**Using MODIS Terra 250 m Imagery to Map**

**Concentrations of Total Suspended Matter in Coastal Waters**

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**Abstract**

High concentrations of suspended particulate matter in coastal waters directly effect or govern numerous water column and benthic processes. The concentration of suspended sediments derived from bottom sediment resuspension or discharge of sediment-laden rivers is highly variable over a wide range of time and space scales. Although there has been considerable effort to use remotely sensed images to provide synoptic maps of suspended particulate matter, there are limited routine applications of this technology due in-part to the low spatial resolution, long revisit period, or cost of most remotely sensed data. In contrast, near daily coverage of medium-resolution data is available from the MODIS Terra instrument without charge from several data distribution gateways. Equally important, several display and processing programs are available that operate on low cost computers.

The utility of MODIS 250 m data for analyzing complex coastal waters was examined in the Northern Gulf of Mexico. Using simple processing procedures, MODIS images were used to map the concentration of Total Suspended Matter (TSM). A robust linear relationship was established between band 1 (620 – 670 nm) MODIS Terra 250 m data and *in situ* measurements of TSM ($r^2 = 0.89$; $n = 52$) acquired during six field campaigns. This study demonstrates that the moderately high resolution of MODIS 250 m data and the operating characteristics of the instrument provide data useful for examining the transport and fate of materials in coastal environments, particularly smaller bodies of water such as bays and estuaries.


**Keywords**: Total suspended matter; MODIS; remote sensing.

## 1. Introduction

Coastal waters are often characterized by high concentrations of suspended organic and inorganic material derived from seabed resuspension or discharge of particle-laden rivers. High concentrations of suspended materials directly affect many water column and benthic processes such as phytoplankton productivity (Cole and Cloern, 1987; Cloern, 1987; Lohrenz et al., 1999; May et al., 2003; Pennock, 1985), coral growth (Dodge, 1974; Miller and Cruise, 1985; McLaughlin et al., 2003; Torres and Morelock, 2002), productivity of submerged aquatic vegetation (Miller, 1980; Dennison et al., 1993), nutrient dynamics (Mayer et al., 1998), and the transport of pollutants (Martin and Windom, 1991) and other materials. The distribution and flux of suspended sediments is highly variable in coastal environments and vary over a broad spectrum of time and space scales. This variability renders most traditional field sampling methods as inadequate in studies to resolve sediment dynamics in complex coastal waters (Miller et al., 2003). As a consequence, there is considerable interest in the use of remotely sensed data to provide synoptic maps of suspended materials such as suspended sediments in coastal waters.

Numerous studies have demonstrated that remotely sensed data can map suspended sediments (see for example, Bilge et al., 2004; Miller and Cruise, 1995; Stumpf, 1987; Stumpf and Pennock, 1998; Tassan, 1994); however, the routine use of remote sensing for monitoring sediment dynamics in many environments has been limited. There are several factors that limit the application of remote sensing to coastal waters. These factors include the characteristics of remote sensing instruments, their associated costs, or the availability of processing software. The most common limitation is an instrument's spatial or ground resolution. For example, the nominal spatial resolution of data from the AVHRR (Advanced Very High Resolution Radiometer), and SeaWiFS (Sea-viewing Wide Field-of-view Sensor) instruments is 1 km, an area typically too large to examine coastal horizontal gradients, particularly in estuaries and bays (Nittrouer and Wright, 1994). In contrast, the Landsat series of instruments (Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+)) have a spatial resolution of 30 m, but the orbital characteristics of the Landsat satellites yield a revisit time of about 16 days. Hence, Landsat sensors cannot capture the temporal dynamics of coastal waters. Although airborne systems have the advantage that the user can define instrument deployment parameters (e.g., time flown, area covered, and spatial resolution), most airborne systems are expensive to operate and processing the data is often costly and difficult. Generally, the limited availability of remote sensing data and processing software has also restricted the widespread application of remote sensing to coastal studies (Miller 1993). With most data, until recently, other limitations were associated with data often limited to commercial systems, scientific algorithms (e.g., atmospheric correction) and software processing systems.

