MISSISSIPPI RIVER AND TRIBUTARIES SYSTEM

2011 POST-FLOOD REPORT

APPENDIX F
ENVIRONMENTAL AND CULTURAL RESOURCES

MISSISSIPPI RIVER AND TRIBUTARIES SYSTEM

2011 POST-FLOOD REPORT

APPENDIX F
ENVIRONMENTAL AND CULTURAL RESOURCES

SECTION I   Environmental Team Rosters

SECTION II   USGS Water Science Center's *Water Quality in the Lower Mississippi-Atchafalaya River Basin During the 2011 Flood, April Through July*

SECTION III   Water Quality Data Collection and Analyses (includes figures and tables referenced in SECTION II)

SECTION IV   USGS Water Science Center's *Water-Quality and Phytoplankton Communities in Lake Pontchartrain Before, During, and After the Bonnet Carré Spillway Openings in 2008 and 2011, Louisiana*

SECTION V   *Entrainment of Pallid Sturgeon Through Floodways During the 2011 Lower Mississippi River Flood,* summarizing the efforts to enumerate and relocate sturgeon that may have been entrained by the various spillways and flood control efforts

SECTION VI   Mississippi Department of Marine Resources report *2011 Mississippi River/Bonnet Carré Spillway Flood Operation* describing the influence of the Bonnet Carré opening on the seafood industry in coastal Mississippi

SECTION II

NOTE: All figures and tables referenced in this Section are found in Section III.

Water quality in the lower Mississippi-Atchafalaya River Basin during the 2011 Flood, April through July. By Heather L. Welch, Brent T. Aulenbach, and Richard H. Coupe

Keywords: Surface water, floods, nutrients, water quality

Heather L. Welch, Hydrologist
U.S. Geological Survey
308 South Airport Road, Jackson, MS 39208
601-933-2924 (office); 601-933-2901 (fax)
hllott@usgs.go*v*

Co-authors:
Brent T. Aulenbach, Hydrologist, U.S. Geological Survey, Atlanta, GA
Richard H. Coupe, Supervisory Hydrologist, U.S. Geological Survey, Jackson, MS

Abstract

In 2011, the lower Mississippi River Basin experienced a flood of historic proportions from April through July. This flood marked the first time in history that all three floodways of the Mississippi River and Tributaries System (MR&T) Project were operated simultaneously. In order to characterize water quality of the River during the flood, the US Geological Survey collected samples for analysis of field properties, suspended sediment, nutrients, and pesticides at the Mississippi River at Thebes, Illinois, the Ohio River at Dam 53 near Grand Chain, Illinois, six sites located in the lower Mississippi River Basin, three sites on the Atchafalaya River, and the three flood-control structures. In addition, oil and gas samples were collected at two sites on the Atchafalaya River. Concentrations of constituents in water from samples collected during the flood were similar to concentrations that have been measured historically. Elevated streamflows associated with the floodwater appeared to dilute concentrations of suspended sediment, total nitrogen, and total phosphorus yet the resulting fluxes were still large – more often in May, the month of the highest average monthly streamflow. Opening two of the three flood control structures – the Bird's Point-New Madrid Floodway and the Morganza Floodway– had little effect on water quality in the lower Mississippi and the Atchafalaya Rivers. Although total nitrogen and total phosphorus concentrations stayed relatively the same throughout the flood period in water from the Mississippi River, there was a decrease in total nitrogen concentrations and an increase in total phosphorus concentrations (primarily in the dissolved phase), from 0.16 to 0.52 milligram per liter with the opening time in the Morganza Floodway which indicates that chemical processing is occurring. Approximately 1.4 million metric tons of suspended sediment, 36,500 metric tons of total nitrogen, 3,300 metric tons of total phosphorus, and 12 metric tons of atrazine were diverted from the main stem of the lower Mississippi River through the Bonnet Carré Spillway into Lake Ponchartrain below Baton Rouge, Louisiana while the Spillway was open in May and June 2011.

Introduction

The Mississippi River Basin (MRB) drains approximately 41 percent of the conterminous United States and is the largest river basin in North America (Figure 1). Citizens of the United States use the river for municipal, industrial, agricultural, and recreational purposes. The majority of corn, soybeans, wheat, cattle, hogs, and to a lesser extent cotton and rice produced in the U.S. originate from regions within the MRB. In order to optimize agricultural production, pesticides and fertilizers are applied to the landscape, and these agricultural chemicals along with sediment from agricultural fields can be transported into streams that eventually flow into the Mississippi River and ultimately to the Gulf of Mexico. Since at least 1980, a zone of hypoxia (containing less than 2 milligram per liter (mg/L) of dissolved oxygen) has formed during the spring and summer in the Gulf of Mexico off the coast of Louisiana. The zone has increased in size since measurements began in the early 1980s, and its extent is positively related to the annual amount of nitrogen entering the Gulf from the Mississippi River (Rabalais et al., 2002). More recently, models have indicated that there is also a positive correlation between phosphorus flux to the Gulf of Mexico and the size of the zone of hypoxia (Scavia et al., 2004; Donner and Scavia, 2007; Scavia and Donnelly, 2007; Turner et al., 2008; Boesch et al., 2009).

In response to the devastating 1927 flood, the MR&T Project was authorized by the Flood Control Act of 1928 which called for the creation of a levee system to prevent overflow on developed alluvial lands, floodways to divert excess streamflow past critical reaches, channel improvements and stabilization, and tributary basin improvement (Mississippi River Commission, 2008). This system was tested in April and May 2011, when the Ohio River Basin and parts of the lower MRB received over 5 times more precipitation than normal (Anderson, 2011). The precipitation combined with snow melt from the upper MRB resulted in historic flood levels. In most areas of the lower MRB, the river remained above flood stage for 2 ½ to 3 months. Due to high streamflows measured along the main stem of the river and to prevent loss of property and life, this was the first time in history that all three floodways were operated simultaneously (Anderson, 2011; Schneider, 2011).

Floods by their very nature inundate lands not usually covered by water, so chemicals and sediment associated with the landscape can be carried by floodwaters great distances from their source area. The introduction of large amounts of water onto the landscape may overwhelm a surface-water system's ability to process agricultural chemicals, such as nutrients and pesticides, which may result in large amounts of these chemicals moving downstream to larger surface-water bodies such as the Gulf of Mexico. The 2011 Flood, in particular, occurred at a time during the year when agricultural chemicals were being applied throughout the Basin, and when fields were being tilled leaving the land more susceptible to overland runoff of chemicals and sediment. In addition to contaminant concerns associated with inundation of the alluvial floodplain, there was some concern that opening the flood-control structures, which inundated additional agricultural acreage and lands containing oil wells and industrial chemicals, would carry any associated chemicals back into the main stem of the Mississippi River when the floodwaters receded.

Although there has been extensive documentation on the water-quality effects of floods (such as the one that occurred in the summer of 1993) in the upper MRB (Horowitz, 2010; Schalk et al., 1998; Holmes, 1996; Taylor et al., 1994; Goolsby et al., 1993), little has been published on water-quality effects in the lower Mississippi-Atchafalaya River Basin (MARB). This paper (1) documents all data collected by the US Geological Survey in the lower MARB during the Mississippi River flood from April through July of 2011, (2) summarizes the water quality of the Mississippi River during the flood

and compares that quality to historical observations (3) compares nitrogen, phosphorus, pesticide, and sediment fluxes at stations in the lower Mississippi River (starting just above the confluence of the Ohio and Mississippi Rivers) for May 2011, and (4) assesses the effects of opening the Bird's Point-New Madrid Floodway and the Morganza Floodway on water quality in the Mississippi River.

Hydrology

The Mississippi River originates in Lake Itasca, Minn., and courses over 3,770 kilometers (km) through the middle United States until it empties into the Gulf of Mexico. The river and its tributaries drain parts or all of 31 states from a basin area of approximately 3.2 million km^2, ranking 3rd in size behind the Amazon and Congo Rivers. The drainage area of the river has been subdivided into three portions: (1) the upper MRB which is the portion upriver from the confluence with the Missouri River; (2) the middle MRB which is inclusive of the Missouri River Basin and upriver from the confluence with the Ohio River; and (3) the lower MRB which is downriver from the confluence with the Ohio River and eventually flows into the Gulf of Mexico. This paper focuses on the response of the river to the 2011 Flood in the lower MRB.

Parts of the lower MRB drain streams located in the Mississippi Alluvial Plain, a relatively flat plain with rich, productive soils that are used extensively for agriculture. There is also contribution from streams located in rangeland, urban areas, and mountainous regions. Many tributaries such as the White River, Arkansas River, Yazoo River, and Big Black Rivers contribute to streamflow in this portion of the MRB; however, only 75 percent of that streamflow enters the northern Gulf of Mexico through the river's delta (Horowitz, 2010). The remaining streamflow is diverted by the Old River control structure downstream from Vicksburg, Miss. where it merges with the Red River to form the Atchafalaya about 40 km upstream from Melville, La. (Meade, 1995; Mossa, 1996). Half of the water discharged to the Gulf of Mexico is contributed by the Ohio River and its tributaries, which represent approximately one-sixth of the total area drained by the Mississippi River; whereas, the Missouri River drains 43 percent of the MRB, but contributes only about 12 percent of the total streamflow to the Gulf of Mexico (Meade, 1995).

There are three major floodways located in the lower MRB: the Bird's Point-New Madrid Floodway, Mo., the Morganza Floodway, La., and the Bonnet Carré Spillway, La. (table 1). Prior to 2011, the Bird's Point-New Madrid Floodway had been operated once, the Morganza Floodway had been operated once, and the Bonnet Carré Spillway had been operated nine times (Schneider, 2011). On May 2nd, 2011 the Bird's Point-New Madrid Floodway was activated followed on May 9th by the opening of the Bonnet Carré Spillway to keep streamflows passing New Orleans, La. at approximately 35,400 m^3/s (Anderson, 2011). Lands were inundated by floodwater through the Bird's Point-New Madrid Floodway through May 19, 2011. The final gates on the Bonnet Carré Spillway were closed on June 20, 2011. The Morganza Floodway was opened on May 14th, 2011 when streamflows in the Mississippi River reached approximately 42,500 m^3/s (Anderson, 2011) and remained open through July 7, 2011.

Water-Quality Sampling Sites

The objective of the USGS National Stream Quality Accounting Network (NASQAN) program in the mid-1970s was to account for quantity and quality of water moving within and from the United States. Since 1995, NASQAN has monitored water quality in the MRB to provide an ongoing

characterization of the concentrations and mass fluxes of sediment and agricultural chemicals at key locations in the Basin, to determine regional source areas for these materials, and to assess the effect of human influences on observed concentrations and fluxes (Coupe and Goolsby, 1999). NASQAN sampling stations were selected at critical junctures within the MRB to provide the essential framework for understanding fluxes of materials within the Basin and to the Gulf of Mexico. An important consideration for station selection was the influence of varying land use, and the presence of major reservoirs and input from major tributaries. Generally, stations were selected where substantial changes in mass flux were expected, such as at confluences of major tributaries or at the downstream end of major reservoirs. The nine NASQAN stations sampled for water quality during the flood are shown in figure 1 and described in table 1. The sampling site at the Mississippi River at Thebes, Ill. will be referred to as the Upper Mississippi River, and the sampling site at the Ohio River at Dam 53 near Grand Chain, Ill. will be referred to as the Ohio River. In addition to NASQAN stations, four additional stations were sampled to quantify the effects of the opening of the Bird's Point-New Madrid Floodway. These stations were at the inlet and outlet of the Bird's Point-New Madrid Floodway (map #s 3 and 4 on figure 1; table 1) and downstream of the Bird's Point-New Madrid Floodway outlet on the Mississippi River at Tiptonville, Tenn. and Memphis, Tenn. Water-quality samples were collected in the Morganza Floodway at the Atchafalaya Floodway near Ramah, La. north of I-10 (map #10, figure 1; table 1), and sediment and streamflow data were collected at the Morganza Spillway at Highway 190 near Lottie, La. Both sites will be collectively referred to as the Morganza Floodway. Water-quality, sediment, and streamflow data were collected from water in the Bonnet Carré Spillway at U.S. Highway 61 near Norco, La. (map #14, figure 1; table 1). In this report, this site will be referred to as the Bonnet Carré Spillway.

Methods

Sample collection, processing, and analysis

Water quality samples are typically collected 12 to 14 times per year at NASQAN sites. From April through July 2011, the frequency of sample collection was increased to monitor the effects of the high-flow event. Samples were collected every other week in April, then weekly starting from the second week in May through the end of June, and every other week in July for a total of 12 samples (Map #s 7 – 9 and 12-14, figure 1; table 1). Exceptions to this sampling protocol were at the Mississippi River at Baton Rouge, La. (map #11, sampled every other week April through June for a total of 6 samples), the Ohio River (map #2, four samples in May, two in June), and the Upper Mississippi River (map #1, sampled every other week April through June and monthly in July for a total of 7 samples). Periodic water quality samples were taken while the Bird's Point-New Madrid Floodway was in operation during the flood. Samples were collected on May 5th at both the inlet and the outlet of the Bird's Point-New Madrid Floodway along with downstream Mississippi River stations at Tiptonville, Tenn. and Memphis, Tenn. A sample was also collected on May 18 at the Mississippi River at Memphis, Tenn. All samples were analyzed for major inorganics, dissolved organic carbon, alkalinity, nutrients, pesticides, turbidity, field parameters, and suspended sediment. Additional analysis was added for particle size determination of the suspended sediment.

Streamflow was measured and sediment samples were collected on the Morganza Floodway at a different location than the other water-quality data. At the Morganza Spillway at Highway 190 near Lottie, La., streamflows were measured daily from May 14th through June 27th, and sediment samples were collected from May 18th through June 10th (figure 1). The Bonnet Carré Spillway was sampled

seven times in May and June, and 28 sediment samples were collected at the site during the same time period. Samples for oil and gasoline analysis were collected at the Atchafalaya River at Melville, La. and the Lower Atchafalaya River at Morgan City, La. seven times in May and June (figure 1). The Acoustic Doppler Current Profiler (ADCP) method described by Olson and Norris (2007) was used by the USGS to measure instantaneous streamflow at the sampled stations, where streamflow is the volume of water moving down a stream or river per unit of time (m^3/s). At four stations (sites 2, 7, 8, and 9; figure 1 and table 1), instantaneous streamflow was measured at a separate location from where the water-quality sample was taken. The mean daily streamflow (Q) was calculated and reported by the USGS according to standard procedures (Rantz, 1982). Daily streamflow at the Mississippi River at Tarbert Landing, Miss. Old River outflow channel near Knox Landing, La. (total outflow) and at the Atchafalaya River at Simmesport, La., is measured by the U.S. Army Corps of Engineers.

Sediment and water-quality samples were collected using isokinetic depth-integrated samplers according to protocols detailed in the USGS National Field Manual for the Collection of Water Quality Data (US Geological Survey, variously dated). The equal-discharge increment (EDI) sampling method was used to collect a streamflow-weighted sample representing the entire flow passing through the cross section. The equal-width increment (EWI) sampling method was used to collect the samples at sites 8 through 15 (figure 1; table 1). Suspended sediment concentration (SSC) samples were analyzed at either the U.S. Geological Survey (USGS) Sedimentation Laboratory in Baton Rouge, La., or the Sedimentation Laboratory in Iowa City, Ia., according to the method described by Guy (1969). Particle size analysis was performed by the USGS Sedimentation Laboratory in Iowa City, Ia.

All samples for analysis of major ions and nutrients were preserved according to standard protocols and those samples along with samples for pesticide analysis were shipped overnight on ice for analysis at the USGS National Water-Quality Laboratory (NWQL) in Denver, Co. Major ions were measured using atomic absorption spectrometry, and nutrient concentrations were quantified using colorimetry (Fishman and Friedman, 1989). Pesticides analyzed at the NWQL were quantified using gas chromatograph-mass spectrometry.

Samples for hydrocarbon analysis were chilled to 4° Celsius and shipped overnight for analysis at TestAmerica Laboratories, Inc. in Arvada, Co. Gasoline range organics were separated using a purge and trap method, and then analyzed using a gas chromatograph with a flame ionization detector (GC-FID) as outlined by the US Environmental Protection Agency (1986). Diesel range organics were extracted using a separatory funnel liquid-liquid extraction method and analyzed for using GC-FID (US Environmental Protection Agency, 1986). Hexane extractible compounds were separated using solid-phase extraction and analyzed for using a gravimetric method (US Environmental Protection Agency, 1999).

Data analysis

Some concentrations of pesticides and nutrients were estimated ("E") by the USGS NWQL. Values coded with a remark code of "E" were treated as detections in this report, unless the value was lower than the method reporting level (MRL) for that constituent. All detected values lower than an established MRL were "censored," or reported as less than (<) the MRL. Table 2 lists selected constituents and their established MRLs.

Flux estimation methods

Streamwater constituent load, also known as mass flux, is the mass of chemical constituent or sediment transported past a point in a stream over a period of time. Flux (Φ) is the product of constituent concentration (*C*) and streamflow (*Q*) integrated over time (*t*):

$$\Phi = \int C(t)Q(t)dt \tag{1}$$

Flux calculations using the integral in equation 1 require a continuous record of concentration and streamflow. Although streamflow can be measured at a sufficiently high frequency, constituent concentration typically is measured less frequently due to the expense and effort of collecting and analyzing water-quality samples. Several flux estimation approaches have been proposed to address the issue of using only discrete concentrations. The approach employed is known as the regression-model method, also known as the rating-curve method, which is a standard statistical technique that can be used to estimate concentration continuously, thus enabling a direct calculation of mass flux. This method uses a regression model relating concentration (or load) to continuous variables such as streamflow and day of year (for example, Johnson, 1979; Cohn and others, 1992). Fluxes were estimated using a seven-parameter regression model equation of the form:

$$\ln(L_i) = a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi\, dtime) + a_4 \cos(2\pi\, dtime)$$
$$+ a_5\, dtime + a_6\, dtime^2 + \varepsilon \tag{2}$$

       where
           ln is the natural logarithm (log base e);
           L_i is the calculated load for sample *i*;
           $\ln Q$ is ln(daily average streamflow) minus center of ln(daily average streamflow);
           dtime is decimal time minus center of decimal time (as defined by Cohn and others, 1992);
           ε is error; and
           $a_0...a_6$ are the fitted parameters in the multiple regression model.

Fluxes were estimated with the regression-model method using Load Estimator (LOADEST), a FORTRAN-based flux estimation program (Runkel and others, 2004). LOADEST allows users to choose from three methods to estimate fluxes based on the statistical distribution of the calibration data set, which includes time series of streamflow, concentration, and other variables. The method selected to estimate fluxes in this report was the adjusted maximum likelihood estimate (AMLE), which is appropriate for estimation when a dataset contains censored data (concentrations less than the MRL). The AMLE method corrects for first-order bias in the regression coefficients (due to the presence of censored data in the calibration data set) and minimizes other biases such as when estimated logarithms of flux are retransformed to original units (Cohn et al., 1992). LOADEST allows users the option to automatically select an optimal model form from the nine possible choices based on equation 2 (model forms include equation 2 and eight subsets of the parameters in equation 2). Auto-selection involves computation of the Akaike Information Criterion (AIC) statistic as described in Judge et al.(1988), and then the model form with the lowest value of the AIC statistic was the one selected.

