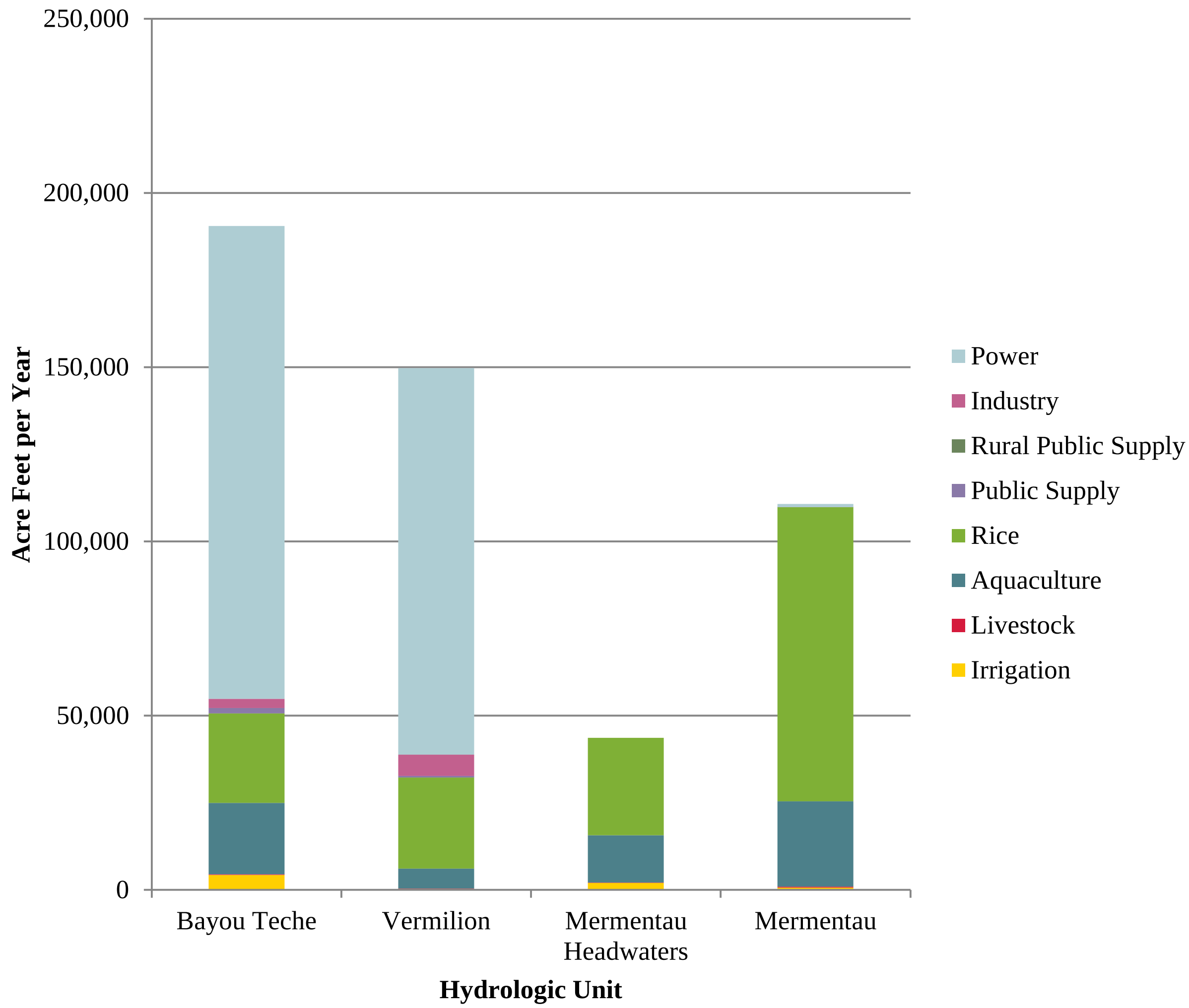


Figure 17: SWLA surface water use by hydrologic unit.

Table 12: Southwest study area summary of surface water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Bayou Teche	5,473,672	2,801,733	2,671,939	+48.8%
Vermilion	4,304,848	2,198,761	2,106,087	+48.9%
Mermentau Headwaters	3,350,916	1,633,156	1,717,760	+51.3%
Mermentau	5,913,295	3,009,574	2,903,721	+49.1%
Total	**19,042,731**	**9,643,224**	**9,399,507**	**+49.4%**

Energy Costs

The amount of energy required to supply water to the populations within the Bayou Teche and Vermilion hydrologic units is significantly higher than in the more rural Mermentau and Mermentau Headwaters units. This is due in large part to the presence of the city of Alexandria in the northern portion of the Bayou Tech unit and the city of Lafayette in the Vermilion unit. Because of the large concentration of population in these cities, a number of public water supply systems of varying sizes are sited there (Figure 17). Particularly in Lafayette, the fourth largest city in Louisiana, a number of small and large public supply systems serve the subdivisions, neighborhoods, and communities. The presence of a relatively shallow aquifer in Lafayette has resulted in a proliferation of public water supply systems, in contrast to Alexandria, which has fewer, but larger, public supply systems, due in part to the deeper water levels in the Williamson Creek and Carnahan Bayou Aquifers of the region.

While the rural areas are serviced by a number of public rural supply systems, a large portion of the population of the region utilize domestic water pumps to draw their own water directly from the aquifers (Figure 18). This is particularly true of the Mermentau and Vermilion units. The wells drilled in these units, particularly in the northern portions, tend to be shallower and thus require less energy costs to extract the water. It is notable that, because of the coastal nature of the Mermentau and Vermilion units, much of the surface water in the southern portion of these units are highly saline, limiting the usefulness of this water for drinking and other domestic uses. In fact, the surface water in approximately fifty percent of each of these units has a mean annual salinity greater than 0.5 parts per thousand (ppt).Wells that are drilled in the coastal zone tend to be much deeper and require a greater amount of energy to bring the water to the surface.

The energy expenditure needed to supply the city of Lafayette and the surrounding communities within the Vermilion hydrologic unit with fresh water is significantly higher than any of the other units in the study area. The combination of public supply systems and individual domestic wells are estimated to consume over 80 million kWh of power annually, nearly double the amount utilized in the Alexandria area and rest of the Bayou Tech hydrologic unit. While the Alexandria area does have a number of large public supply systems, the number of individual domestic wells is relatively small. This is likely due in large part to the increased depth needed to reach water and the corresponding increase in energy expenditure and costs.

The patterns of energy expenditure to treat wastewater are similar to those observed in the public supply systems in the region, with the urban areas expending far more energy than the more rural locations (Figure 19). One additional limiting factor in the location of the wastewater treatment plants is the presence of a waterway of sufficient size into which to release the treated water. The larger plants in the southwest study area are located in both Lafayette and Alexandria with other large plants spread out along Bayou Teche, the waterway that divides the Bayou Tech and Vermilion hydrologic units. The larger wastewater plants are located on some of the region’s larger waterways. Conversely, the wastewater plants in the rural areas and in the smaller towns tend to be smaller as they serve smaller populations.

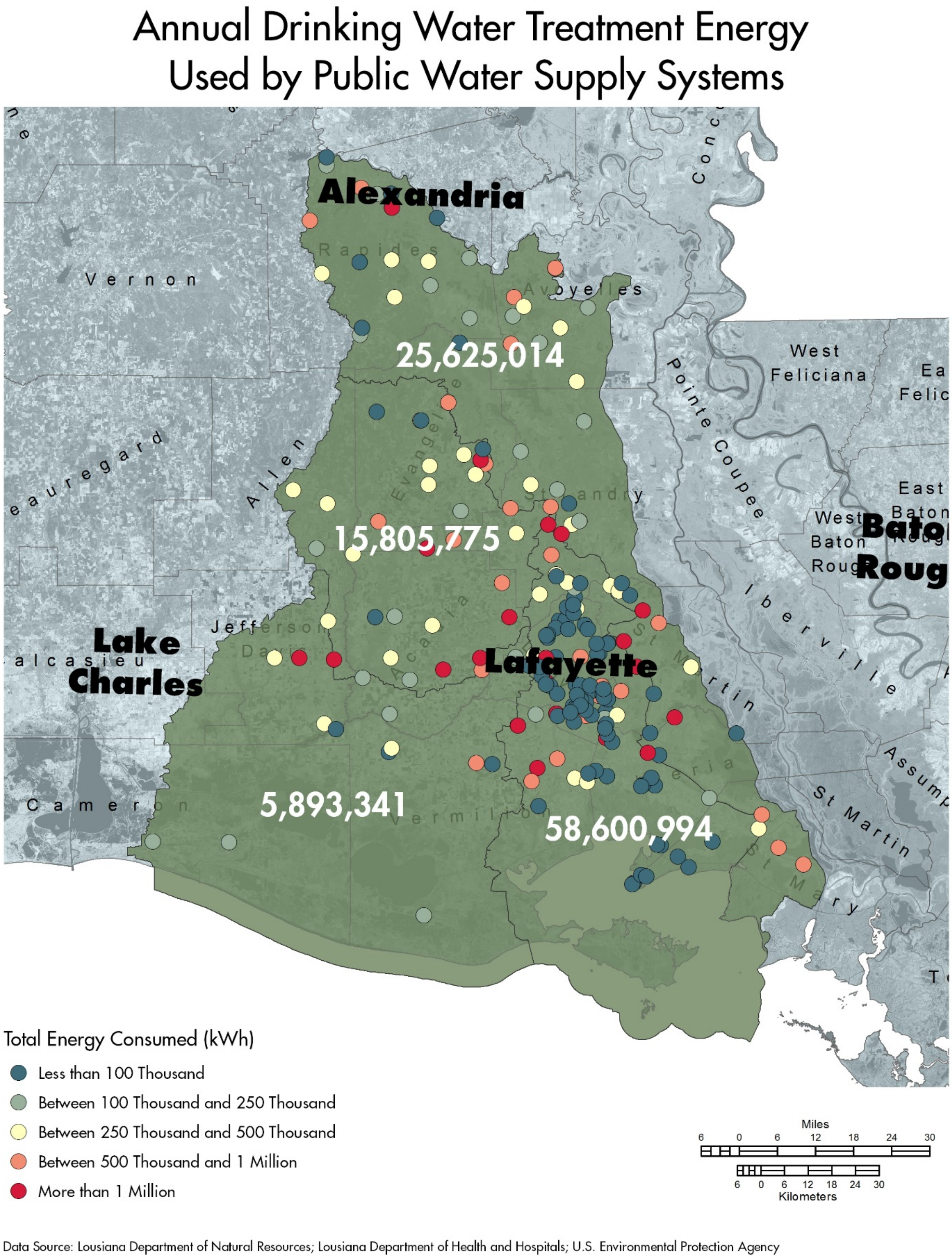


Figure 18: SWLA annual drinking water treatment energy used by public water supply systems.

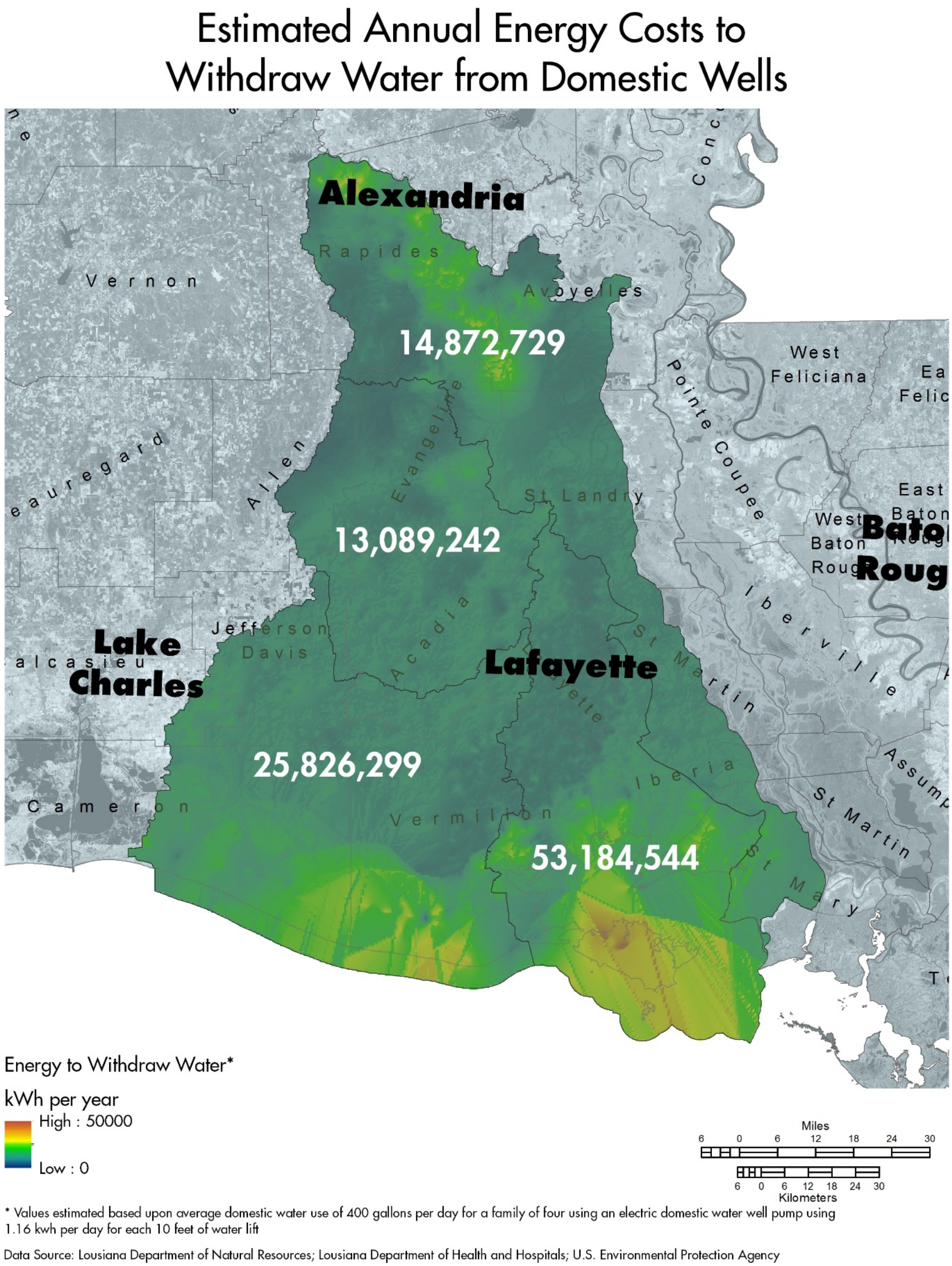


Figure 19: SWLA estimated annual energy consumption to withdraw water from domestic wells.

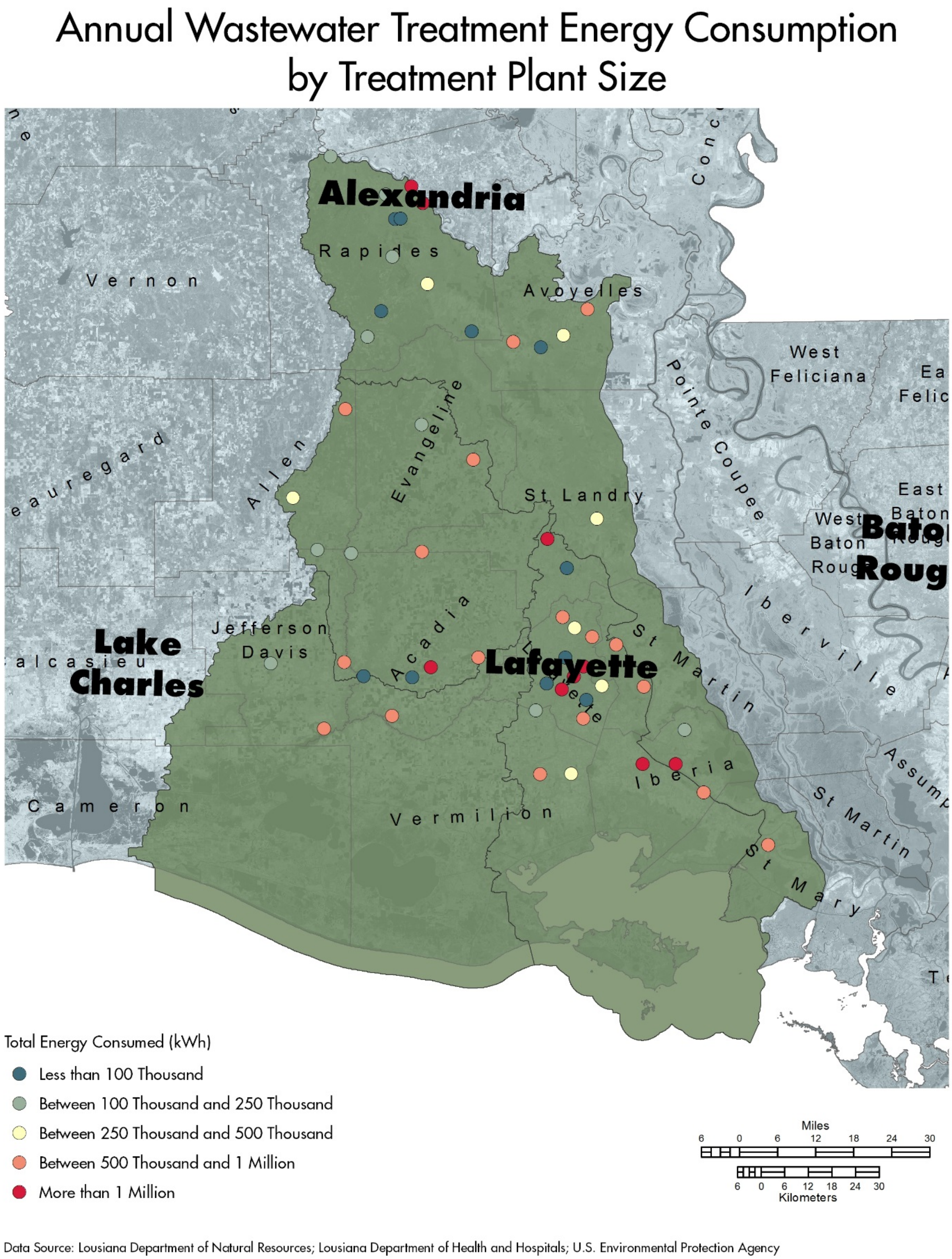


Figure 20: SWLA annual wastewater treatment energy consumption by treatment plant size.

Water Quality Impacts on Fresh Water Availability

The availability of surface water for ecological and societal uses is often limited by water quality. In the SWLA study area, the Vermilion River and its tributaries are major areas of concern, particularly downstream from the cities of Lafayette and Abbeville. Like other urban waters that receive wastewater discharge, the Vermilion River has had problems with low dissolved oxygen (DO) levels, high concentrations of fecal coliform bacteria, and biochemical oxygen demand (BOD) loadings. While the framework developed here can be adapted to remove large volumes of water from the budget calculations, additional research is needed to identify water quality needs for different consumptive uses. Additional considerations about the surface water, including delivery and energy costs to treat and convey it may diminish the usability of this excess supply and require further study. The effects of seasonality should be considered in future studies, as not all surface water is available for use at all times. The effects of user distance to surface water bodies should also be explored, as surface water usability is affected by distance and the cost to convey it over increased distances. Because the study area watersheds discharge surface water to the coastal zone, the minimum ecological flow required to sustain healthy coastal ecosystems should also be considered and quantified in future studies. Further study is needed to determine the amount of fresh water needed to support this function. In many locations within the study unit, saltwater intrusion and the resulting high levels of total dissolved solids (TDS), chloride, and sulfate may limit the usefulness of the surface water for such uses as drinking water and rice irrigation. Elevated salinities in the coastal (southern) portions of the study area limit the geographic use of surface water by up to -54.6% in coastal watersheds (Figure 20). For the purposes of this study, surface water seaward of the line where mean annual salinity levels are greater than 0.5 ppt is considered unusable. The effects on availability of surface water in the four watersheds are seen in Table 13. Bayou Teche and Mermentau Headwaters watersheds are relatively unaffected by coastal salinity impacts, with only the southern tip of the Bayou Tech unit reaching the identified salinity zone. However, when these coastal salinity impacts are taken into account for the Vermilion and Mermentau watersheds, results show deficiencies of fresh surface water supplies in those watersheds. Changes in future conditions, such as coastal land loss, sea level rise, and other factors, may further affect the usability of surface water in the coastal zone.

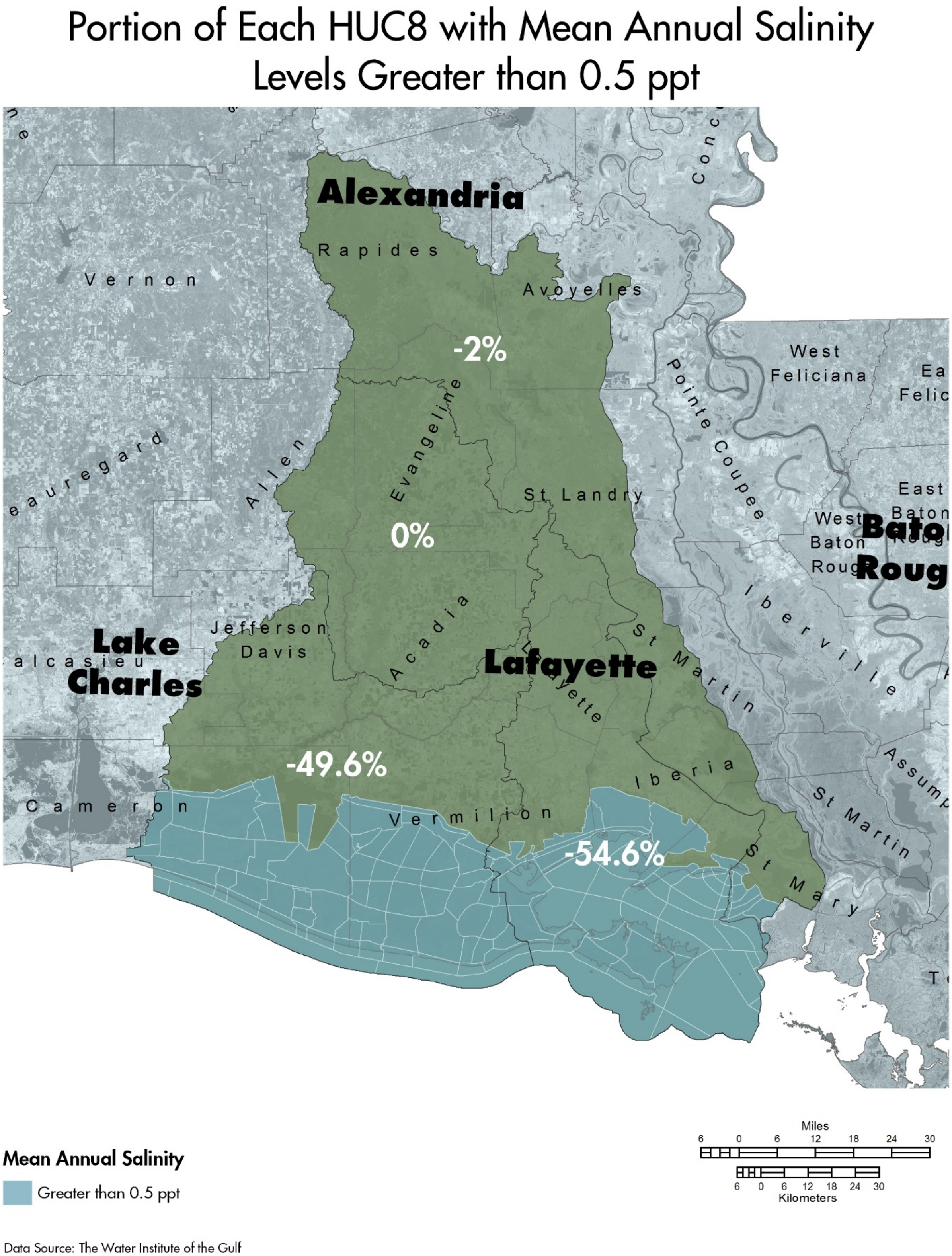


Figure 21: Portion of each HUC8 with mean annual surface water salinity levels greater than 0.5ppt.

