Project Description for the Regional Assessment of Trends in Nutrient and Sediment Concentrations and Loads in Major River Basins, South-Central United States

by

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INTRODUCTION

The U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program is conducting regional assessments of water-quality conditions and trends in 16 principal aquifers and eight major river basins (Hamilton and others, 2005). These assessments build on the NAWQA studies conducted from 1991 to 2001 in 51 river basins (fig. 1). NAWQA studies were designed to describe how natural features, land use, and human activities interact with and affect ground- and surface-water quality and aquatic communities. The regional assessments began in 2004 and will continue with findings and final publications scheduled to be available in 2007.

The intent of these assessments is to summarize water-quality conditions in a regional context. The regional assessments of the eight major river basins (MRB) (fig. 1) will focus on chemicals in water and other water-quality issues relevant to surface waters in each region (Hamilton and others, 2005). In general, each MRB regional assessment will address trends in nutrients and sediment, pesticides, and biological-response data (chlorophyll, algae). The study area for each MRB regional assessment comprises more than one NAWQA study unit, and data used for trend testing will include data from NAWQA studies supplemented with data from other USGS studies, as well as available data collected by other agencies. In addition, trend tests will be coordinated to document temporal changes and spatial differences for a particular water-quality constituent, not only within a particular MRB study area, but also among study areas nationwide.

The USGS Mississippi Water Science Center will complete an assessment of trends in nutrient and suspended-sediment concentrations and loads for rivers in the study area of the south-central United States, which is defined as the Lower Mississippi, Arkansas-White-Red, and Texas-Gulf Region in figure 1. Several reports describe trends in nutrient and sediment data for this region. For example, studies by Van Metre and Reutter (1995), Demcheck and others (2004), Davis and Bell (1998), and Coupe (2002) document loads and trends in concentrations and loads of nutrients and/or sediments for statewide assessments or for selected river basins included in this region. National studies, such as work by Mueller and others (1995), include assessments of nutrient data from both ground-water wells and surface-water data-collection sites within this region. Studies summarized by Goolsby and Battaglin (2000), Meade (1995), and Turner and Rabalais (2004) assess nutrient concentrations and loads delivered by the Mississippi River Basin to the Gulf of Mexico; although these studies include data and results from this particular region, most of their focus is on the Upper Mississippi River Basin upstream of this region. The U.S. Environmental Protection Agency recently released results from its Nutrient Pilot Study, which included an assessment of nutrient concentration and loads from coastal or near-coastal waters draining into the northern Gulf of Mexico from Louisiana, Mississippi, and Alabama (U.S. Environmental Protection Agency, 2004). Therefore, this assessment is unique and timely in that it primarily will be focused on the entire Lower Mississippi, Arkansas-White-Red, Texas-Gulf Region, not just portions of the region.

The water-quality constituents included in this assessment are dissolved ammonia, total ammonia plus organic nitrogen, nitrite plus nitrate, dissolved orthophosphate, total phosphorus, suspended sediment, and total suspended solids. Loads will be calculated, and both temporal and spatial trends for constituent concentrations and loads will be investigated. Trends in sources of nutrients (point and nonpoint) and sediment will be used to explain trends in the surface-water data that are identified. This assessment will help resource managers understand changes in concentrations and loads of nutrients and sediment entering the northwestern Gulf of Mexico from the study area. This paper presents descriptions of the study area, data sources, site selection, and methods of analysis to be used in the regional assessment of trends in nutrient and sediment data from rivers in the south-central United States.

STUDY AREA

The study area comprises river systems in the following 2-digit hydrologic unit codes: 08, Lower Mississippi Region; 11, Arkansas-White-Red Region; and 12, Texas-Gulf Region (fig. 2; U.S. Geological Survey, 1998; Seaber and others, 1987). The study area includes all of Oklahoma and Arkansas; nearly all of Texas and Louisiana; and parts of Mississippi, Tennessee, Kentucky, Missouri, Kansas, Colorado, and New Mexico (fig. 3). Major cities in the study area include: Memphis, New Orleans, Baton Rouge, San Antonio, Houston, Dallas, Ft. Worth, Tulsa, Oklahoma City, Colorado Springs, Little Rock, Wichita, and Springfield (fig. 3). Major rivers in the study area include the lower Mississippi, Yazoo, Canadian, Cimarron, Arkansas, White, Red, Trinity, Brazos, Colorado, and Guadalupe (fig. 3).