There have been significant recent advances in remote sensing technology and in the development of instrument-specific data distribution and processing systems. These advances have greatly facilitated the use of remotely sensed data by a larger user community beyond traditional instrument science teams. Key ~~examples are the SeaWiFS and AVHRR projects where effective web-based data distribution gateways~~ have been established. Additionally, the SeaWiFS project has developed a robust data display and processing software package (SeaDAS, SeaWiFS Data Analysis System) that is freely distributed to the user community. This approach is now a critical element of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) which consists of a suite of satellite instruments, processing software, and data distribution systems.

The Terra spacecraft was launched as the first EOS mission on December 18, 1999. The Moderate-resolution Imaging Spectroradiometer (MODIS) instrument on Terra provides data, and subsequent operational products, for the land, ocean, cryosphere, and atmosphere. Another EOS spacecraft, Aqua, was launched in May 2002 and carries a second MODIS instrument. The MODIS instruments collect reflected and emitted energy from the Earth surface in 36 spectral bands from 0.4 µm to 14.4 µm (Table

1). High sensitivity radiometric data are recorded at nominal spatial resolutions of 250 m (bands 1-2), 500 m (bands 3-7), and 1000 m (bands 8-36). Terra and Aqua are in sun-synchronous orbits. The Terra (formally EOS AM) spacecraft crosses the equator at 10:30 AM local time (descending node), and the Aqua (formally EOS PM) spacecraft crosses at 1:30 PM local time (ascending node) thereby potentially providing two views of a given area each day. Each instrument acquires near-global coverage every one to two days. The instruments began providing science data in February 2000 and June 2002 on the Terra and Aqua spacecraft, respectively.

The use of remote sensing to map suspended sediment concentration is well established for a variety of water types. A common method is to relate remotely-sensed reflectance measured in the red portion (ca 600-700 nm) of the visible spectrum to parameters of water column sediment or particulate matter concentration. This approach is reasonably robust in coastal and inland waters because scattering from suspended materials frequently dominate the reflectance spectra when compared to pure water and phytoplankton absorption (Kirk, 1994, Mobley, 1994). MODIS band 1 provides coverage in the red spectral region (620 – 670 nm) at a sensitivity sufficient for coastal water studies. Therefore, the characteristics of MODIS band 1 data, such as its medium spatial resolution (250 m), red band reflectance, high sensitivity, and near daily coverage, suggests that these images may be well suited for examining suspended particulates in coastal environments, particularly smaller bodies of water such as bays and estuaries.

This study examined the relationship between MODIS Terra band 1 data and concentrations of Total Suspended Matter (TSM) obtained from 3 coastal systems of the Northern Gulf of Mexico, USA. In addition, a simple procedure was developed for the selection, acquisition, processing, and display of MODIS 250 m data such that the algorithm derived can easily be applied by most users to a wide range of studies of suspended matter in coastal waters.

## 2. **Methods**

### 2.1 *Field samples*

Surface water samples were obtained from three different environments in the Northern Gulf of Mexico (Lake Pontchartrain, Mississippi River Delta, and Mississippi Sound) during six field campaigns (Table 1) and filtered for the determination of Total Suspended Matter (TSM). Lake Pontchartrain is a shallow urbanized estuary adjacent to New Orleans, LA where suspended matter is primarily derived from bottom sediment resuspension (Miller et al., 2004). The bottom sediment type of Lake Pontchartrain is generally homogenous dominated by small grain size particles consisting of clay, silty-clay, and silt, with only very small pockets of large grain size particles such as sand and silt-sand (Flowers et al., 1985). The input of suspended sediments from the Mississippi River dominates the particulate environment (water column and seabed) of the Mississippi River Delta region. Surface shelf sediments adjacent to the Mississippi River are homogeneously fine-grained (silts and clays) in the upper meter of the seabed and within the river plume (Abu and Coleman, 1985; Corbett et al., 2004). Mississippi Sound is a protected shallow environment developed by the coast and a barrier island system. Suspended materials of fine-grained sediments (silts and clays) are derived from several rivers and bottom sediment resuspension (Doyle and Sparks, 1980).