Table 13: SWLA study area surface water balance, including impacts of coastal salinity on water usability

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Reduced Water Inflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Bayou Teche	5,473,672	5,364,198	109,474	-2.0%
Vermilion	4,304,848	1,954,401	2,350,447	-54.6%
Mermentau Headwaters	3,350,916	3,350,915	1	0.0%
Mermentau	5,913,295	2,980,300	2,932,995	-49.6%
Total	**19,042,731**	**13,649,814**	**5,392,917**	**-28.3%**

Water quality potentially affects the availability of surface water in hydrologic units across the SWLA study area. Streams and lakes in all four watersheds of the SWLA study area are listed as impaired under Clean Water Act Section 303(d). A map of the impaired surface water bodies is shown in Figure 21. More study is needed to determine the amount and usability of these impacted waters. To demonstrate the possible effects of quality impacts on surface water supply in the SWLA study area, the water budget was recalculated to show the impacts of a 10% reduction in surface water supply. Results of this exercise are shown in Table 14.

Table 14: SWLA study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Reduced Water Inflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Bayou Teche	5,639,321	5,091,954	547,367	-10.7%
Vermilion	4,385,187	3,954,702	430,485	-10.9%
Mermentau Headwaters	3,409,647	3,074,555	335,092	-10.9%
Mermentau	6,031,190	5,439,860	591,330	-10.9%
Total	**19,465,345**	**17,561,071**	**1,904,273**	**-10.8%**

Future Scenarios

When urban land use projection models were examined within the southwest Louisiana study area, predicted growth was seen in many of the currently developed areas (Figure 22). Linear growth patterns were seen along the major highway and interstate corridors. In these areas, we see predicted urban growth ranging from 6 to 7.4 percent of the total land area. Outside of the major transportation corridors very little growth is expected, especially within the coastal zone. The Mermentau hydrologic unit in the southwestern portion of the study area, for example, is only expected to see about a 1% change in development over the next 50 years.

Figure 22: SWLA waters listed as impaired under Clean Water Act Section 303(d).

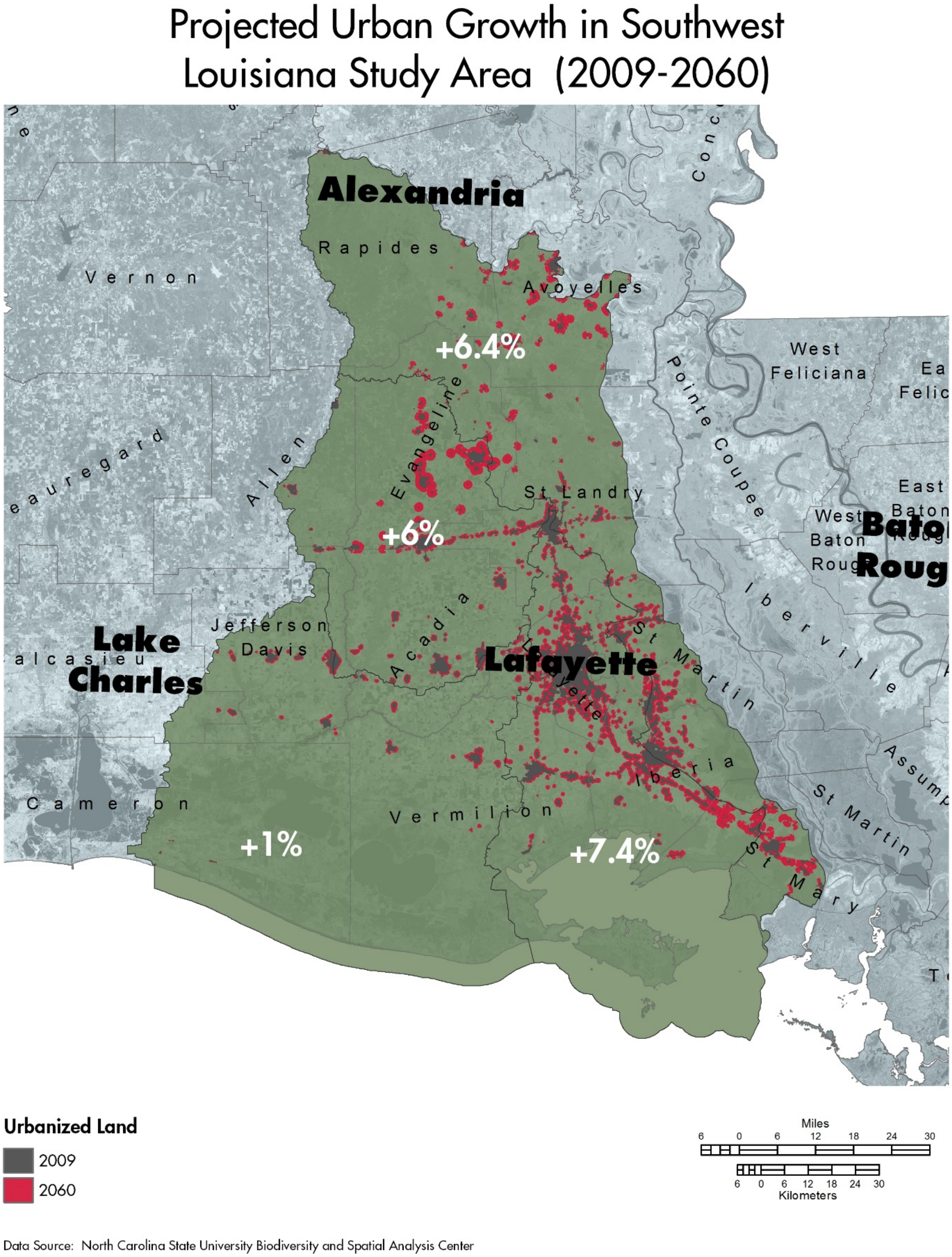


Figure 23: SWLA projected urban growth (2009-2060).

If it is assumed that urbanization results in the conversion of open land to land consisting of 75% to 100% impervious surface, the overall water balance remains fairly stable, with slight gains occurring overall due to the lessened evapotranspiration rates. Examined separately, it is seen that increased runoff would result in a net positive gain in the surface waters and a slight drop in groundwater levels across all hydrological units (Table 15). The Bayou Teche hydrologic unit exhibits slightly elevated losses of groundwater due to the presence of a portion of the Chicot Aquifer area in the northern reach of the unit.

Table 15: SWLA total water balance change under future urbanization scenario.

Hydrologic Unit	Change in Groundwater Input (acre-feet/year)	% Change in Groundwater Input	Change in Surface Water Input (acre-feet/year)	% Change in Surface Water Input
Bayou Teche	-1,798	-1.1%	32,743	+0.6%
Vermilion	-70	-0.1%	63,892	+1.5%
Mermentau Headwaters	-105	-0.2%	36,439	+1.1%
Mermentau	-63	-0.1%	9,104	+0.2%

While the greatest spatial extent of urbanization is predicted to occur in the Bayou Teche hydrologic unit, the neighboring Vermilion unit, containing the city of Lafayette, is projected to experience the greatest population growth, upwards of 9% (Figure 23). While the extent of urbanization affects the supply side of the water budget, population growth will increase demand for fresh water and will have impacts on the outputs to the budget. When the impacts of this population growth are entered into the water balance equation, groundwater withdrawals for public water supplies, including rural supply systems, have a far more significant effect on the water balance than the supply impacts of development (Table 16). Outside of the Lafayette metropolitan region, the rest of the hydrologic units in the southwest study area only show slight increases, with the Mermentau Headwaters unit projected to experience a slight drop in population. It is important to note that population and development projections for communities such as Lafayette that are highly dependent on a single industry, such as oil and gas, may experience unanticipated growth or declines as global markets change. Such factors are often difficult to capture in population estimates.

Table 16: SWLA total water balance change under urbanization and population growth scenarios.

Hydrologic Unit	Change in Groundwater Output (acre-feet/year)	% Change in Groundwater Output	Change in Surface Water Output (acre-feet/year)	% Change in Surface Water Output
Bayou Teche	945	+0.6%	34	<0.1%
Vermilion	4,420	+5.5%	40	<0.1%
Mermentau Headwaters	-49	-0.1%	0	0.0%
Mermentau	119	+0.1%	0	0.0%

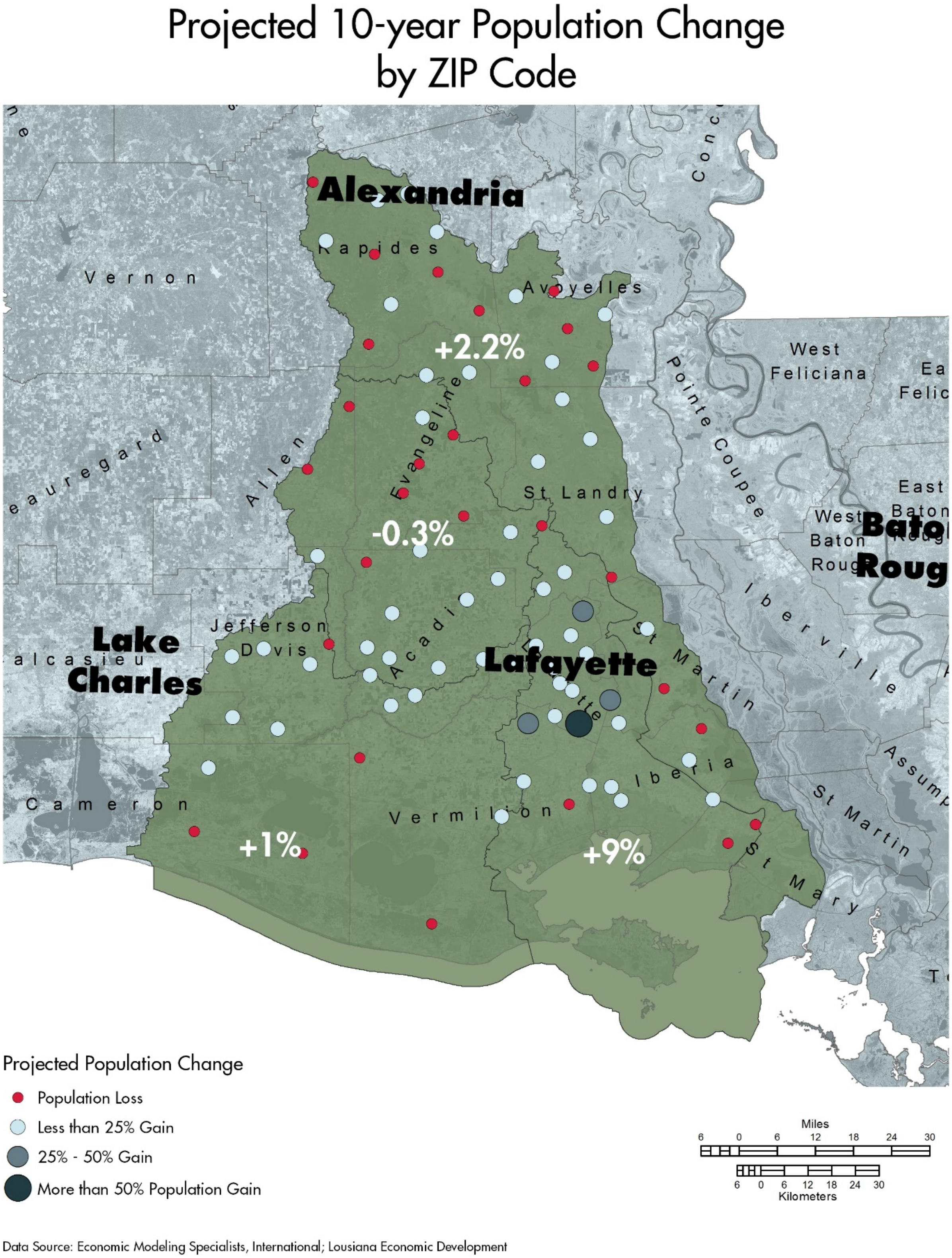


Figure 24: SWLA projected 10-year population change by ZIP code.

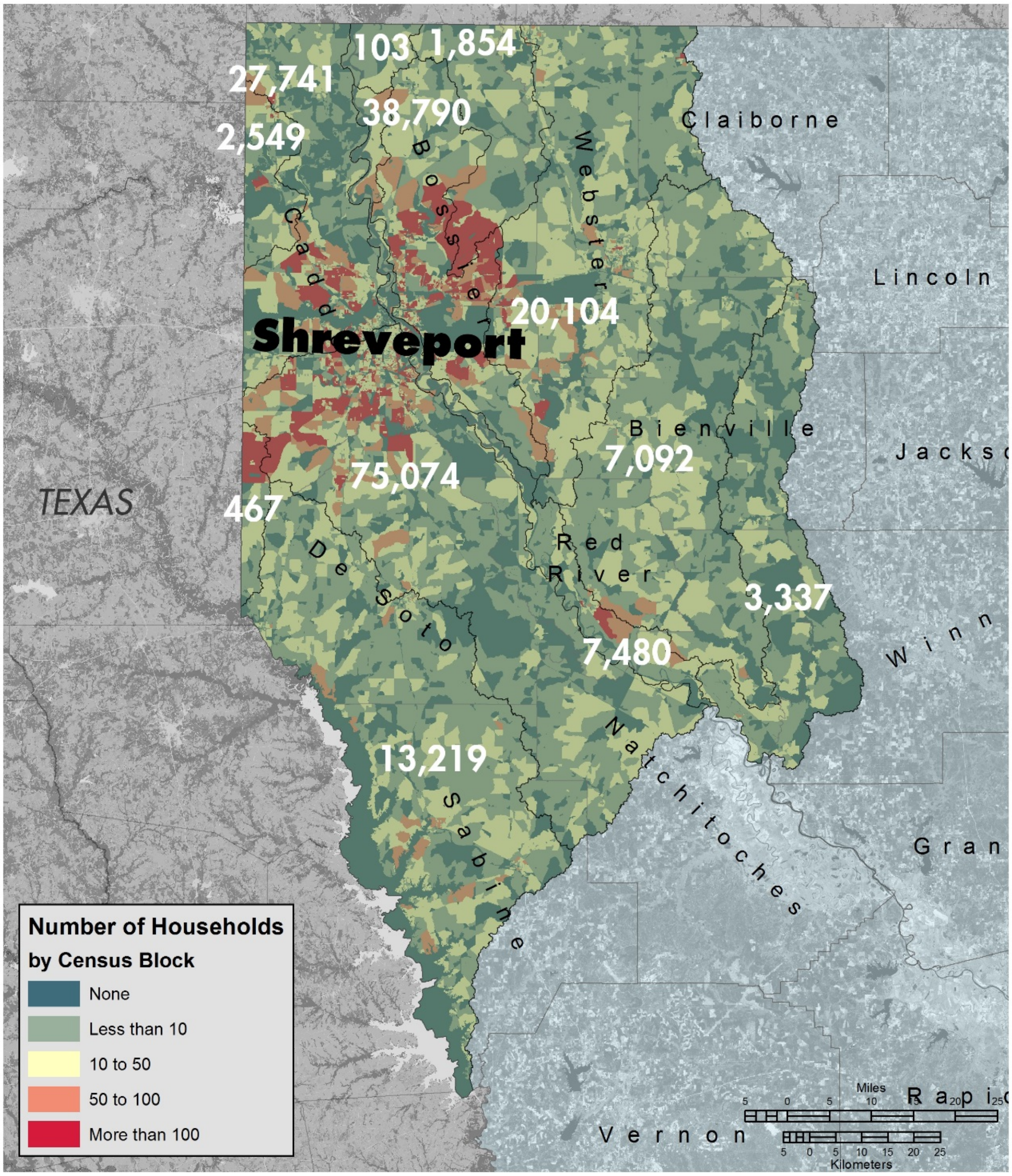
Northwest Louisiana Study Area

The northwest study area includes much of the Carrizo-Wilcox Aquifer as well as a portion of the Red River surface water unit. Bossier City's source of water is the Red River surface unit. The water drawn from the Carrizo-Wilcox is used primarily for public supply, followed by rural domestic use and general irrigation. This aquifer serves a small area of Louisiana but does supply water to Caddo Parish and Desoto Parish rural areas outside the city of Shreveport. Surface water from Cross Lake Reservoir supplies water to the city of Shreveport in Caddo Parish and Barksdale Air Force Base in Bossier City, Bossier Parish. Most of the study area relies on a combination of surface and groundwater for its public water supplies (Table 17). Most of the population (Figure 24), and thus the demand for fresh water (Figure 25), is centered on the heavily developed areas around Shreveport and Bossier City. The rest of the study area tends to be highly rural and reliant on domestic wells for fresh water. The northwest study area has also experienced growth in industry, most notably, shale gas extraction. The development of the Haynesville shale play expanded dramatically in 2008 and continued to grow until 2012, when gas process began to drop. The development of the Haynesville Shale utilized a large amount of groundwater and surface water for hydraulic fracturing. Researchers estimate that shale gas development in the region requires up to 5,000,000 gallons of water for each well (Hanson, 2009). Although initially heavily reliant on groundwater, industry has transitioned to other more sustainable sources of water, including the Toledo Bend Reservoir and the Red River.

Table 17: NWLA population, public supply, and domestic well information

Hydrologic Unit	Number of Households	Estimated Freshwater Demand (acre-feet/year)	Number of Public Supply Systems	Population Served	Number of Domestic Water Wells
McKinney	103	46	0	0	35
Middle Red Coushatta	7,480	3,351	9	8,617	265
Loggy Bayou	20,104	9,008	50	69,300	1,182
Red Chute	38,790	17,380	18	98,503	1,672
Bodcau	1,854	831	2	1,300	282
Bayou Pierre	75,074	33,637	37	253,087	3,081
Saline Bayou	3,337	1,495	15	11,843	200
Black Lake Bayou	7,092	3,178	22	18,964	588
Cross Bayou	27,741	12,430	17	18,205	750
Caddo Lake	2,549	1,142	2	2,999	80
Middle Sabine	467	209	1	600	73
Toledo Bend Reservoir	13,219	5,923	23	41,730	1,202

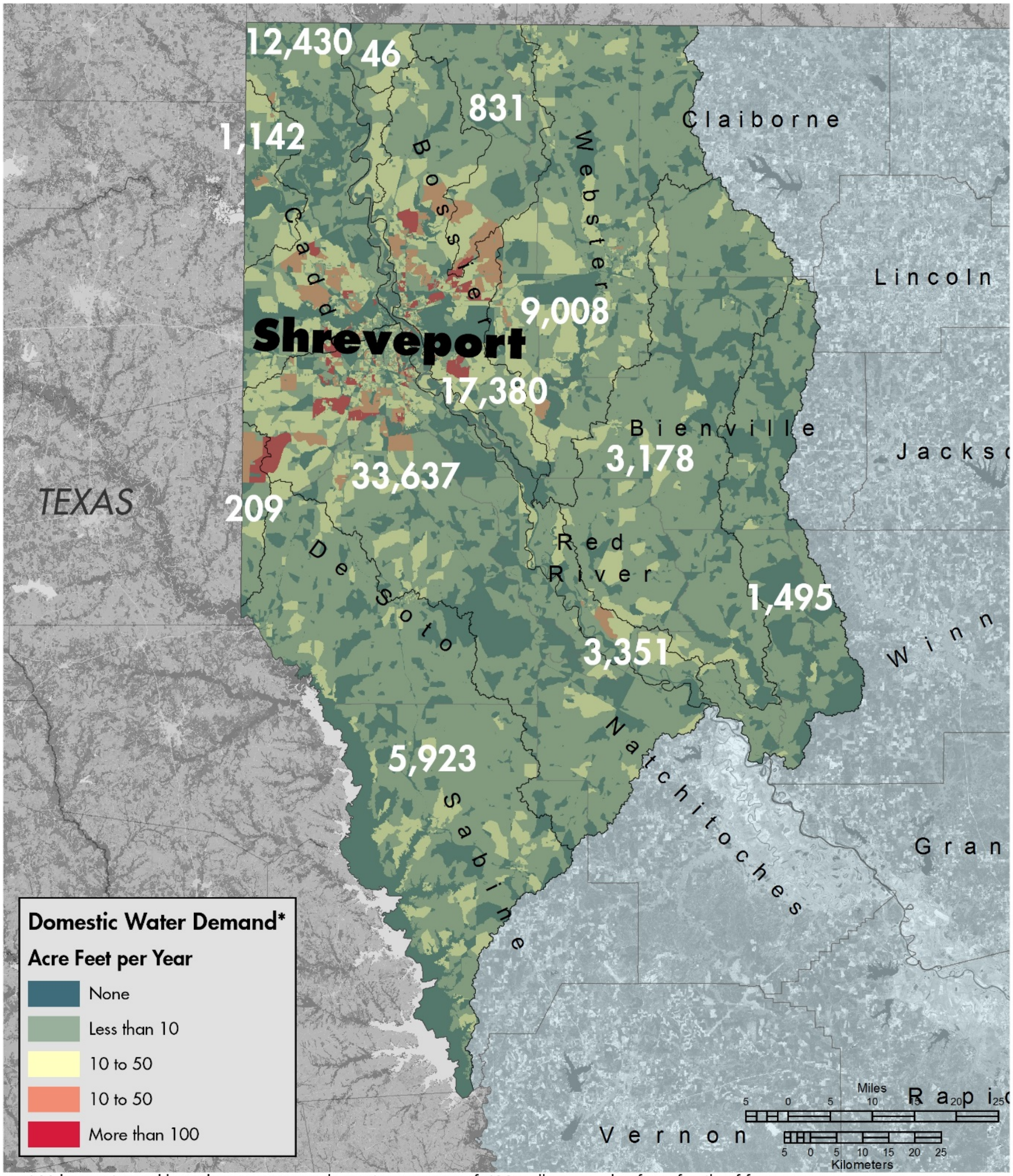
Total Number of Households by HUC8 in Northwest Louisiana Study Area (2010)



Data Source: U.S. Census Bureau

Figure 25: NWLA total households by HUC8.