The geology, geography, hydrology, and land use within the boundaries of the study area are complex and diverse. The western part of the study area is fairly arid [annual rainfall less than about 25 inches total per year (Owenby and others, 2001)] with topography ranging from flat to gentle, rolling hills within the Great Plains and Interior Highlands (Birdsall and Florin, 1998) and is fairly rural with few large cities. Land use primarily is grass and fallow land with some row and small grain crops (fig. 4). Water-resource issues in this part of the study area are related to water use, water rights, and irrigation as much as they are related to water quality. The eastern part of the study area has a humid, sub-tropical climate with annual rainfall amounts ranging from 40 to greater than 50 inches per year (Owenby and others, 2001); subsequently, water resources are fairly abundant. Elevations decrease from west to east toward the Mississippi River, and decrease from north to south toward the Gulf-Atlantic Coastal Plain (Birdsall and Florin, 1998). Land use in the eastern part of the study area is primarily forest and pasture land; however, row crops are abundant in the fertile Mississippi River Alluvial Valley (fig. 4). The eastern part of the study area is fairly rural with respect to land area, but is the more populous part and contains many of the previously mentioned cities (fig. 3). With the extreme ranges in geology, geography, hydrology, and land use within the study area, it is expected that trends in concentrations and loads of nutrients and sediment in surface waters also will vary considerably.

DATA SOURCES

The two types of data that will be assembled for this assessment are the water-chemistry and flow data used for trend and load analyses, and ancillary data used to assist in explaining any identified trends. All data assembled for this assessment will be stored and archived in the databases of the USGS Mississippi Water Science Center.

The primary source of water-chemistry and flow data for this assessment will be from the USGS. Since the early 1970's, the USGS has collected water-quality information from major river basins throughout the United States as part of three national programs: the Hydrologic Benchmark Network (HBN), the National Stream Quality Accounting Network (NASQAN), and the NAWQA Program. In addition, other long-term water-quality monitoring stations operate as part of USGS cooperative projects in the various States. All data from these USGS efforts have been compiled and are available to the public by means of the internet as part of the National Water Information System web-server (NWISweb). Another source of water-chemistry and flow data that will be considered is from ambient data-collection programs of each State within the study area. These data typically are stored and archived in the U.S. Environmental Protection Agency's (USEPA) Legacy Data Center (LDC) and the Storage and Retrieval (STORET) database (U.S. Environmental Protection Agency, 2004). Prior to being used, State's data sets will be evaluated as to their compatibility with USGS data sets. Differences among analytical methods, sample-collection protocols, and quality-assurance procedures are important issues to be considered.

In order to explain trends in surface water-quality data, it is important to identify and understand temporal and spatial patterns in source data. For example, land is constantly being converted in favor of urban development; therefore, can trends in phosphorus data for a particular sub-basin in this region be attributed to a change from a nonpoint agricultural source of phosphorus to a waste-water treatment plant point source as land is converted during the study period? For this assessment, ancillary data sources will be identified to assess trends in both point and nonpoint sources of pollutants. An example of point source information includes locations, waste streams, and loading amounts from municipal and industrial wastewater treatment plants. Such information typically is provided by the treatment plant operators to State regulatory agencies, who then submit this information to the USEPA Permit Compliance System (PCS) database (U.S. Environmental Protection Agency, 2005). An example of nonpoint source information are aggregate Geographical Information System (GIS) data layers of agricultural-related statistics for the study area, such as those available from the U.S. Department of Agriculture, Natural Resources Conservation Service, National Resources Inventory (U.S. Department of Agriculture, 2004).