While AMLE fluxes are estimated by LOADEST on a daily time-step, fluxes are reported here on a monthly time-step because of potentially large errors in estimating fluxes for short time intervals. Even at a monthly time-step, fluxes can be imprecise. As a means to describe uncertainty, LOADEST provides lower and upper 95 percent confidence intervals for each flux estimate. The confidence intervals are based on the standard error of prediction which includes both the estimate of parameter uncertainty and the unexplained variability about the model, referred to as random error (Runkel and others, 2004). When describing uncertainty and errors associated with using a regression based approach, such as LOADEST, an assumption is made that there is negligible error in the measurements of daily streamflow. While potential errors in measuring streamflow are generally small, uncertainty estimates are likely to be somewhat understated due to this false assumption. Therefore, confidence intervals are included with each monthly flux estimate in the report such that the differences in flux estimates can be assessed appropriately.

It should be noted that flux estimates presented in this report are calculated using the same approach as Aulenbach et al. (2007). In their paper, dissolved nitrate plus nitrite, total nitrogen, total phosphorus, and other nutrient fluxes were estimated for the Mississippi-Atchafalaya River Basin (to determine delivery to the Gulf of Mexico) and for many smaller subbasins within the MARB for each station's period of record through 2005 and are updated annually by the USGS (*http://toxics.usgs.gov/hypoxia/mississippi/flux_ests/index.thml*).

In addition to the LOADEST AMLE flux estimates, fluxes were also estimates using the composite method during this period (Aulenbach and Hooper, 2006). The composite method is a hybrid flux estimation method that combines aspects of two commonly used methods: the regression-model method, which is used by the composite method to predict variations in concentrations between collected samples; and a period-weighted approach, which is used by the composite method to apply the residual concentrations from the regression model over time. Residual concentrations are the difference between the observed and model-predicted concentrations. In this approach, on days with observations, the model-predicted concentrations are adjusted to observed concentrations; and on days between observations, the model-predicted concentrations are adjusted by applying a piece-wise linear function of the residual concentrations as per a period-weighted approach. This approach is useful in situations in which there is serial autocorrelation in the residuals – residuals are not independent and identically distributed – such that there is structure (or patterns) in the residuals that contain some meaningful information that can be used to improve flux estimates. When sampling frequency is increased, serial autocorrelation between samples generally increases, and the composite method should improve adjusting predicted regression model concentrations to observed concentrations, thereby improving model fit.

The composite method fluxes presented here are based on the same regression models used to estimate LOADEST AMLE fluxes. Composite method flux estimates have previously been reported in Aulenbach, et al. (2007), but only for the two lower Mississippi-Atchafalaya River Basin stations (Mississippi River near St. Francisville, La. and Atchafalaya River at Melville, La.). The composite method flux estimates may be the preferred flux estimates during the flood period because for many constituents and stations, the sampling frequency is either weekly or bi-weekly during the April through July flood period. An unpublished sub-sampling analysis using a daily suspended sediment dataset indicated that, for flux estimation for large rivers, the composite method can improve flux estimates for sampling frequencies of at least 15-days while also reducing variability observed within the calibration period. However, for the particular sub-sampling analysis, the composite method did

not improve flux estimates over the AMLE approach for monthly sampling frequencies. Another consideration for using the composite method is that the regression models may be poorly constrained at the highest streamflows during the flood because: (1) some constituents exhibit hysteresis in which the concentrations on the rising limb of the flood hydrograph do not match the falling limb of the hydrograph (regression model will predict average response at a particular streamflow); and (2) there are only a few observations of water-quality at the highest flows. For this report, the composite model can improve flux estimation during the flood by adjusting the AMLE predicted concentrations to the observed concentrations. Unfortunately, there is no way to estimate uncertainty associated with the composite method. But, it can be reasonably assumed that for periods with sampling frequencies of at least 15-days, loads estimated using the composite method should compare as well to observed loads as do loads estimated using the LOADEST AMLE method.

Fluxes of selected pesticides for April through July 2011 that did not have a strong concentration-streamflow relationship necessary for use in a regression-model method approach, or had an insufficient long-term dataset from which to create a concentration model with LOADEST, were estimated using a period-weighted approach in which measured concentrations were assumed to represent a period around which the sample was collected. A piecewise linear function implementation was used in which sample concentrations were linearly interpolated through time between sample collections (e.g. Larson et al., 1995). The products of concentration and streamflow were summed through time to estimate flux. All samples collected were used in the estimation, and there was no preconceived model for concentration. The flux estimate was sensitive to sampling frequency and distribution, and there was no estimate of error.

Flux Estimation Implementation

Fluxes were estimated for the April through July 2011 Flood period and were summarized in this report on a monthly basis. Fluxes were estimated for 22 constituents: dissolved nitrate plus nitrite, total organic nitrogen plus ammonia (total Kjeldahl nitrogen), dissolved organic nitrogen plus ammonia (dissolved Kjeldahl nitrogen), total particulate nitrogen, and dissolved ammonia, total phosphorous, dissolved orthophosphate, particulate carbon, particulate inorganic carbon, particulate organic carbon, dissolved organic carbon, dissolved silica, dissolved chloride, suspended sediment, total dissolved solids (residue on evaporation),simazine, prometon, cyanazine, metolachlor, atrazine, alachlor, and acetochlor. In addition to these species, total nitrogen fluxes were estimated by summing dissolved nitrite plus nitrate and total Kjeldahl nitrogen fluxes. Fluxes were estimated for only seven constituents at the Red River at Alexandria, La. This is not a NASQAN station, so the water-quality constituents collected there are not the same as those collected at NASQAN sites. Thirteen constituent fluxes were estimated for the Yazoo River near Long Lake. This was recently added as a NASQAN station, and there were not five-years of water-quality data to calibrate regression models for all constituents. LOADEST requires a minimum of 12 samples, 7 of which must be uncensored, in order to calibrate a regression model and estimate fluxes. The water-quality dataset was prepared and screened for outliers as per Aulenbach et al. (2007). A change was made to these protocols for days with multiple samples. In lieu of averaging all sample concentrations collected on that day (including replicates), concentrations were instead designated from the first available sample that had a concentration for that constituent by sorting all samples according to: (1) routinely collected samples; (2) arranging samples in decreasing order by the number of water-quality constituents each sample contained in the analysis; and (3) ordering the samples by collection time from earliest to latest.

Regression models were calibrated using the samples collected during the 5-year period water years 2006 through 2011. The calibration period is set such that it is long enough to contain enough sample concentrations to sufficiently develop the regression model while not being so long that there are significant changes, or drift, in the model regression over the calibration period. The calibration period used corresponds to the calibration period that will be used for estimating fluxes at NASQAN sites for the 2011 water year (water year is the same as the Federal fiscal year). Hence, the results herein should be consistent with results published later by the USGS for the 2011 water year. One exception to the 5-year calibration period was for the station Mississippi River above Vicksburg, which was calibrated for only three years, 2009 through 2011, as water-quality sampling at this station only recently initiated.

The fluxes for the Mississippi River near St. Francisville (downstream of the Old River diversion where about, on average, 25 percent of the Mississippi River streamflow is diverted to the Atchafalaya River) are estimated using a more complex regression model that is used by the USGS NASQAN program (Aulenbach et al., 2007). The streamflow used in the regression model is not the streamflow of the Mississippi River at Tarbert Landing, but is the Tarbert Landing streamflow combined with the streamflow diverted via the Old River representing the total lower MRB flow. Furthermore, it was found that variations in water quality at St. Francisville were related to variations in streamflow contributions of the upper Mississippi plus Missouri River Basins, and the Ohio plus Tennessee River Basins. Therefore, flow and flow-squared terms for the Upper Mississippi River and the Ohio River at Metropolis, Ill. were added to the regression models. These flows were lagged by 10-days to account for travel times for streamwater from these upstream stations to reach St. Francisville during about average flow conditions. The use of a custom model form with additional variables precluded the use of the LOADEST feature of auto-selecting the best model by using the lowest value of the AIC statistic. Hence, all model terms were always included. So that flux estimates represented only fluxes at the Mississippi River near St. Francisville, daily flux estimates were multiplied by the ratio of the streamflow at the Mississippi River at Tarbert Landing, Miss. and the total lower MRB streamflow before summarizing fluxes at other time steps.

Fluxes were not directly estimated at the Old River Diversion, Bonnet Carré Spillway, and Morganza Floodway as there was insufficient long-term water quality sampling at these stations to develop regression models. Instead, fluxes were calculated based on fluxes estimated using the water quality at St. Francisville prorated on a daily basis based on comparison of streamflows of the Old River Diversion, Bonnet Carré Spillway, and Morganza Floodway with respect to the streamflows at Tarbert Landing. These flux estimates were likely reasonable for dissolved constituents as these streamflow diversions were in the vicinity of St. Francisville, and dissolved constituents were likely to be reasonably well mixed in the water column. Suspended sediment, particulate, and total constituent flux estimates may be over-representative of actual flux due to suspended material settling out of the water column before entering these diversions. It should be noted that the Morganza Floodway is upstream of the Mississippi River near St. Francisville water-quality station, but downstream of the Mississippi River at Tarbert Landing streamflow station. Therefore, the flux estimates for the Morganza Floodway are representative of the streamflow at Tarbert Landing as the streamflows used to estimate the fluxes did not take into account the streamflows diverted upstream of St. Francisville when the Morganza Floodway was in operation during the flood.

May flux estimates for the Yazoo River below Steele Bayou near Long Lake, Miss. were complicated by backwater conditions that occurred during the flood that month. Backwater conditions, in which

water from the flooding in the Mississippi River flowed upstream in the lower Yazoo River, resulted in 20 days of negative daily average streamflow in May at the Yazoo River station. For these days, it was assumed the stream water-quality was similar to that of the Mississippi River above Vicksburg, Miss. Therefore, the flux on these days were calculated as the daily flux from Mississippi River above Vicksburg, prorated by a ratio of streamflow of the Yazoo River and the Mississippi River above Vicksburg. It should be noted that the streamflow station for the Mississippi River is at Vicksburg, Miss., downstream of the confluence of the Yazoo River – hence, the streamflow for the Mississippi River above Vicksburg is calculated as the difference between the streamflow at the Mississippi River at Vicksburg and streamflow of the Yazoo River. The average streamflow and all of the fluxes on the Yazoo River are negative in May, indicating net streamflow and fluxes going upstream from the Mississippi River back-flooding into the lower Yazoo River Basin (presented as a negative average streamflow and as negative fluxes of suspended sediment, nitrogen, and phosphorus).

The monthly fluxes for streamflow, total nitrogen, total phosphorus, atrazine, metolachlor, and suspended sediment are discussed for May 2011 and are compartmentalized for discussion by comparing inputs from the Upper Mississippi River and the Ohio River to outputs to the Gulf of Mexico, which are calculated by adding fluxes from the Wax Lake, Morgan City, and Tarbert Landing sites and then subtracting fluxes from the Morganza Floodway and Bonnet Carré Spillway. One issue with this approach is travel time between the sites, for example, sites located close together do not exhibit the same time lag in constituent travel as those located further apart.

Results

Streamflow

Peak flows measured during the 2011 Flood (April through July) were 24,150 m^3/s at the Upper Mississippi River, 35,700 m^3/s at the Ohio River, 65,400 m^3/s at Vicksburg, 45,800 m^3/s at St. Francisville, 40,500 m^3/s at Baton Rouge, and 34,800 m^3/s at Belle Chasse (table 1). In the Upper Mississippi River and the Ohio River, median instantaneous streamflow (at the time of water-quality sampling) was almost three times higher than the historical median instantaneous streamflow (figure 2). Median instantaneous streamflow measured during the flood at the four sites on the main stem of the lower Mississippi River were approximately twice as high as median instantaneous streamflows measured for the period of record at those sites.

Average monthly streamflow was highest for the flood period during May 2011. Approximately 16,700 m^3/s and 25,600 m^3/s contributed to streamflow in the lower MARB from the Upper Mississippi River and the Ohio River, respectively. Average monthly streamflow was 35 percent higher in the Mississippi River at Vicksburg than the streamflow of the Upper Mississippi and the Ohio River combined (figure 3). In fact, the highest average monthly flow for the entire flood period was measured in May at Vicksburg (56,900 m^3/s). Below Vicksburg, Miss., about 30 percent of the Mississippi River flow was diverted through the Old River Channel and about 4 percent moved through the gates of the Morganza Floodway. The remaining 70 percent moved past St. Francisville, La. and Baton Rouge, La (locations in figure 1). Below Baton Rouge, flow was further dispersed with approximately 14 percent of what remained diverted into Lake Pontchartrain through the Bonnet Carré Spillway.

Sediment

Suspended sediment concentrations measured in surface water at four sites in the lower MRB, the Upper Mississippi River, and the Ohio River during the 2011 Flood were within the range of concentrations measured historically at these sites (figure 4). In fact, median suspended sediment concentrations measured at Vicksburg, Miss., St. Francisville, La., Baton Rouge, La., and Belle Chasse, La. measured during the 4-month flood period were lower than the median suspended sediment concentration at each site from samples collected over the period of record. The median suspended sediment concentration for samples collected during the flood in the Upper Mississippi River was slightly higher than the historical median of samples collected at this site (figure 4).

Higher concentrations of suspended sediment were measured in water from the Mississippi River at Vicksburg, Miss., and St. Francisville, La. in early March (figure 5). Sampled sites upstream and downstream of these two sites also had high suspended sediment concentrations in March (data not shown). Concentrations of suspended sediment on March 1 at Vicksburg were 5 times higher than the median suspended sediment concentration measured during the flood period, but streamflow at the site on March 1 was 45 percent less than the median streamflow measured during the flood. Suspended sediment concentrations measured on March 8 at St. Francisville were 7 times higher than the median concentration of suspended sediment during the flood. The streamflow associated with the high suspended sediment concentration in March at St. Francisville was 25 percent less than the median streamflow measured during the flood period.

Average monthly suspended sediment fluxes were highest during May 2011 with the exception of Tarbert Landing (flux was approximately the same in April and May) and the Upper Mississippi River (fluxes in June and July were about 14.3 and 15.3 million metric tons, respectively). Suspended sediment flux from the Upper Mississippi River was 1.7 times higher than the suspended sediment flux entering the lower MARB from the Ohio River. During May, the highest average flux of suspended sediment was measured at Vicksburg, Miss. (18.8 million metric tons). There is a 7.5 million metric ton loss between the flux at Vicksburg and the fluxes entering the Old River Channel and the fluxes moving past Tarbert Landing down the main stem of the Mississippi River. Approximately, 171,000 metric tons of the loss is due to backwater conditions in the Yazoo River. Four times more suspended sediment is leaving the Atchafalaya River Basin than is entering through the Old River Channel. Between the entry of the water into the Old River Channel and Melville, there is a tripling in suspended sediment flux, and the flux again increases between Melville and the bifurcation of the water at Wax Lake and Morgan City (increase in suspended sediment flux of 1.3 times). Although not quantified, the Red River may have added up to 6 million metric tons to the Atchafalaya system in May 2011. Comparing the inputs of suspended sediment flux (the Upper Mississippi River plus the Ohio River) with the outputs (Wax Lake plus Morgan City plus Tarbert Landing minus the Morganza Floodway and Bonnet Carré Spillway); there is a cumulative gain of 2.2 million metric tons of suspended sediment flux in the lower MARB in the month of May.

Nutrients

Nutrient concentrations measured during the flood were of the same magnitude as concentrations measured historically at the Upper Mississippi River, the Ohio River, and the four downstream sites along the main stem (Fig 7; a and b). Median concentrations of total nitrogen were approximately the same as the median concentration for the period of record, except in the Upper Mississippi River

where concentrations measured during the flood were higher than the historical median total nitrogen concentration (figure 7a). Median total phosphorus concentrations during the flood (figure 7b) were higher at the Upper Mississippi River and the Ohio River; however, median concentrations of total phosphorus were less than the median for the period of record at St. Francisville and Baton Rouge.

The highest concentrations of total nitrogen measured in water from the Mississippi River at Vicksburg, Miss., occurred before and after the period when maximum streamflows were measured in the river (figure 8). On March 1st, the total nitrogen concentration was 3.3 mg/L which was the largest concentration measured from January through August 2011 and was 1.5 times higher than the median total nitrogen concentration (2.2 mg/L) during the flood period. Total nitrogen concentrations increased in mid-June and remained above 2 mg/L until August. The total phosphorus concentration measured on March 1st was almost 3 times higher than the median concentration for total phosphorus in water at Vicksburg during the flood (0.19 mg/L). In fact, the concentration measured on March 1st was the highest concentration measured from January through August – measured concentrations from this time period ranged from 0.16 to 0.23 milligrams per liter.

Total nitrogen fluxes in the lower MARB during the flood period were highest in May 2011 at all sampled sites. The flux of total N entering the lower MARB was 35 percent more from the Upper Mississippi River than from the Ohio River (figure 9). The maximum total N flux in May 2011 occurred at Vicksburg (262,000 metric tons); of this flux, 6-percent was lost, 26-percent was diverted through the Old River outflow, and 68-percent moved along the main stem past Tarbert Landing. A portion of the 6-percent loss is attributed to backwater conditions in the Yazoo River where there was a 1,800 metric ton loss in total nitrogen. There was a 7-percent increase in total N flux leaving the Atchafalaya River Basin from the total N flux that entered at the Old River outflow. The gain occurred between the confluence of the Red River with the Atchafalaya and the sampled site at Melville. The majority of the total N flux leaving the lower MARB and entering the Gulf of Mexico is through the main stem (Approximately 143,100 metric tons from Tarbert Landing minus the Morganza Floodway and Bonnet Carré Spillway compared to approximately 73,000 metric tons from the Atchafalaya River Basin computed from the loads at Wax Lake and Morgan City). Comparing the inputs of total N fluxes (the Upper Mississippi River plus the Ohio River) with the outputs (Wax Lake plus Morgan City plus Tarbert Landing minus the Morganza Floodway and Bonnet Carré Spillway); there is a cumulative loss of 56,630 metric tons of total nitrogen in the lower MARB in the month of May.