TSM concentration (mg/l) was determined gravimetrically (Mueller and Austin, 1995) by filtering a known volume of water through either pre-weighed 0.2 μm Nuclepore nylon filters (Lake Pontchartrain and Mississippi River Delta samples) or 0.7 μm GF/F filters (Mississippi Sound samples). All filters were rinsed with Milli-Q water to remove salts, dried, and then reweighed on a high precision balance. Samples were filtered at sea or stored in acid-washed amber plastic bottles until filtered. These water samples were obtained by two independent research teams for investigations not directly related to remote sensing. Only samples obtained within 30 min before or after a MODIS Terra overpass were used in this analysis.

2.2 *MODIS imagery*

MODIS data are available without charge from several data archive and distribution centers. Specific data can be selected for a given geographic region and time period using a web-based query and ordering system offered at several data portals. For example, data for this study were obtained directly from the NASA EOS Data Gateway (EDG). The EOS gateway provides links to data from NASA and its affiliated centers. Access is available to most users. MODIS data is readily available from the NASA Goddard Earth Science (GES) Distributed Active Archive Center (DAAC).

MODIS imagery were obtained for days corresponding to field measurements of TSM (described below). MODIS data are stored as data granules (5 minutes time of data collection) in the HDF-EOS format. HDF (Hierarchal Data Format) is an efficient structure for storing multiple sets of scientific, image and ancillary data, in a single file. The DAAC data sets MOD02QKM (calibrated radiances level L1b full swath at 250 m) and MOD03 (geolocation fields level L1A at 1 km) were ordered and downloaded via ftp (file transfer protocol) client software. MOD02QKM files contain the MODIS 250 m band 1 and 2 image data. Earth geolocation points for georeferencing the image data are maintained in a corresponding MOD03 file. Individual data sets are embedded in the file as an SDS (Scientific Data Set). The SDS name for MODIS 250 m image data in a MOD02QKM file is EV_250_RefSB.

Upon downloading MODIS 250 m data to a local system, the data were displayed to access image quality and then processed using the HDFLook 4.1 software. HDFLook was developed under collaboration between the Laboratoire d'Optique Atmospherique and Goddard Earth Science (GES) DAAC for the XWindows computer environment and has been tested on all major UNIX platforms, Linux and MAC OS. Hence, HDFLook can be operated on a wide range of low cost computer systems.

HDFLook is available free of charge from several NASA MODIS web sites. HDFLook batch scripts were used to extract a region of interest corresponding to field measurements from the main MOD02QKM file, convert the data from calibrated radiances to surface reflectance, georeference the image, and output the image as a generic two band HDF file.

Although HDFLook is a useful program to display and extract sub-scenes from MODIS data files, the ENVI 3.4 (Research Systems, Inc., Boulder, CO) image analysis software was used to further process and analyze the HDFLook generated data files. The geopositional accuracy of each file was assessed by overlaying a high resolution vector coastal database onto each image. The file map coordinates were adjusted manually, if necessary, by changing the coordinate offsets. Land and clouds were masked using an empirical threshold algorithm based on band 2 reflectance. Atmospheric radiance was removed using a simple clear water (dark-pixel subtraction) technique (see for example, Gordon and Morel, 1983). Due to the limited number of field samples, data match-ups were made by manually navigating to a sample location and then recording the MODIS reflectance value for the corresponding pixel.

## 3. **Results and discussion**

A significant ($r^2$ = 0.89, n=52) relationship was observed between TSM concentration (mg/l) and atmospherically corrected MODIS Terra band 1 data used in this study (Fig. 1). The relationship is consistent over the wide range of TSM concentrations measured – offshore (clear water) stations to Mississippi River plume stations (highly turbid). Moreover, the relationship is reasonably robust in that TSM data were acquired from three distinct systems by three different investigators. The simple atmospheric correction scheme also appears to be effective for the wide range of sky conditions that occurred during the sample dates (Table 1).