SITE SELECTION

Site selection primarily is dependent upon three issues for this assessment: time period, minimum data requirements for analysis, and spatial coverage. There are at least two time periods under consideration for this assessment. The first time period considered is near-term and is defined as the most recent period of available USGS data, 1993-2003. This period provides the most recent decadal “snapshot” of nutrients and sediment being discharged from this region to the northern Gulf of Mexico. In addition, this near-term period is being considered as a common time period to interpret results from all MRB’s to provide national perspective for recent trends in nutrient and sediment data. Such information will be the most useful to resource planners and regulatory agencies who are responsible for developing Total Maximum Daily Loads (TMDLs), nutrient criteria, and remediation or restoration efforts in impaired watersheds. A second time period under consideration is longer term, 1980-2003. Sites which have continuous or near continuous data for this longer period will help provide perspective to trends found in the shorter 1993-2003 time period. For example, if a trend is detected in total phosphorus data at a particular site that only has near-term data available, did that trend occur during a period of record flooding, average flow conditions, or drought for that particular watershed? Alternate time periods may be considered if data from more sites become available for the alternate time period. However, for this study area, it appears from initial site and data inventories that the time period 1993-2003 has the most sites available to be considered for analysis.

Site selection also is dependent upon the amount and frequency of data required to complete the statistical analysis used in this assessment (described in the next section). In general, data requirements include a minimum of 5 years of data and at least 50 data points. However, a certain number of samples per year with minimal gaps in the period of record for that data set to be considered for analysis is also required. For this assessment, there must be a minimum of quarterly samples in at least 70 percent of the years for the trend time period, and at least 4 samples per year in the first and last 20 percent of years sampled (D.K. Mueller, USGS, written commun., 2005). In addition, daily values of streamflow are necessary to calculate loads at each of the sites.

Finally, site selection (and to some extent, data source) is dependent on spatial coverage. For this analysis, lists of USGS sites will be generated from NWISweb by time period (1993-2003 and 1980-2003) for each of the constituents considered for trend analysis and load calculation. These sites will be plotted on a map that includes all of the State boundaries, majors rivers and streams, and the study area boundary. All of the major rivers and streams in the study area should have an adequate number of sites to address trends and loadings from that particular watershed. Ideally for the study area, sites would be selected with respect to spatial distribution as follows:

- At or near termination points for rivers that empty into the Gulf of Mexico (but upstream of tidal influences);
- On major rivers with drainage areas larger than about 10,000 square miles;
- Near locations where major tributaries empty into rivers;
- Upstream of Gulf of Mexico and tributary entry points at equidistant locations (about every 100 miles) or above/below strategic tributary locations; and
- Smaller tributaries primarily influenced by a specific land-use type.

Where USGS sites do not provide adequate spatial coverage, other data sources such as USEPA’s LDC and STORET will be considered to complete spatial coverage. In addition, previously-mentioned time periods may require some adjustment in order to increase the number and spatial distribution of sites considered for analysis.

METHODS OF ANALYSIS

This section includes a general discussion of trend test selection and a discussion of methods used to estimate loads and test for trends for this assessment. This section also documents specific computer programs and software packages used to analyze the data.

Trend Test Selection: A trend is defined as a systematic change in a water-quality constituent over time (D.L. Lorenz, USGS, written commun., 2004). In order to complete trend tests for water-quality data, one must understand the complexities and processes that influence water-quality conditions in surface waters. Natural influences include climate, hydrology, precipitation, soil erosion, chemical reactions, and biological activities. Human influences include chemical applications, flow regulation, addition or removal of wastewater treatments plants, and land-use changes. The difficulty in interpreting trends in water-quality data is the ability to separate actual trends in the data from natural variability, as well as from artificial trends (trends resulting, for example, from database artifacts related to changes in method reporting levels for nutrient species through the time period of interest).

There are other characteristics that can influence water-quality data sets used for trend tests. Water-quality data are highly variable and do not follow any “known” distribution pattern such as a normal distribution. Water-quality databases can include “censored” data, which are values in which a constituent is detectable but reported as below some value (for example, an orthophosphate value of less than 0.01 milligram per liter). Other characteristics include changes in sample collection, sample processing, and laboratory analytical methods over time. All of these influences and characteristics must be considered when interpreting results of trends analysis in water-quality data.

There are many methods of analysis that can be used to determine trends. For example, highly sophisticated deterministic models can be used. These models require a large amount of input data such as flow, basin characteristics, chemical sources, and transport mechanisms at multiple locations throughout a particular watershed for calibration purposes. These models can be used to assess trends, but also can be used to “predict” trends should influences or stressors change over time.