Estimated Annual Household Demand for Fresh Water by HUC8 (2010)



* Values estimated based upon average domestic water use of 400 gallons per day for a family of four

Data Source: U.S. Census Bureau

Figure 26: NWLA estimated annual household demand by HUC8 (2010).

The Carrizo-Wilcox Aquifer system consists of the Carrizo Sand of the Eocene Claiborne group and the undifferentiated Wilcox group of Eocene and Paleocene age (LDEQ, 2006). Primary recharge of the Carrizo-Wilcox Aquifer occurs from direct infiltration of rainfall in interstream, upland outcrop-subcrop areas. Recharge to the aquifer is generally from the west. Water also moves between overlying alluvial and terrace aquifers, the Sparta Aquifer, and the Carrizo-Wilcox Aquifer, according to hydraulic head differences. The range of thickness of the freshwater interval in the Carrizo-Wilcox is 50 to 850 feet. Water level fluctuations are mostly seasonal, and the hydraulic conductivity varies between 2-40 feet/day. (LDEQ, 2006). The maximum depths of occurrence of fresh water in the Carrizo-Wilcox range from 200 feet above sea level, to 1,100 feet below sea level. The depths of the Carrizo-Wilcox wells that were reported in the Baseline Monitoring Project range from 105 to 410 feet (LDEQ, 2006). A summary of the hydraulic characteristics of the Carrizo Sand and the Wilcox Sand is presented in Table 18 below.

Table 18: Hydraulic characteristics of the Carrizo-Wilcox Aquifer

Aquifer Unit	Min Thickness (ft)	Max Thickness (ft)	Mean Thickness (ft)	Thickness Source	Hydraulic Conductivity (ft/day)	Hydraulic Conductivity Source
Carrizo Sand	25	75	51	Rapp, 1992	12	Martin & Early, 1987
Wilcox Sand			32	Calculated from Martin & Early, 1987	13.5	Martin & Early, 1987

The Carrizo Sand, also referred to as the top zone, is discontinuous and consists of well-sorted, fine to medium grained, cross-bedded sands, with some silt and lignite. It is considered the basal unit of the Claiborne Group in Arkansas, Louisiana, and Texas. In Caddo Parish, an area of demand for groundwater, the Carrizo Sand varies from approximately 25 to 75 feet thick. (Rapp, 1992) A thickness of 51 feet was calculated from Martin and Early (1987), and used for this study. Martin and Early (1987) calculated hydraulic conductivity of 12 ft/day, with transmissivity of 615 ft^2/day, and a specific capacity of 2 gal/min/ft of drawdown for the Carrizo Sand.

The underlying Wilcox Group is hydraulically connected to the Carrizo Sand. They are considered to be one hydrologic unit. The Wilcox deposits, outcropping in northwestern Louisiana, are the oldest deposits in the state containing fresh water. This unit, also called the bottom zone of the Carrizo-Wilcox, makes up the bulk of the sands of the aquifer. Well yields are restricted because the sand beds are typically thin, lenticular, interbedded with thin clay beds, and fine textured. A thickness of 32 feet was calculated from Martin and Early (1987), and used for this study. Reported hydraulic conductivity for this zone ranges from 10 ft/day (Ryals, 1983) to 17 ft/day (Martin and Early, 1987). An average hydraulic conductivity of 13.5 ft/day was used for this study. Transmissivity for this zone ranges from 255 ft^2/day (Rapp, 1992) to 605 ft^2/day (Martin and Early, 1987). An average transmissivity of 430 ft^2/day was used here. The system is confined downdip by the clays and silty clays of the overlying Cane River Formation and the regionally confining clays of the underlying Midway Group.

Water Balance Results

Overall, the water budget shows a surplus of total water resources (including surface and groundwater) of 4,488,415 acre-feet/year, or about 48.0% of the total water input to the NWLA study area (Figure 26). Excesses were calculated in all of the watersheds – McKinney, Middle Red-Coushatta, Loggy Bayou, Red Chute, Bodcau, Bayou Pierre, Saline Bayou, Black Lake Bayou, Cross Bayou, Caddo Lake, Middle Sabine, and Toledo Bend Reservoir (Table 19). But, due to the magnitudes of the surface and groundwater supply differences (surface water supply in the NWLA study area is 30 times greater than the groundwater supply), the overall surplus shown is dominated by the surplus of surface water.

Table 19: Northwest study area summary of overall water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
McKinney	27,286	14,325	12,960	+47.5%
Middle Red Coushatta	164,444	101,045	63,400	+38.6%
Loggy Bayou	1,228,754	628,390	600,363	+48.9%
Red Chute	573,459	290,839	282,620	+49.3%
Bodcau	399,551	200,986	198,565	+49.7%
Bayou Pierre	1,701,555	846,087	855,468	+50.3%
Saline Bayou	793,224	402,766	390,458	+49.2%
Black Lake Bayou	1,755,488	889,649	865,838	+49.3%
Cross Bayou	746,168	408,016	338,152	+45.3%
Caddo Lake	221,563	175,636	45,927	+20.7%
Middle Sabine	63,702	31,823	31,879	+50.0%
Toledo Bend Reservoir	1,678,170	875,385	802,785	+47.8%
Total	**9,353,364**	**4,864,947**	**4,488,415**	**+48.0%**

Total Water Balance in Northwest Louisiana Study Area

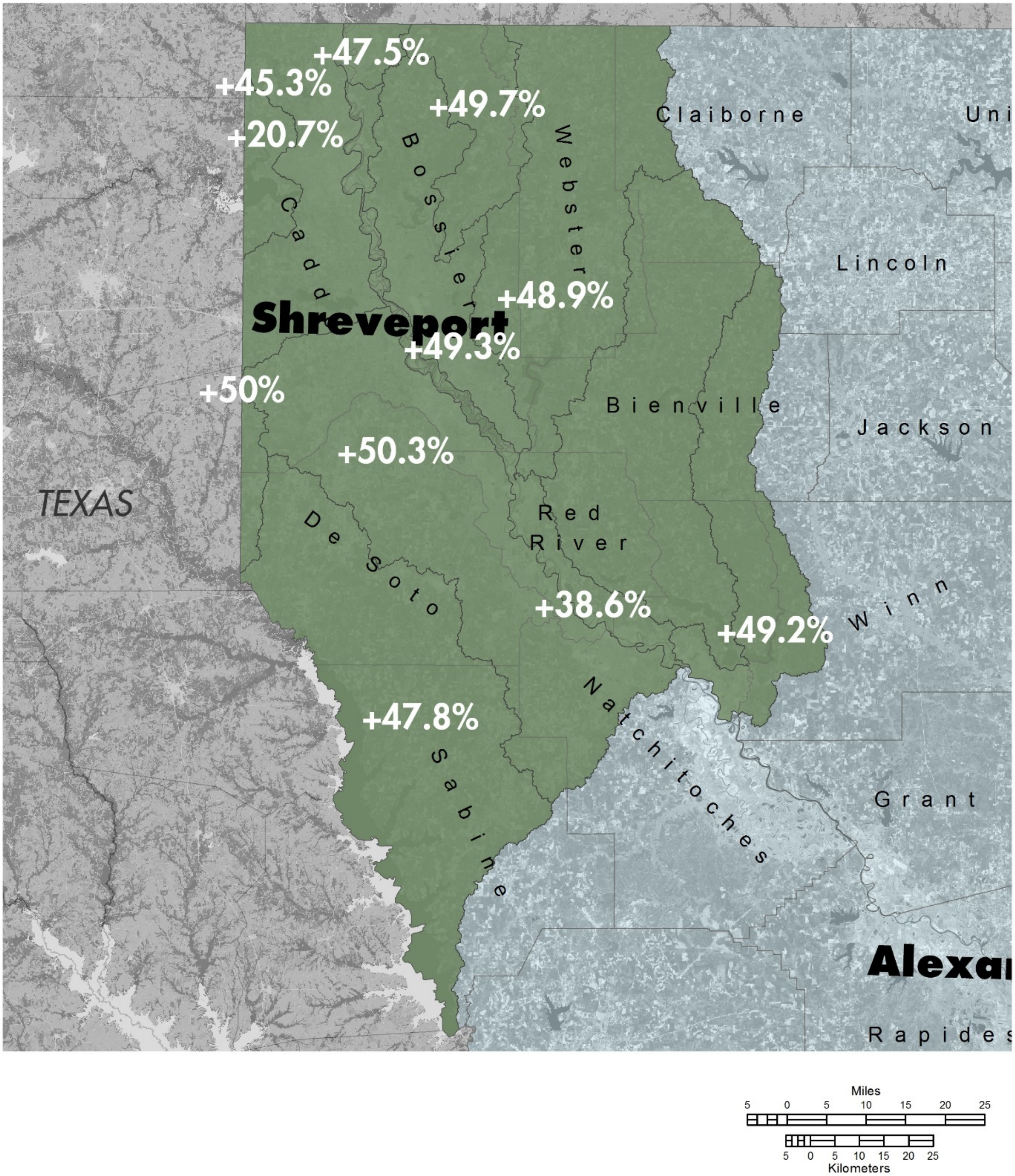


Figure 27: NWLA total water balance by HUC8.

In terms of groundwater resources in the Carrizo-Wilcox Aquifer within the study area, there is a calculated surplus of 87,673 acre-feet/year, or 29.2% of the annual groundwater available in the study area portion of the Carrizo-Wilcox Aquifer (Figure 27). The groundwater balance for all 12 watersheds in the NWLA study area varies from –8.9% (Loggy Bayou) to 59.3% (Bayou Pierre) (Table 20). Groundwater use types vary across the NWLA study area, with irrigation dominating use in Caddo Lake and Cross Bayou watersheds. Industrial withdrawals are significant in Black Lake Bayou and Bayou Pierre. There are very few groundwater withdrawals from the Carrizo-Wilcox Aquifer in McKinney, Middle Sabine, and Bodcau watersheds, mainly for public supply. Power supply withdrawals dominate groundwater use in the Toledo Bend Reservoir watershed, accounting for 77.3% of all groundwater use in the watershed (Figure 28). Much (77.7%) of the groundwater withdrawn for power generation use is returned to surface water via return flows. Public supply dominates withdrawals of groundwater in the Loggy Bayou watershed, accounting for 78.5% of all groundwater use in the Loggy Bayou watershed. In general, groundwater use from the Carrizo-Wilcox Aquifer in the study area is of a smaller magnitude than in the SELA and SWLA study areas. This is mainly attributable to the generally lower yields of the Carrizo-Wilcox Aquifer compared to the Chicot and Southern Hills Aquifer systems.

Table 20: Northwest study area summary of groundwater balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
McKinney	1,634	1,460	173	+10.6%
Middle Red Coushatta	7,457	8,102	-645	-8.6%
Loggy Bayou	28,677	31,222	-2,545	-8.9%
Red Chute	18,751	14,212	4,539	+24.2%
Bodcau	12,184	7,421	4,763	+39.1%
Bayou Pierre	92,937	37,822	55,115	+59.3%
Saline Bayou	16,524	15,241	1,283	+7.8%
Black Lake Bayou	33,824	28,767	5,057	+15.0%
Cross Bayou	30,662	19,128	11,534	+37.6%
Caddo Lake	5,569	5,675	-106	-1.9%
Middle Sabine	3,546	1,894	1,652	+46.6%
Toledo Bend Reservoir	48,903	42,050	6,853	+14.0%
Total	**300,668**	**212,994**	**87,673**	**+29.2%**

Groundwater Balance in Northwest Louisiana Study Area by HUC8

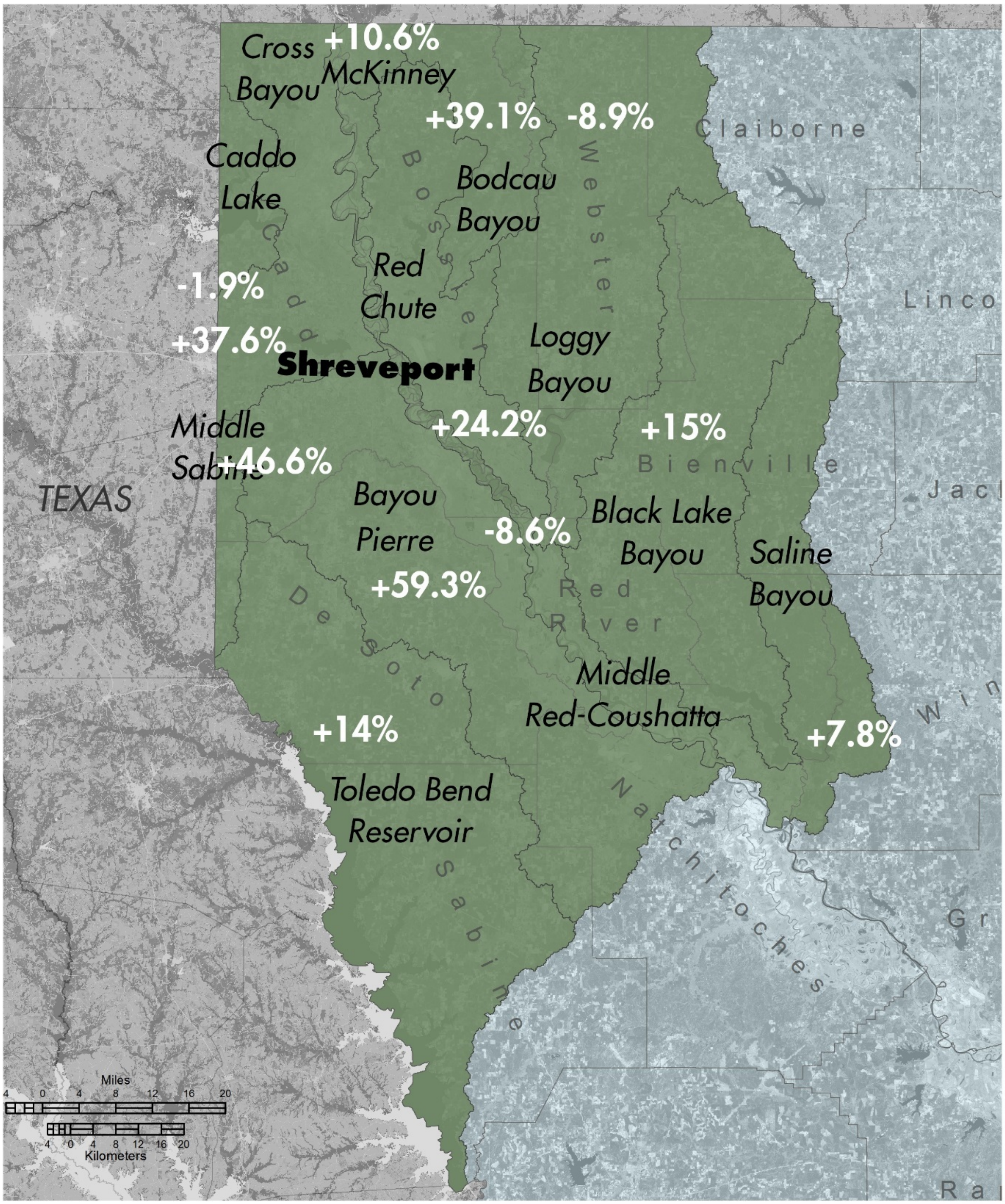


Figure 28: NWLA groundwater balance by HUC8.

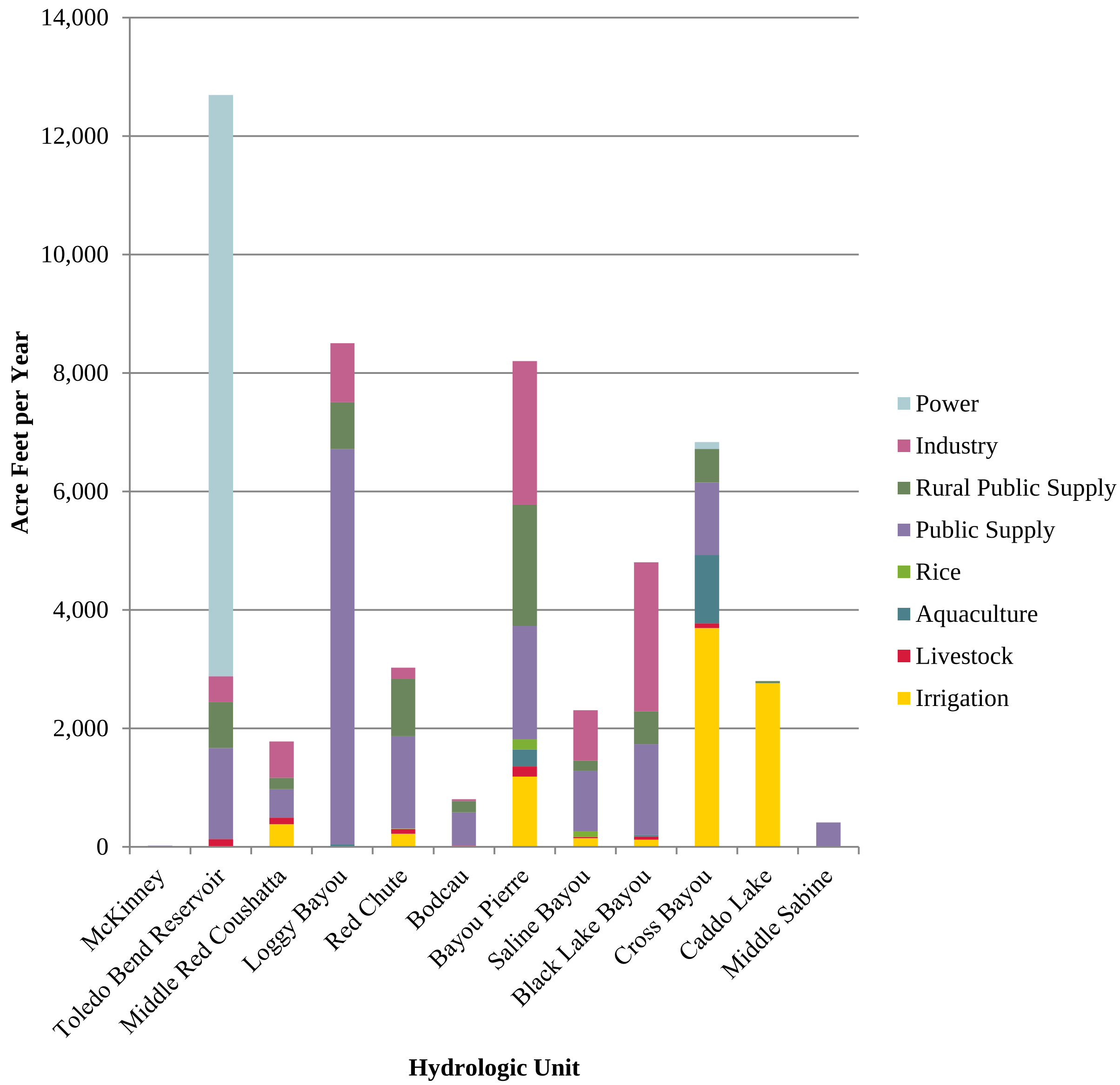


Figure 29: NWLA groundwater use by hydrologic unit.

Supplies of surface water resources in the four watersheds show a surplus of 4,400,742 acre-feet/year (Table 21), or 48.6% of the surface water in the study area remains available (Figure 29). Withdrawals of surface water in the Caddo Lake watershed are dominated by power generation, and account for 97.8% of all surface water used in the watershed. (Figure 30). Twenty-two percent of that water withdrawn for power generation is consumptively used, while 78% of it is returned to surface water via return flows. There is no significant surface water use in McKinney, Loggy Bayou, Red Chute, Bodcau, Bayou Pierre, Saline Bayou, and Black Lake Bayou watersheds. Public supply dominates withdrawals of surface water in the Cross Bayou watershed, accounting for 96.3% of all surface water use in the Cross Bayou watershed. Considerations about surface water, including water quality, delivery, and energy costs to treat and convey it may diminish the usability of this excess supply and require further study. The minimum ecological flow required to sustain healthy riparian ecosystems should also be considered. Further study is needed to determine the amount of fresh water needed to support this function.

Table 21: Northwest study area summary of surface water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
McKinney	25,652	12,865	12,787	+49.8%
Middle Red Coushatta	156,987	92,943	64,045	+40.8%
Loggy Bayou	1,200,077	597,168	602,908	+50.2%
Red Chute	554,708	276,627	278,081	+50.1%
Bodcau	387,367	193,565	193,802	+50.0%
Bayou Pierre	1,608,618	808,265	800,353	+49.8%
Saline Bayou	776,700	387,525	389,175	+50.1%
Black Lake Bayou	1,721,664	860,882	860,781	+50.0%
Cross Bayou	715,506	388,888	326,618	+45.6%
Caddo Lake	215,994	169,961	46,033	+21.3%
Middle Sabine	60,156	29,929	30,227	+50.2%
Toledo Bend Reservoir	1,629,267	833,335	795,932	+48.9%
Total	**9,052,696**	**4,651,953**	**4,400,742**	**+48.6%**

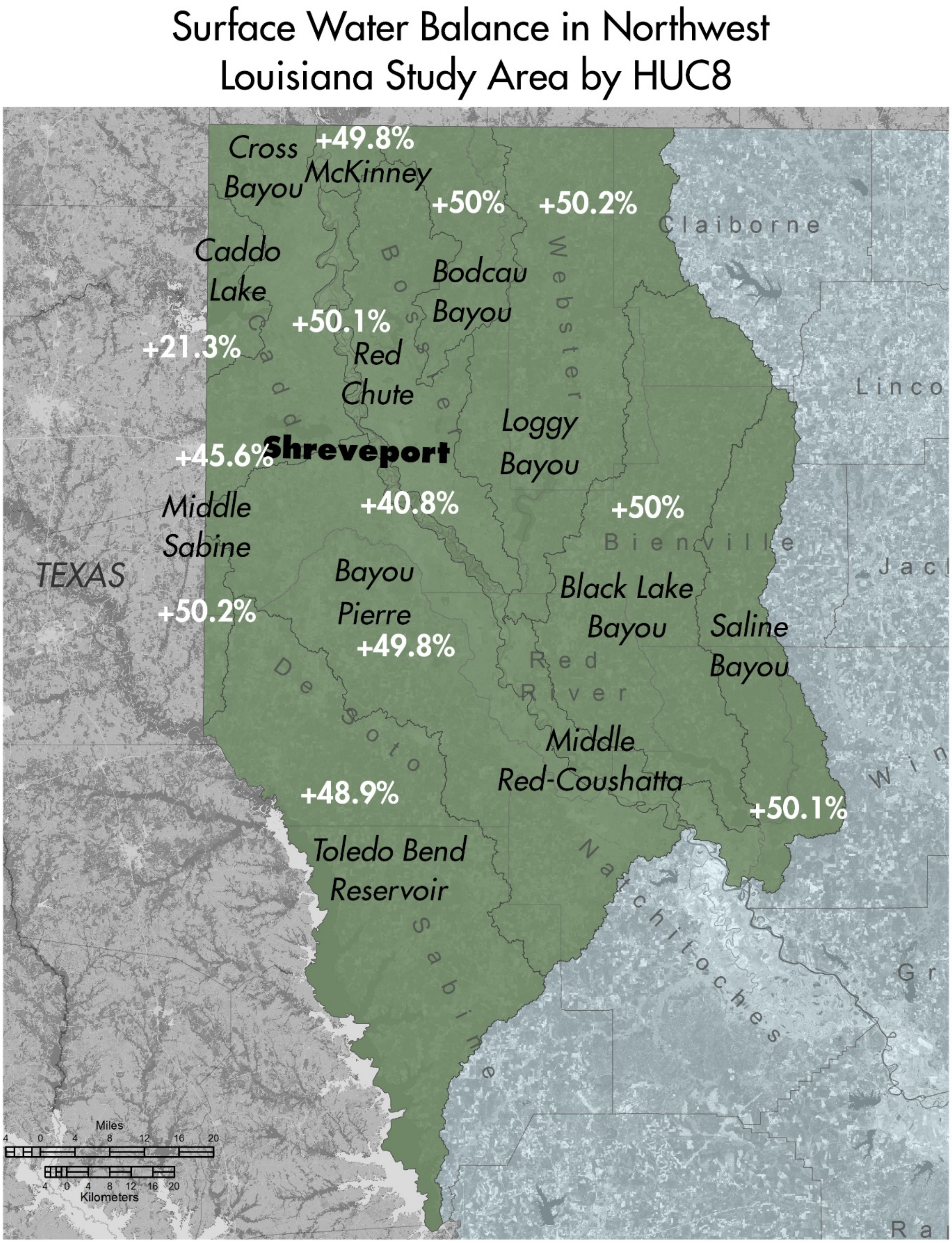


Figure 30: NWLA surface water use by hydrologic unit.