Total phosphorus fluxes in the lower MARB during the flood period were highest in May 2011 at all sampled sites except for the Upper Mississippi River where total P fluxes in June and July were about 15,000 metric tons. The flux of total P entering the lower MARB was 18 percent more from the Upper Mississippi River than from the Ohio River (figure 10). The maximum total P flux in May 2011 occurred at Vicksburg (26,200 metric tons); of this flux, 12-percent was lost, 24-percent was diverted through the Old River outflow, and 63-percent moved along the main stem past Tarbert Landing. There was a 45-percent increase in total P flux leaving the Atchafalaya River Basin from the total P flux that entered at the Old River outflow. The gain occurred between the confluence of the Red River with the Atchafalaya and the sampled site at Melville and again between Melville and the bifurcation at Wax Lake and Morgan City. More of the total P flux leaves the lower MARB and enters the Gulf of Mexico through the main stem than through the Atchafalaya River (approximately 13,400 metric tons compared to 11,600 metric tons, respectively). Comparing the inputs of total P fluxes (Upper Mississippi River plus the Ohio River) with the outputs (Wax Lake plus Morgan City

plus Tarbert Landing minus the Morganza Floodway and Bonnet Carré Spillway); there is a cumulative loss of 320 metric tons of total phosphorus in the lower MARB in the month of May.

Pesticides

Atrazine and metolachlor are two of the most commonly detected pesticides in water from the Mississippi River (Meade, 1995; Pereira and Rostad, 1990). Concentrations of pesticides are seasonal; thus, concentrations measured during the flood were compared to concentrations collected from April through July for the period of record at each site. Concentrations of both constituents were of the same magnitude during the flood as concentrations detected historically in April through July at the Upper Mississippi River, the Ohio River, and the four downstream sites (figures 11a and 11b). Median atrazine concentrations measured during the flood were highest in the Upper Mississippi River and the Ohio River (figure 11a). Lower median atrazine concentrations were measured at St. Francisville and Baton Rouge when compared to the median concentrations from water collected April through July for the period of record (figure 11a). Similar to atrazine, median metolachlor concentrations during the flood were highest in the Upper Mississippi River and the Ohio River (figure 11b). Median concentrations of metolachlor were lower than the historical April through July median concentrations at St. Francisville, Baton Rouge, and Belle Chasse (figure 11b).

Concentrations of atrazine and metolachlor were at or below the MRL through early April in water samples from the Mississippi River at Vicksburg (figure 8). Atrazine concentrations increased as streamflow increased from April 20th through May 4th, but concentrations decreased and remained around 0.45 µg/L throughout the month of May which was the time of peak streamflow at Vicksburg (figure 8). As streamflow began to decrease, the atrazine concentration peaked at 0.9 µg/L. Metolachlor concentrations followed the same pattern with streamflow as atrazine, but peaked a week later on June 8th with a concentration of 0.88 µg/L.

The highest monthly flux of atrazine, 74 metric tons, was delivered to the Gulf of Mexico in May 2011 (figure 12). Atrazine flux increased 5 times from April to May, and the flux in June (69 metric tons) was nearly the same as it was in May. However, by July, the flux of atrazine had decreased by half from its peak. The highest monthly flux of metolachlor, 60.6 metric tons, entered the Gulf of Mexico in June (figure 12). This flux was almost 11 times greater than the monthly flux in April and three times greater than the flux in May. By July, the flux of metolachlor entering the Gulf of Mexico had decreased to 46.6 metric tons, and this flux was greater than the atrazine flux in July.

Water quality of the three floodways

Bird's Point-New Madrid Floodway

Opening the Bird's Point-New Madrid Floodway late on May 2, 2011 inundated 53,824 hectares of agricultural land (Olson and Morton, 2012). The inflow and the outflow of the Floodway were sampled four hours apart on May 4, 2011, almost 48 hours after the first breech in the levee. Total nitrogen concentrations at the inflow and outflow were 3.0 mg/L and 2.65 mg/L, respectively (Appendix 2). The total nitrogen concentration measured upstream of the breech in the Upper Mississippi River on April 26, 2011 was 3.1 mg/L and in the Ohio River on May 3, 2011 was 1.6 mg/L (Appendix 2). Total nitrogen concentrations ranged from 1.6 to 1.8 mg/L downstream at Vicksburg during the month of May.

Nitrate concentrations at the inflow and outflow were approximately 2 mg/L (Appendix 2). The nitrate concentration measured in water from the Upper Mississippi River on April 26, 2011 was about the same as the concentrations in the Floodway; however, the concentration in the Ohio River on May 3, 2011 was half the measured nitrate concentration at the Upper Mississippi River and in the Floodway. It appears that there is incomplete mixing of water in the Floodway from the two source streams. The nitrate concentrations measured at Vicksburg in May ranged from 1.09 to 1.23 mg/L which are lower than concentrations in the Floodway and in the Upper Mississippi River.

Atrazine concentration measured on May 4, 2011 at the inflow and outflow in the Floodway were 0.49 µg/L and 0.60 µg/L, respectively (Appendix 4). These concentrations were about half the atrazine concentration measured in the Upper Mississippi River on April 26, 2011 (0.95 µg/L), but they were greater than the concentration measured in the Ohio River on May 3rd (0.415 µg/L). The Floodway concentrations were also higher than the median atrazine concentration of 0.45 µg/L for water samples collected in May at Vicksburg.

Morganza Floodway

The Morganza Floodway was opened on May 14, 2011 and diverted flow from the Mississippi River above St. Francisville and Baton Rouge to the Atchafalaya River Basin. The decision to open the Floodway is made when flows are predicted to reach 42,500 m^3/s at the Red River Landing. Inundated land in the Basin consists of swamps, small farms, and thousands of oil and gas wells. Streamflows in the Floodway ranged from 100 to 5,500 m^3/s, with a median streamflow of 3,100 m^3/s for the period that it was opened (May 14 through July 7, 2011; table 1). This median streamflow was approximately 14-percent of the median streamflow measured during the flood period at Vicksburg (located upstream of the Floodway) and 12-percent of the median streamflow measured at Tarbert Landing and 18-percent of the median streamflow measured at Baton Rouge (both downstream of the Floodway). Median streamflow in the Floodway was approximately 29-percent of the median streamflow measured at Melville and 84-percent of the median streamflow measured at Morgan City (table 1).

Suspended sediment concentrations (Appendix 6) measured in the Floodway ranged from 8 to 31 mg/L with a median concentration of 16.5 mg/L. There was a direct relationship between streamflow and suspended sediment concentrations in the Morganza Floodway– as streamflow decreased, suspended sediment concentrations decreased (not shown; data in Appendix 6). This decrease also corresponded with the length of time that the Floodway had been open. Suspended sediment concentrations in the Floodway were 5 to 8 times less than the concentrations that were measured at Vicksburg, St. Francisville, and Baton Rouge. Suspended sediment concentrations in the Floodway were 9 to 10 times less than concentrations measured at Melville (upstream of the Floodway's confluence with the Atchafalaya River) and Morgan City (downstream of the Floodway's confluence with the Atchafalaya River), respectively (Appendix 3 and Appendix 6).

Total nitrogen concentrations, which were composed of mostly nitrate, in water from the Morganza Floodway ranged from 0.90 to 1.6 mg/L, with a median concentration of 1.1 mg/L (Appendix 2). The highest concentrations were measured in May, soon after the gates to the Floodway were first opened. Concentrations declined steadily throughout June. The lowest total nitrogen concentrations measured in water from Vicksburg (upstream of the inlet to the Floodway) and St. Francisville and Baton Rouge (both downstream of the inlet) were higher than the highest total nitrogen concentrations measured in

the Floodway. All total nitrogen concentrations measured at Melville (upstream of the Floodway outlet into the Atchafalaya River) were higher than the concentration measured in the Floodway. Downstream of the outlet, total nitrogen concentrations at Morgan City were generally higher than concentrations measured in the Floodway. However, there were two sampling dates where samples from Morgan City had a concentration less than or about equal to the concentration in the Floodway – May 25, 2011 and June 16, 2011.

Total phosphorus concentrations in water from the Morganza Floodway ranged from 0.16 to 0.52 mg/L, with a median concentration of 0.22 mg/L (Appendix 2). In contrast to total nitrogen and nitrate concentrations, total phosphorus increased in the Floodway with length of time that the Floodway was open (figure 14). Most of the increase in total phosphorus was due to an increase in orthophosphate concentrations (figure 14). Total phosphorus concentrations at Vicksburg, St. Francisville, and Baton Rouge were lower than the concentrations measured in the Floodway. Maximum concentrations at the main stem sites were about the same as the median concentration of the samples collected in the Floodway (figure 13). Highest concentrations in the Mississippi River were measured in late June-July as the streamflow in the river decreased. Maximum total phosphorus concentrations measured in water at Melville and Morgan City were 0.30 mg/L and 0.34 mg/L, respectively, but the median concentration at both sites was 0.19 mg/L which was lower than the median concentration for the Floodway (Appendix 2).

Atrazine concentrations in water from the Morganza Floodway ranged from 0.295 to 0.67 µg/L with a median concentration of 0.57 µg/L (Appendix 4). The highest concentrations were measured in June. Median concentrations of atrazine measured at Vicksburg, St. Francisville, and Baton Rouge from May 14, 2011 to July 7, 2011 (period that the Floodway was open) were 0.53, 0.48, and 0.56 µg/L, respectively. All of these medians are less than the median concentration in the Floodway. Similarly, the median concentrations for atrazine at Melville and Morgan City were 0.53 and 0.49 µg/L, respectively, lower than the median concentration in the Floodway for the sampling period.

Water samples were analyzed for evidence of contaminants from oil and gasoline at Melville, La. (upstream of the Morganza Floodway outlet) and at Wax Lake (downstream of the Morganza Floodway outlet) from May 19 through June 29, 2011, while the Floodway was in operation. There was one low-level detection of diesel the week of May 23rd in water upstream of the outflow (figure 14). Concentrations of gasoline, oil and grease, and petroleum hydrocarbons were about the same in the upstream and downstream samples for all weeks except the weeks of May 23rd and May 30th. Gasoline concentrations were twice as high in the downstream samples as in the upstream samples the week of the 23rd. However, the following week gasoline concentrations were twice as high in the upstream samples as in the downstream samples (figure 14).

Bonnet Carré Spillway

The first bays on the Bonnet Carré Spillway were opened on May 9, 2011 and diverted flow from the Mississippi River below Baton Rouge into Lake Ponchartrain. The decision to open the Bonnet Carré Spillway was made when the volume of water predicted to pass New Orleans, La. was 35,400 m³/s. Streamflows in the Spillway ranged from 1,000 to 11,200 m³/s with a median streamflow of 8,000 m³/s (table 1) for the period that it was opened (May 9th through June 20, 2011). This median streamflow was approximately 32-percent of the median streamflow measured during the flood period at Tarbert Landing and 47-percent of the median streamflow measured at Baton Rouge (both

downstream of the Spillway). Median streamflow in the Spillway was 51-percent of the median streamflow measured during the flood period at Belle Chasse (downstream of the Spillway).

Suspended sediment concentrations in the Bonnet Carré Spillway ranged from 43 to 177 mg/L with a median concentration of 111 mg/L (Appendix 6). The trend in suspended sediment concentration in the Spillway appeared to follow closely with streamflow (figure 15). As streamflow increased with the opening of the bays, suspended sediment concentrations increased; however, concentrations began to decline in late May as streamflow started to decrease which corresponded also with the length of time that the bays had been opened (figure 16). In comparison to sites on the main stem above and below the Spillway inflow, the median suspended sediment concentration was only 1.2 times less than the median concentrations at Baton Rouge (upstream) and Belle Chasse (downstream) during the flood period. Median suspended sediment concentrations at St. Francisville were 1.3 times less than the median concentration measured in the Spillway.

Total nitrogen concentrations in water from the Bonnet Carré Spillway ranged from 1.5 to 1.9 mg/L, with a median concentration of 1.7 mg/L (Appendix 2). Concentrations increased with increasing streamflow after the bays were opened. In early June, concentrations decreased slightly; however, there was another increase in concentration as bays in the Spillway were being closed. Total nitrogen concentrations in the Spillway were about the same as concentrations measured upstream at St. Francisville and Baton Rouge and downstream at Belle Chasse while the bays were open.

Total phosphorus concentrations in water from the Bonnet Carré Spillway ranged from 0.11 to 0.17 mg/L, with a median concentration of 0.16 mg/L (Appendix 2). The relationship between streamflow and total phosphorus was similar to the relationship observed between streamflow and total nitrogen. Total phosphorus concentrations initially increased as the bays were opened in May. There was a decrease in concentration in early June; however, concentrations began to increase until the bays were closed. Total phosphorus concentrations upstream of the Spillway at St. Francisville and Baton Rouge were about the same or lower than concentrations in the Spillway during May and early June. By mid-June, the concentrations at these two sites had increased and were greater than the 0.17 mg/L measured in the Spillway on June 22nd. Total phosphorus concentrations downstream at Belle Chasse averaged about 1.5 times more than concentrations in the Spillway while it was in operation.

Atrazine concentrations in water from the Bonnet Carré Spillway ranged from 0.14 to 0.44 µg/L, with a median concentration of 0.31 µg/L (Appendix 4). The highest concentration was measured in June, almost one month after the first bays were opened. Median atrazine concentrations measured upstream at St. Francisville and Baton Rouge were 0.48 and 0.46 µg/L, respectively. The median concentration downstream at Belle Chasse was 0.46 µg/L. All measured concentrations at the 3 main stem sites were higher than any detection in the Spillway. Similar to the Spillway, the highest atrazine concentration at the three main stem sites was detected in water collected in early June.

Discussion

Streamflow

During the 2011 Flood, most of the sampled sites remained above flood stage for 2 ½ to 3 months, and measured instantaneous streamflows for the period were higher than historical median streamflow measurements. Record rainfall in the Ohio River Basin was the primary contributor to streamflow in

the MRB during the months of April and May (figure 16). Snow melt and precipitation in the Upper MRB during June and July composed the majority of streamflow that moved into the lower MRB. The Ohio River Basin is more urban and forested in land use; whereas, the Missouri River and Upper MRB are primarily agricultural with some rangeland. The timing and contribution of the streamflow from the two different source areas is important as to what chemicals and other contaminants might enter the lower MRB via overland runoff or recedence of water from inundated lands.

Sediment

The low median suspended sediment concentrations measured at Vicksburg and St. Francisville are most likely due to a storm event in early March that diminished the supply of suspended sediment that was available for transport when the flood occurred (figure 5). Suspended sediment concentrations measured during the flood were similar to concentrations that had been measured historically in the lower MRB; however, fluxes were quite high due to the high streamflows. Despite the fact that the majority of the flow introduced into the Lower MRB was from the Ohio River and the previous construction of reservoirs on the Missouri and Arkansas Rivers has cut off the largest natural source of sediment to the Mississippi River (Meade, 1995), the majority of the suspended sediment flux introduced into the Basin during the flood was through the Upper MRB (Thebes; figure 6). Seventy percent of the sediment flux moving into the lower MRB was through the Upper Mississippi River, which is close to the 75-percent estimated by Pereira and Rostad (1990). Flux estimates for the month of May show approximately 1.5 times more suspended sediment moved into the Gulf of Mexico from the Atchafalaya River Basin than through the Mississippi River main stem. According to Roberts (1998), the Atchafalaya/Wax Lake delta is the only place in the MARB where there is sufficient sediment for actual delta-building to occur. In contrast, the Bird's Foot delta of the Mississippi River main stem is eroding (Roberts, 1998).

As the water moved through the Old River Outflow below Vicksburg, a gain in suspended sediment flux occurred before the water reached Melville. There is a depositional area at the bend in the Atchafalaya River and the confluence with the Red River (Barb Kleiss, personal communication), but high streamflows in May mostly likely resuspended the deposited sediment and moved it downstream. In addition, the Red River could have contributed up to 6 million metric tons to the suspended sediment flux measured at Melville. The further increase in flux between Melville and the outlets at Wax Lake and Morgan City can be explained by the resuspension of sediment by high flows. Suspended sediment concentrations during the flood were similar in the Bonnet Carré Spillway and the Mississippi River at Baton Rouge (figure 15); however, suspended sediment flux estimates in the Spillway were calculated based on concentrations measured at St. Francisville, which were lower than in the Spillway and at Baton Rouge. Flux estimates for the Bonnet Carré Spillway are most likely higher for the period that it was opened than was estimated by the model.

High streamflows are effective transport mechanisms for sand-sized particles (Allison et al, 2012). There was a decreasing trend in sand fraction percentage in the Upper Mississippi River and the Ohio River during the flood period; yet, sand size fraction percentage generally increased during the flood period in water from sites in the Lower MRB. This suggests that the Upper Mississippi River and the Ohio River were not the source of the sand-size particles in the Lower MRB during the flood period. Allison, et al. (2012) noted that the Mississippi River and Atchafalaya distributary pathways are efficient at sequestering suspended sediments, particularly the sand size fraction. During the flood period, the sand-size fraction of the suspended sediment concentration increased in May at most sites

in the lower MRB (figure 17). Maximum streamflows in the Atchafalaya River Basin occurred in the first week of June, and the increase in percentage of the larger size fraction corresponds to the increase in streamflow. Increases in the sand-size fraction of the suspended sediment flux was most likely not a result of new sediment being introduced from the Upper Mississippi and Ohio Rivers, but rather a result of high streamflows within the lower MRB and Atchafalaya River resuspending previously deposited sediment.

Nutrients

Higher total nitrogen and total phosphorus concentrations during the flood compared to historical data in the Upper Mississippi River (and to a lesser extent the Ohio River), might be attributed to the flood occurring during application of agricultural chemicals in the Missouri River Basin, the Upper MRB, and to a lesser extent in the Ohio River Basin (figure 7). In early March, water samples from Vicksburg contained higher concentrations of suspended sediment, total nitrogen, and total phosphorus than concentrations measured during the flood (figure 5; figure 8). This was observed in water from other NASQAN stations in the lower MRB also, but water-quality at Vicksburg is used as the example here because it represents the greatest amount of water streamflow by the river while it is still confined to a single channel. Lower concentrations of total nitrogen, total phosphorus, and suspended sediment are likely a result of dilution and a lack of available material since high concentrations of the three constituents were measured in surface water samples collected in March.

The largest cumulative monthly fluxes of total nitrogen and total phosphorus occurred in water from most of the lower MARB sites during May, which corresponds to the highest average monthly streamflow. The Upper Mississippi River contributed about 60-percent of the total nitrogen flux in May, which is slightly higher than the 50 percent documented by Meade (1995) and Goolsby and Battaglin(1997). Higher suspended sediment fluxes might also be a contributor to chemical transport since many hydrophobic chemical compounds have a tendency to adsorb to sediments, particularly fine-grained silts and clays (Horowitz et al., 2008). Phosphorus has a strong tendency to bind with soil particles, such as clay. Total phosphorus fluxes in the Upper Mississippi River were highest in June and July which corresponds to suspended sediment fluxes that were also highest during these two months from the Upper Mississippi River.