Statistical methods also can be used for trend testing. These methods are less data intensive compared to deterministic models, are empirically based, and are more widely applicable and useful. To select an appropriate statistical method, several questions must be answered about the data set to be tested. First, is the distribution of the data set known? Parametric tests, such as simple linear regression, can be used for data that are normally distributed. Ordinary least squares is the method for calculating the slope and intercept coefficients for a linear regression equation. Another example of a parametric trend test is Tobit regression, which is utilized for data sets that contain censored data. Tobit regression is similar to linear regression except that maximum-likelihood estimation (MLE) is used to estimate values below censoring levels (Helsel and Hirsch, 1992). If the distribution of the data does not follow a normal distribution, then non-parametric, or distribution-free, methods should be used to test for trends. Non-parametric trend tests include the Mann-Kendall test, where time is considered a variable and the median value of a particular water-quality constituent is tested to determine if it changes over time.

The second question to be answered is related to study period and whether or not gaps exist in the data set to be tested for trends. For shorter study periods (less than about 15 years) and either no gaps or a limited number of gaps in the data set, then monotonic trends tests, such as linear regression or the Mann-Kendall test, can be used. Trends detected in monotonic tests indicate changes in the data set that are gradual and continuing over time. Results of monotonic trends tests give the overall direction of the trend if detected, and the slope of that trend is linear. For longer study periods (greater than about 15 years) that have no major gaps, non-monotonic trends tests such as time-series analysis can be used. Non-linear variations in trend direction that correspond to stressors or climatic changes can be observed in time series results. If there are large gaps in the data set, or if there is a known event that may have caused a dramatic change in trend direction (for example, construction and subsequent operation of a dam), then step trend methods, such as the two-sample t-test for parametric data sets or the rank-sum test for non-parametric data sets, should be used (Helsel and Hirsch, 1992).

The third question involves adjusting trend tests to account for natural variability, primarily seasonality and streamflow. An example of seasonal variability in nutrient and sediment data includes peak concentrations that occur in the spring shortly after fertilizers are applied to freshly plowed agricultural fields. These peak events typically occur each year, and their influence in water-quality trend results must be accounted for or removed. Seasonal terms, such as a sine or cosine function, can be added in linear regression (parametric) trend tests to account for seasonal variability. The Seasonal Kendall (non-parametric) trend test is a variation of the Mann-Kendall test in that trend statistics (Kendall's Tau) are computed for specified seasons (for example, quarterly or monthly) and then summed to determine the trend in the data for an overall time period.

Flow adjustment is a technique used to understand actual changes in a water-quality constituent without influence of trends in flow. Data are flow adjusted by establishing a relation between flow and the water-quality constituent prior to trend testing. This relation is developed by means of regression or by using a smoothing technique such as Locally Weighted Scatterplot Smooth (LOWESS, Helsel and Hirsch, 1992). Once a relation is developed, then a particular trend test can be run on residuals produced from that relation (residuals are the differences between actual and predicted data).

It is important to decide if flow adjustment is necessary in trend testing. If trends tests are used to determine impacts to aquatic communities, then flow adjustment is not important. For example, total ammonia (NH_3 plus NH_4^+) exceeds chronic criterion for aquatic organisms for concentrations above about 2.1 milligrams per liter (when pH is within the range of 6.5 to 9.0 and temperature from 0 to 30 degrees Celsius) (Mueller and others, 1995). Therefore, to determine the effects to a particular ecosystem, it is not pertinent that increases in streamflow were the primary cause for the increases in total ammonia over time, but simply that ammonia concentrations increased and exceeded the criterion. However, if it is important to understand why ammonia concentrations exceeded the criterion over time, then the trend test should be run with flow-adjusted data to determine if the trend is retained once adjusted for the effect of streamflow. If the trend was retained using the flow-adjusted ammonia data, then the increase may have been caused by a human-related action such as an increase in fertilizer usage. For this example of ammonia, it is important to the study objectives to run trends tests on both the unadjusted and the flow-adjusted data to understand the overall "picture" of what was happening in relation to ammonia concentrations within this watershed.