A comparison of MODIS 250 m and 1 km data is shown in Fig 2. As expected, the 250 m data provides considerably more detail in the horizontal distribution of suspended particulates, contains more pixels in small areas such as Biloxi Bay, and allows a closer inspection of water features closer to the shore and barrier islands.

The TSM algorithm was applied to daily MODIS Terra images acquired for the coastal region associated with the Mississippi River Delta during 21-23 October 2003 (2003294 – 2003296). The processed images for 2003294 and 2003296 are shown of Fig 3. October is a period of moderately low discharge from the Mississippi River. Data were obtained through the EDG from the Goddard Space Fight Center Distributed Active Archive Center (GSFC-ECS) one day following acquisition. Independent ground stations such as the X-band system at the NASA Stennis Space Center, MS can provide data within a few hours of acquisition. Again, MODIS 250 m data provides sufficient spatial resolution to resolve fine-scale features in the images such as the plume from individual delta passes, complexity of TSM concentrations in nearshore waters, the sediment distribution in the associated bays, and the clear demarcation of frontal boundaries. This short time series clearly shows the significant effect of a frontal system passage 12 hours prior to 2003296 MODIS overpass in which winds dramatically increased (2 m/s to sustained winds of 10 m/sec) from the NW (variable, 270-360°). The characteristics of the Mississippi River plume rapidly changed from a generally diffuse, lobe-like plume to a distinct more concentrated plume extending to the south east. The capability to resolve and track these features is key to numerous investigations that study the transport and fate of materials (including carbon), the coupling of seabed deposition with river discharge, and water column phytoplankton production.

## 4. **Conclusions**

Mapping the distribution of suspended particulates in coastal waters is critical to many scientific and environmental studies. Environmental managers and local decision makers must often know water quality parameters as well as the transport of materials over large areas of a coastal region. Frequently, data are acquired involving expensive and labor-extensive field programs to obtain data at the appropriate temporal and spatial scales. Although previous studies have shown a direct relationship between concentrations of suspended matter and remotely sensed data, the spatial resolution or frequency of remotely sensed data was inadequate to fully examine the dynamics of most coastal or smaller bodies of water (i.e., bays and estuaries). In addition, the availability of software and instrument specific algorithms to process remotely sensed data were often absent or restricted to a limited user community.

This study demonstrated that the characteristics of the MODIS Terra instrument provides data well suited for the study of suspended matter in dynamic coastal waters. The moderately high resolution of MODIS 250 m data was useful for mapping small-scale features of TSM concentration in different inland and coastal waters. Using simple processing procedures and readily available software, rapid acquisition processing, and analysis of MODIS data was possible. The near daily revisit period of the MODIS instrument enabled an analysis of short-term, yet significant, changes in the horizontal distribution of the sediment plume of the Mississippi River. Equally important to the potential widespread use of MODIS images in coastal studies is the significant advances in the development and open distribution of analysis software including instrument specific algorithms. Similarly, the development of effective distribution gateways of MODIS data has greatly facilitated its widespread use.

The availability of two MODIS instruments (morning, afternoon) should greatly extend the utility of MODIS data as shown in this study. It is expected that a similar robust relationship will exit between

MODIS Aqua data and TSM. This relationship will be examined in future studies dedicated to developing real-time applications of remotely sensed data for coastal studies.

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**Figure Legends**

Figure 1. Total Suspended Matter (TSM) concentration as a function of atmospherically corrected MODIS Terra 250 m band 1 reflectance. TSM data were obtained from six field campaigns: open circles, Mississippi Sound, 5/16/2001; closed circles, Mississippi River Delta (MRD), 3/17/02; closed squares, Lake Pontchartrain (LP), 5/19/02; open triangles, LP, 5/23/02; open squares, MRD, 7/15/03; and closed triangle, MRD, 10/20/03. The line is the least-squares fit to the data (r2 = 0.89, n = 52).

Figure 2. Comparison of MODIS Terra 250 m band 1 (620 – 670 nm; A) and band 13 (662 – 672 nm; B) 1 km reflectance images of the Mississippi Sound (30 - 30.5° N, 88 - W) acquired 4 April 2004. Land and clouds are masked black.