To assess the influence of the receding floodwaters from agricultural lands inundated by the Bird's Point-New Madrid Floodway, a hypothetical calculation of contribution to the total nitrogen flux in the Mississippi River below the outlet was made. In this worst case scenario, 100 kg/ha of nitrogen fertilizer (applied amount depends on soil type and agricultural management practices, and 100 kg/ha is on the lower end of recommended application amounts for corn) was applied to the entire 53,824 hectares inundated by the floodwaters. If all of the water that inundated the hectares receded back into the Mississippi River, the Bird's Point-New Madrid Floodway might possibly contribute about 5,400 metric tons of total nitrogen flux to the Mississippi River below the outlet, which is approximately 2 percent of the total nitrogen flux for May at Vicksburg (figure 18).

Nitrogen and phosphorus concentrations and fluxes were lower in the Morganza Floodway compared to water at sites in the lower Mississippi River. Total nitrogen and nitrate concentrations decreased with the length of time that the Floodway was open which seems to indicate that there is processing of nitrate in the Floodway, either by denitrification or another type of assimilation pathway (Appendix 2). Total phosphorus in the Floodway is likely not associated with suspended sediment since suspended

sediment concentrations are low (median of 16.5 mg/L). And in contrast to total nitrogen and nitrate concentrations, total phosphorus concentrations and orthophosphate concentrations in the Floodway increased with the length of time that the bays were opened (figure 13). This suggests that phosphorus transformation is occurring.

Pesticides

Large amounts of herbicides are flushed into streams during storm runoff in late spring and summer each year, following herbicide application (Meade, 1995). The Missouri, Illinois, and Ohio Rivers are the major source of herbicides and their degradation products to the lower MRB (Pereira and Rostad, 1990). Elevated fluxes of atrazine in May and metolachlor in June is associated with the highest streamflows of the flood period that promote the movement of herbicides off of agricultural lands through overland runoff. Median concentrations of both atrazine and metolachlor were higher in the Upper Mississippi River and the Ohio River than median concentrations measured at four sites downstream (figure 11) which is most likely due to intense rainfall occurring during the time of agricultural chemical application which did not allow for much processing of the herbicides before they were transported into the Mississippi River. Unlike concentrations of suspended sediment, total nitrogen, and total phosphorus, highest concentrations of herbicides were measured in May and June, not March (figure 8). The most likely reason is that herbicides had not yet been applied in March.

Atrazine fluxes were highest in May; whereas, metolachlor fluxes were highest in June, which most likely corresponds with application time and the source area for the water (figure 12). Atrazine is a common herbicide applied to not only agricultural crops, but has non-agricultural uses as well, such as weed control on lawns and highway rights-of-way. The main contributor to stream streamflow in April and May was the Ohio River, a more urbanized source area with atrazine use. In June and July, the Missouri River/Upper Mississippi River contributed the majority of the streamflow to the lower MRB. Metolachlor is heavily used in this Basin on soybeans and corn, which is planted later in the season. This correlates with the higher concentrations and fluxes of metolachlor in June.

To assess the influence of the receding floodwaters from agricultural lands inundated by the Bird's Point-New Madrid Floodway, a hypothetical calculation of contribution to the atrazine flux in the Mississippi River below the outlet (Vicksburg) was made. In this worst case scenario, corn was presumed to be the only crop planted and1 kg/ha of atrazine was applied to the entire 53,824 hectares inundated by the floodwaters – this is the application amount recommended for corn. If all of the water that inundated the hectares receded back into the Mississippi River, the Bird's Point-New Madrid Floodway might possibly contribute 2.7 metric tons to the atrazine flux in the Mississippi River below the Spillway outlet, or approximately 3.4 percent of the monthly atrazine load measured at Vicksburg in May (figure 19).

Summary and Conclusions

High streamflows associated with the April through July flood of 2011 forced the opening of all three flood-control structures in the lower MRB for the first time in history in order to manage the amount of water moving through the system. Concentrations of sediment, nutrients, and pesticides were similar to historical concentrations measured in the stream. However, time series data show surface water contained higher concentrations of suspended sediment, total nitrogen, and total phosphorus in early March than concentrations that were measured during the flood. In addition, concentrations of

these three constituents decreased during the flood which indicates that there was dilution occurring by the increased streamflow and that the source of material or constituents was not present during the flood period (i.e. a large portion had been removed or transported in March).

Although constituent concentrations were not higher than normal, historic streamflows resulted in high fluxes of sediment and agricultural chemicals moving through the lower MRB and eventually into the Gulf of Mexico. The highest fluxes of sediment, nutrients, and pesticides occurred at most sites in the lower MRB during the month of May which corresponds with the month of highest streamflow. More suspended sediment was introduced into the lower MRB from the Upper Mississippi River than was introduced from the Ohio River despite the fact that the majority of streamflow in April and May came from the Ohio River. A larger suspended sediment flux entered the Gulf of Mexico from the Atchafalaya River Basin than the flux that entered from the main stem of the Mississippi River. Approximately 2.2 million metric tons more suspended sediment left the lower MRB than entered from the Upper Mississippi and the Ohio Rivers due to the high streamflows that resuspended coarser-grained bed material. In contrast with suspended sediment, the majority of the total nitrogen, total phosphorus, atrazine, and metolachlor fluxes entered the Gulf of Mexico through the main stem as opposed to the Atchafalaya River Basin. There was a loss in the fluxes of total nitrogen and total phosphorus with transport through the lower MRB. Atrazine and metolachlor fluxes peaked in different months (June for atrazine; July for metolachlor) most likely due to differing application times and a change in the source of streamflow to the lower MRB from the Ohio River to the Upper Mississippi River that occurred from June to July.

The openings of the New Madrid-Bird's Point Floodway and the Morganza Floodway were of concern because of potential water-quality impacts in the Mississippi River once the water receded from lands that normally are not inundated by stream waters. Oil and gas samples collected upstream and downstream of the Morganza Floodway's confluence with the Atchafalaya River show similar concentrations except for the a 2-week period in late May. Decreases in total phosphorus and total nitrogen concentrations with length of time that the Morganza Floodway was open indicate that there is processing of phosphorus and nitrate occurring in the system. Diverting flow from the Mississippi River through the Bonnet Carré Spillway into Lake Ponchartrain led to a slight decrease in the fluxes of total nitrogen, total phosphorus, atrazine, and suspended sediment that moved down the main stem into the Gulf of Mexico.

References

Allison, MA, Demas, CR, Ebersole, BA, Kleiss, BA, Little, CD, Meselhe, EA, Powell, NJ, Pratt, TC, Vosburg, BM (2012) A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008-2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology 432-433: 84-97.

Anderson, B (2011) Operation watershed: floodfight 2011. Inland Port May/June 2011 24 p.

Aulenbach, BT, Hooper, RP (2006) The composite method: an improved method for stream-water solute load estimation. Hydrological Processes 20: 3029-3047.

Aulenbach, BT, Buxton, HT, Battaglin, WA, Coupe, RH (2007) Streamflow and nutrient fluxes of the Mississippi-Atchafalaya River Basin and subbasins for the period of record through 2005. US Geol Surv Open-File Report 2007-1080, accessed 11/17/2011 at *http://toxics.usgs.gov/pubs/of-2007-1080/*.

Boesch, DF, Boynton, WR, Crowder, LB, Diaz, RJ, Howarth, RW, Mee, LD, Nixon, SW, Rabalais, NN, Rosenberg, R, Snaders, JG, Scavia, D, Turner, RE (2009) Nutrient enrichment drives Gulf of Mexico hypoxia. EOS, Transactions of the American Geophysical Union 90(14): 117-118.

Cohn, TA, Caulder, DL, Gilroy, EJ, Zynjuk, LD, Sommers, RM (1992) The validity of a simple statistical model for estimating fluvial constituent loads: an empirical study involving nutrient loads entering Chesapeake Bay. Water Resources Research 28: 2352-2363.

Coupe, RH, Goolsby, DA (1999) Monitoring the water quality of the nation's large river: Mississippi River Basin NASQAN program. US Geol Surv Fact Sheet FS-055-99, 6 p.

Donner, SD, Scavia, D (2007) How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico. Limnology and Oceanography 52(2): 856-861.

Fishman, MJ, Friedman, LC, eds. (1989) Methods for determination of inorganic substances in water and fluvial sediments. US Geol Surv Techniques of Water-Resources Investigations, book 5, chapter A1, 545 p.

Goolsby, DA, Battaglin, WA (1997) Sources and transport of nitrogen in the Mississippi River Basin. Presented at the American Farm Bureau Federation Workshop, St. Louis, Missouri, July 14-15, 1997.

Goolsby, DA, Battaglin, WA, Thurman, EM (1993) Occurrence and transport of agricultural chemicals in the Mississippi River Basin, July through august 1993. US Geol Surv Circular 1120-C, 22 p.

Guy HP (1969) Laboratory theory and methods for sediment analysis. Techniques of Water-Resources Investigations of the US Geological Survey, book 5, chap. C1.

Helsel, DR, Hirsch, RM (2002) Statistical methods in water resources. Techniques of Water-Resources Investigations of the US Geological Survey, book 4, chap. A3.

Holmes, RR (1996) Sediment transport in the lower Missouri and the central Mississippi rivers, June 26 through September 14, 1993. US Geol Surv Circular 1120-I, 23 p.

Horowitz, AJ (2010) A quarter century of declining suspended sediment fluxes in the Mississippi River and the effect of the 1993 flood. Hydrological Processes 24: 13-34.

Horowitz, AJ, Elrick, KA, Smith, JJ (2008) Monitoring urban impacts on suspended sediment, trace element, and nutrient fluxes within the City of Atlanta, Georgia, USA: program design, methodological considerations, and initial results. Hydrological Processes 22: 1473-1496.

Johnson, AH (1979) Estimating solute transport in streams from grab samples. Water Resources Research 15(5): 1224-1228.

Judge, GR, Hill, C, Griffiths, WE, Lutkepohl, H, Lee, TC (1988) Introduction to the theory and practice of econometrics, 2nd ed. John Wiley & Sons, Inc., New York, USA, pp. 878-882.

Larson, SJ, Capel, PD, Goolsby, DA, Zaugg, SD, Sandstrom, MW (1995) Relations between pesticide use and riverine flux in the Mississippi River Basin. Chemosphere 31(5): 3305–3321.

Meade, RH, ed. (1995) Contaminants in the Mississippi River, 1987-1992. U.S. Geol Surv Circular 1133, 140 p.

Mississippi River Commission (2008) The Mississippi River & Tributaries Project: designing the project flood. Mississippi River Commission Information Paper April 2008, 7 p.

Mossa, J (1996) Sediment dynamics in the lowermost Mississippi River. Engineering Geology 45: 457-479.

Olson, KR, Morton, LW (2012) The impact of 2011 induced levee breaches on agricultural lands of Mississippi River Valley. Journal of Soil and Water Conservation 67(1): 5A-10A.

Olson, SA, Norris, JM (2007) US Geological Survey streamgaging from the National Streamflow Information Program. US Geol Surv Fact Sheet 2005-3131, 4 p.

Pereira, WE, Rostad, CE (1990) Occurrence, distributions, and transport of herbicides and their degradation products in the Lower Mississippi River and its tributaries. Environmental Science and Technology 24(9): 1400-1406.

Rabalais, NN, Turner, RE, Wiseman, Jr., WJ (2002) Gulf of Mexico hypoxia, a.k.a. "The Dead Zone". Annual Review of Ecological Systems 33: 235-263.

Rantz, SE. 1982. Measurement and computation of streamflow: volume 1. Measurement of stage and discharge and Volume 2. Computation of discharge. US Geological Survey Water Supply Paper 2175, 681 p.

Roberts, HH (1998) Delta switching: early responses to the Atchafalaya River diversion. Journal of Coastal Research 14(3): 882-899.

Runkel, RL, Crawford, CG, Cohn, TA (2004) Load estimator (LOADEST) – a FORTRAN program for estimating constituent loads in streams and rivers. US Geol Surv Techniques and Methods book 4, chapter A5. Accessed online on 11/17/2011 at *http://pubs.usgs.gov/tm/2005/tm4A5*.

Scavia, D, Donnelly, KA (2007) Reassessing hypoxia forecasts for the Gulf of Mexico. Environmental Science and Technology 41: 8111-8117.

Scavia, D, Justic, D, Bierman, VJ (2004) Reducing hypoxia in the Gulf of Mexico – advice from three models. Estuaries 27(3): 419-425.

Schalk, GK, Holmes, RR, Johnson, GP (1998) Physical and chemical data on sediments deposited in the Missouri and the Mississippi River flood plains during the July through August 1993 flood. US Geol Surv Circular 1120-L, 62 p.

Schneider, K (2011) Laying the groundwork. US Army Corps of Engineers Our Mississippi, 12 p.

Taylor, HE, Antweiler, RC, Brinton, TI, Roth, DA (1994) Major ions, nutrients, and trace elements in the Mississippi River near Thebes, Illinois, June through September 1993. US Geol Surv Circular 1120-D, 21 p.

Turner, RE, Rabalais, NN, Justic, D (2008) Gulf of Mexico hypoxia – alternate states and a legacy. Environmental Science and Technology 42(7): 2322-2327, doi:10.102/es071617k.

US Environmental Protection Agency (1999) Method 1664, Revision A: n-hexane extractable material (HEM; oil and grease) and silica gel treated n-hexane extractable material (SGT-HEM; non-polar material) by extraction and gravimetry. EPA -821-R-98-002, February 1999, 28 p.

US Environmental Protection Agency (1986) Test methods for evaluating solid water, physical/chemical methods. SW-846, 3rd edition, various updates, available online at *http://www.epa.gov/osw/hazard/testmethods/sw846/index.htm.*

US Geological Survey (2009) USGS hypoxia in the Gulf of Mexico studies. US Geol Surv web site accessed on 11/17/2011 at *http://toxics.usgs.gov/hypoxia/.*

US Geological Survey (variously dated) National field manual for the collection of water-quality data. US Geol Surv Techniques of Water-Resources Investigations, book 9, chapters A1-A9, available online at *http://water.usgs.gov/owq/Field Manual/.*

Appendix

Appendix I. Field parameters and inorganic constituents collected in water samples from selected sites in the lower Mississippi-Atchafalaya River Basin, April through July 2011.

Appendix II. Nutrients collected in water samples from selected sites in the lower Mississippi-Atchafalaya River Basin, April through July 2011.

Appendix III. Suspended sediment and particle size analysis collected in water samples from selected sites in the lower Mississippi-Atchafalaya River Basin, April through July 2011.

Appendix IV. Pesticides collected in water samples from selected sites in the lower Mississippi-Atchafalaya River Basin, April through July 2011.

Appendix V. Pesticides sampled for but not-detected in water from selected sites in the lower Mississippi-Atchafalaya River Basin, April through July 2011.

Appendix VI. Suspended sediment and particle size analysis collected in water samples from three flood-control structures in the lower Mississippi River Basin, April through July 2011.

Appendix VII. Oil and gas data collected at selected sites in the Atchafalaya River Basin, May

SECTION III. WATER QUALITY SAMPLING

Table 1. Station Names, Station Identification Numbers, Drainage Basin Areas, Map Number, and Minimum, Maximum, and Median Flow Data for the Period April-July, 2011 Calculated at 9 Sites on the Mississippi and Atchafalaya Rivers and Their Major Tributaries (Site # column refers to the numbered sites identified on figure 1; km^2, square kilometers; m^3/s, cubic meters per second)

Station Name	Site #	Station ID	Basin Area (km^2)	Streamflow, m^3/s (April through July 2011)		
				Minimum	Maximum	Median
Mississippi River at Thebes, Ill. (Upper Mississippi River)	1	07022000	1,847,180	3,300	24,200	12,100
Ohio River at Dam 53 Near Grand Chain, Ill. [A] (Ohio River)	2	03612500	526,027	750	35,700	5,000
Birds Point Levee Breach Inflow (BPNM)	3	365659089073101	NA	10	11,400	4,040
New Madrid Floodway Inflow Outflow No. 2 (BPNM)	4	363618089251701	NA	500	10,800	6,800
Mississippi River At Tiptonville, Tenn. [B]	5	362146089301901	NA	40,200	57,400	52,300
Mississippi River At Memphis, Tenn.	6	07032000	2,415,941	51,200	62,200	51,200
Mississippi River above Vicksburg at Mile 438, Miss. [C]	7	322023090544500	2,964,241	8,700	66,000	22,600
Mississippi River near St. Francisville, La. [D]	8	07373420	2,914,514	12,500	45,800	25,200
Atchafalaya River at Melville, La. [E]	9	07381495	241,687*	5,400	19,600	10,800
Atchafalaya Floodway near Ramah, La. North of I-10 F (Morganza Floodway)	10	302410091305201	NA	100	5,500	3,100
Mississippi River at Baton Rouge, La.	11	07374000	2,915,835	6,100	40,500	16,900
Lower Atchafalaya River at Morgan City, La.	12	07381600	NA	1,200	13,800	3,700
Wax Lake Outlet at Calumet, La.	13	07381590	NA	1,100	8,900	3,300
Bonnet Carré Spillway at U S Hwy #61 nr Norco, La. (Bonnet Carré Spillway)	14	300115090245000	NA	1,000	11,200	8,000
Mississippi River at Belle Chasse, La.	15	07374525	2,926,687	5,700	34,800	15,700

[A] Flow from Ohio River at Metropolis, Ill (03611500)

[B] Flow from Mississippi River at Tiptonville, Tenn. (U.S. Army Corps of Engineers site MS116)

[C] Flow from Mississippi River at Vicksburg, Miss. (07289000)

[D] Flow from Mississippi River at Tarbert Landing, Miss. (U.S. Army Corps of Engineers site 01100)

[E] Flow from Atchafalaya River at Simmesport, La. (U.S. Army Corps of Engineers site 03045)

[F] Flow from Morganza Spillway at Hwy 190 near Lottie, La. (07381530)

"NA" indicates indeterminate value

* Excludes contribution from Mississippi River Basin

Table 2. Method Reporting Level for Selected Constituents Analyzed, April Through July, 2011
(mg/L, milligram per liter; µg/L, microgram per liter)