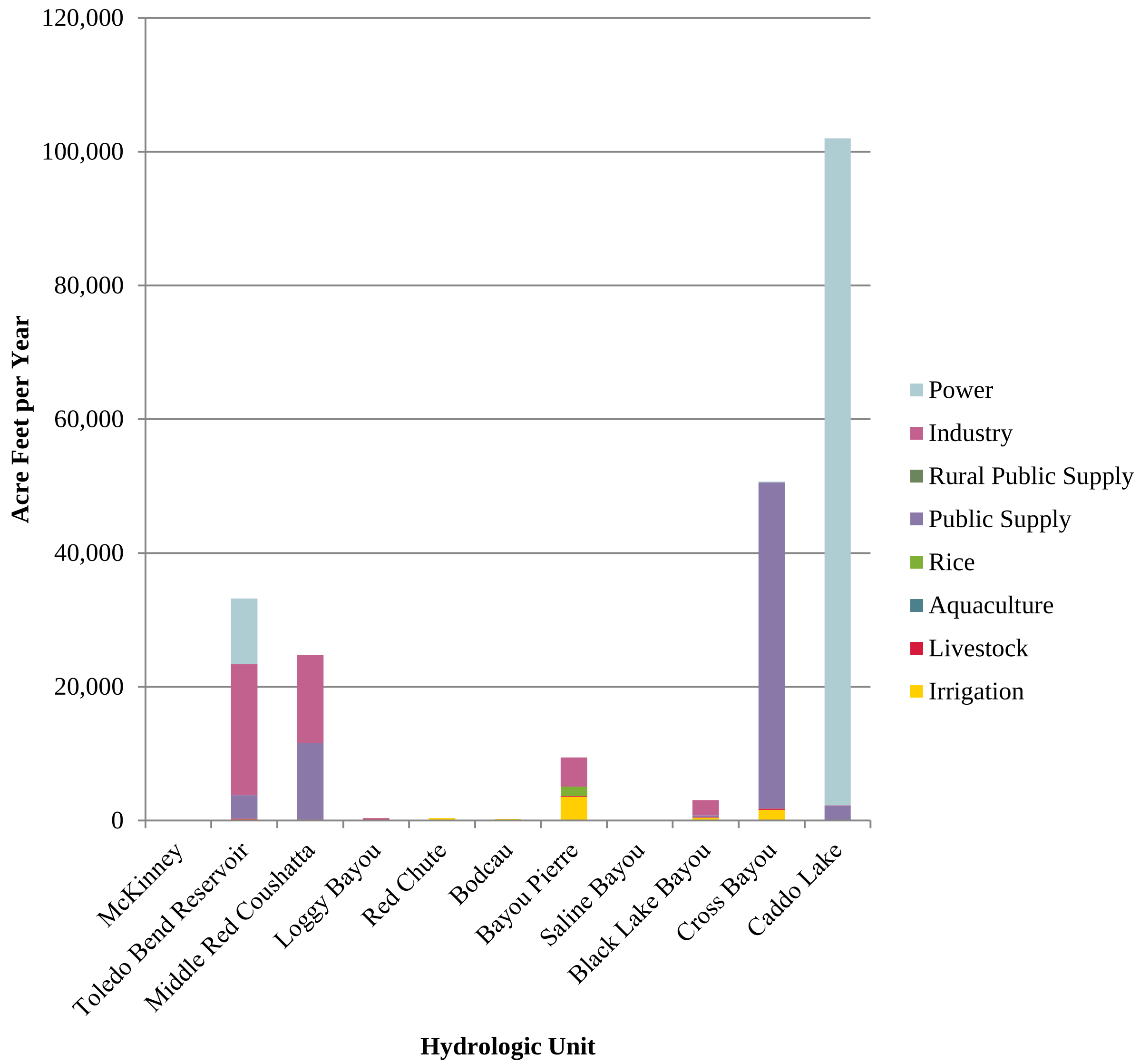
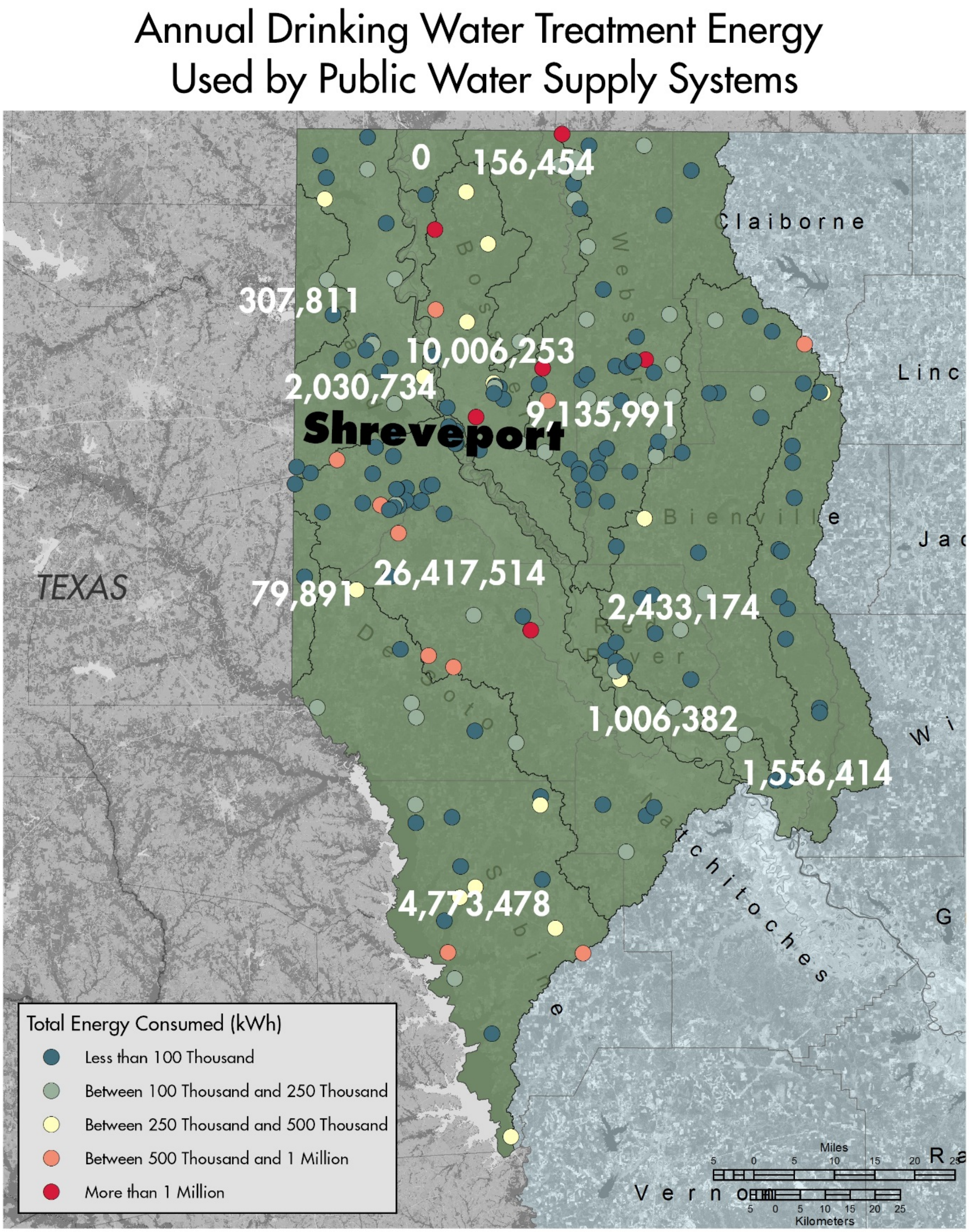


Figure 31: NWLA surface water use by hydrologic unit.

Energy Costs

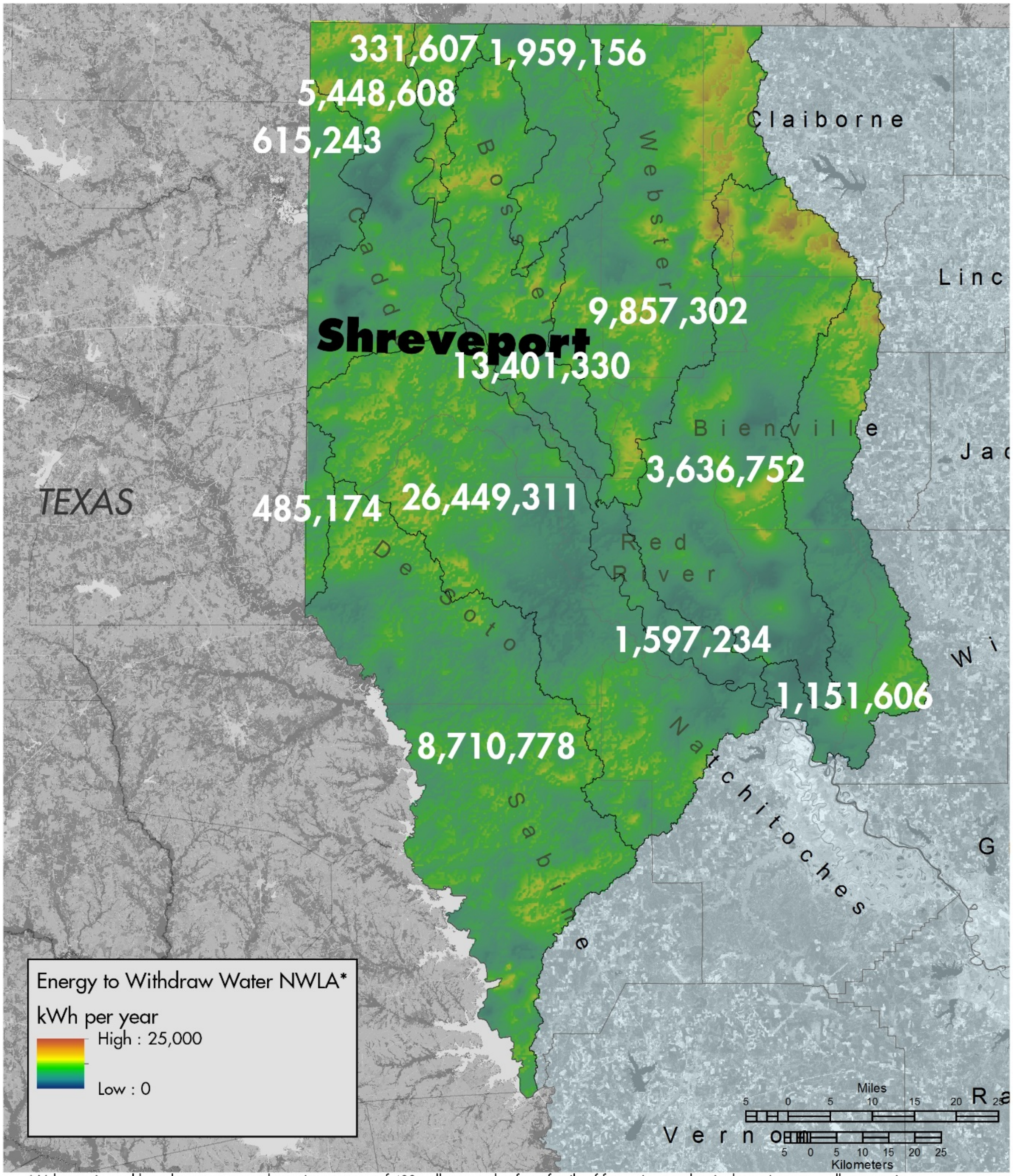
The Bayou Pierre hydrologic unit, which includes much of the area of Shreveport, the third largest city in Louisiana, requires the highest amount of energy in the study area to meet its freshwater needs. The total energy consumption to extract and treat fresh water within the unit is nearly evenly split between public supply systems and individual domestic wells (Figure 31). A similar division of surface water and groundwater usage is observed in the other hydrologic units of the Shreveport area, Red Chute Bayou and Loggy Bayou. Outside of these units, the use of domestic water wells becomes more dominant, particularly in the northern and southern portions of the study area (Figure 32). This is likely due to the dispersed population in these areas, reducing the viability of a centralized water collection system.



Data Source: Lousiana Department of Natural Resources; Lousiana Department of Health and Hospitals; U.S. Environmental Protection Agency

Figure 32: NWLA annual drinking water treatment energy used by public water supply systems.

Estimated Annual Energy Costs to Withdraw Water from Domestic Wells



* Values estimated based upon average domestic water use of 400 gallons per day for a family of four using an electric domestic water well pump using 1.16 kwh per day for each 10 feet of water lift

Data Source: Lousiana Department of Natural Resources; Lousiana Department of Health and Hospitals; U.S. Environmental Protection Agency

Figure 33: NWLA estimated annual energy consumption to withdraw water from domestic wells.

A number of larger public water supply systems (those consuming more than 1 million kWh of power annually) are located throughout the study area, although none are located in the eastern and southern reaches of the study area. The public water supply systems in the study area draw from both surface water and groundwater sources, with the surface water being drawn largely from the Red River alluvial region and the Toledo Bend Reservoir.

The patterns in the amount of energy expended to treat wastewater are similar to those observed in the public supply systems in the region, with the urban areas expending far more energy than the more rural locations (Figure 33). The location of the wastewater treatment plants is driven by the need for a large population center to support and the presence of a waterway of sufficient size into which to release the treated water. The largest wastewater plants are located in the cities of Shreveport and Bossier City on the Red River and the City of Minden located just north of Lake Bistineau. Fewer small wastewater treatment plants are spread throughout the rural areas serving smaller towns and population centers.

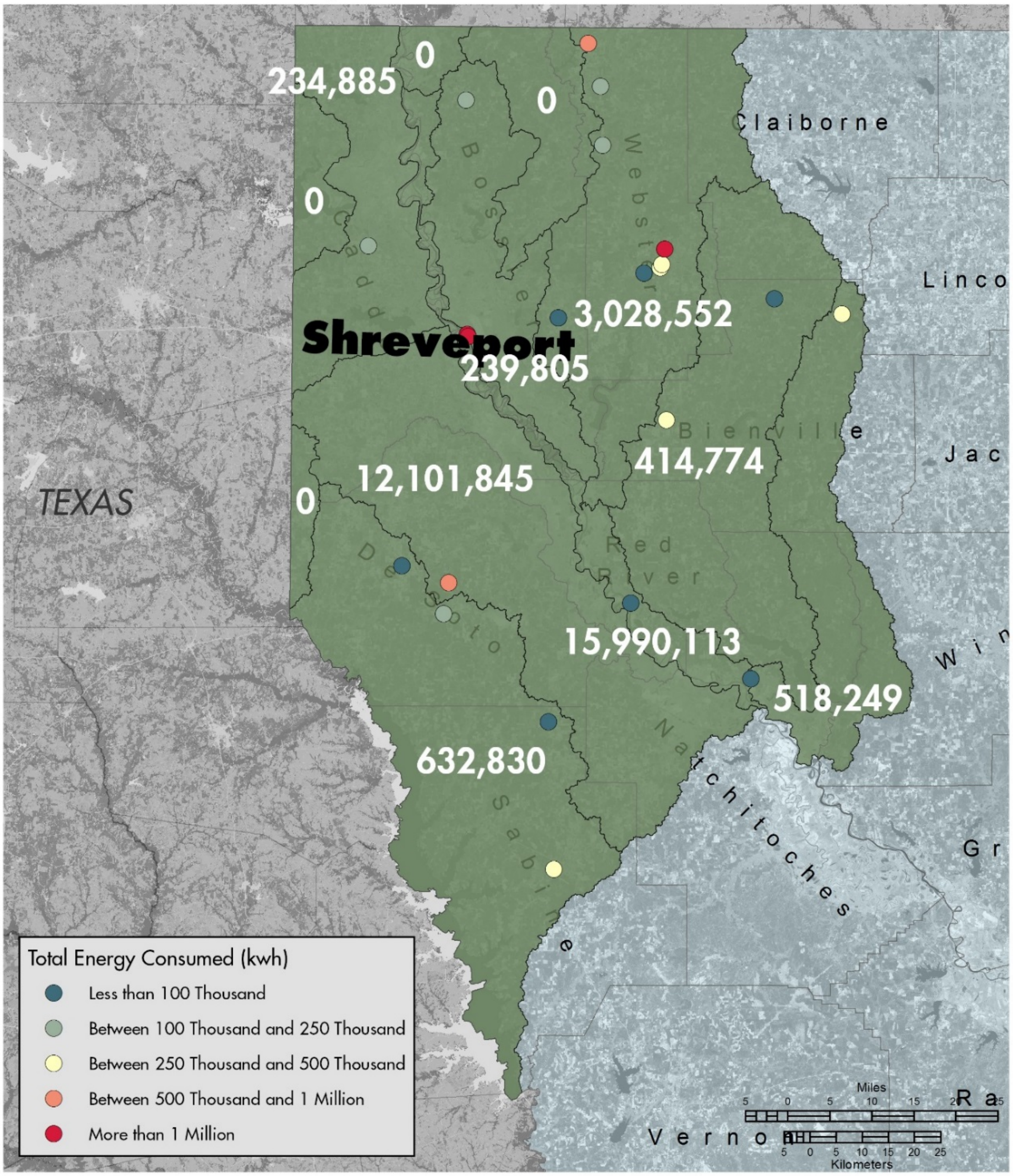
Water Quality Impacts on Fresh Water Availability

Water quality impacts the availability of surface water in the NWLA study area. Streams and lakes in most of the watersheds of the SWLA study area are listed as impaired under Clean Water Act Section 303(d). A map of the impaired surface water bodies is shown in Figure 34. More study is needed to determine the amount and usability of these impacted waters. To demonstrate the possible effects of quality impacts on overall water supply in the NWLA study area, the water budget was recalculated to show the impacts of a 10% reduction in surface water supply. Results of this exercise are shown in Table 22.

Table 22: Northwest study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Reduced Water Inflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
McKinney	27,286	24,720	2,565	-9.4%
Middle Red Coushatta	164,445	148,746	15,699	-9.5%
Loggy Bayou	1,228,754	1,108,746	120,008	-9.8%
Red Chute	573,459	517,988	55,471	-9.7%
Bodcau	399,551	360,815	38,737	-9.7%
Bayou Pierre	1,701,556	1,540,694	160,862	-9.5%
Saline Bayou	793,224	715,554	77,670	-9.8%
Black Lake Bayou	1,755,488	1,583,321	172,166	-9.8%
Cross Bayou	746,167	674,617	71,551	-9.6%
Caddo Lake	221,563	199,964	21,599	-9.7%
Middle Sabine	63,702	57,686	6,016	-9.4%
Toledo Bend Reservoir	1,678,171	1,515,244	162,927	-9.7%
Total	**9,353,364**	**8,448,094**	**905,270**	**-9.7%**

Annual Wastewater Treatment Energy Consumption
by Treatment Plant Size



Data Source: U.S. Environmental Protection Agency

Figure 34: NWLA annual wastewater treatment energy consumption by treatment plant size.

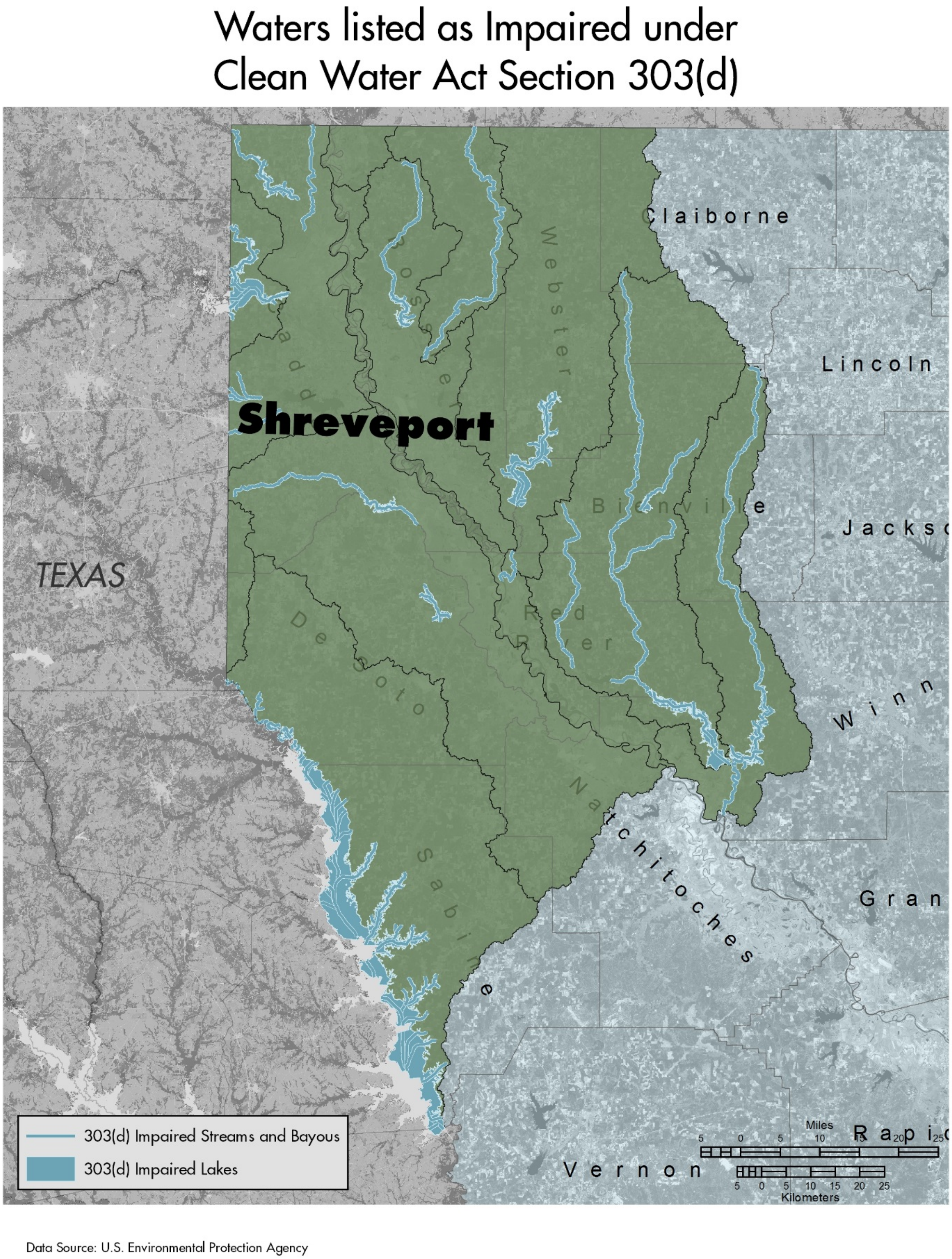


Figure 35: NWLA waters listed as impaired under Clean Water Act Section 303(d).