Figure 3. Calibrated images of TSM derived from MODIS Terra Band 1 data for 2003294 (A) and 2003296 (B). Land is masked to black. High spatial variability is observed within each image as well as significant differences in the horizontal distribution of suspended particulates between the two days resulting from an increase in wind speed from the northwest prior to the MODIS overpass on 2003296.

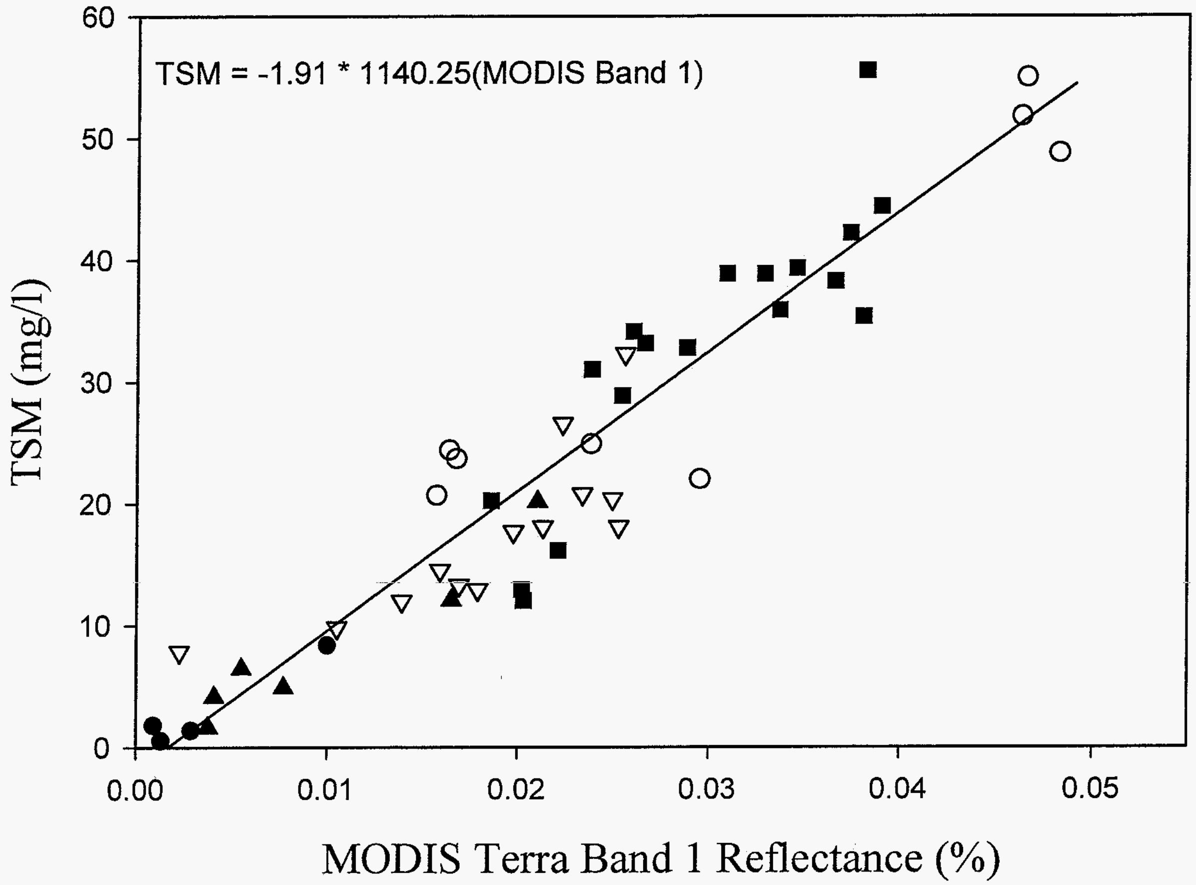
TSM = -1.91 * 1140.25(MODIS Band 1)
60
50
40
30
20
10
0
TSM (mg/l)
0.00
0.01
0.02
0.03
0.04
0.05
MODIS Terra Band 1 Reflectance (%)

Figure 1.