Constituent	Method Reporting Level
Nitrate plus nitrite, in mg/L	0.05
Total phosphorus, unfiltered, in mg/L	0.10
Orthophosphate, in mg/L	0.02
Simazine, in µg/L	0.05
Prometon, in µg/L	0.05
Deethyl atrazine, in µg/L	0.05
Metolachlor, in µg/L	0.05
Atrazine, in µg/L	0.10
Acetochlor, in µg/L	0.05
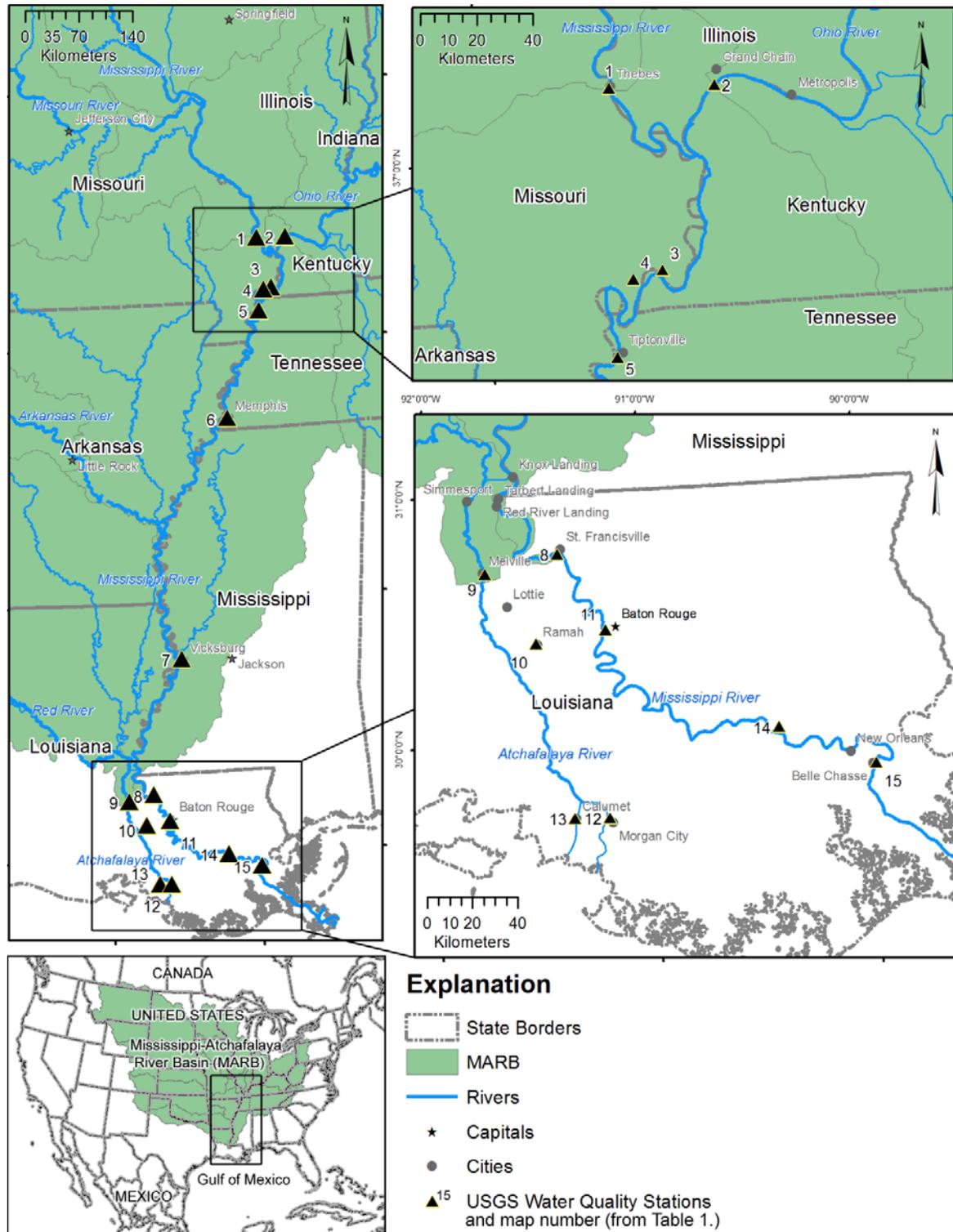
Figure 1. Map showing the Mississippi River Basin. Inset map shows the lower Mississippi-Atchafalaya River Basin with the location of sampled sites during the 2011 Flood (April through July).
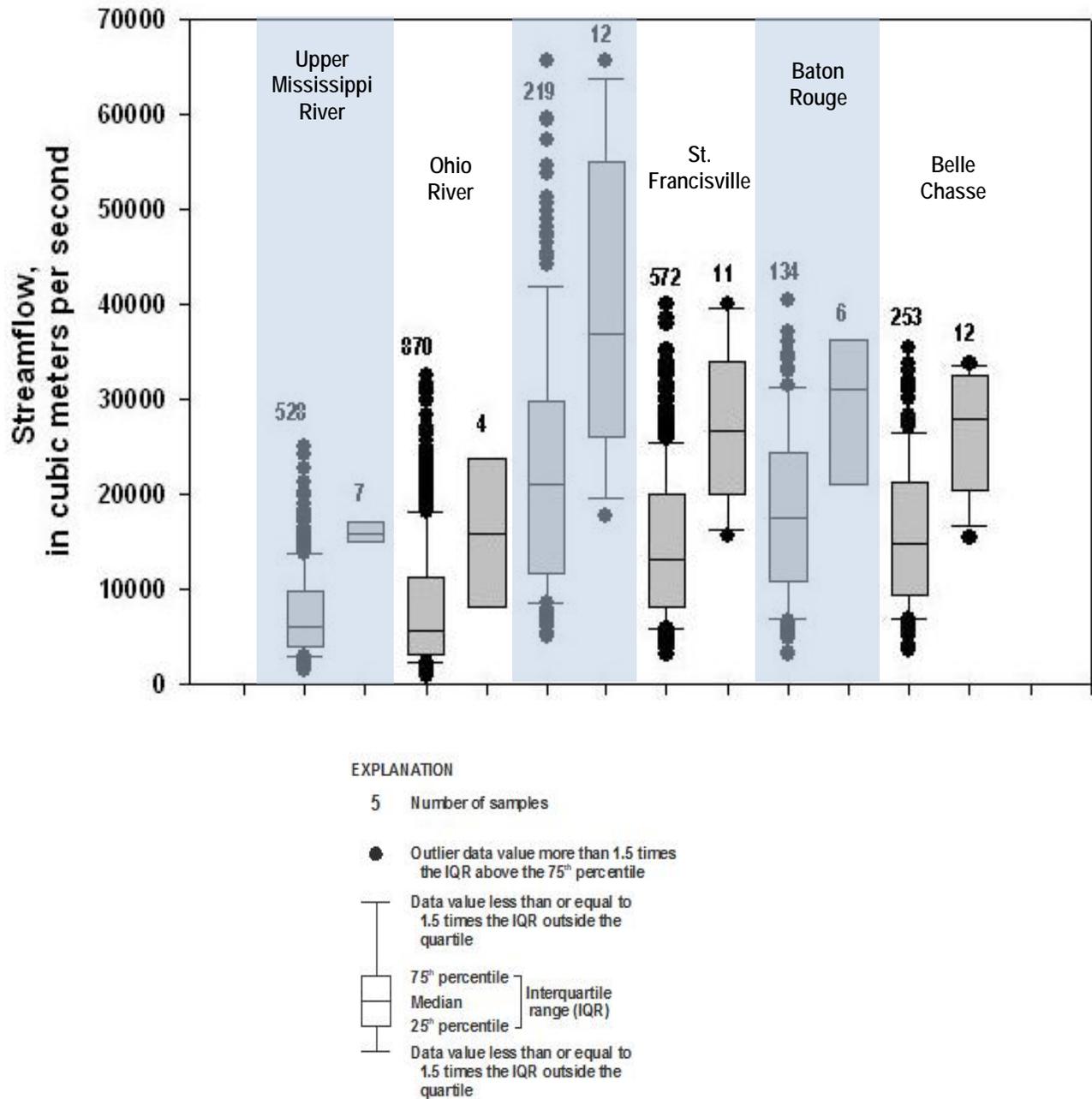
Figure 2. Instantaneous streamflow for the period of record at six sites in the lower Mississippi River-Atchafalaya River Basin compared to measured streamflow during the 2011 Flood (April through July). The first box in each pair is the historical data, and the second box is the flood data, April through July 2011.
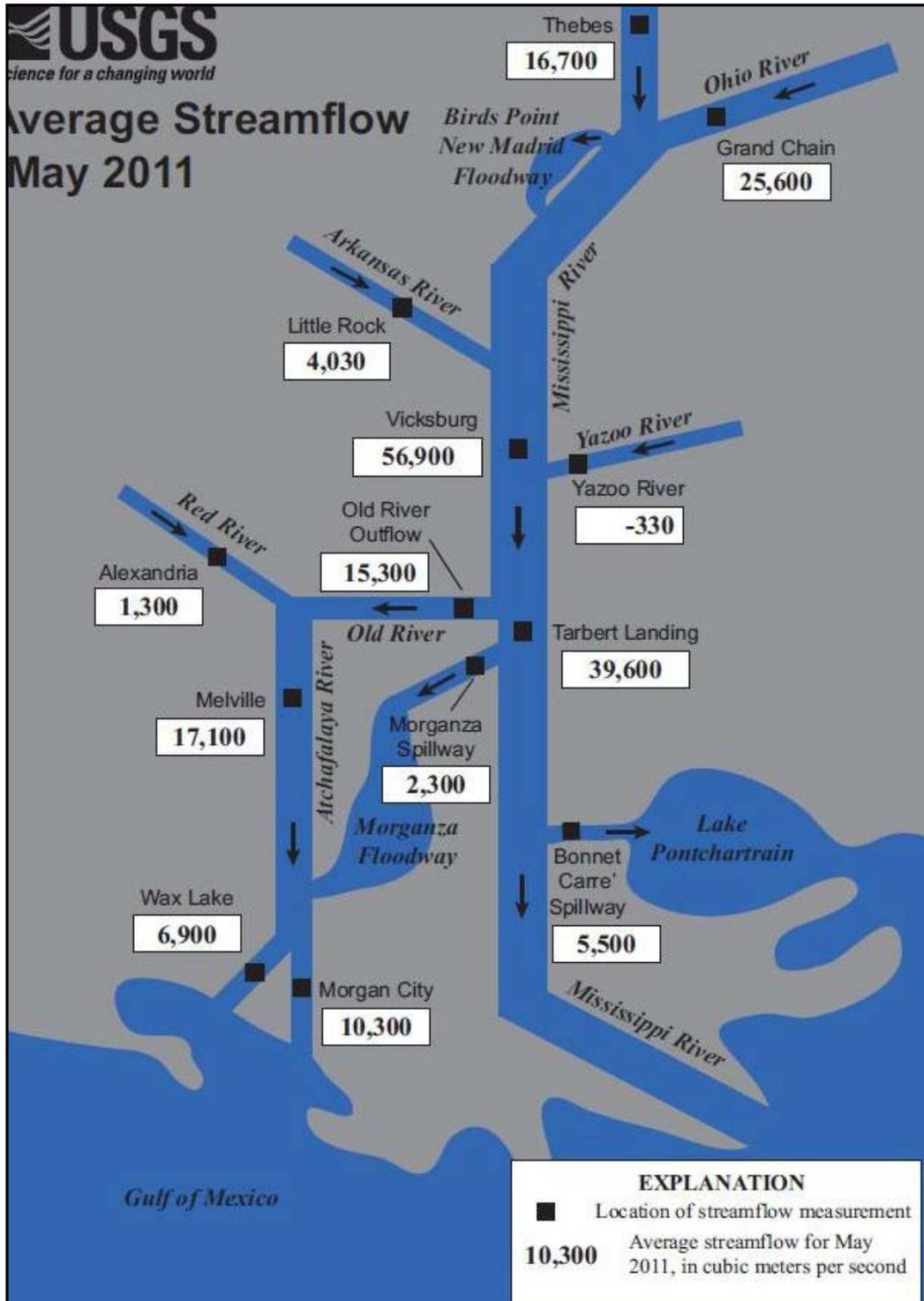
Figure 3. Average streamflow in May 2011 for sites located in the lower Mississippi-Atchafalaya River Basin. The average monthly flow calculated for the Morganza Floodway and Bonnet Carré Spillways did include days when the structures were not open. On these days, flow was 0 m^3/s. Not to scale.
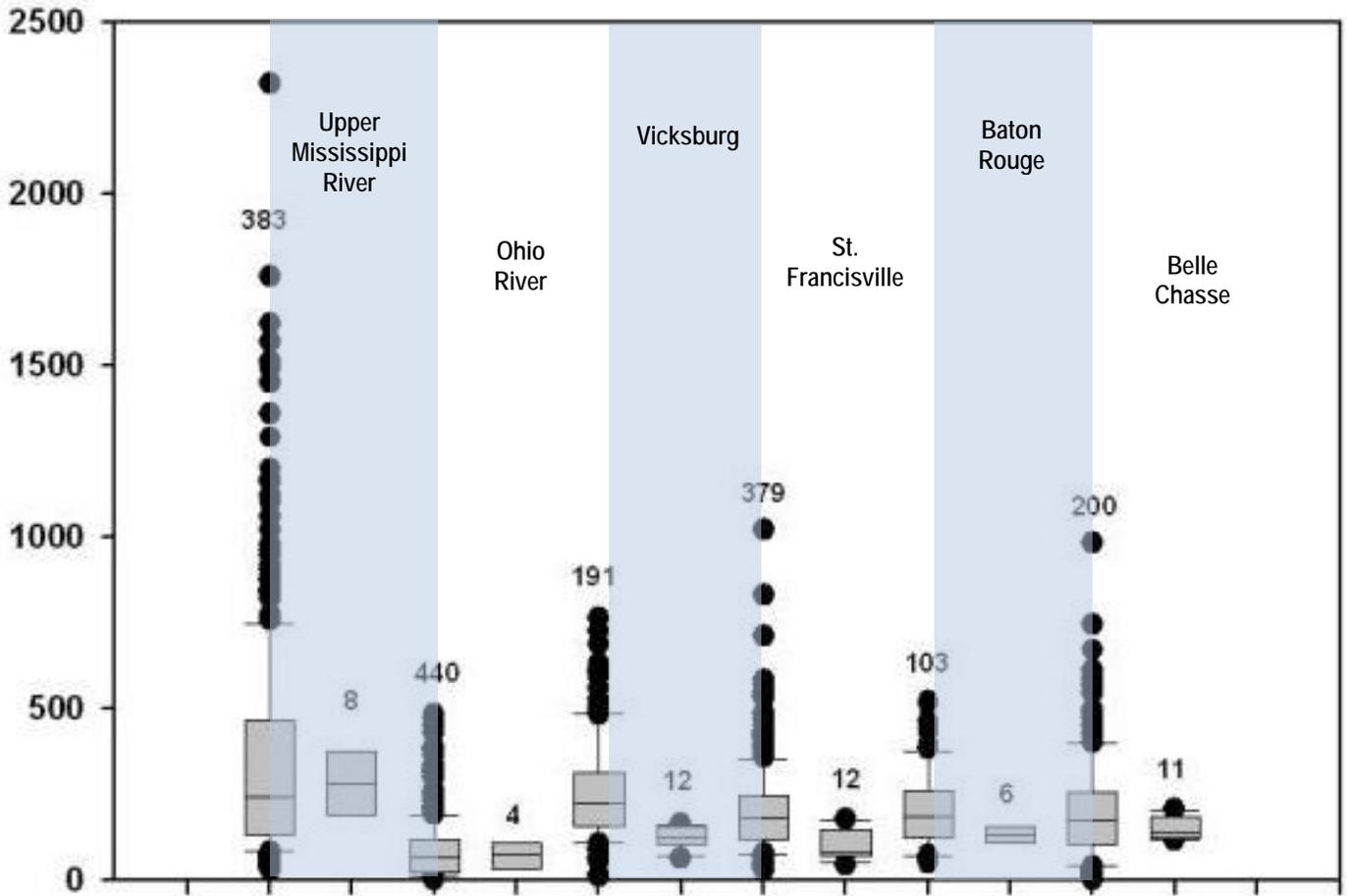
Figure 4. Suspended sediment concentrations in surface water sampled during the 2011 Flood (April through July) compared to suspended sediment concentrations observed for the period of record at selected sites in the lower Mississippi River Basin. The first box in each pair is the historical data, and the second box is the flood data, April through July 2011.
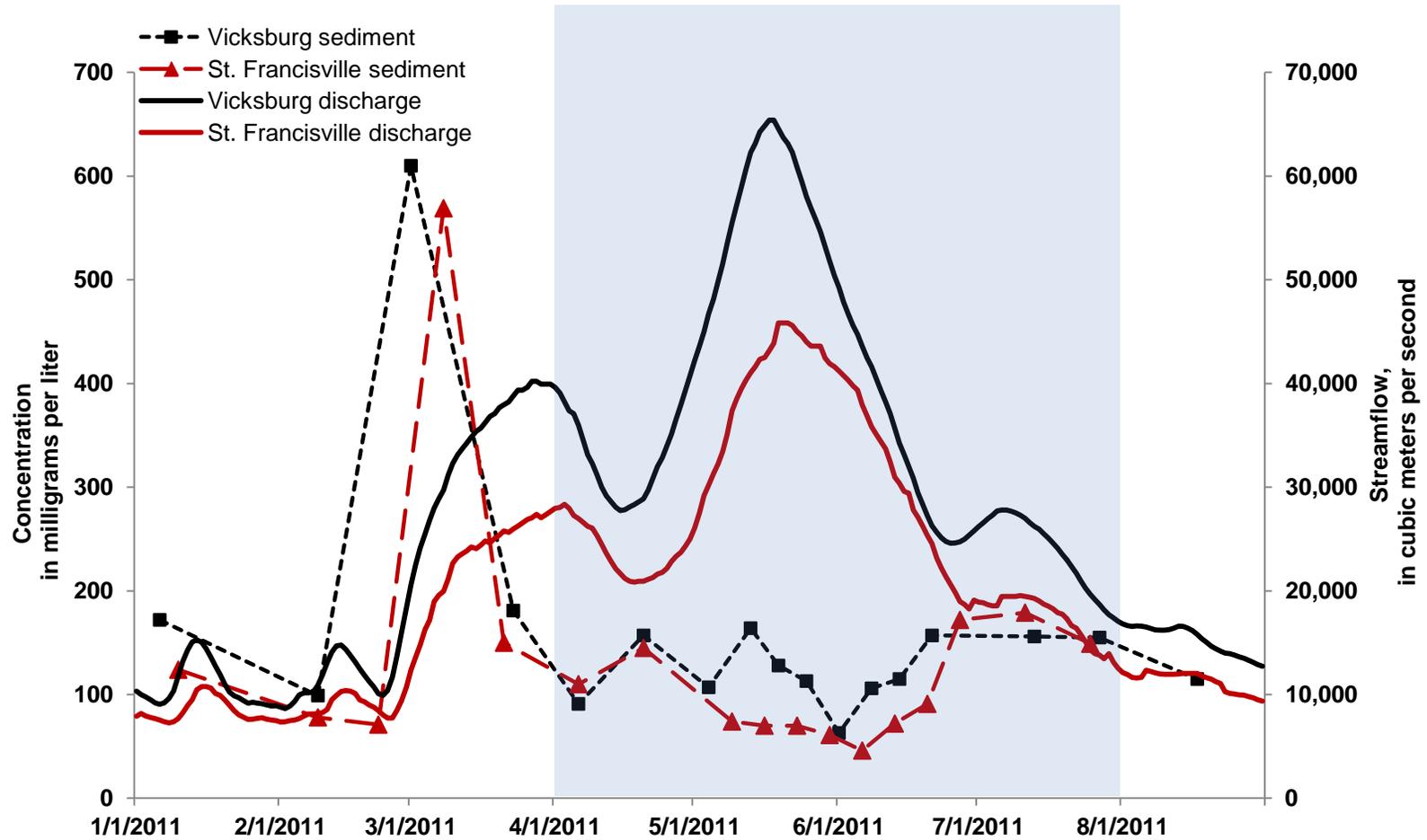
Figure 5. Time series plot of suspended sediment and streamflow at the Mississippi River at Vicksburg, Miss., and the Mississippi River at St. Francisville, La., for January through August 2011. The blue shaded area denotes samples collected during the flood period.
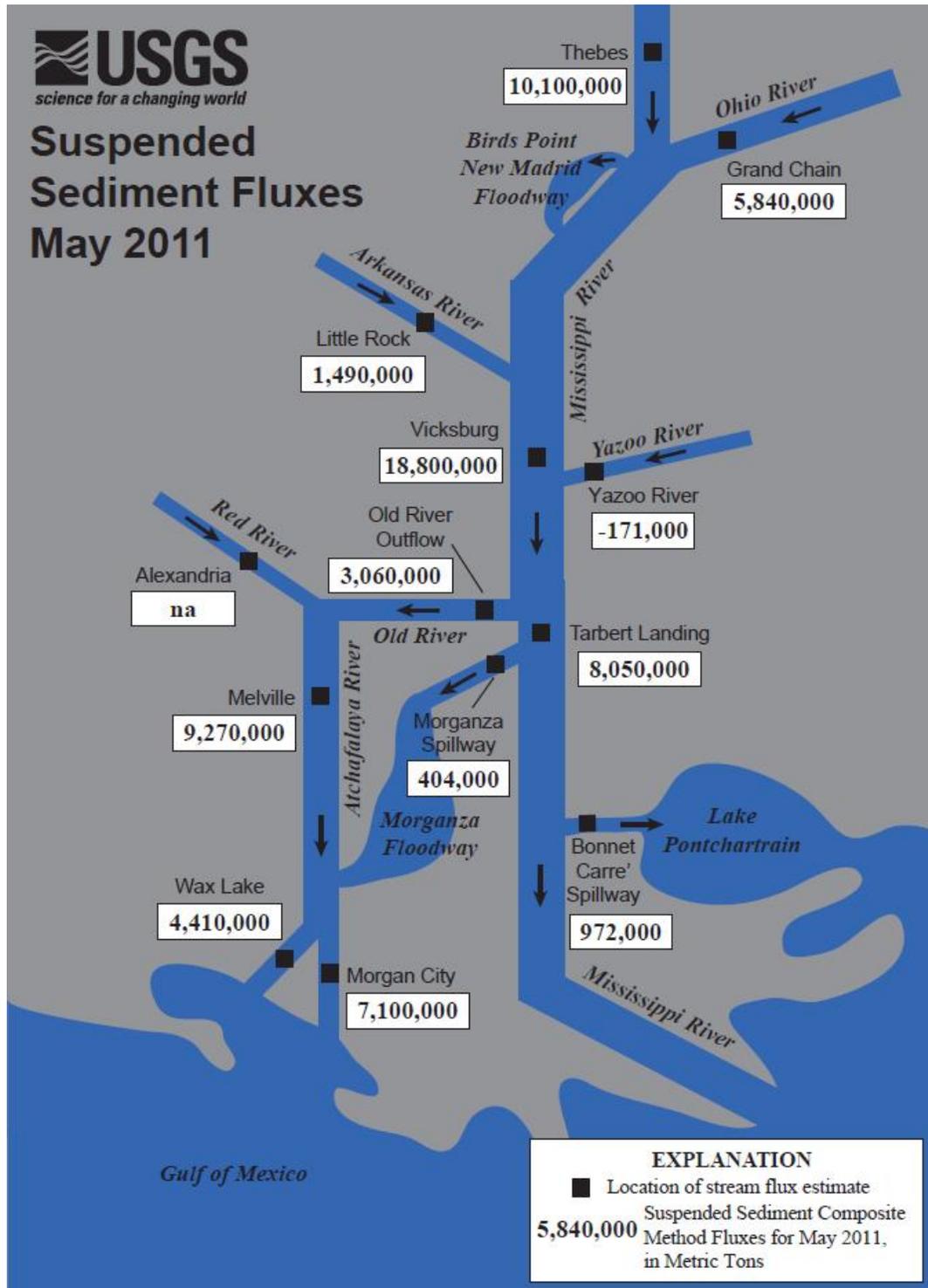