Load Estimation and Trend Test Methods Used In This Assessment: A load is defined as the mass of a water-quality constituent that passes a point on a river over a given amount of time (D.L. Lorenz, USGS, written commun., 2004). Loads will be estimated using the USGS computer program Load Estimator, or LOADEST (Runkel and others, 2004), for this assessment. LOADEST utilizes a seven-parameter linear regression model that incorporates flow, time, and seasonal terms to estimate loads of concentration over time for specific time periods (annual, monthly, or daily loads). The calibration and estimation procedures within LOADEST are based on three statistical estimation methods. The first two methods, MLE and Adjusted Maximum Likelihood Estimation (AMLE) are appropriate when the calibration model residuals are normally distributed. Of the two, AMLE is more appropriate when the calibration data set (time series of streamflow and concentration data) contains censored data. The third method, Least Absolute Deviation (LAD), is an alternative to MLE when residuals are not normally distributed (Runkel and others, 2004). Once calibrated, daily values of streamflow are used as independent variables to produce the load results. LOADEST is available as a "USGS plug-in" (S-LOADEST) to the S-PLUS statistical software package, which is a PC-based statistical software package (Insightful, 2002).

Statistical methods will be used to test for trends in nutrient and sediment concentrations and loads in this assessment. Tobit regression trend tests will be used for sites that have near-term data (1993-2003). Tobit regression is preferred because of the likelihood that censored values will exist in the data sets used in this assessment. Although Tobit regression is considered a parametric test, it also can be used with non-parametric data sets by transforming streamflow and water-quality data (using transformations such as common logs, exponentials, hyperbolic, or some other mathematical change), and then developing the liner regression model with the transformed data. Because the LOADEST program uses Tobit regression (seven parameter model), LOADEST will be used to estimate trends in the near-term data sets, and AMLE will be the preferred choice for calibration of the model coefficients. Trend direction and magnitude are estimated using the coefficient for time in the LOADEST program. Because flow terms are incorporated into the seven-parameter model in LOADEST, the trend results are considered flow adjusted and represent trends in concentration data caused by some external influence such as a change in fertilizer inputs. In order to analyze the concentration data to determine impacts to aquatic communities, the LOADEST model and/or results will require some modification to identify trends in unadjusted concentrations.

The Seasonal Kendall Test will be used on unadjusted and flow-adjusted concentrations for data sets that are non-parametric or for data sets that cannot be transformed to parametric using a mathematical expression. Results of the Seasonal Kendall test include trend direction and magnitude. The computer program Estimate Trend, or ESTREND, developed by the USGS, includes the Seasonal Kendall Test (Schertz and others, 1991), and ESTREND is also a “USGS plug-in” to S-PLUS (S-ESTREND).

Time series modeling will be used to estimate trends (nonlinear, non-monotonic) for sites that have long-term data (1980-2003). In time series analysis, flow and concentration data are modeled at the same time, thus sites that have poor relations between flow and concentration can be modeled more successfully using the time series model. The time series model is also based on MLE, and the model can be used for explanatory purposes. Ancillary data can be incorporated in the time series model, and results can include a detailed analysis from several inter-related sites from the same watershed. The USGS computer program QWTREND will be used for time series modeling. Data requirements for QWTREND are fairly complex: period of record is at least 15 years (but not necessarily consecutive); there must be an average of at least 4 samples per year, although the sampling frequency may vary from year to year; at least 10 samples during each 3-month season (January to March, February to April, March to May … December to February); less than 10 percent censored data; and full record of daily streamflow from 5 years before the first year through the period of record (A.V. Vecchia, Jr., USGS, written commun., 2004).

SUMMARY

The USGS will assess trends in nutrient and suspended-sediment concentrations and loads for rivers in the South-Central United States, which is defined as the Lower Mississippi, Arkansas-White-Red, and Texas-Gulf Region. Water-quality constituents included in this assessment are dissolved ammonia, total ammonia plus organic nitrogen, nitrite plus nitrate, dissolved orthophosphate, total phosphorus, suspended sediment, and total suspended solids. Both temporal and spatial trends for each constituent will be investigated, and loads will be estimated. Trends in sources of nutrients (point and nonpoint) and sediments will be investigated to help explain those trends that are identified in the nutrient and sediment data. This assessment will help resource managers understand changes in concentrations and loads of nutrients and sediments to the northwestern Gulf of Mexico.