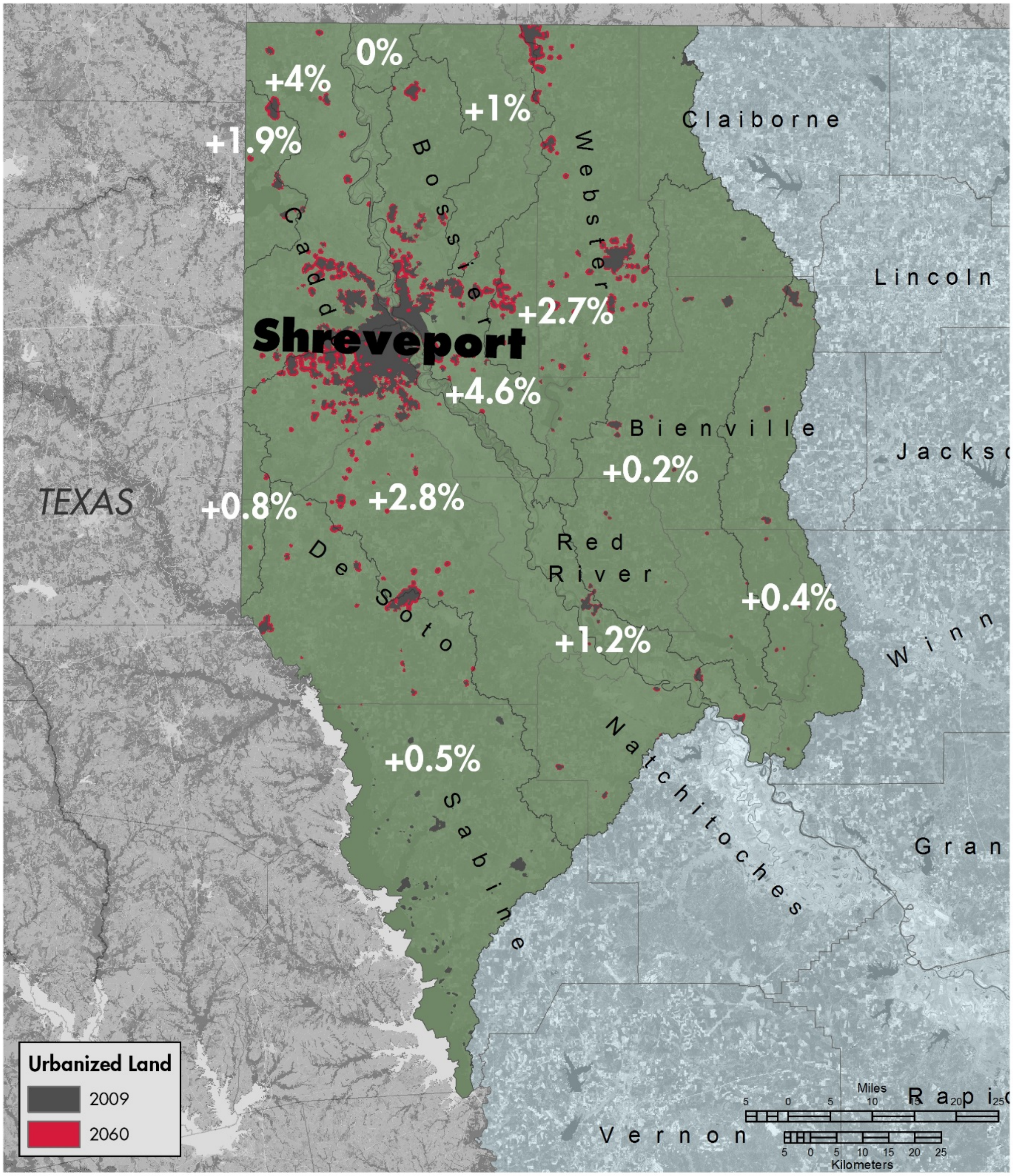
Future Scenarios

For this research, future water use in the NWLA study area is modeled based upon future population growth and urban development. The urban growth model used for this study reveals much lower predicted levels of urbanization in northwest Louisiana than seen in either the southeast Louisiana study area or the southwest Louisiana study area. While the City of Shreveport is expected to increase in size at a rate consistent with that of Baton Rouge, urban growth in Bossier City is expected to be greater than city of Shreveport. Growth in the surrounding hydrologic units is expected to be minimal. In several of the outer units, the expected areal growth is 1% or less (Table 23). As a result, it is anticipated that the impacts of urbanization on both groundwater and surface water units will be minimal within the northwest study area (Figure 35). If it is assumed again that urbanization progresses such that development results in 75% to 100% impervious surface, there is a slight increase in total available water due to reduced evapotranspiration. Ultimately, however, this excess water is predicted to end up in the region's surface water units. Overall, the moderate levels of anticipated population growth are expected to have minimal impacts on the overall water budget of the region. Other factors, such as future oil and gas development, certainly have the potential to impact the overall water budget much more significantly. Increased energy development could potentially result in both increased water usage by industry as well as an influx of population.

Table 23: NWLA total water balance change under future urbanization scenario

Hydrologic Unit	Change in Groundwater Input (acre-feet/year)	% Change in Groundwater Input	Change in Surface Water Input (acre-feet/year)	% Change in Surface Water Input
McKinney	0	0.0%	0	+0.0%
Middle Red Coushatta	-4	-0.1%	316	+0.2%
Loggy Bayou	-56	-0.2%	8,736	+0.7%
Red Chute	-122	-0.7%	2,141	+0.4%
Bodcau	-19	-0.2%	790	+0.2%
Bayou Pierre	-620	-0.7%	13,392	+0.8%
Saline Bayou	-5	0.0%	791	+0.1%
Black Lake Bayou	-7	0.0%	1,287	+0.1%
Cross Bayou	-257	-0.8%	6,778	+0.9%
Caddo Lake	-18	-0.3%	582	+0.3%
Middle Sabine	-6	-0.2%	118	+0.2%
Toledo Bend Reservoir	-34	-0.1%	3,237	+0.2%

Projected Urban Growth in Northwest Louisiana Study Area (2009-2060)



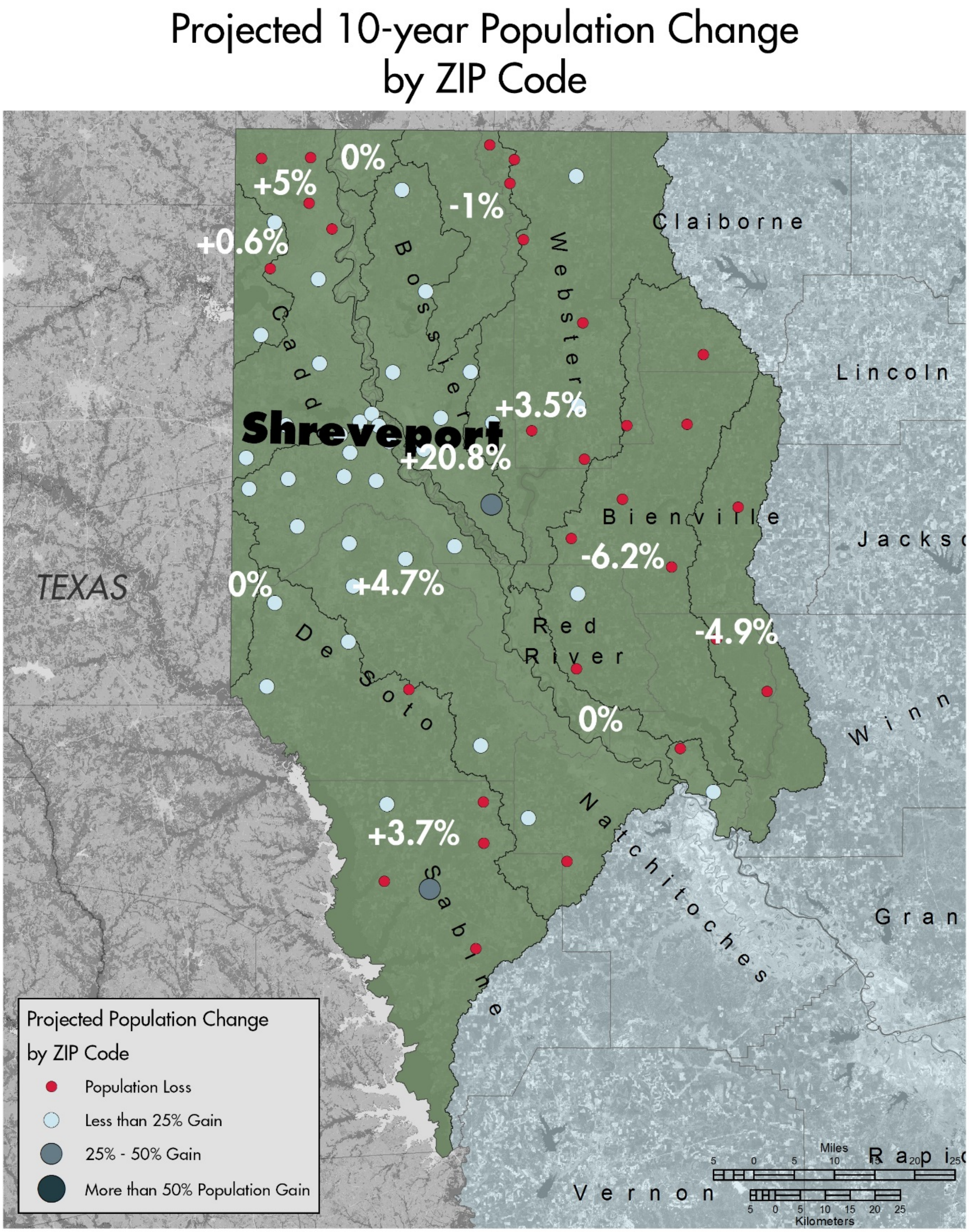
Data Source: North Carolina State University Biodiversity and Spatial Analysis Center

Figure 36: NWLA projected urban growth (2009-2060).

Despite the large growth projections predicted for the Shreveport area, located largely within the Red Chute hydrologic unit, the total change in the volume of water withdrawn for public supply and rural domestic supply is not as significant as that seen in the other two study areas (Table 24). This is likely due to the lower base population of the Shreveport metropolitan area as well as the projected loss of population in most of the ZIP code areas outside of Shreveport and its immediate environs (Figure 36).

Table 24: NWLA total water balance change under urbanization and population growth scenarios

Hydrologic Unit	Change in Groundwater Output (acre-feet/year)	% Change in Groundwater Output	Change in Surface Water Output (acre-feet/year)	% Change in Surface Water Output
McKinney	0	0.0%	0	0.0%
Middle Red Coushatta	0	0.0%	0	0.0%
Loggy Bayou	261	+0.9%	0	0.0%
Red Chute	524	+2.8%	0	0.0%
Bodcau	-8	-0.1%	0	0.0%
Bayou Pierre	186	+0.2%	0	0.0%
Saline Bayou	-58	-0.4%	0	0.0%
Black Lake Bayou	-129	-0.4%	-16	0.0%
Cross Bayou	90	+0.3%	2,440	+0.3%
Caddo Lake	0	0.0%	2	0.0%
Middle Sabine	0	0.0%	0	0.0%
Toledo Bend Reservoir	85	+0.2%	130	0.0%



Data Source: Economic Modeling Specialists, International; Lousiana Economic Development

Figure 37: NWLA projected 10-year population change by ZIP code.

Southeast Louisiana Study Area

The southeast study area includes a portion of the Mississippi River as well as much of the Southern Hills Aquifer System, which extends from the northern limit of Vicksburg, Mississippi to Baton Rouge, Louisiana. This aquifer is composed of thirteen independent aquifer units that make up the overall system and serves as the source of drinking water for Baton Rouge (Table 25). Baton Rouge, one of the most densely populated cities in Louisiana, (Figure 37) is heavily dependent on the Southern Hills Aquifer System for its water supply (Figure 38). The USEPA has designated this aquifer as a sole-source aquifer for ten parishes in southeastern Louisiana. All of the public water supplied in the Baton Rouge area was groundwater while several industrial facilities, primarily located along the Mississippi River, also utilize groundwater resources for both drinking water and industrial processes (Heywood & Griffith, 2013; Sargent, 2010). Outside of the densely populated core of the city, groundwater supplies approximately 84% of agricultural water use in the study area. Extensive groundwater withdrawals in the Baton Rouge area have resulted in the development of cones of depression beneath the industrial groundwater and public water supply wells that have begun to accelerate the infiltration of salt water into the freshwater sand underlying Baton Rouge. This accelerated saltwater intrusion has the potential to reduce the available groundwater available for consumption and other industrial and agricultural uses. Surface water resources in the southeast study area, particularly in the Baton Rouge area, are dominated by industrial use, although some surface water is used for livestock in the rural areas around the city (White & Prakken, 2015).

Table 25: SELA population, public and domestic water demand summary

Hydrologic Unit	Number of Households	Estimated Freshwater Demand (acre-feet/year)	Number of Public Supply Systems	Population Served	Number of Domestic Water Wells
Lower Mississippi-Baton Rouge	479	215	0	0	9
Tickfaw	37,618	16,855	45	62,925	3,466
Bayou Sara-Thompson	22,060	9,884	22	30,579	293
Amite	213,926	95,851	49	663,741	3,155

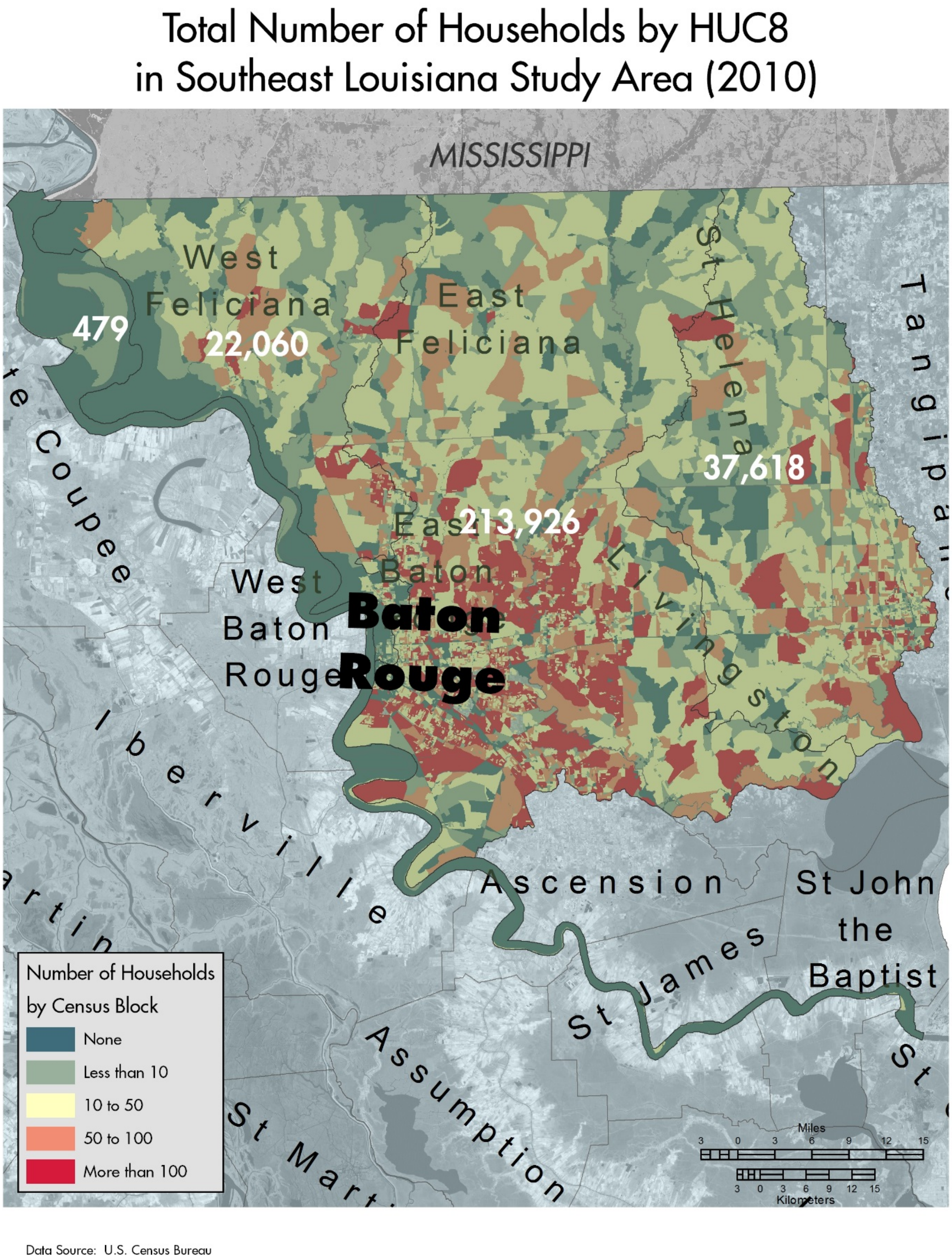
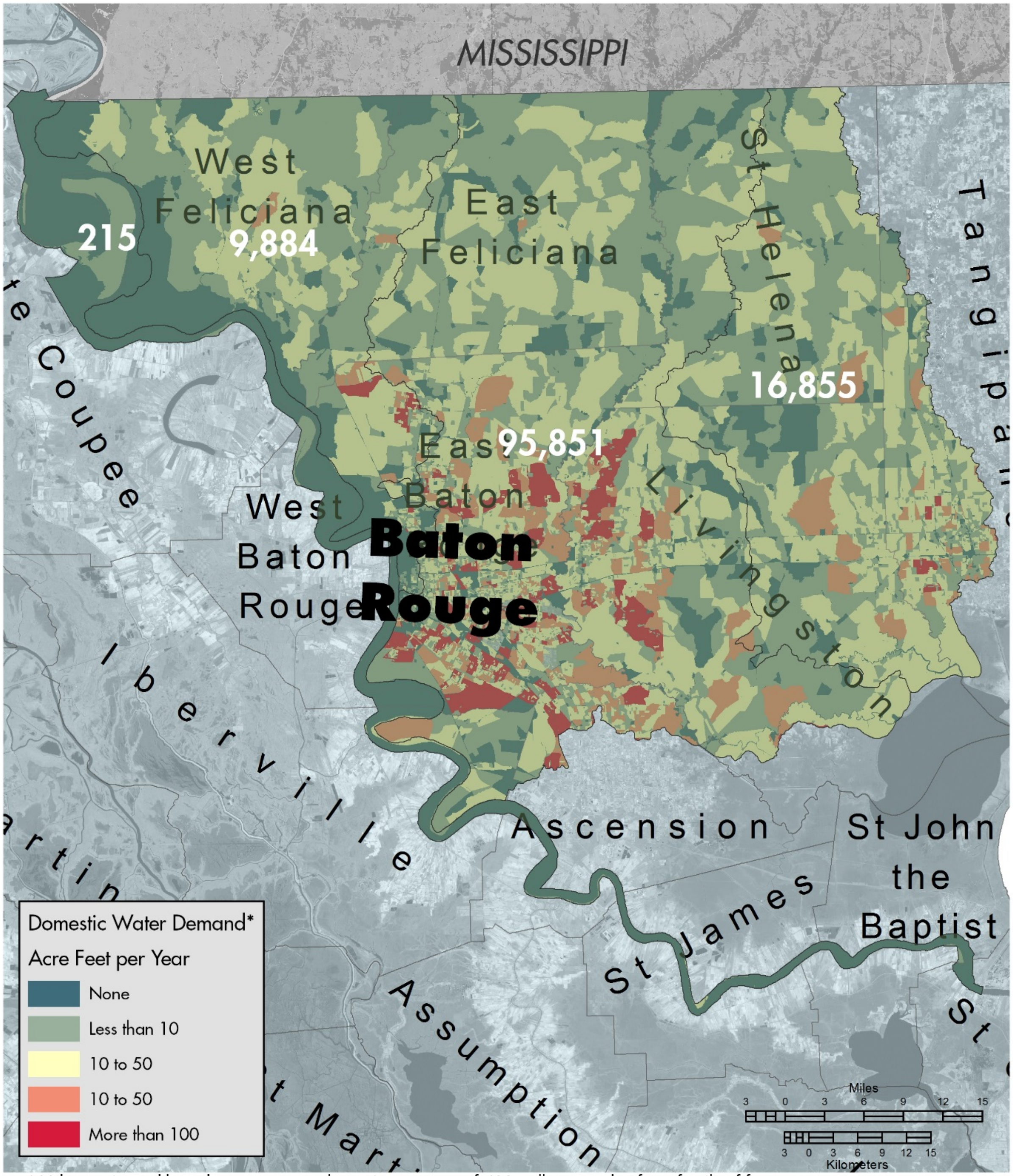


Figure 38: SELA total households by HUC8.

Estimated Annual Household Demand for Fresh Water by HUC8 (2010)



* Values estimated based upon average domestic water use of 400 gallons per day for a family of four

Data Source: U.S. Census Bureau

Figure 39: SELA domestic water demand by HUC8 (2010).