Figure 6. Cumulative suspended sediment flux for May 2011 at selected sites in the lower Mississippi River-Atchafalaya River Basin. Fluxes at Tarbert Landing, La., in the Morganza Floodway, and in the Bonnet Carré Spillway are calculated based on water-quality samples collected at St. Francisville, La. Not to scale.
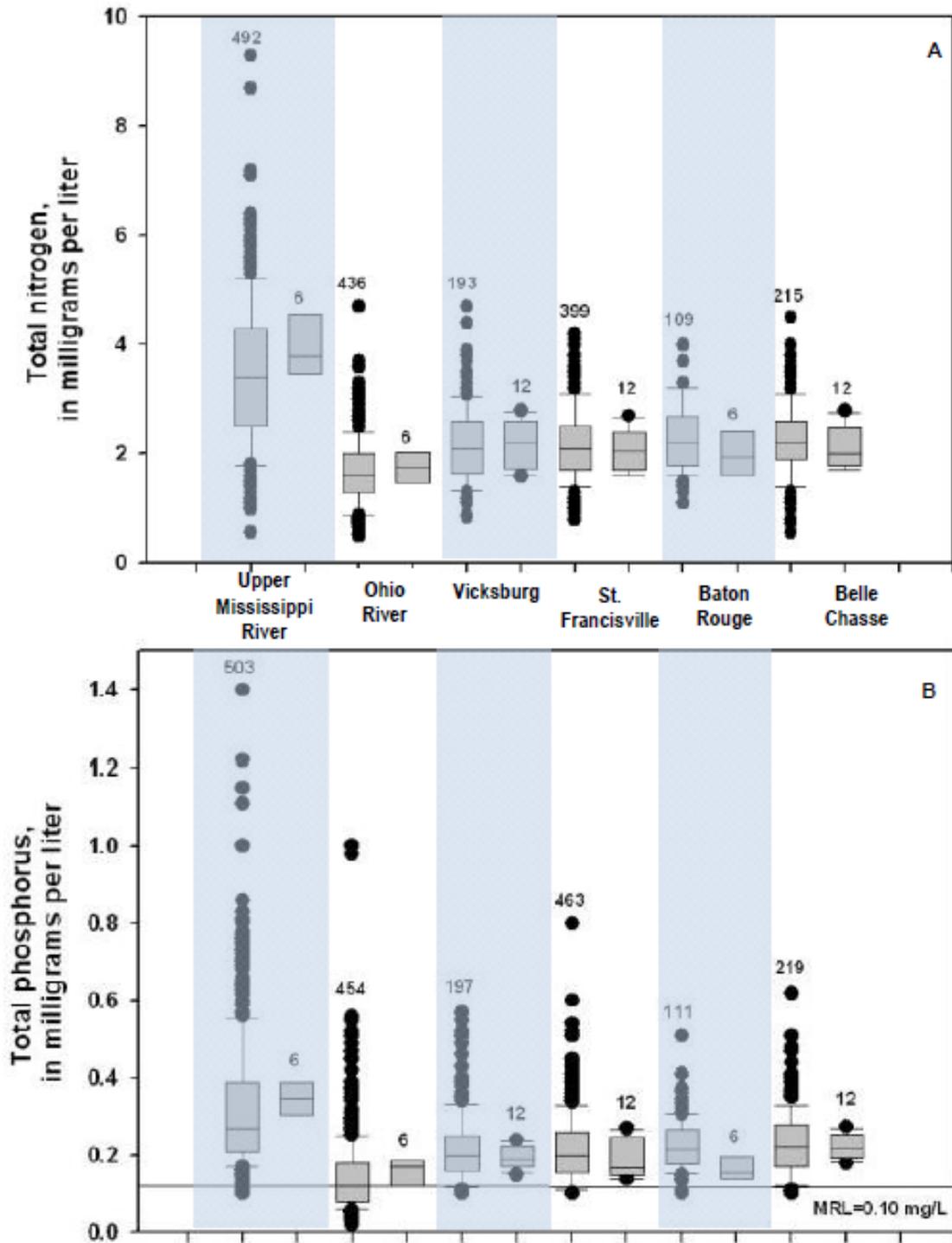
Figure 7. Concentrations of (a) Total N and (b) Total P measured during the flood compared to concentrations measured at these sites in the lower Mississippi River Basin for the period of record. The first box in each pair is the historical data, and the second box is the flood data, April through July 2011. [MRL = method reporting level
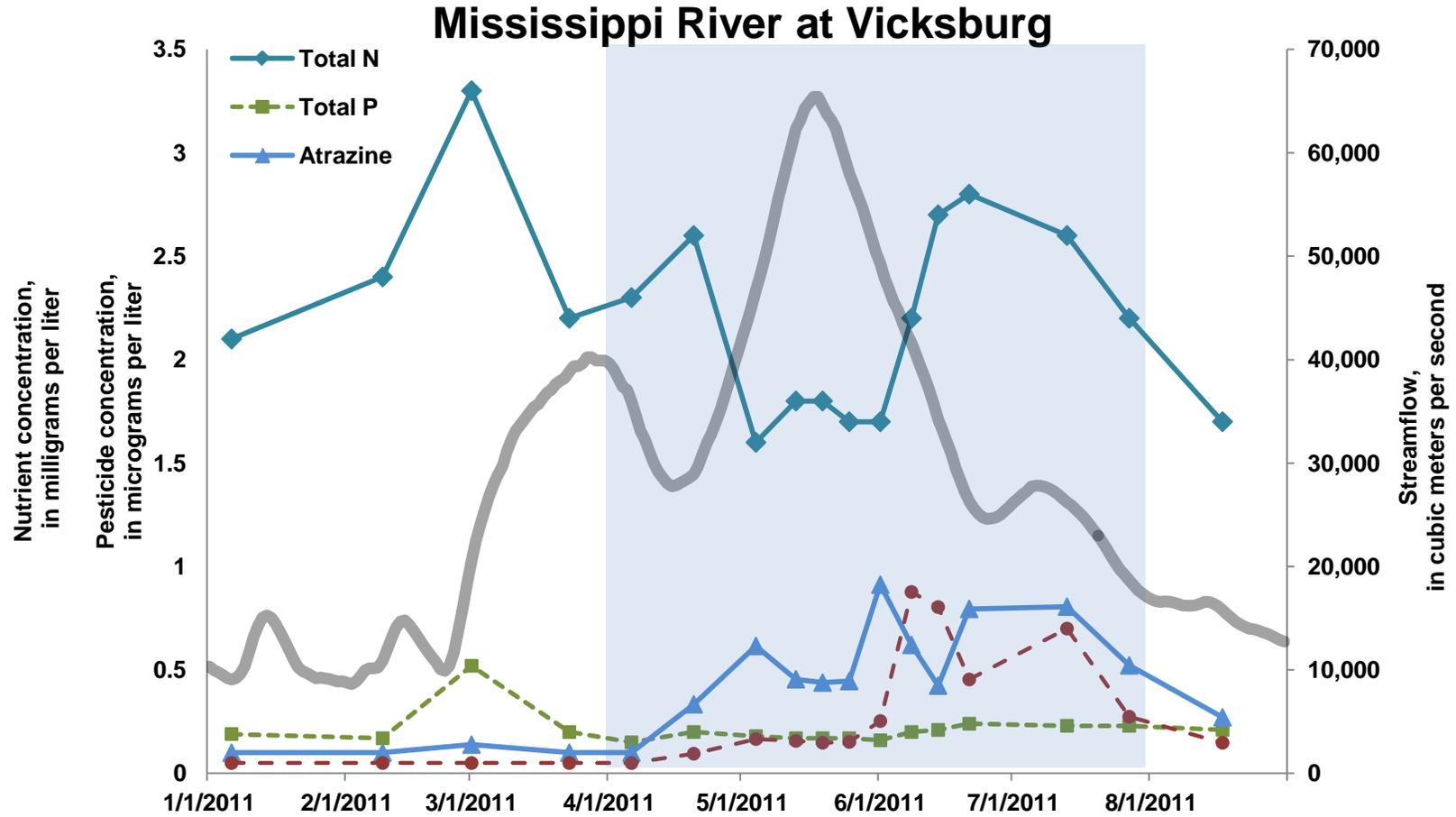
Figure 8. Time series plot of total nitrogen, total phosphorus, atrazine, metolachlor, and streamflow at the Mississippi River at Vicksburg, Miss., for January through August 2011. The blue shaded area denotes samples collected during the flood period.
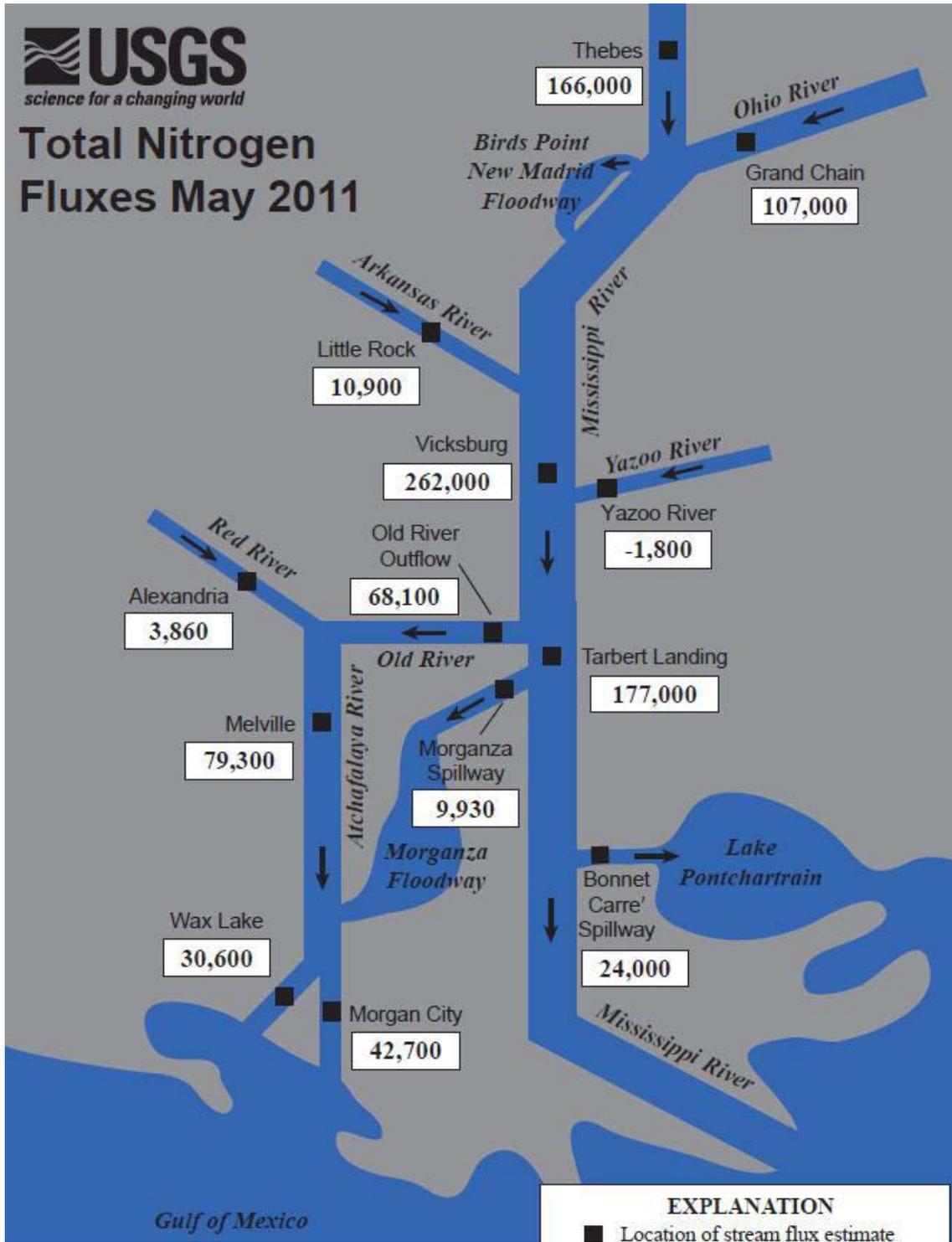
Figure 9. Total nitrogen flux for May 2011 at selected sites in the lower Mississippi River-Atchafalaya River Basin. Fluxes at Tarbert Landing, La. ,in the Morganza Floodway, and in the Bonnet Carré Spillway are calculated based on water-quality samples collected at St. Francisville, La. Not to scale.
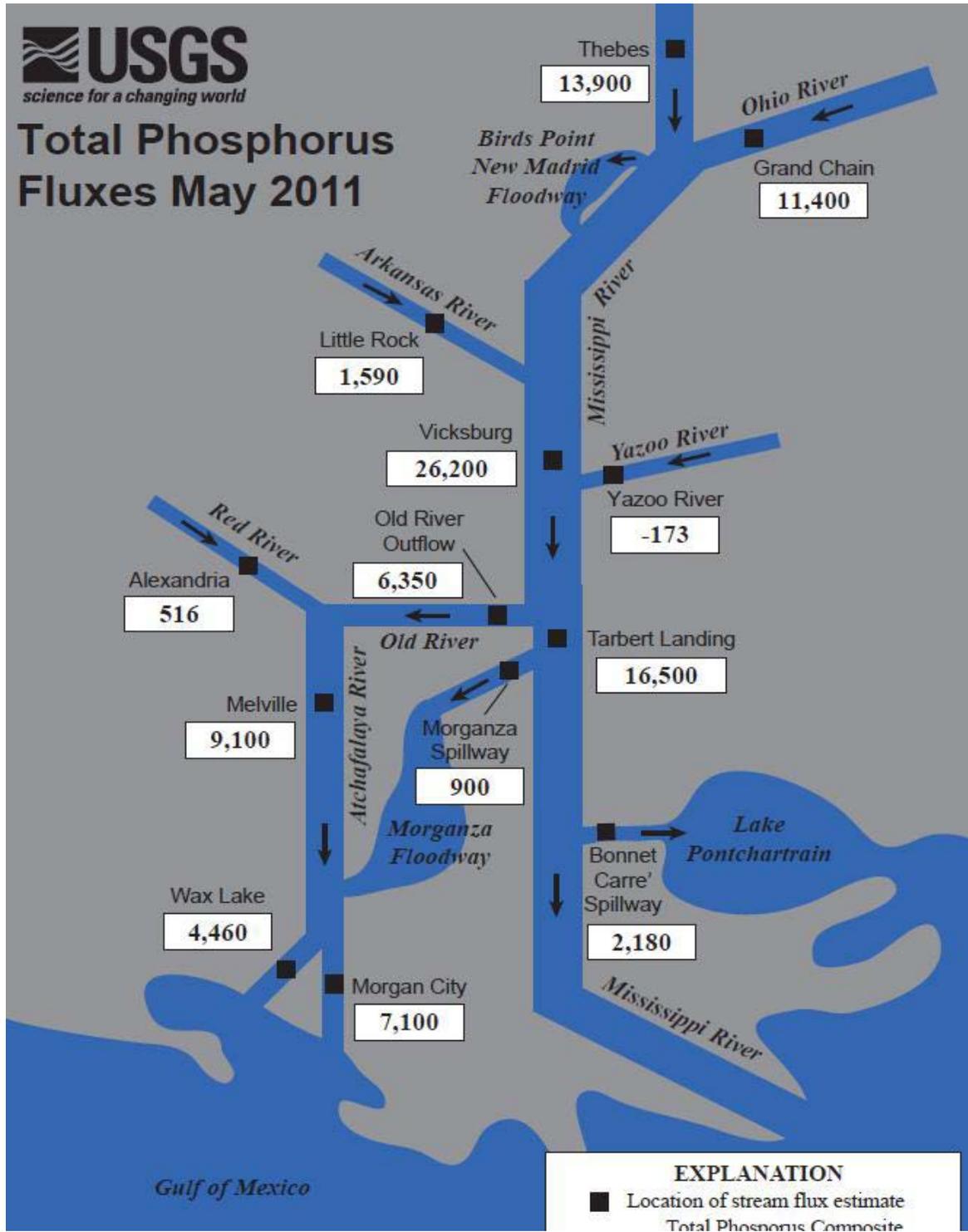
Figure 10. Total phosphorus flux for May 2011 at selected sites in the lower Mississippi River-Atchafalaya River Basin. Fluxes at Tarbert Landing, La. ,in the Morganza Floodway, and in the Bonnet Carré Spillway are calculated based on water-quality samples collected at St. Francisville, La. Not to scale.
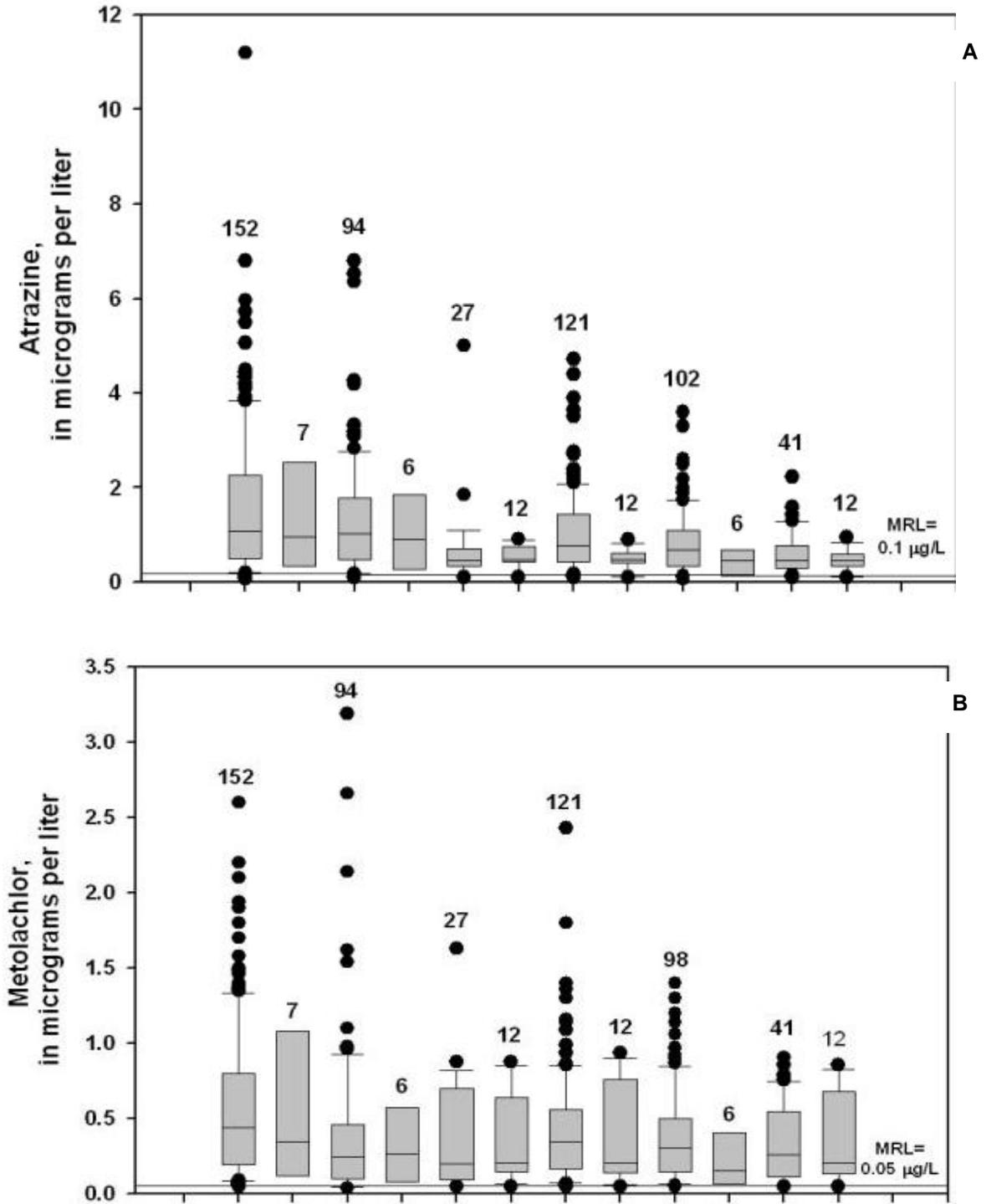
Figure 11. Concentrations of (a) atrazine and (b) metolachlor measured during the flood compared to concentrations measured at these sites in the lower Mississippi River Basin for the months of April through July for the period of record. The first box in each pair is the historical data, and the second box is the flood data, April through July 2011. [MRL = method reporting level]