The study area includes all or parts of 11 States. The geology, geography, hydrology, and land use within the boundaries of the study area are complex and cover a range of extremes. Therefore, it is expected that trends in concentrations and loads of nutrients and sediment in surface waters within the study area also will vary considerably.

The primary source of water-chemistry and flow data for this assessment will be data collected at USGS water-quality sites that were part of three national USGS programs and data collected as part of other USGS projects in the various States in the study area. Other sources of data will be considered, such as from State ambient data-collection programs. If used, State data sets will be assessed as to their compatibility with USGS data sets. Ancillary data sources will be identified to explain trends that are identified. Ancillary data sources will address both point and nonpoint sources of pollutants.

Site selection primarily is dependent upon three issues: time period used for analysis, minimum data requirements for analysis, and spatial coverage. There are at least two time periods under consideration for this assessment. The first time period under consideration is near term and is defined as the most recent period of available USGS data, 1993-2003. A second time period under consideration is longer term, 1980-2003. Sites which have continuous or near continuous data for this longer period will help provide perspective to trends found in the shorter 1993-03 time period. In general, data requirements include a minimum of 5 years of data and at least 50 data points. However, software may also require a certain number of samples per year with minimal gaps in the period of record for that data set to be considered for analysis. With regard to spatial coverage, all of the major rivers and streams in the study area should have an adequate number of sites to address trends and loadings from that particular watershed.

Statistical methods for load estimation and trends testing will be used for this assessment. Loads will be estimated using a seven-parameter linear regression model that incorporates flow, time, and seasonal terms to estimate loads of concentration over time for specific time periods (annual, monthly, or daily loads). Once calibrated, daily values of streamflow are used as independent variables to produce the load results. Tobit regression, which is based on the same regression methods used for load estimation, will be used to estimate trends for sites that have near-term data (1993-2003). Time series modeling will be used to estimate trends (nonlinear, non-monotonic) for sites that have long-term data (1980-2003).

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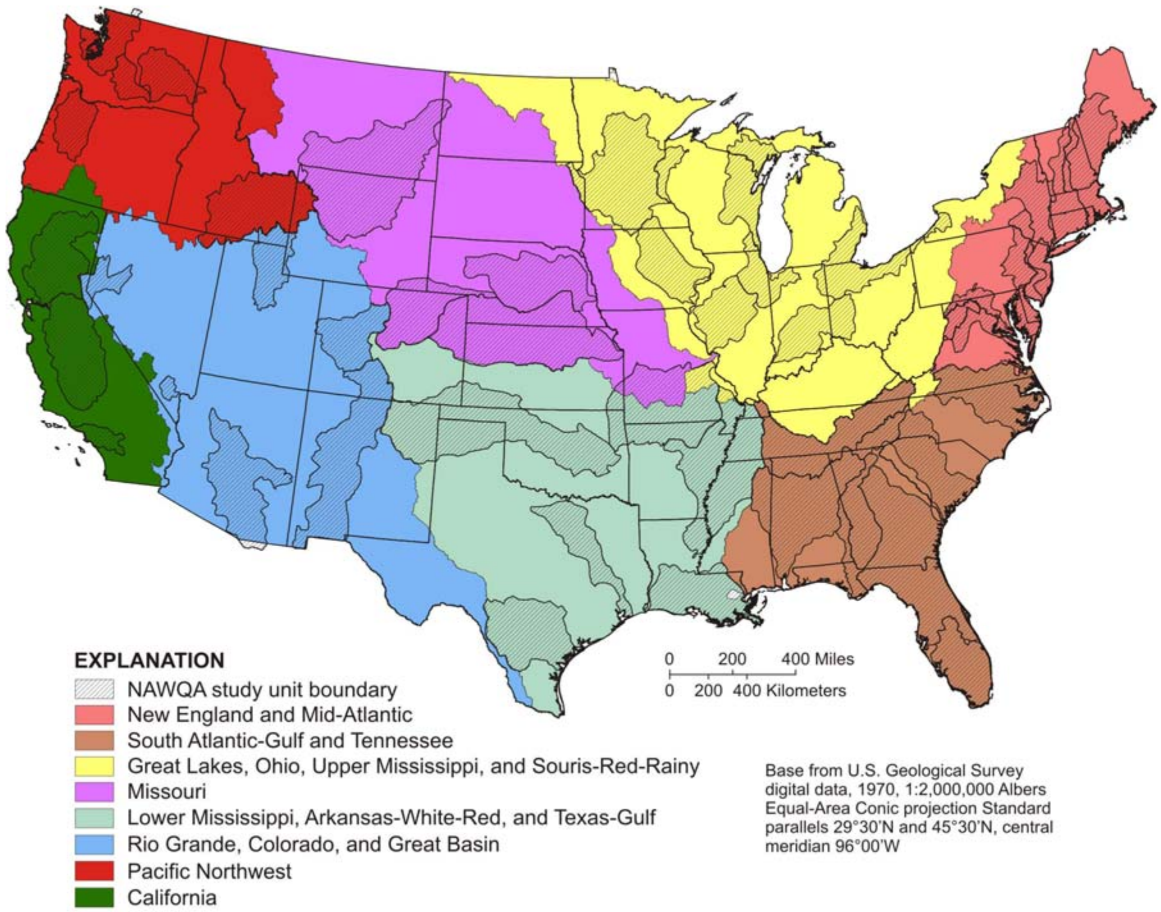