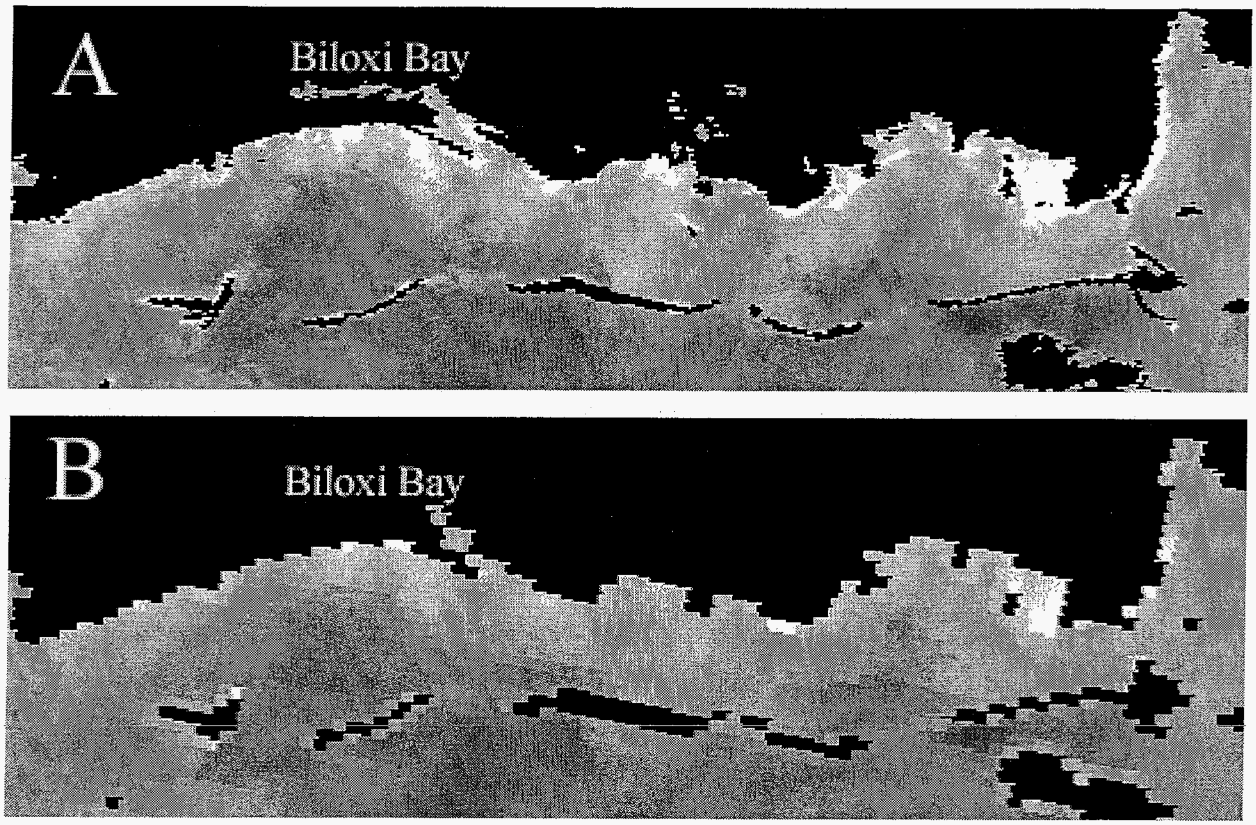


Figure 2.