GEOLOGY OF THE SOUTHEAST STUDY AREA

Aquifers containing fresh water in the Baton Rouge area (Figure 39) are generally part of the Southern Hills Regional Aquifer System and include the Mississippi River Alluvial Aquifer, the shallow sands of the Baton Rouge area, the upland terrace aquifer, the “400-foot” sand, “600-foot” sand, “800-foot” sand, “1,000-foot” sand, “1,200-foot” sand, “1,500-foot” sand, “1,700-foot” sand, “2,000-foot” sand, “2,400-foot “sand, and “2,800-foot” sand of the Baton Rouge area and the Catahoula Aquifer (Heywood and Griffith, 2013). The Mississippi River Alluvial Aquifer and the shallow sands of the Baton Rouge area are the shallowest aquifers in the Baton Rouge area. The Mississippi River Alluvial Aquifer is composed of continuous 200 to 600 foot thick deposits of sand and gravel, stratigraphically above deposits of Pliocene and Pleistocene age in the Baton Rouge area (Kuniansky et al., 1989). Deeper aquifers in the Baton Rouge area include aquifers that are named for their depth of occurrence in the Baton Rouge industrial district and the Catahoula Aquifer. Although the Catahoula Aquifer contains fresh water in some areas, it is generally too deep and contains too much salt water to be an economically viable water resource in the Baton Rouge area (Heywood and Griffith, 2013). Freshwater aquifers in the Baton Rouge area range in composition from very fine to coarse sand with some pea-to-cobble-sized gravel (Griffith, 2003) and are sufficiently permeable to yield economically substantial quantities of water to wells. Vertical groundwater flow is limited by confining units composed of material ranging from solid clay to sandy and silty clay (Heywood and Griffith, 2013).

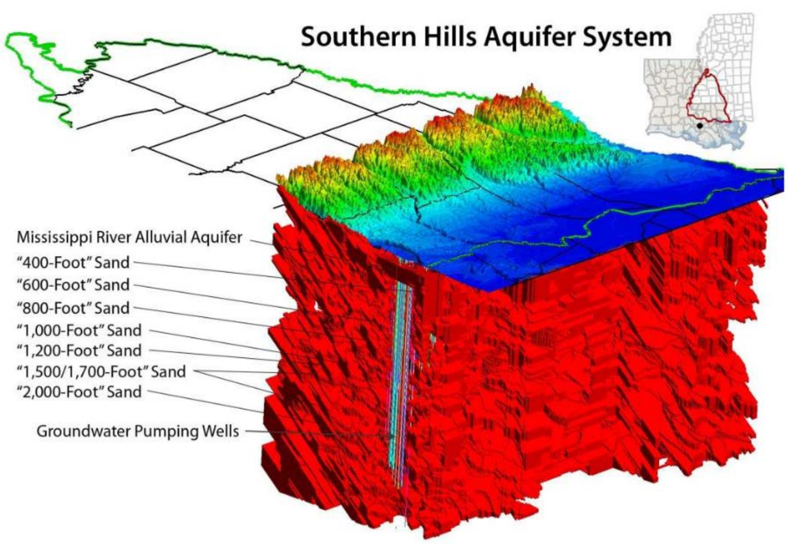


Figure 40: Geological architecture of the aquifers in the SELA study area (Tsai, 2013).

The Southern Hills Regional Aquifer System is the primary source of water for public and domestic use in 10 parishes of southeastern Louisiana. The aquifer system sediments dip and thicken toward the Gulf of Mexico, and generally range in age from Pleistocene or Pliocene at the top to Miocene at the base. The system extends from the northern limit of the recharge area in the vicinity of Vicksburg, Mississippi, southward approximately to the Baton Rouge fault in the Baton Rouge area and the southern part of the eastern Florida Parishes of southeastern Louisiana (Heywood and Griffith, 2013).

In southeastern Louisiana, the aquifer system has been divided into as many as 13 aquifer units that are recognized to decrease in number northward where aquifer units coalesce because many of the separating clay layers disappear or are no longer mappable, or where younger formations in the geologic sequence pinch out in the updip section. Although the system has been locally divided into many aquifer units, these aquifers are recognized to be interdependent, collectively forming the Southern Hills Regional Aquifer System.

The Baton Rouge fault zone acts as a barrier to groundwater movement and is approximately the southern limit of fresh water in the system. South of the fault zone, water within the formations that compose the aquifer system is saline and not usable for potable water. The western extent of the Southern Hills Aquifer System is marked by a zone of saline water within the Pliocene and Miocene sediments that lie beneath the Mississippi River alluvial valley. This zone represents the limit of flushing of saline water from the Pliocene and Miocene aquifers by groundwater moving southeasterly and southwesterly toward the Mississippi River alluvial valley. For the purposes of this study, which focuses on the water resources of the Baton Rouge area, the hydrologic divide running north-south across the center of Tangipahoa Parish was chosen as the boundary of the study area, as water on the other side of that divide would have negligible effect on water availability in the Baton Rouge area, which includes East and West Baton Rouge, Pointe Coupee, and East and West Feliciana Parishes.

Water within the aquifer system moves very slowly, ranging from a few tens of feet per year to several hundreds of feet per year (Heywood and Griffith, 2013). A summary of the hydraulic characteristics of the Southern Hills Aquifer System is presented in Table 26. The “400-foot", "600-foot", and “800-foot” sands are interconnected in many places. Sands of the “400-foot" sand are most continuous, and sands of the “800-foot” sand are the least continuous.

The “1,500-foot” sand and “2,000-foot” sand, like other freshwater aquifers in the study area, generally dip and thicken to the south and consist of single or multiple 65- to 95-ft thick intervals of fine to medium sand and 100 to 300 ft of medium sand. Where the aquifers contain multiple sand intervals, the intervals are separated by clays. The “1,500-foot” sand is about 1,500 ft deep beneath Baton Rouge north of the Baton Rouge Fault, but is displaced deeper south of the fault. The “1,500-foot” sand is continuous throughout the study area except in parts of Avoyelles, East and West Baton Rouge, Livingston, and Point Coupee Parishes and in most of Mississippi. The “2,000-foot” sand is about 2,000 ft deep beneath Baton Rouge north of the Baton Rouge Fault, but is also displaced deeper south of the fault. The “2,000-foot” sand is continuous throughout the study area.

Table 26: Hydraulic characteristics of the Southern Hills Aquifer System

Aquifer Unit	Min Thickness (ft)	Max Thickness (ft)	Mean Thickness (ft)	Thickness Source	Hydraulic Conductivity (ft/day)	Hydraulic Conductivity Source
“800-foot” sand	50	150	100	(Griffith, 2003)	36	(Griffith, 2003)
“1,000-foot” sand	40	90	65	(Griffith, 2003)	n/a	n/a

“1,200-foot” sand	40	150	95	(Griffith, 2003)	119	(Griffith, 2003)
“1,500-foot” sand	65	95	80	(Griffith, 2003)	142	(Griffith, 2003)
“1,700-foot” sand	130	130	130	(Griffith, 2003)	33	(Griffith, 2003)
“2,000-foot” sand	100	300	200	(Griffith, 2003)	175	(Griffith, 2003)
“2,400-foot” sand	50	250	150	(Griffith, 2003)	79	(Griffith, 2003)
“2,800-foot” sand	50	350	200	(Griffith, 2003)	n/a	n/a

Water Balance Results

Overall, the water budget shows a surplus of total water resources (including surface and groundwater) of 1,089,348 acre-feet/year, or about 12.3% of the total water input to the study area (Table 27). Excesses were calculated in three of the four watersheds – Tickfaw, Bayou Sara-Thompson, and Amite (Figure 40). But, due to the magnitudes of the surface and groundwater supply differences (surface water supply in the SELA study area is 13 times greater than the groundwater supply), the overall surplus shown is dominated by the surplus of surface water. The Lower Mississippi River-Baton Rouge hydrologic unit showed an overall water deficit of -14.4%, but this only includes water generated by rainfall within the hydrologic unit, and does not include the flow of the Mississippi River from upriver. The mean annual flow of the Mississippi River at Baton Rouge USGS 07374000 gage, from 2004-2015, was 383,638,642 acre-feet/year.

Table 27: Southeast study area summary of overall water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Lower Mississippi-Baton Rouge	3,333,881	3,813,720	-479,839	-14.4%
Tickfaw	1,403,552	895,899	507,652	+36.2%
Bayou Sara-Thompson	1,386,342	831,533	554,810	+40.0%
Amite	2,700,491	2,193,767	506,725	+18.8%
Total	**8,824,266**	**7,734,919**	**1,089,348**	**+12.3%**

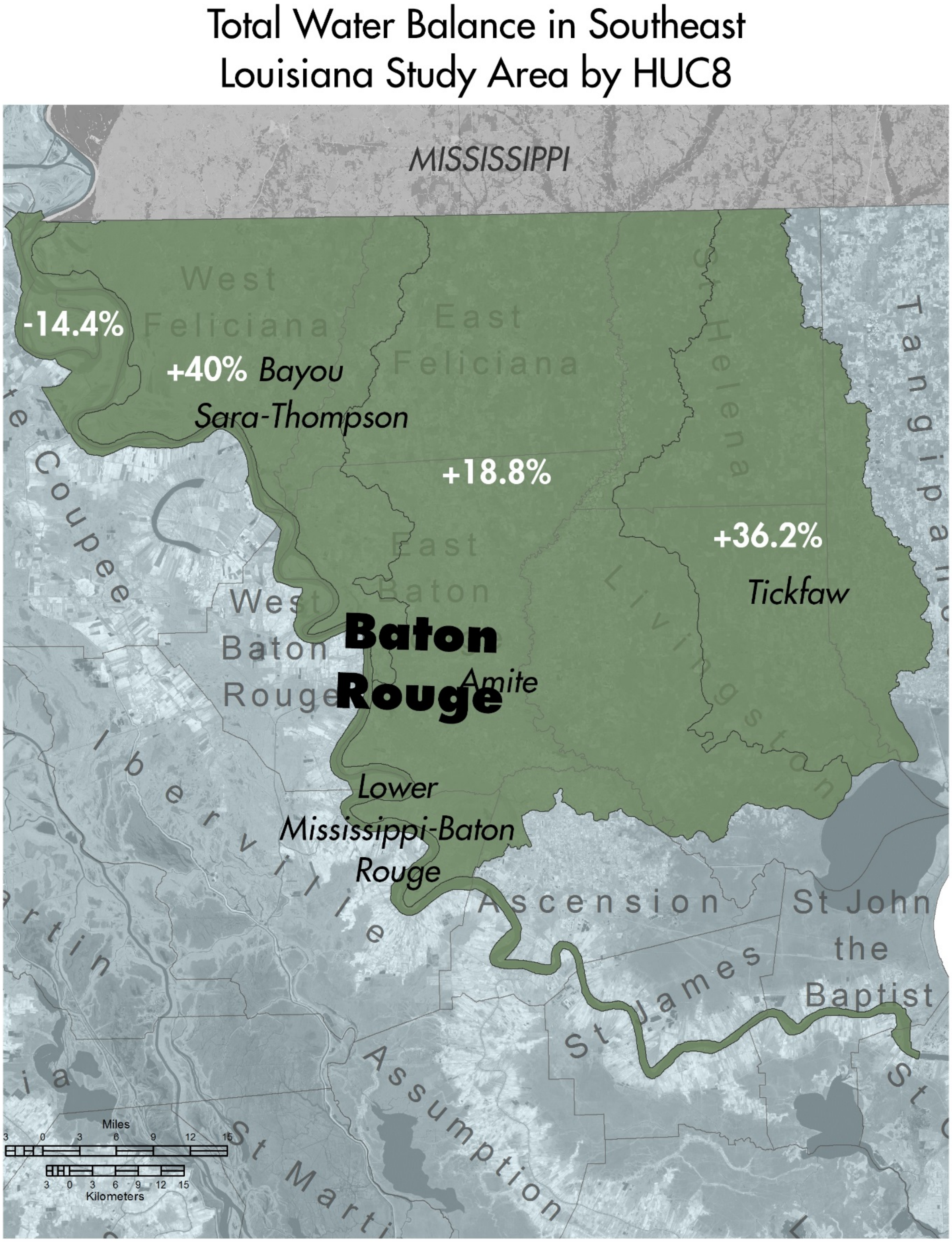


Figure 41: SELA total water balance by HUC8.

In terms of groundwater resources in the Southern Hills Aquifer System within the study area, there is a calculated deficiency of -36,130 acre-feet/year, or -5.7% of the annual groundwater available in the study area portion of the Southern Hills Aquifer System (Figure 41). The groundwater balance for all four watersheds in the SELA study area varies from -49.5% (Bayou Sara-Thompson) to 20.7% (Tickfaw) (Table 28). Industrial withdrawals dominate groundwater use in the Bayou Sara-Thompson watershed, accounting for 63.8% of all groundwater use in the watershed, and 80% of the groundwater deficit for the Bayou Sara-Thompson watershed (Figure 42). Much (89%) of the groundwater withdrawn for industrial use is returned to surface water via return flows. Public supply dominates withdrawals of groundwater in the Amite and Tickfaw watersheds, accounting for 80.2% of all groundwater use in the Amite watershed.

Table 28: Southeast study area summary of groundwater balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Lower Mississippi-Baton Rouge	55,292	52,698	2,594	+4.7%
Tickfaw	206,969	164,051	42,917	+20.7%
Bayou Sara-Thompson	155,182	232,032	-76,849	-49.5%
Amite	212,027	216,819	-4,792	-2.3%
Total	**629,470**	**665,600**	**-36,130**	**-5.7%**

Supplies of surface water resources in the four watersheds show a surplus of 1,125,478 acre-feet/year (Table 29), or 13.7% of the surface water in the study area remains available (Figure 43). Withdrawals of surface water in the Lower Mississippi River-Baton Rouge watershed are dominated by power generation, and account for 74.7% of all surface water used in the watershed. (Figure 44). Twenty-two percent of that water withdrawn for power generation is consumptively used, while 78% of it is returned to surface water via return flows. After consideration of these return flows, only 17.9% of the surface water supply is consumptively used by power generation. There is no significant surface water use in Tickfaw, Bayou Sara-Thompson, and Amite watersheds.

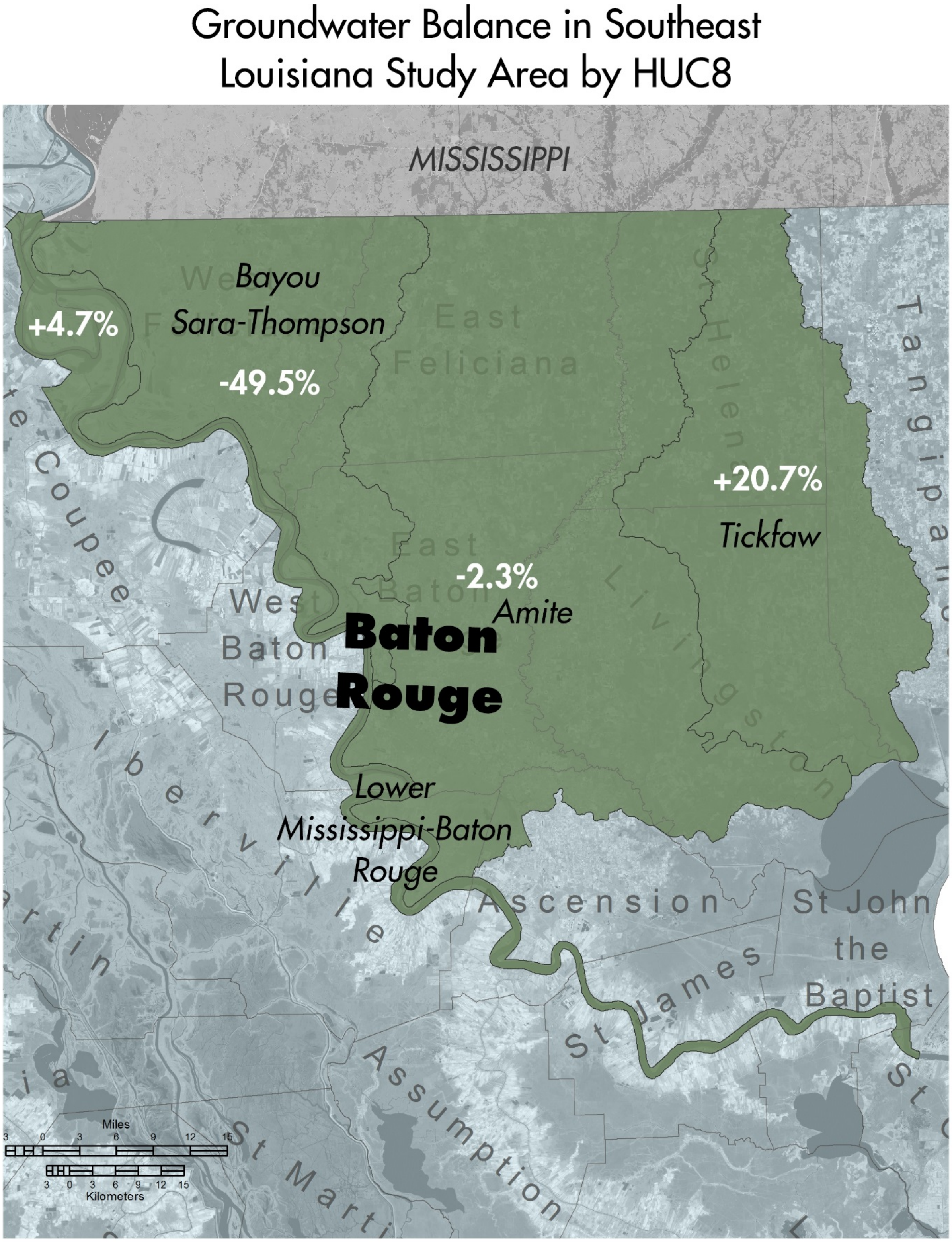


Figure 42: SELA groundwater balance by HUC8.

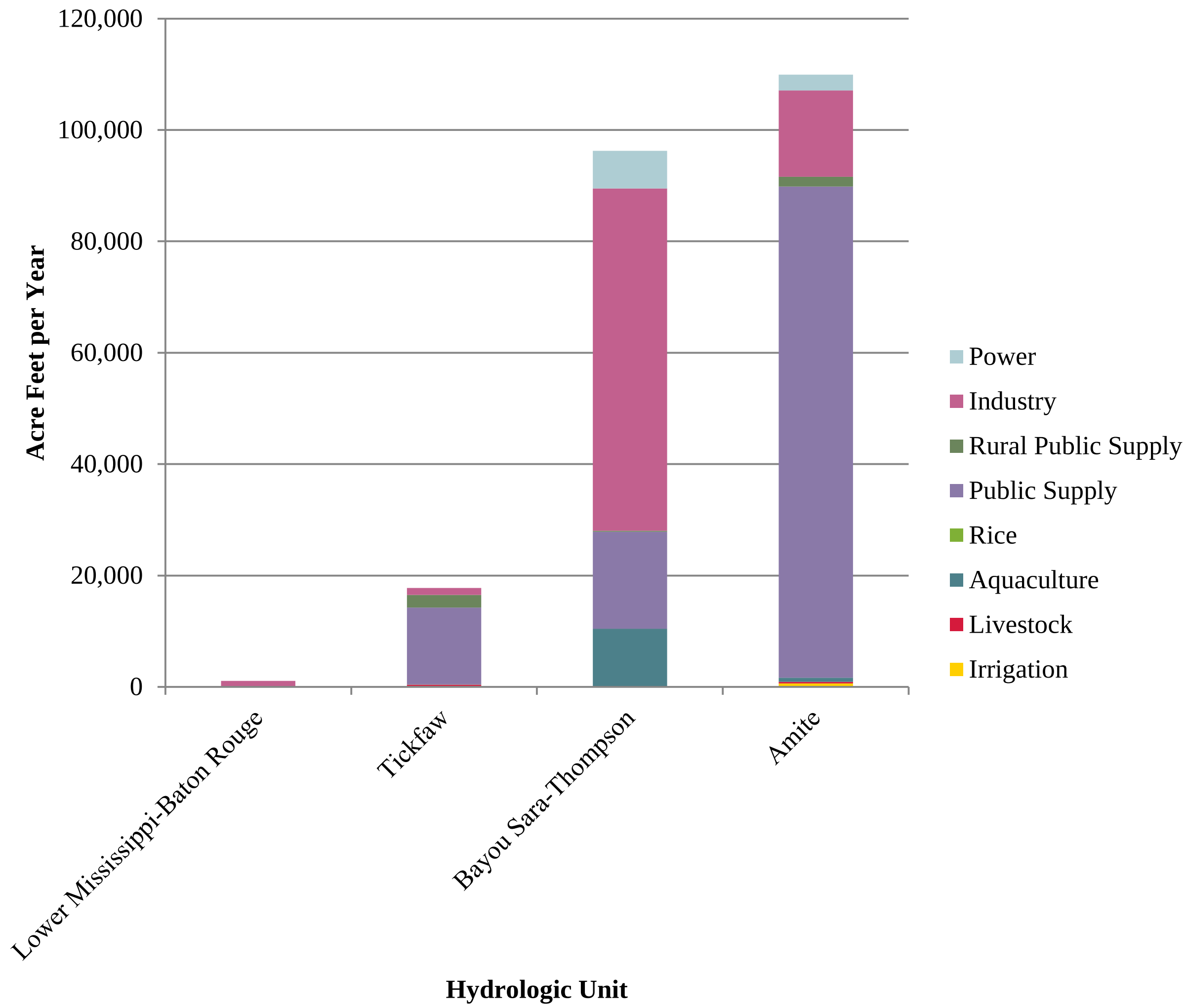


Figure 43: SELA groundwater use by hydrologic unit.