Figure 1. Locations of major river basin (MRB) and National Water-Quality Assessment (NAWQA) study areas.

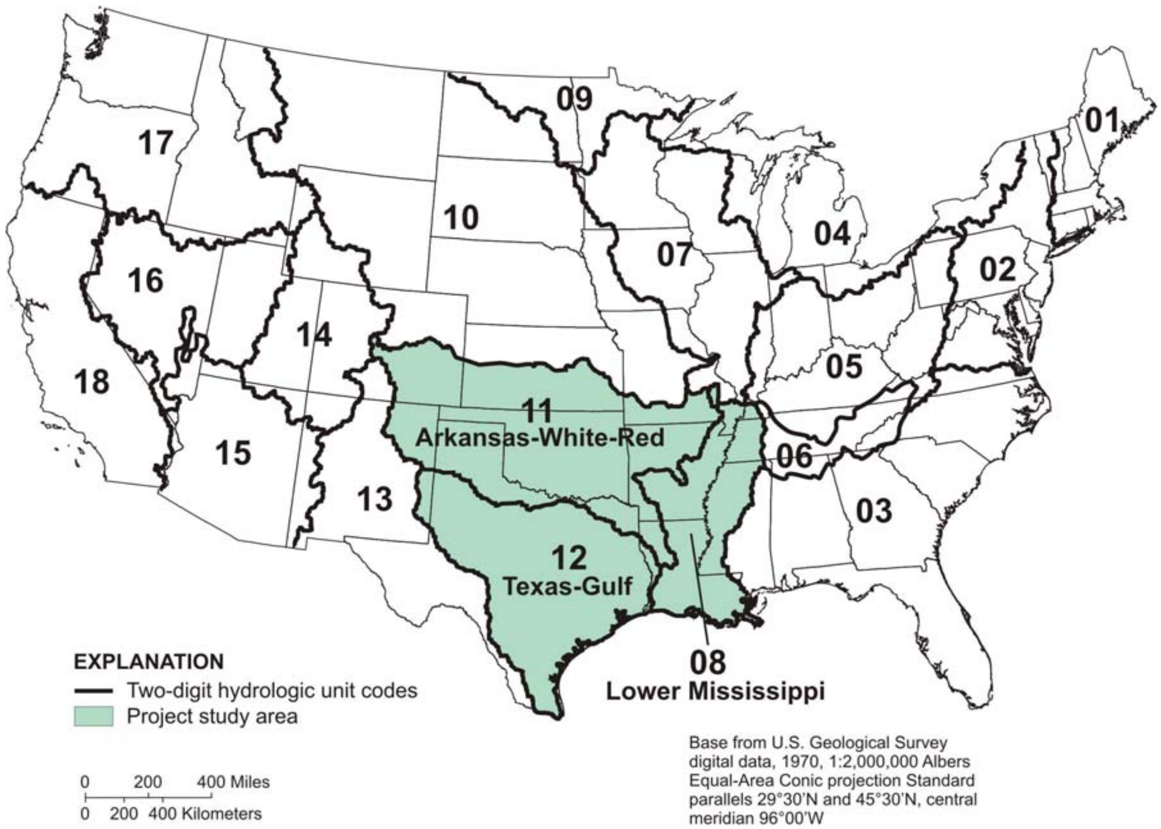

Figure 2. Two-digit hydrologic unit codes and the study area.