Flux of pesticides delivered to the Gulf of Mexico
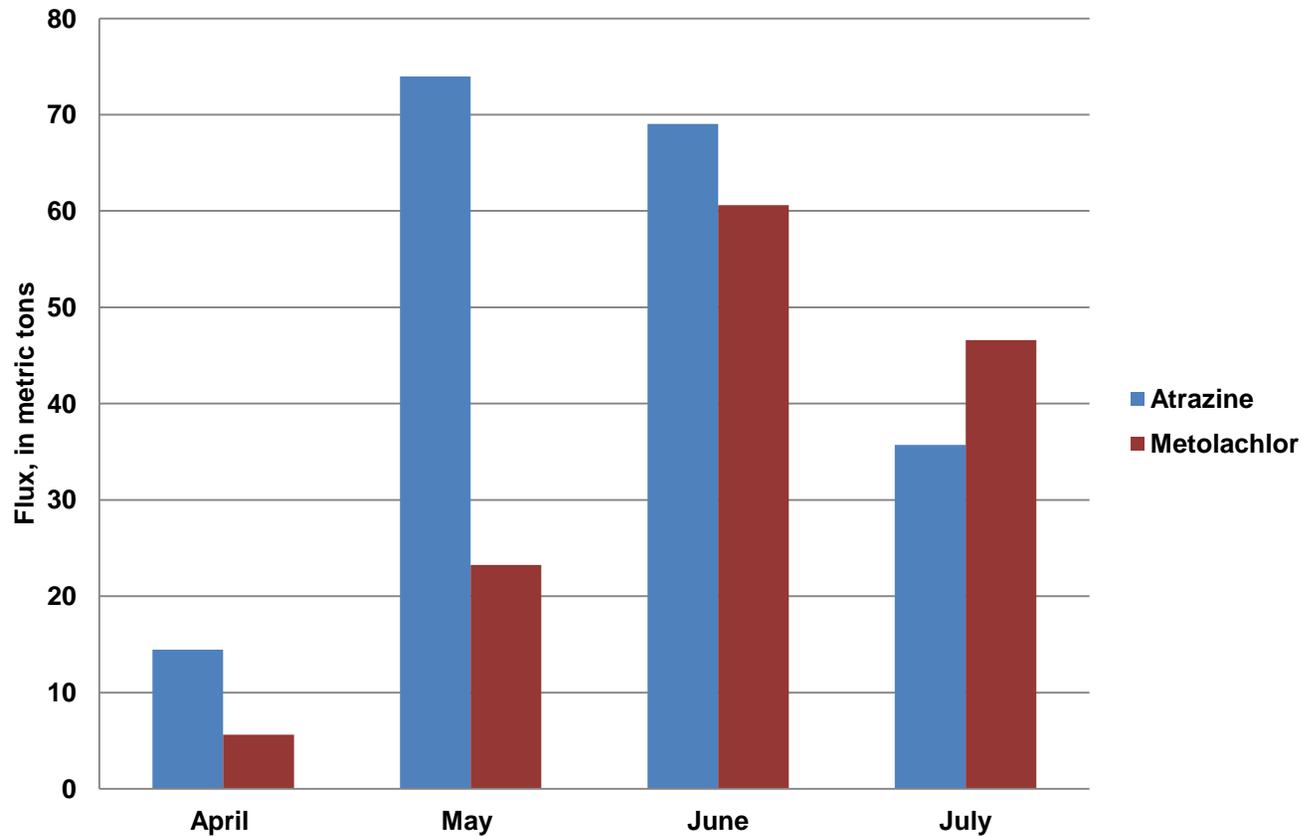
Figure 12. Cumulative monthly flux of atrazine and metolachlor delivered to the Gulf of Mexico from April through July 2011. Delivery to the Gulf of Mexico is determined by adding the fluxes at the Atchafalaya River at Melville, La., with the fluxes as the Mississippi River near St. Francisville, La.
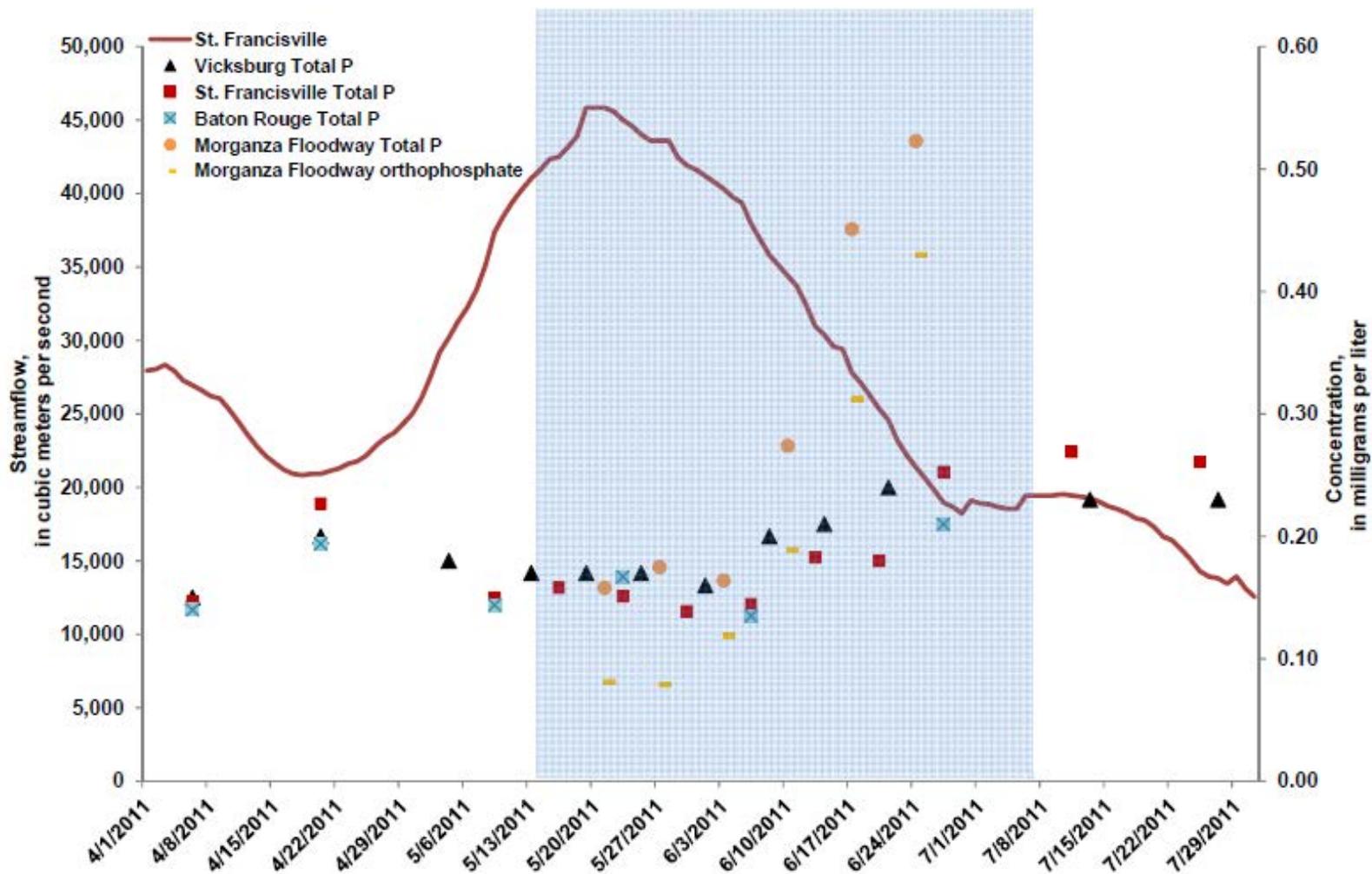
Figure 13. Streamflow and total phosphorus concentrations measured during the flood period at sites above and below the Morganza Floodway and the total phosphorus concentrations and orthophosphate concentrations measured in the Morganza Floodway. The blue-shaded area denotes the period of time that the Morganza Floodway was open.
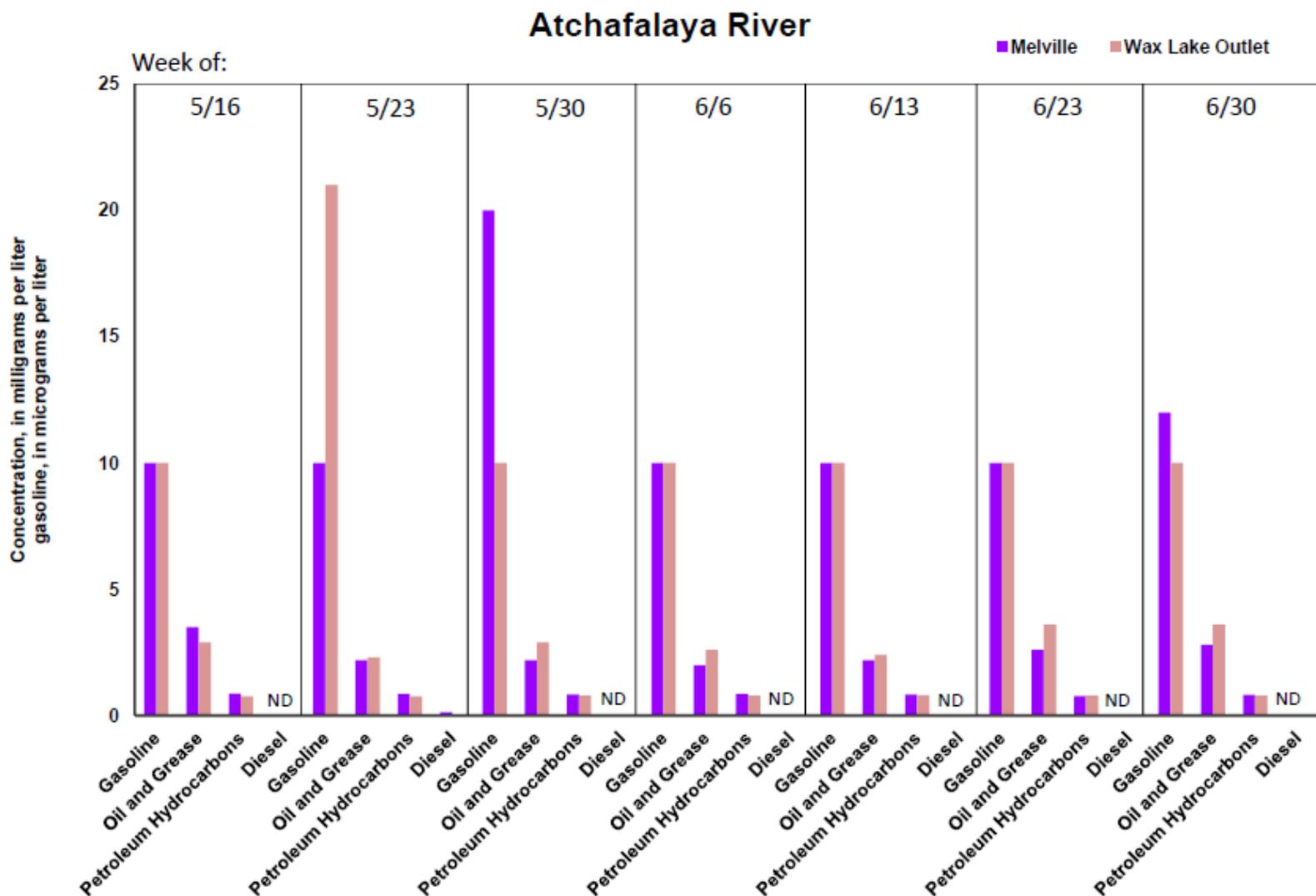
Figure 14. Oil and Gas Data Collected Weekly Above and Below the Outlet of the Morganza Floodway
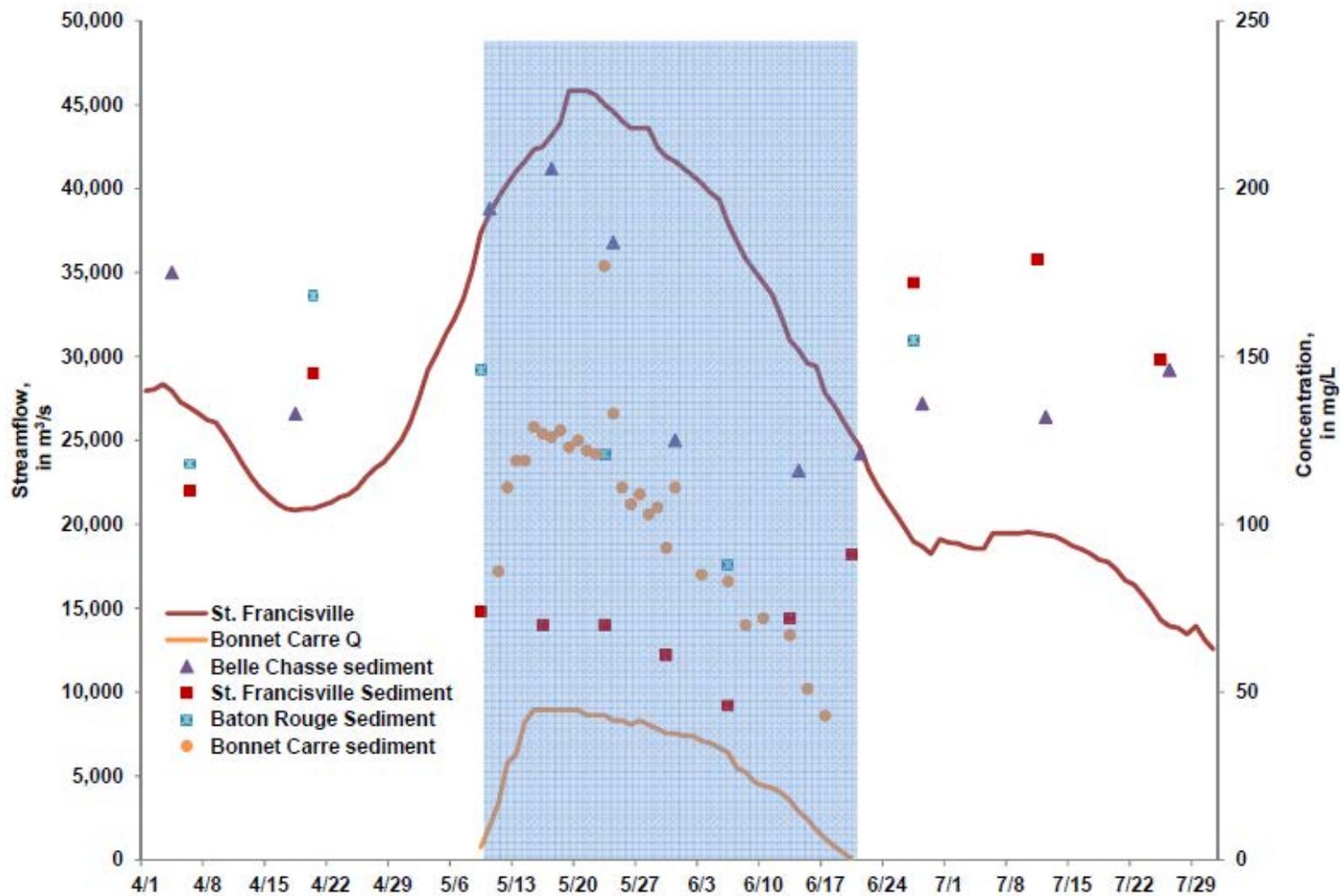
Figure 15. Streamflow and suspended sediment concentrations measured during the flood period at sites above and below the Bonnet Carré Spillway and the suspended sediment concentrations and streamflow measured in the Bonnet Carré Spillway. The blue-shaded area denotes the period of time that the Bonnet Carré Spillway was open.