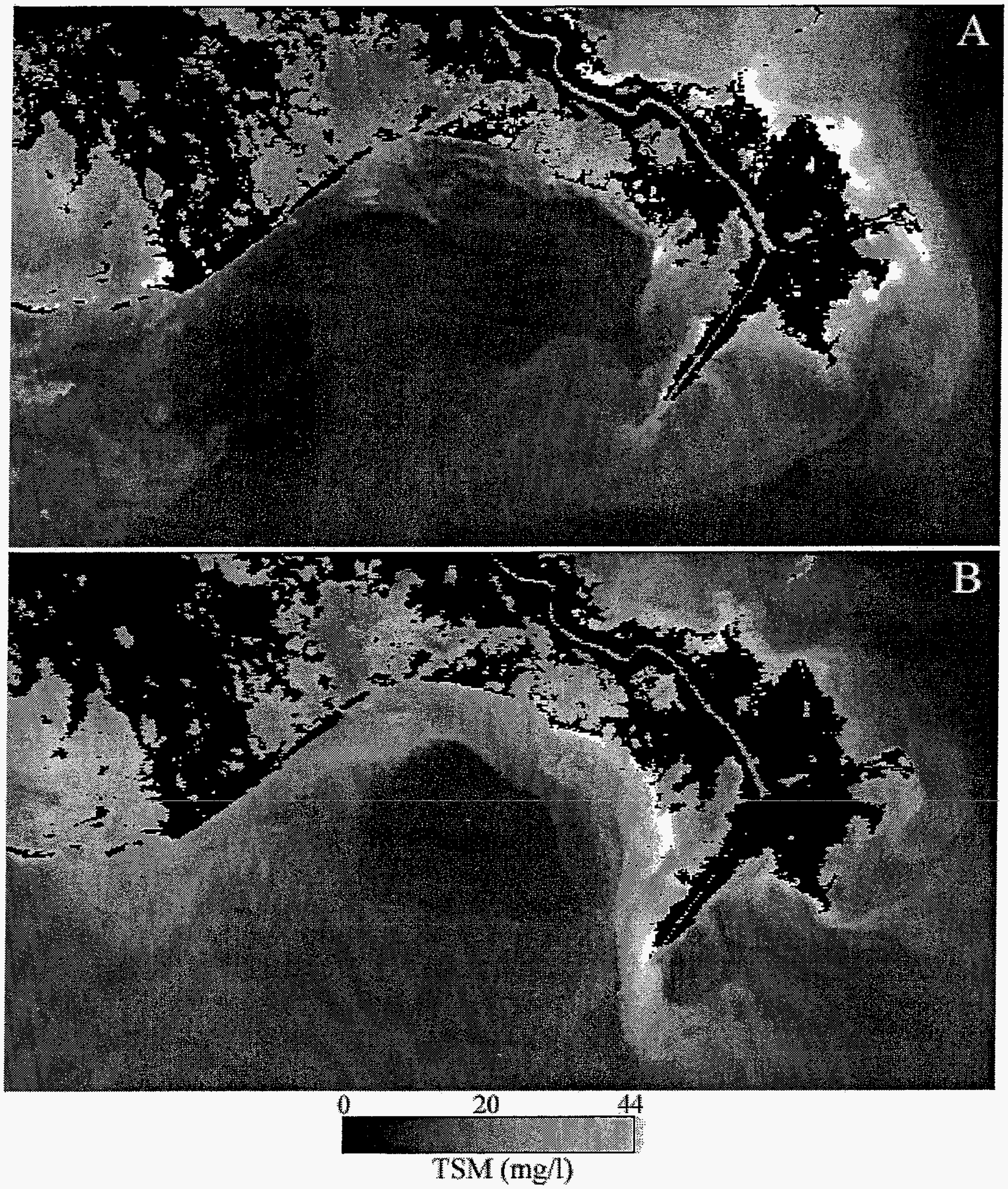


Figure 3.

Table 1. Location, date, and source of TSM samples used in this study.

| Environment | Date | Source |
|---|---|---|
| Lake Pontchartrain, LA | 19 May 2002 | McKee[1] |
| Lake Pontchartrain, LA | 23 May 2002 | McKee[1] |
| Mississippi River Delta | 15 July 2003 | McKee[1] |
| Mississippi River Delta | 10 October 2003 | McKee[1] |
| Mississippi River Delta | 17 March 2002 | Miller[2] |
| Mississippi Sound, MS | 16 May 2001 | Moncreiff[3] |

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