Figure 3. States, cities, and major rivers in the study area.

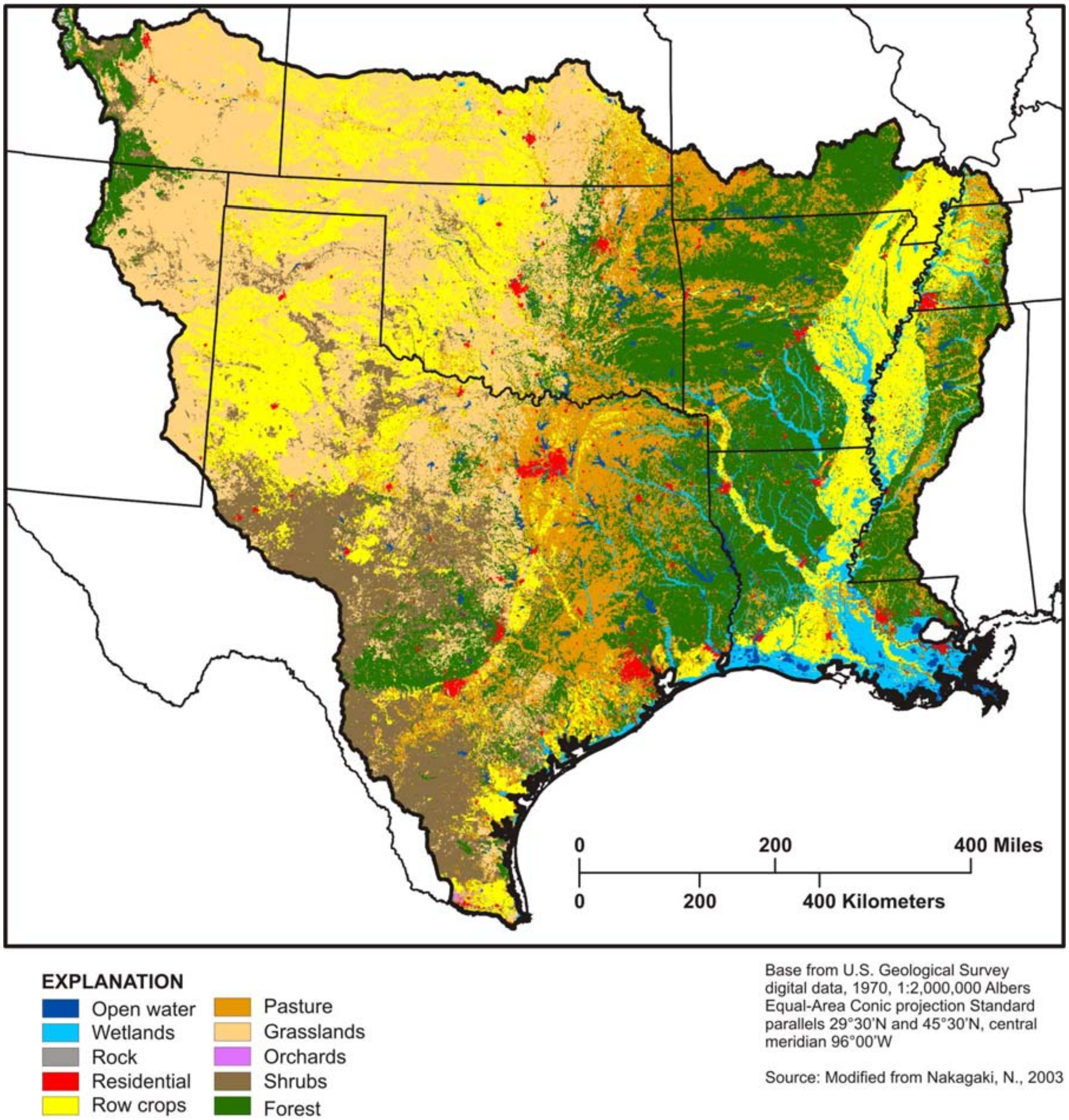

Figure 4. Land use within the study area.