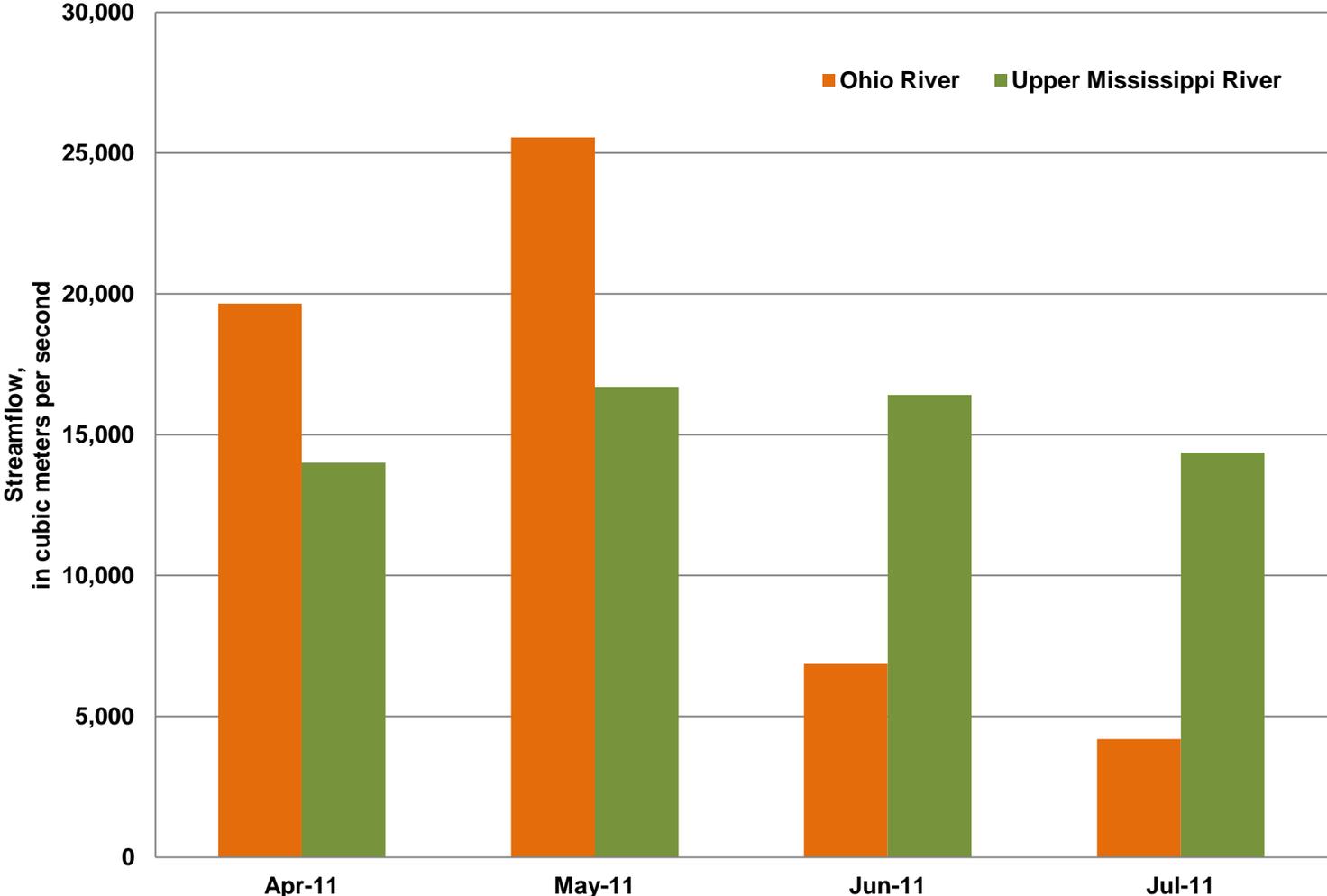
Figure 16. Average Monthly Streamflow for the Flood Period at the Upper Mississippi River and the Ohio River
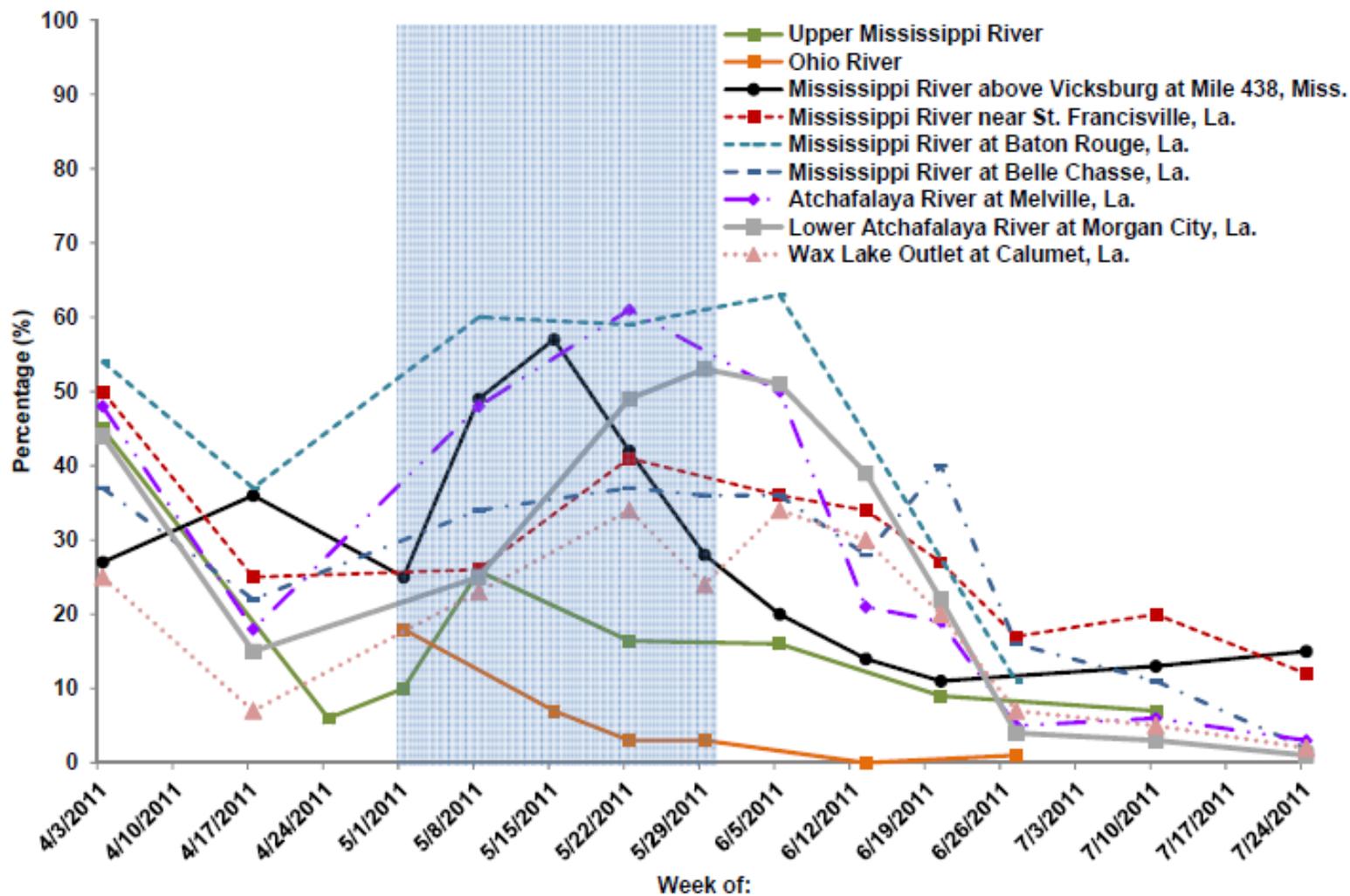
Figure 17. Fraction of the suspended sediment concentration that was sand-sized. Blue shaded area denotes the month with the highest average streamflow.
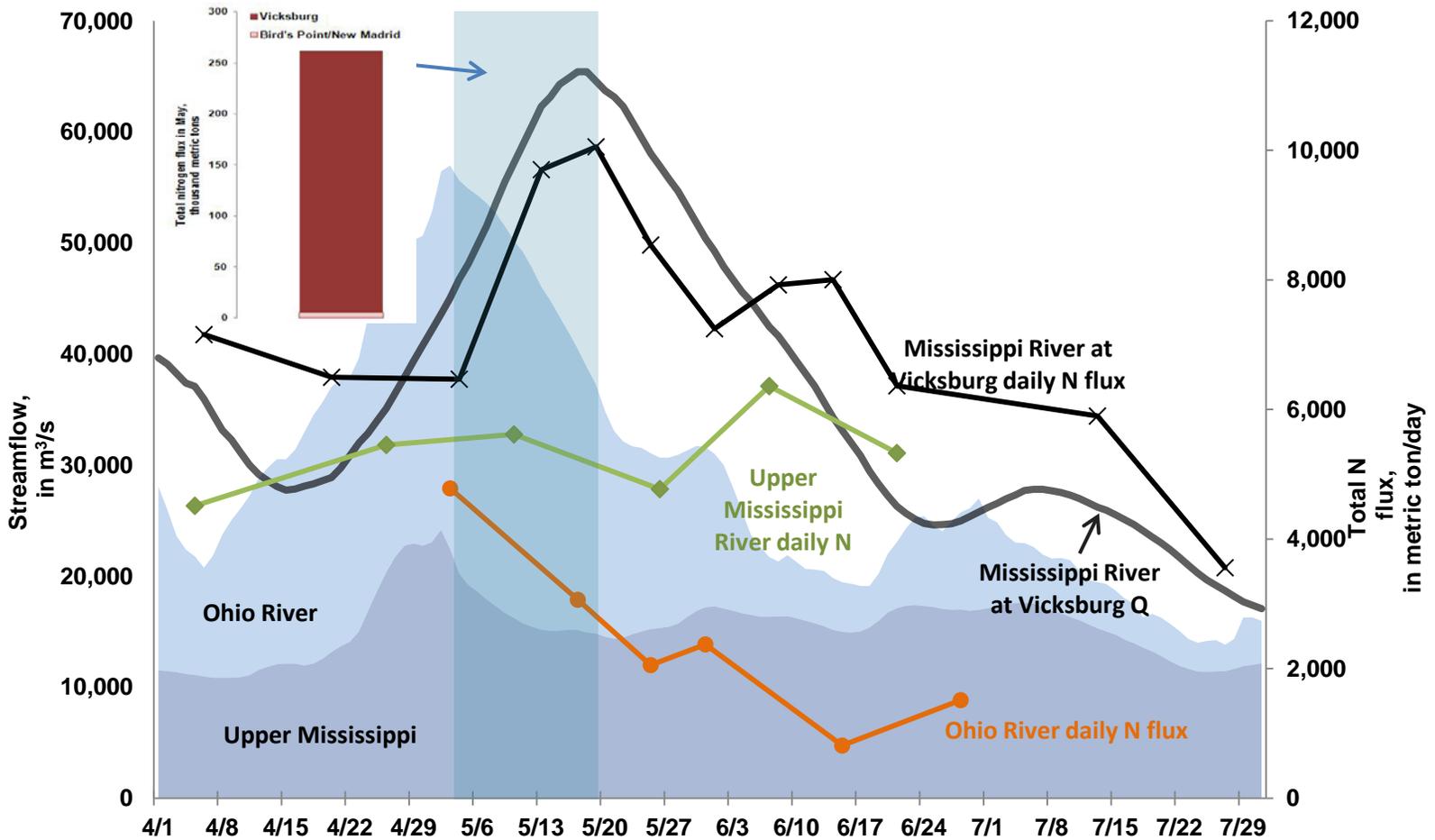
Figure 18. Plot of streamflow from the upper Mississippi River Basin, the Ohio River Basin, and the Mississippi River at Vicksburg and the daily total N flux. Inset chart shows the possible contribution from the BPNM to the May monthly total N flux at Vicksburg. The light blue box represents the time period that the BPNM was in operation.
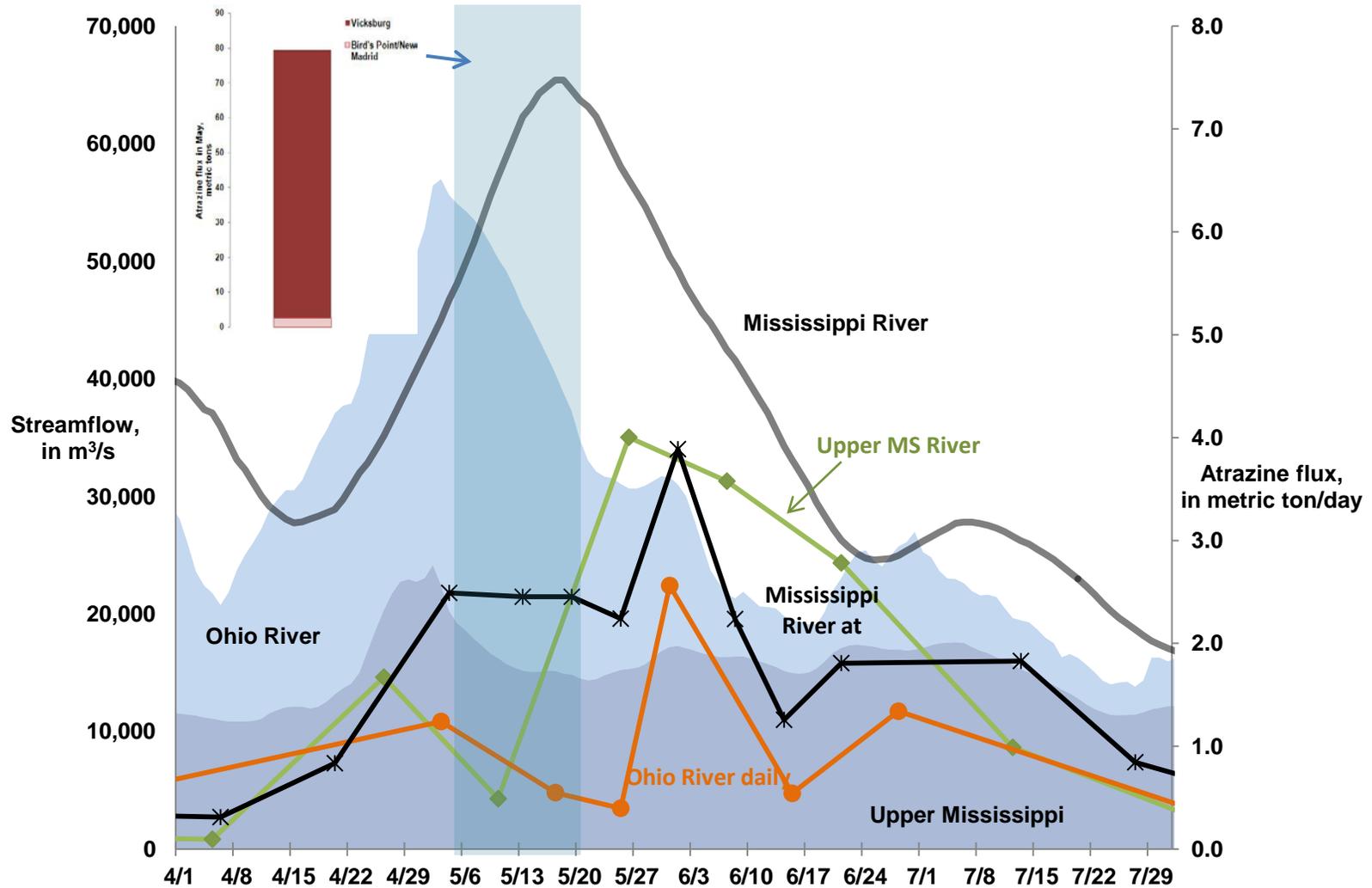
Figure 19. Plot of streamflow from the upper Mississippi River Basin, the Ohio River Basin, and the Mississippi River at Vicksburg and the daily atrazine flux. Inset chart shows the possible contribution from the BPNM to the May monthly atrazine flux at Vicksburg. The light blue box represents the time period that the BPNM was in operation