Table 29: Southeast study area summary of surface water balance

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Total Water Outflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Lower Mississippi-Baton Rouge	3,278,589	3,761,022	-482,433	-14.7%
Tickfaw	1,196,583	731,848	464,735	+38.8%
Bayou Sara-Thompson	1,231,160	599,501	631,659	+51.3%
Amite	2,488,464	1,976,948	511,517	+20.6%
Total	**8,194,796**	**7,069,319**	**1,125,478**	**+13.7%**

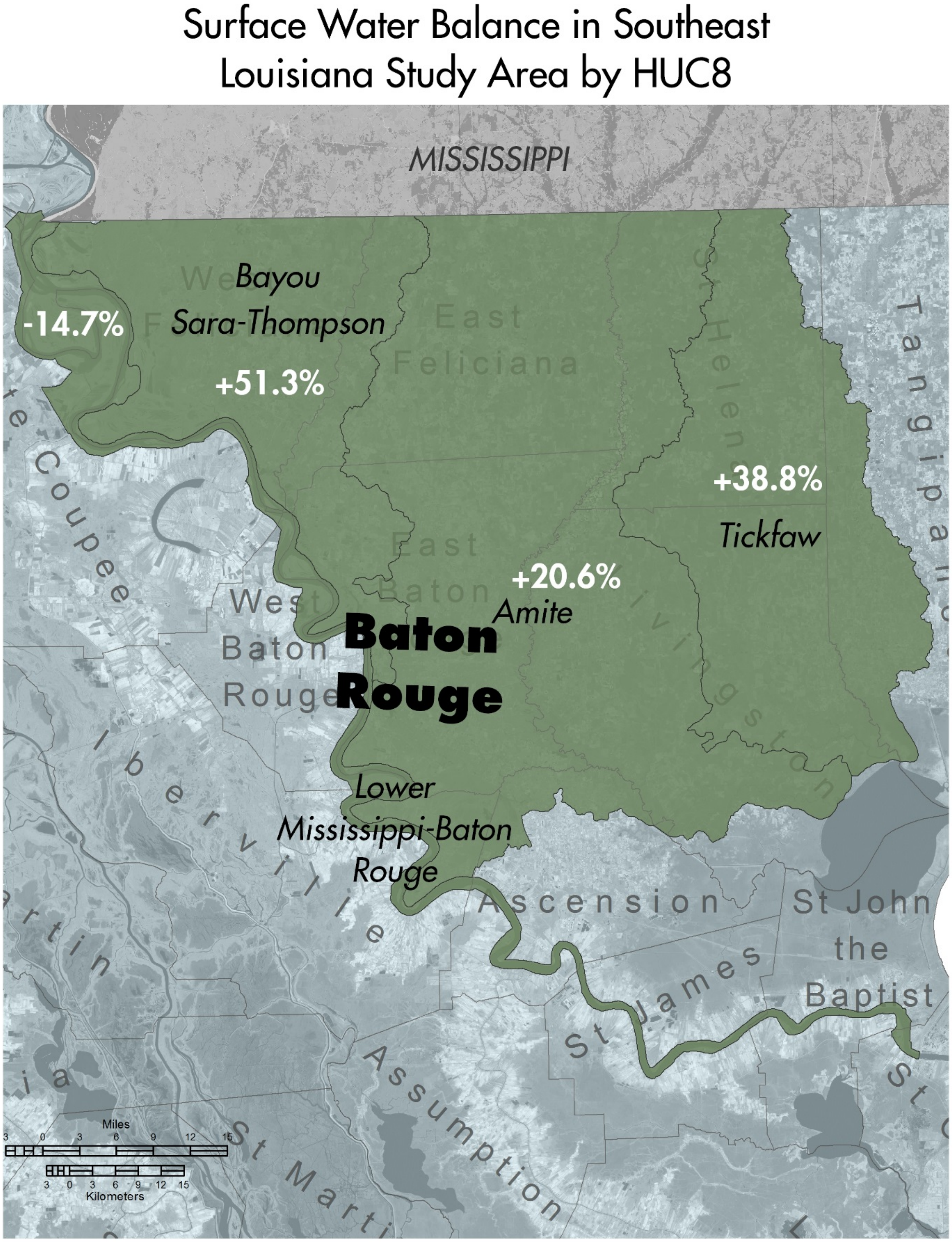


Figure 44: SELA surface water balance by HUC8.

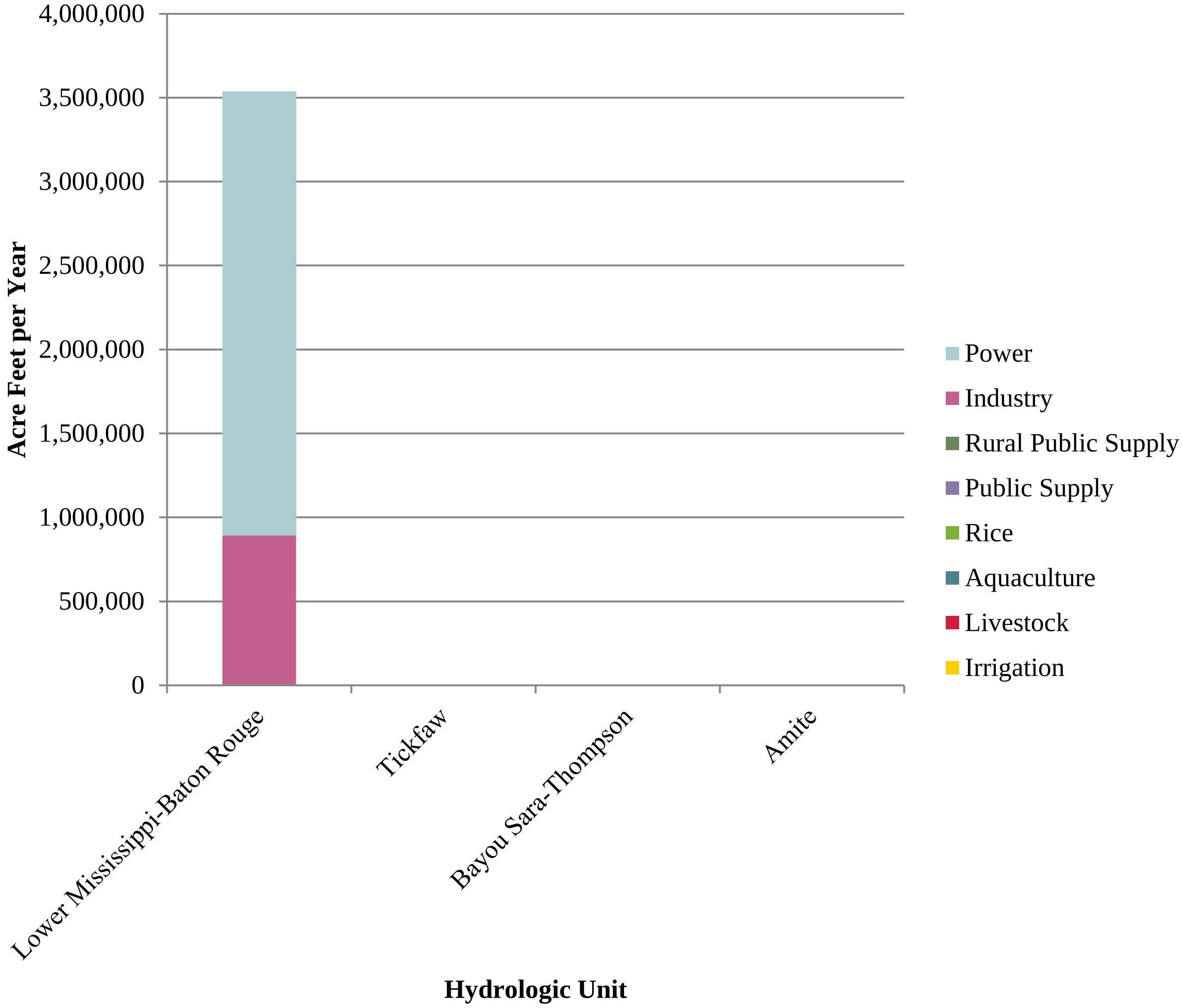


Figure 45: SELA surface water use by hydrologic unit.

Energy Costs

The energy expenditure needed to serve the city of Baton Rouge and the surrounding communities within the Amite hydrologic unit with fresh water is significantly higher than any of the other units in the study area. In fact, the combination of public water supply systems and individual domestic wells in the Amite unit are estimated to consume over 133 million kWh of power annually, the highest combined total in this study. Because of the large concentration of population in these cities, a number of public water supply systems of varying sizes are cited there (Figure 45).

Unlike other large urban areas examined in this study, such as Shreveport and Lafayette, relatively few individual public supply systems serve specific subdivisions, neighborhoods, and communities in the Baton Rouge area. Instead, most of the population is served by a fewer number of large facilities. In contrast, to the immediate east of the Baton Rouge metropolitan area, in Livingston Parish, the population is served by a combination of small, medium, and large water supply systems. Many of the smaller water systems in this area serve individual subdivisions, many of which have been built in the last two decades, particularly in the immediate aftermath of Hurricane Katrina in 2005.

Further to the east, within the Tickfaw hydrologic unit, along the eastern portion of the study area, significantly more energy is expended on individual wells than public supply systems (Figure 46). The Tickfaw unit includes the city of Hammond and several smaller communities along Interstate Highway 55. While several public supply systems are located along this corridor, including one large facility that consumes more than 1 million kWh of electricity annually, significantly more energy is expended drawing water from individual residential wells. In contrast, upriver from Baton Rouge, in the Bayou Sara-Thompson unit, extending into West Feliciana Parish, public supply energy expenditures are evenly divided between publicly supplied water sources and individual domestic wells.

The location of the largest wastewater treatment plants in the southeast study area closely match the location of the large water supply systems, with two located along the Mississippi River in Baton Rouge, one in Livingston Parish, and one located in Hammond, along the southeastern edge of the study area. Each of these plants serves large population centers and is located along a major waterway. The two large Baton Rouge plants discharge into the Mississippi River while the plant in Livingston Parish serves the suburban communities around Denham Springs. Finally, the City of Hammond, located on the Tangipahoa River, is the largest city in the Tickfaw hydrologic unit.

As with the public supply systems, the amount of energy expended to treat and release wastewater within the Amite unit is the highest of any of the units examined in this study (Figure 47). Despite the relatively large size of the Hammond treatment plant, the overall energy consumed within the Tickfaw unit is the smallest in the southeastern study area, with the exception of the unpopulated Lower Mississippi River hydrologic unit. This is due in large part to the fact that each of the other hydrologic units in the study area converge in the City of Baton Rouge and have plants that serve that population. Within the Bayou Sara-Thompson unit, for example, the single large wastewater plant is located at the southern tip of the unit, in Baton Rouge. The majority of this unit is upriver from this point, largely rural, and is not serviced by a wastewater treatment plant.

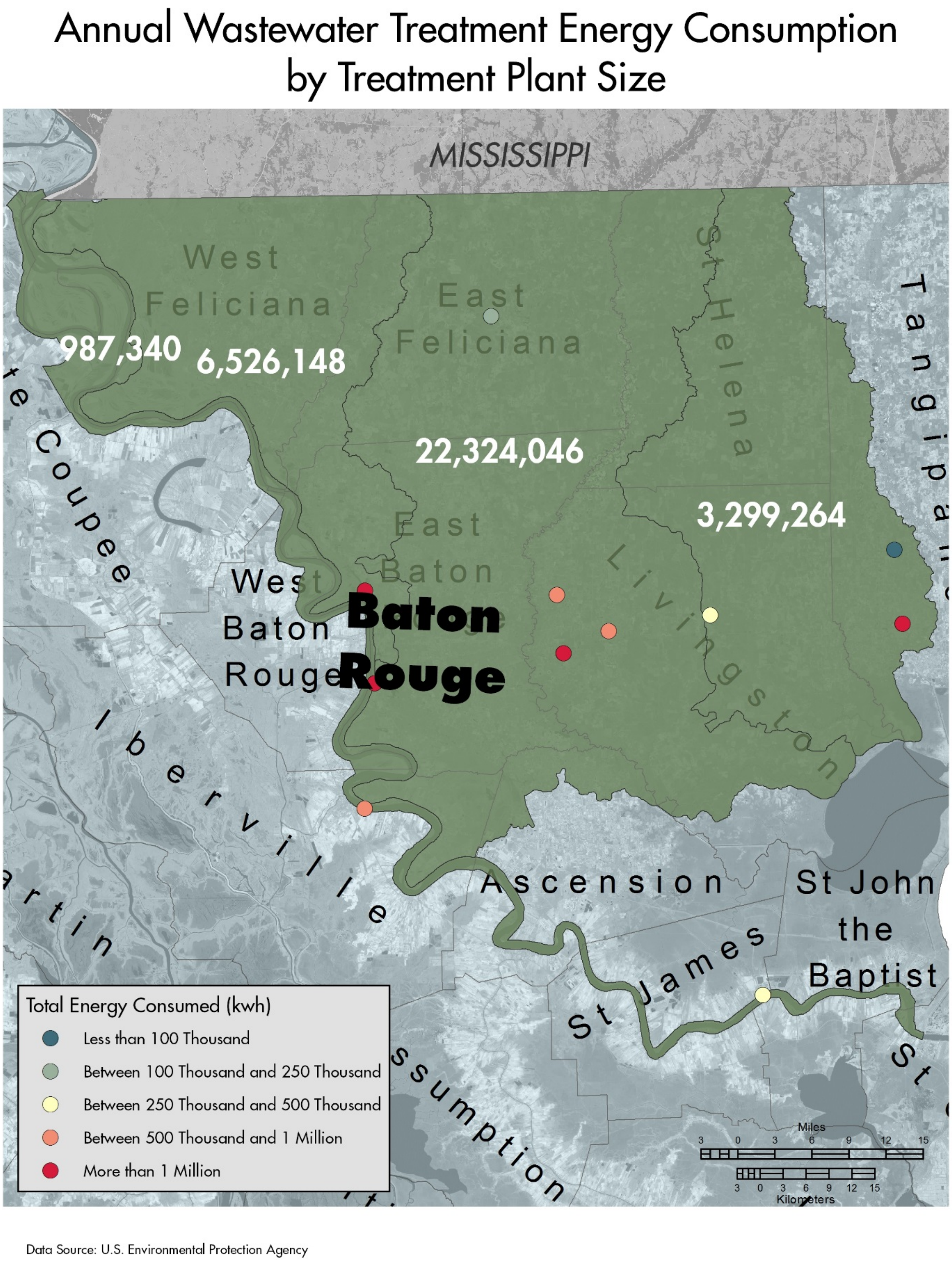


Figure 46: SELA annual drinking water treatment energy used by public water supply systems.

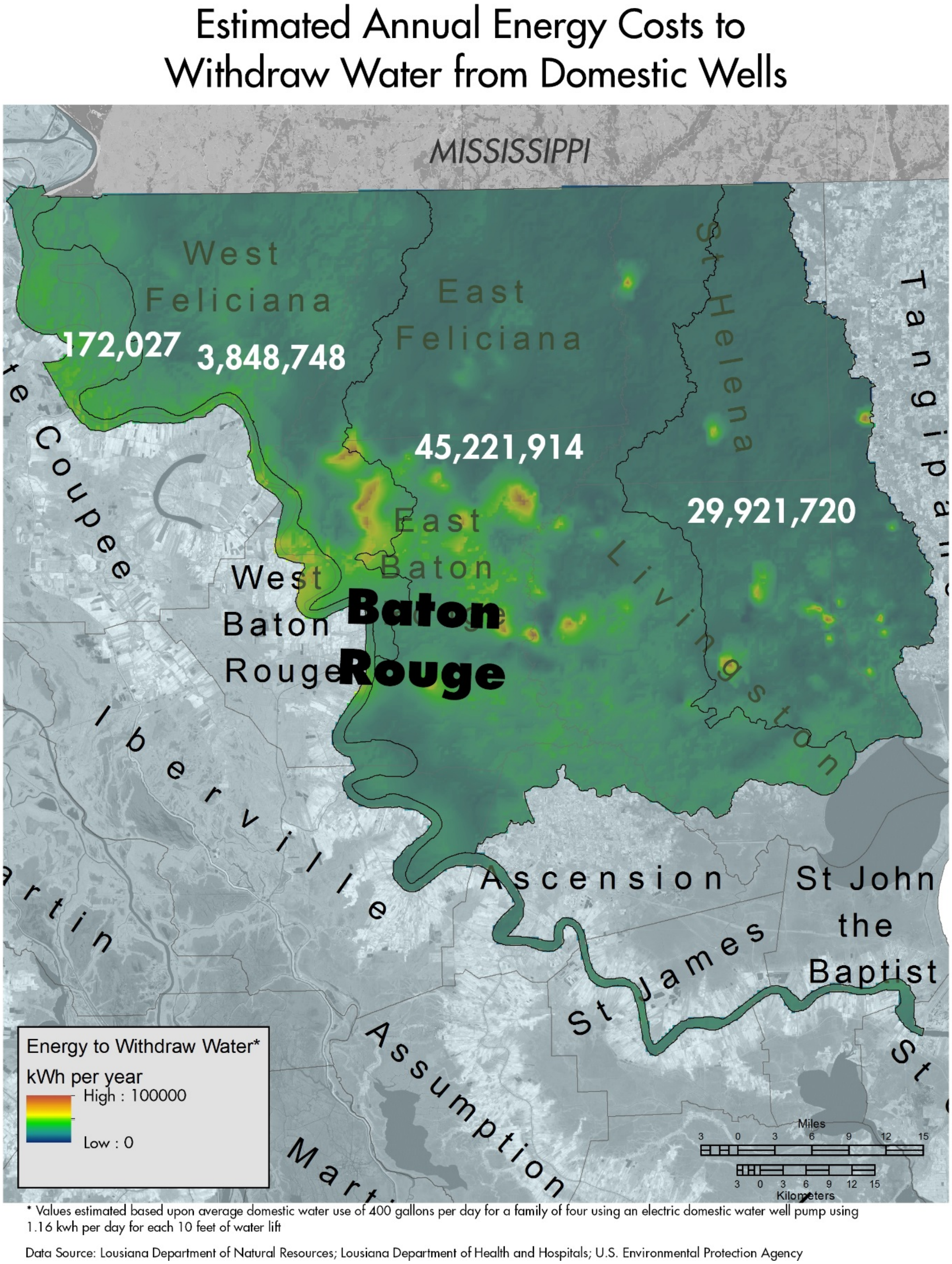


Figure 47: SELA estimated annual energy consumption to withdraw water from domestic wells.

Annual Wastewater Treatment Energy Consumption by Treatment Plant Size

Data Source: U.S. Environmental Protection Agency

Figure 48: SELA annual wastewater treatment energy consumption by treatment plant size.

Water Quality Impacts on Fresh Water Availability

The upstream flow of the Mississippi River is a significant supply of surface water. The mean annual withdrawals for the entire study area (3,537,048 acre-feet/year) would account for only 0.9% of the supply from the Mississippi River. Considerations about surface water, including water quality, delivery, and energy costs to treat and convey it may diminish the usability of this excess supply and require further study. As the study area watersheds discharge surface water to the coastal zone, the minimum ecological flow required to sustain healthy coastal ecosystems should also be considered. Further study is needed to determine the amount of fresh water needed to support this function.

Water quality impacts the availability of surface water in the SELA study area. The cones of depression beneath the industrial groundwater wells and public water supplies have resulted in a pressure imbalance that has begun to accelerate the infiltration of salt water into the freshwater sand underlying Baton Rouge presenting a risk to groundwater supplies. To compound these water quality issues, many streams and lakes in most watersheds of the SELA study area are listed as impaired under Clean Water Act Section 303(d). A map of the impaired surface water bodies is shown in Figure 48. Additional study is needed to determine the amount and usability of these impacted waters. The severity of pollution levels as well as the sensitivity of specific water uses to this pollution has the potential to alter the overall water budget within each hydrologic unit. To demonstrate the possible effects of quality impacts on surface water supply in the SELA study area, the water budget was recalculated to show the impacts of a 10% reduction in surface water supply. Results of this exercise are shown in Table 30.

Table 30: SELA study area summary of overall water balance, including impacts of 10% impaired quality on surface water usability.

Hydrologic Unit	Total Water Inflow (acre-feet/year)	Reduced Water Inflow (acre-feet/year)	Unallocated Water (acre-feet/year)	Percent Unallocated
Lower Mississippi-Baton Rouge	3,333,881	3,006,023	327,858	-9.8%
Tickfaw	1,403,552	1,283,894	119,658	-8.5%
Bayou Sara-Thompson	1,386,342	1,263,227	123,115	-8.9%
Amite	2,700,491	2,451,645	248,846	-9.2%
Total	**8,824,266**	**8,004,788**	**819,478**	**-9.3%**

Figure 49: SELA waters listed as impaired under Clean Water Act Section 303(d).

Future Scenarios

The City of Baton Rouge is the defining urban feature of the southeast study area. However, as with the other regions, linear development along major highways is expected to drive future urban development. Within the southeast study area, most of the urban growth is anticipated to occur in a linear pattern moving south towards the more suburban Ascension Parish along Interstate 10 and eastward across the study area along Interstate 12. Outside of these corridors and Baton Rouge proper, very little urban development is expected to occur.

With the exception of the Lower Mississippi River itself, the southeast study area is expected to see moderate urbanization occurring over the next 50 years (Table 31), with urban expansion expected to cover 3.4 to 4.5 percent of the hydrologic units in the study area (Figure 49). The Amite unit is expected to see the greatest decline of groundwater due to urban expansion, a value of 1,656 acre feet of water lost due to a lack of groundwater infiltration. This number is very similar to that seen in the Bayou Teche hydrologic unit in the southwest study area. It should be noted, however, that this value still represents a relatively small proportion of the total groundwater inputs in the region.

Table 31: SELA total water balance change under future urbanization scenario

Hydrologic Unit	Change in Groundwater Input (acre-feet/year)	% Change in Groundwater Input	Change in Surface Water Input (acre-feet/year)	% Change in Surface Water Input
Lower Mississippi-Baton Rouge	-116	-0.2%	6,268	+0.2%
Tickfaw	-828	-0.4%	6,925	+0.6%
Bayou Sara-Thompson	-231	-0.1%	5,868	+0.5%
Amite	-1,656	-0.8%	16,250	+0.7%

While population growth has a spatial component that impacts the inputs to the water budget, there are also societal impacts in the form of increased demand for fresh water that are expected to impact the outputs to the budget. In the case of the Baton Rouge area, population projections indicate that there are expected to be modest increases in population in the City of Baton Rouge, and some areas of population decline (Figure 50). However, the greatest population increases are predicted to occur in the areas outside of the city proper, including those suburban areas to the east and southeast (Table 32). When the impacts of this population growth are entered into the water balance equation, we see that groundwater withdrawals for public water supplies, including rural supply systems, have a fairly significant effect on the water balance. Note that the delineation of the Lower Mississippi River hydrologic unit does not include any population centers. Thus, the public supply withdrawals taken from the river (approximately 6,329 acre feet per year) are not included in the population change estimates.

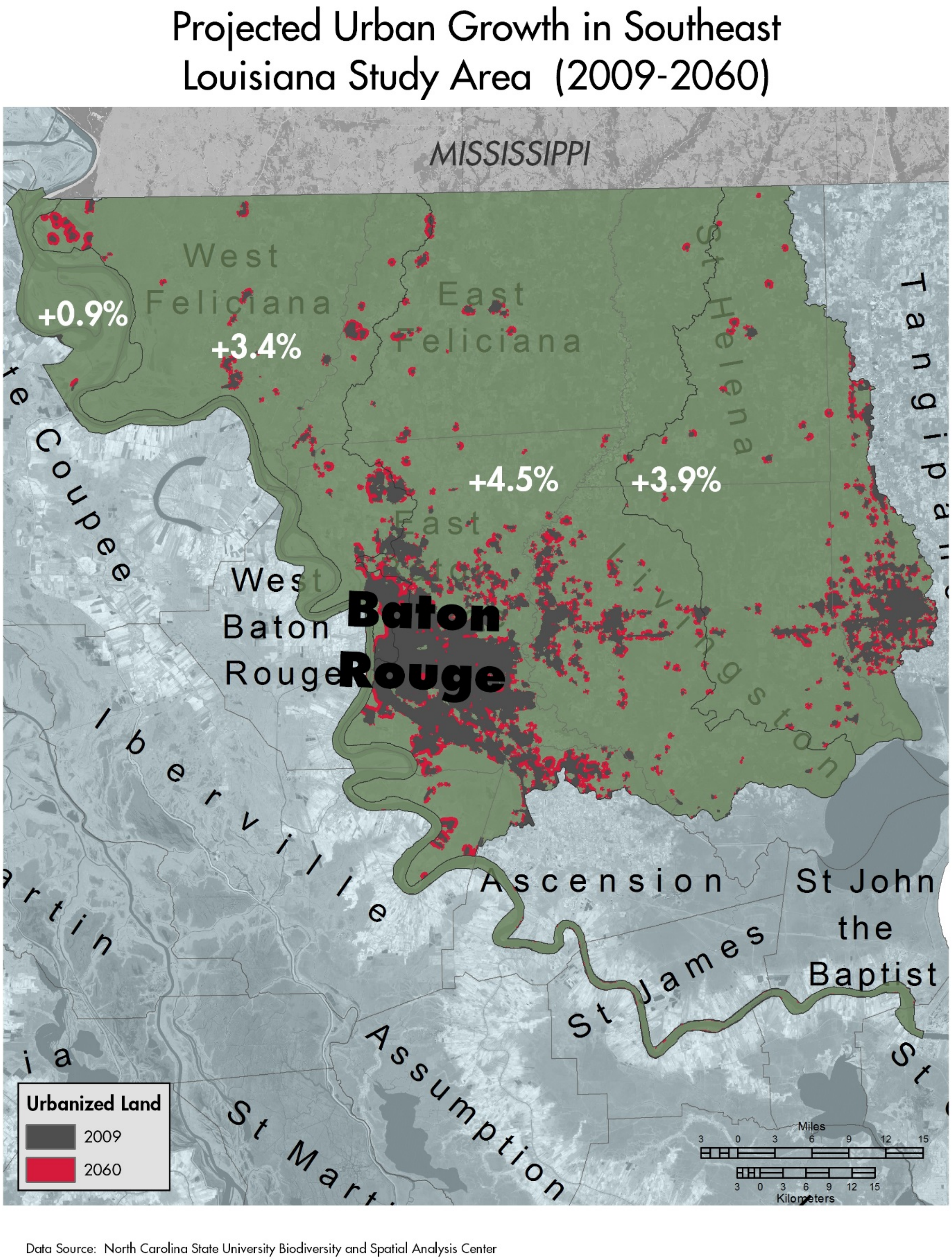


Figure 50. SELA projected urban growth (2009-2060).

Projected 10-year Population Change by ZIP Code

Data Source: Economic Modeling Specialists, International; Lousiana Economic Development

Figure 51: SELA projected 10-year population change by ZIP code.

Table 32: SELA total water balance change under urbanization and population growth scenarios

Hydrologic Unit	Change in Groundwater Output (acre-feet/year)	% Change in Groundwater Output	Change in Surface Water Output (acre-feet/year)	% Change in Surface Water Output
Lower Mississippi-Baton Rouge	0	0.0%	0	0.0%
Tickfaw	2,011	+1.0%	0	0.0%
Bayou Sara-Thompson	1,936	+1.2%	0	0.0%
Amite	7,017	+3.3%	0	0.0%

Conclusions

The assessment framework developed here was used to examine the water balance in each hydrologic unit within the study areas. Due to the total volume of surface water available for use in each of the hydrologic units, the overall water balance remains positive, with inputs exceeding outputs. However, in several hydrologic units across all study areas, groundwater outflow exceeds inflow, resulting in declining groundwater levels. Statewide, the greatest volume of groundwater withdrawal is used for rice irrigation, followed by public supply, and then industry. In terms of surface water withdrawals, power generation and industry are the largest consumers of fresh water. Similar water use patterns were seen in each of the case study areas, having a direct impact on the overall water balance.

WATER USAGE AND SUSTAINABILITY

The sustainability of Louisiana’s water resources is heavily dependent upon the management of water withdrawals and usage. Any water pumped from groundwater and surface water will result in a change in the overall water budget. The water resources assessment has revealed many instances where the removal of water stored in the system exceeds the amount of water recharging the system. Each hydrologic unit was found to have certain unique combinations of water usage, with agriculture and industry often dominating the overall water balance. One thing that all hydrologic units in the study areas have in common is that they require a large amount of drinking water to support their urban and rural population centers. Projections of future population growth reveal that, absent adaptations to change, patterns of water level decline can be expected to continue.

Agriculture and Aquaculture

Rice cultivation, is a water intensive industry that, in Louisiana, requires 2.1 acre-feet of water for each acre of rice grown. In southwest Louisiana, rice season generally runs from February to June and the fields are often rotated out with other crops or dual-cropped with crawfish. Southwest Louisiana has been a center of rice production since colonial times due in large part to the supply of high-quality water and the presence of an impervious clay layer beneath the ground surface that retains irrigation water in the fields above. While regional streams and impoundments have long been sources of irrigation water in the region, shallow groundwater wells are commonly used as a primary source of water. In fact, areas like Acadia Parish use 3.7 times as much groundwater for rice cultivation as surface water. Similar proportions of groundwater usage for rice cultivation were found across the southwest study area, indicating potential issues with supply sustainability. As water levels decline and more water is drawn from the bottom of the aquifer, water quality and increased salinity levels could become a concern. Because rice is more sensitive to salinity than most crops, rice cultivators have begun to investigate surface water resources, which are rarely affected by salinity and cost less to pump than groundwater.

Industry

Industry is one of the primary users of groundwater and surface water in the state. The largest groundwater imbalance in the southeast study area is due largely to industrial groundwater use in the Baton Rouge area, particularly within the Bayou Sara-Thompson watershed. Over 76,000 more acre-feet of water are withdrawn from groundwater than are replenished via inflow in this unit. The aquifer system under Baton Rouge is made up of ten separate water bearing units, each named for their general depth beneath the ground surface of the industrial area in north Baton Rouge. Industrial groundwater usage, drawn from the 2,000-foot sands, has a rate of removal that far exceeds the natural recharge rate of the Southern Hills Aquifer System, of which the 2,000-foot sands are a part of.

In addition to causing an overall imbalance in the water budget via groundwater withdrawals, the levels of industrial groundwater withdrawals have also reduced the available groundwater due to accelerated saltwater intrusion. The cone of depression beneath the industrial groundwater wells has resulted in a pressure imbalance that has begun to accelerate the infiltration of salt water into the freshwater sand underlying Baton Rouge. The Capital Area Ground Water Conservation Commission (CAGWCC) developed a plan to mitigate the impacts of salt water migration into the Baton Rouge sands. In the industrial area, this plan involves placing limits on the amount of water pumped annually and assuring that any new industrial water wells will be placed away from the fault line across which salt water is being drawn.

In northwest Louisiana, there are fewer groundwater imbalances in the water budget. Industrial water withdrawals from the Carrizo-Wilcox Aquifer are at roughly the same levels as those for general irrigation and agriculture, behind both public supply and rural domestic water supply. Much of the industrial water usage in northwest Louisiana in 2010 was for the hydraulic fracturing of shale from the Haynesville shale play to derive natural gas. Although water usage for hydraulic fracturing declined significantly as gas prices began to drop in 2012, the industry still represent a potential source of future water imbalance. For this reason, early efforts were made in the NWLA study area to assure that water availability was accounted for in shale development. Initially during the rapid expansion of the industry in the area in 2008, approximately 90% of the water used for hydraulic fracturing was derived from groundwater. Industry groups and government agencies, coordinated by the Red River Watershed Management Institute and the Red River Waterway Commission, developed a plan for industry to voluntarily shift to surface water sourcing for Haynesville shale gas extraction and by 2011, approximately 75% of water used was from surface water, primarily the Red River. This shift in usage has resulted in a more sustainable water footprint, reducing the level of groundwater decline within the Carrizo-Wilcox Aquifer.

Public Supply

In both the northwest and southeast study areas, public water supply and rural domestic water supply are the primary usages of groundwater. In the southwest study area, public water supply is second to rice cultivation in total volume of water used. In all study areas, the most densely populated hydrologic units have groundwater imbalances that are driven by domestic water needs. Cities such as Lafayette and Baton Rouge all contribute tremendously to these groundwater imbalances. In some cases, extensive groundwater withdrawal has led to secondary water quality impacts. In Baton Rouge, for example, where groundwater for public supply is withdrawn largely from the 1,500-foot sands of the Southern Hills Aquifer System, salt water has begun to intrude into the freshwater sands. In much the same way that industry in Baton Rouge is drawing salt water across the Baton Rouge Fault, public supply systems are drawing salt water into the base of the aquifer. As part of its plan to mitigate the impacts of saltwater migration into the Baton Rouge sands, the CAGWCC will limit public water supply production from the 1,500-foot sands. The commission has also permitted a scavenger well system in the 1,500-foot sands and is working to develop one for the 2,000-foot sands that will capture and remove salt water from the base of the aquifer.

Population Change

Domestic demand for fresh water, from both public supply and rural domestic systems, is a primary consumptive use of fresh water in all study areas in the state. The assessment framework was used to analyze potential shifts in the overall water balance that would result from future population change. Each case study area includes large urban centers that were used to analyze the impacts of future population growth and urban expansion. The potential impacts of increased urbanization, specifically due to the conversion of open space to impermeable surface, include increased runoff, decreased infiltration of fresh water into the confined and unconfined aquifers, and a decrease in evapotranspiration rates. The ultimate effect of these changes on the overall budget is the reduction of groundwater inflow and a corresponding increase in runoff flowing to the surface waters, via either overland flow or through storm water management systems.

While the impacts of the spatial extent of urbanization on the overall budget were, in general, found to be minimal, increasing population levels were found to be much more impactful. Increasing population levels would be expected to have a similar corresponding increase in water consumption. The increased demand for water would be expected to place a greater amount of strain on groundwater resources in areas with sole source aquifers, such as the Chicot and Southern Hills systems.

References Cited

Alley, W. M., Reilly, T. E., & Franke, O. L. (1999). Sustainability of ground-water resources (Circular No. 1186). Denver, CO: U.S. Geological Survey.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. Journal of the American Planning Association, 62(2), 243–258.

Baker, N. T. (1988). Hydrologic Features and Processes of the Vermilion River, Louisiana (Water-Resources Investigations Report No. 88-4019). Department of the Interior, US Geological Survey. Retrieved from http://pubs.usgs.gov/wri/1988/4019/report.pdf

Barlow, P. M., Cunningham, W. L., Zhai, T., & Gray, M. (2015). U.S. Geological Survey Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0)—User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge From Streamflow Data (Techniques and Methods No. Book 3 Chapter B10). Reston, VA: U. S. Geological Survey.

Barlow, P. M., & Dickerman, D. C. (2001). Numerical-simulation and conjunctive-management models of the Hunt-Annaquatucket-Pettaquamscutt stream-aquifer system, Rhode Island (Professional Paper No. 1636). Denver, CO: US Geological Survey.

Beigi, E., and F. T.-C. Tsai. (2014). A GIS-Based Water Budget Framework for Parallel Computing High-Resolution Groundwater Recharge in Humid Regions. Journal of Hydrologic Engineering, 19(8), 05014004, doi:10.1061/(ASCE)HE.1943-5584.0000993.

Belyea, C. M., & Terando, A. J. (2013). Urban Growth Modeling for the SAMBI Designing Sustainable Landscapes Project. Raleigh, NC: NC State University Biodiversity and Spatial Information Center.

Bennett, B., Park, L., & Wilkinson, R. (2010). Embedded Energy in Water Studies-Study 2: Water Agency and Function Component Study and Embedded Energy-Water Load Profiles. Sacramento, CA: California Public Utilities Commission.

Boniol, D. P., Birnbaum, S., Autin, W.J., & Monday, J. (1988). Recharge potential of Louisiana aquifers. Louisiana Geological Survey, Baton Rouge, LA.

Borrok, D. M., & Broussard, W. P. (2016). Long-term geochemical evaluation of the coastal Chicot aquifer system, Louisiana, USA. *Journal of Hydrology*, *533*, 320–331.

Branch, B. (2004). Salt water and irrigation in Louisiana. Louisiana Agriculture, 47(2), 33.

Buono, A. (1983). The Southern Hills Regional Aquifer System of Southeastern Louisiana and Southwestern Mississippi. U.S. Geological Survey Water Resources Investigations Report No. 83-4189. Baton Rouge, LA.

California Energy Commission. (2005). California's Water–Energy Relationship. Sacramento, CA: California Energy Commission.

California Water Plan Update (2009). Integrated Water Management: Volume 2 Resource Management Strategies. Bulletin 160-09. California Department of Water Resources. Sacramento, CA.

Carr, J. E., Chase, E. B., Paulson, R. W., & Moody, D. W. (1990). National water summary 1987: Hydrologic events and water supply and use (Water Supply Paper No. 2350). Denver, CO: U.S. Geological Survey.

Clark, B. R., Westerman, D. A., & Fugitt, D. T. (2013). Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) Groundwater-Flow Model and Simulations of Sustainable Water-Level Scenarios. Reston, VA: US Geological Survey Scientific Investigations Report, 5161, 2013.

Couvillion, B. R., Barras, J. A., Steyer, G. D., Sleavin, W., Fischer, M., Beck, H., Trahan, N., Griffin, B., & Heckman, D. (2011). *Land Area Change in Coastal Louisiana (1932 to 2010)*. US Department of the Interior, US Geological Survey.

Delin, G.N. and Risser, D.W. (2007). Ground-Water Recharge in Humid Areas of the United States—A Summary of Ground-Water Resources Program Studies, 2003-06. U.S. Geological Survey Ground-Water Resources Program. Reston, VA.

DeWalle, D. R., Swistock, B. R., Johnson, T. E., & McGuire, K. J. (2000). Potential effects of climate change and urbanization on mean annual streamflow in the United States. Water Resources Research, 36(9), 2655–2664.

Doll, P. & Fiedler, K. (2008). Global-scale modeling of groundwater recharge. Hydrology and Earth System Sciences, vol. 12, pp. 863–885. Published by Copernicus Publications on behalf of the European Geosciences Union.

Ecology and Environment. (2011). Recommendations for a Statewide Ground Water Management Plan (p. 512). Baton Rouge, LA.

Electric Power Research Institute. (2002). Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment—The Next Half Century (Topical Report No. 1006787). Palo Alto, CA: EPRI.

Environmental Systems Research Institute (2011). ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Faulkner, S. (2004). Urbanization impacts on the structure and function of forested wetlands. Urban Ecosystems, 7(2), 89–106.

Gardner-Outlaw, T., & Engelman, R. (1997). Sustaining water easing scarcity: a second update. Population Action International.

Gleick, P. H. (1994). Water and energy. Annual Review of Energy and the Environment, 19(1), 267–299.

Griffith, J. M., (2003). Hydrogeologic Framework of Southeastern Louisiana. U.S. Geological Survey Water Resources Technical Report No. 72. Published by the Louisiana Department of Transportation and Development, Baton Rouge, LA.

Hanson, G. M. (2009). Water: a natural resource critical for development of unconventional resource plays. Gulf Coast Association of Geological Societies Transactions, 59, 325–328.

Healy, R. W., Winter, T. C., LaBaugh, J. W., & Franke, O. L. (2007). Water budgets: Foundations for effective water-resources and environmental management (Circular No. 1308). Reston, VA: US Geological Survey.

Heywood, C. E., & Griffith, J. M. (2013). Simulation of groundwater flow in the“ 1,500-foot” sand and“ 2,000-foot” sand and movement of saltwater in the“ 2,000-foot” sand of the Baton Rouge area, Louisiana (Open-File Report No. 2013–1153). Reston, VA: US Geological Survey.

Karstensen, K. A., & Sayler, K. L. (2009). *Land-Cover Change in the Lower Mississippi Valley, 1973-2000* (Open-File Report No. 2009-1280). Reston, VA: US Geological Survey.

Kuniansky, E.L., Dial, D.C., & Trudeau, D.A., (1989), Maps of the “400-foot,” “600-foot,” and Adjacent and Confining Beds, Baton Rouge Area, Louisiana. U.S. Geological Survey Water Resources Technical Report No. 48. Louisiana Department of Transportation and Development, Baton Rouge, LA, 23 p.

Kunkel, K. E., Stevens, L. E., Stevens, S. E., Sun, L., Jannsen, E., Weubbles, D., Konrad, C. E., Fuhrmann, C. M., Keim, B. D., Kruk, M. C., Billot, A., Needham, H., Shafer, M., & Dobson, J. G. (2013). Regional climate trends and scenarios for the U.S. national climate assessment, Part 2: Climate of the southeast United States (Technical Report NESDIS No. 142-2). Silver Spring, MD: NOAA.

Leberg, P. (2015). 2017 Coastal Master Plan Modeling: C3-7 – Green-winged Teal, Anas crecca, Habitat Suitability Index Model. Version I. (pp. 1-17). Baton Rouge, Louisiana: Coastal Protection and Restoration Authority.

Lester, G.D., Sorensen, S.G., Faulkner, P.L., Reid, C.S., & Maxit I.E. (2005). Louisiana Comprehensive Wildlife Conservation Strategy. Louisiana Department of Wildlife and Fisheries. Baton Rouge. 455 pp

Louisiana Department of Environmental Quality (2006). Carrizo-Wilcox Aquifer Summary Baseline Monitoring Program, Baton Rouge, LA.

Louisiana Department of Environmental Quality, (2008). Chicot Aquifer Summary, Aquifer Sampling and Assessment Program. Baton Rouge, LA.

Lovelace, J. K., Fontenot, J. W., & Frederick, C. P. (2004). *Withdrawals, water levels, and specific conductance in the Chicot aquifer system in southwestern Louisiana, 2000-03* (Scientific Investigations Report No. 2004-512). Reston, VA: U. S. Geological Survey.

L′vovich, M. I. (1979). World Water Resources and Their Future. Russian Edition published by Mysl’P.H., Moscow. Translation by the American Geophysical Union. Printed by Lithocrafters, Inc., Chelsea, Michigan.

Martin, A. & Early, D.A., (1987). Statistical Analysis of Aquifer-Test Results for Nine Regional Aquifers in Louisiana. U.S. Geological Survey Water Resources Investigations Report No. 87-4001. Baton Rouge, LA.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., (2014). Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http://dx.doi.org/10.3133/cir1405.

McKee, P. W., & Hays, P. D. (2002). The Sparta Aquifer: A Sustainable Water Resource? (Fact Sheet). Reston, VA: U. S. Geological Survey.

McKee, P. W., & Clark, B. R. (2003). Development and calibration of a ground-water flow model for the Sparta Aquifer of southeastern Arkansas and north-central Louisiana and simulated response to withdrawals, 1998-2027 (Water Resources Investigations Report No. 03-4132). Little Rock, AR.

Medalie, L., & Horn, M. A. (2010). Estimated water withdrawals and return flows in Vermont in 2005 and 2020 (Scientific Investigations Report No. 2010-5053). Reston, VA: US Geological Survey.

Mermentau Basin. (2005). In Louisiana Comprehensive Wildlife Conservation Strategy (pp. 246–249).

Molina-Rivera, W. L., & Gomez-Gomez, F. (2008). Estimated water use in Puerto Rico, 2005 (Open-File Report No. 2008-1286). Reston, VA: US Geological Survey.

Mu, Q., Zhao, M., & Running, S. W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sensing of Environment, 115(8), 1781–1800.

Navigant Consulting, Inc. (2006). Refining Estimates of Water-Related Energy Use in California (No. CEC-500-2006-118). Sacramento, CA: California Energy Commission, PIER Industrial/Agricultural/Water End Use Energy Efficiency Program.

Nelms, D. L., Messinger, T., & McCoy, K. J. (2015). Annual and Average Estimates of Water-Budget Components Based on Hydrograph Separation and PRISM Precipitation for Gaged Basins in the Appalachian Plateaus Region, 1900-2011 (Data Series No. 944). Reston, VA: US Geological Survey.

Nyman, D. J., K. J. Halford, & A. Martin. (1990). Geohydrology and simulation of flow in the Chicot aquifer system of southwestern Louisiana. Louisiana Department of Transportation and Development Water Resources Technical Report 50. Baton Rouge, LA.

Pappas, M. (2011). Unnatural resource law: Situating desalination in coastal resource and water law doctrines. *Tulane Law Review*, *86*, 81.

Rapp, T.R. Louisiana Department of Transportation and Development, (1992). Ground-Water Resources of Caddo Parish, Louisiana. Water Resources Technical Report No. 58.

Reilly, T. E., Dennehy, K. F., Alley, W. M., & Cunningham, W. L. (2008). Ground-water availability in the United States (Circular No. 1323) (p. 70). Reston, VA: Geological Survey (US).

Romaire, Robert P. (2014). 2017 Coastal Master Plan Modeling: C3-19 – Crayfish, Procambarus clarkii and P. zonangulus, Habitat Suitability Index Model. Version I. (pp. 1-31). Baton Rouge, Louisiana: Coastal Protection and Restoration Authority.

Roy, S. B., Ricci, P. F., Summers, K. V., Chung, C.-F., & Goldstein, R. A. (2005). Evaluation of the Sustainability of Water Withdrawals in the United States, 1995 to 2025. Journal of the American Water Resources Association, 41(5), 1091–1108.

Saichuk, J., Branch, B., & Theunissen, S. (2004). Saving water in Louisiana rice production. Louisiana Agriculture, 47(2), 14.

Sanford, W. E, and Selnick, D. L., (2013) Estimation of evapotranspiration across the conterminous United States using a regression with climate and land-cover data: Journal of the American Water Resources Association, v. 49, p. 217-230.

Sargent, B. P., Vairin, B. A., Demcheck, D. K., Lovelace, J. K., & Arcement, G. J. (2011). Water use in Louisiana, 2010. Louisiana Department of Transportation and Development.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal, 10(1), 18–39.

Sloto, R. A., & Crouse, M. Y. (1996). HYSEP, a computer program for streamflow hydrograph separation and analysis (Water Resources Investigations Report No. 96-4040). Lemoyne, PA: US Department of the Interior, US Geological Survey.

Smith, C. A., Belles, R. D., & Simon, A. J. (2011). Estimated Water Flows in 2005: United States (No. LLNL-TR-475772) (p. 65). Livermore, CA: Lawrence Livermore National Laboratory.

Stillwell, A. S., King, C. W., Webber, M. E., Duncan, I. J., & Hardberger, A. (2011). The Energy-Water Nexus in Texas. Published by the University of Texas and the Environmental Defense Fund, Austin, TX.

Tetra Tech. (2007). Water Resource Inventory Area 54 (Lower Spokane) Watershed Plan Phase 2, Level 1 Data Compilation and Technical Assessment. Seattle, WA: Tetra Tech/KCM.

Tsai, F.T.C. (2013). Hydrostratigraphy Modeling of the Southern Hills Aquifer System and Faults. Baton Rouge, LA: Louisiana Water Resources Research Institute.

U.S. Army Corps of Engineers (n.d.). Ther Mermentau Basin Project. Public Affairs Office Brochure. New Orleans District, New Orleans, LA.

Water in the West. (2013). Water and Energy Nexus: A Literature Review (p. 146). Stanford, CA: Water in the West.

White, V.E., and Prakken, L.B. (2015). Water resources of East Baton Rouge Parish, Louisiana: U.S. Geological Survey Fact Sheet 2015–3001, 6 p.

THE WATER INSTITUTE
OF THE GULF®

301 NORTH MAIN STREET, SUITE 2000
BATON ROUGE, LA 70825

(225) 448-2813
WWW.THEWATERINSTITUTE.ORG