Characterization of Flood Sediments from Hurricanes Katrina and Rita and Potential Implications for Human Health and the Environment

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The flooding in the greater New Orleans, La., area that resulted from Hurricanes Katrina and Rita in August and September 2005 left behind accumulations of sediments up to many centimeters thick on streets, lawns, parking lots, and other flat surfaces (fig. 1). During the flood dewatering and subsequent cleanup, there were concerns that these sediments might contain pathogens and chemical contaminants that would pose a health risk to emergency responders, cleanup workers, and local residents who came into contact with the wet sediments or inhaled dusts generated from dried sediments. In response to these concerns, U.S. Geological Survey (USGS) scientists and colleagues characterized the potential environmental and health hazards of hurricane flood sediments from the greater New Orleans and Slidell, La., area.

Introduction

Samples were collected in September and October 2005 from 25 localities (fig. 2). A wide variety of physical, inorganic and organic chemical, and microbial characterization methods were applied to the samples at USGS analytical facilities in Denver, Colo.; Reston, Va.; St. Petersburg, Fla.; Columbia, Mo.; and Menlo Park, Calif. Additional characterization studies were performed on splits of the same samples by external collaborators at the Colorado School of Mines (CSM), U.S. Environmental Protection Agency (EPA) National Enforcement Investigations Center (Denver), University of California–Davis, and State University of New York (SUNY)–Stony Brook.

The USGS studies of the flood sediments were designed to produce data and interpretations to help (1) understand sources of the sediments, (2) understand how the sediments and any contained contaminants may respond to environmental processes, and (3) identify sediment characteristics of potential concern from a human health standpoint.

The USGS study complements extensive sampling and analysis by the EPA and the Louisiana Department of Environmental Quality (LDEQ), which focused primarily on collecting and analyzing a large number of flood-sediment samples over a broad area including Lake Pontchartrain for a wide variety of metal and organic compounds (U.S. Environmental Protection Agency, 2006). Early USGS study results were released in November 2005 to Federal and State hurricane response officials and can be found in Plumlee and others (2006).

Multiple Sources of Flood Sediments

Two important overall findings of the USGS study are that the flood sediments were derived from multiple sources and that spatial variations in sediment makeup and chemical composition across the New Orleans area reflect variable contributions from these different sources. Flood-sediment samples from areas near marshes (Chalmette, Violet, and inland Slidell, La.) are dominated by marsh muds with abundant pyrite (an iron sulfide) and diatom frustules (silica-rich skeletal remains of various types of algae) (figs. 3*A* and 3*B*). The microscopic pyrite grains commonly exhibit a “framboidal morphology” (resembling microscopic raspberries, fig. 3*A*) that is diagnostic of an origin in marine sediments where seawater sulfate has been reduced by bacterial action to sulfide and the sulfide has reacted with iron in the sediments to produce the pyrite. Analysis of sediment cores from the marshes east of Violet (samples provided by the U.S. Army Corps of Engineers (USACE)) has identified similarly abundant pyrite framboids (fig. 3*C*).

Sediment samples from areas close to the breached canals or Lake Pontchartrain (Ninth Ward, Lakeview, The Rigolets, and nearshore Slidell) had abundant clays, diatoms, and sandy material but generally had smaller amounts of pyrite, indicating that they were derived from remobilized bottom sediments from Lake Pontchartrain and materials eroded from the levees or from beneath the canals. In contrast, samples from downtown New Orleans (defined here as an area including portions of the French Quarter, Mid-City, and Bywater neighborhoods) were composed of mud- and sand-sized material with no pyrite but more abundant particles of urban construction and commercial materials such as soda lime glass, glass fibers, concrete, nails, paper, and glass jewelry beads. Variable amounts of plant material (leaves, grass, needles) were present in all samples collected.

The downtown New Orleans samples typically had substantially higher concentrations of metals such as lead, zinc, copper, arsenic, cadmium, and mercury than did the samples dominated by lake-bottom mud or marsh mud; the lead tends to occur as microscopic discrete lead metal or lead oxide particles (fig. 3*D*). For many of these elements, concentrations in downtown samples exceed EPA or LDEQ soil-quality criteria. Lead concentrations, for example, range from 95 to 2,180 parts per million (ppm) in the downtown samples, with most having levels above the 400 ppm

Figure 1. Widespread accumulations of flood sediments were left behind in New Orleans, La., neighborhoods after the flood waters from Hurricanes Katrina and Rita were pumped away. (*A*) September 16, 2005, photograph. The sediments deposited in a Chalmette neighborhood were in the process of drying out. While wet, the sediments are the consistency of a thick mud. Sediments in the lower right portion of the photograph are beginning to show cracks that typically form as muddy sediments dry. (*B*) October 7, 2005, photograph. These sediments deposited in a Lakeview neighborhood have shrunken considerably in volume because of the loss of water during drying.

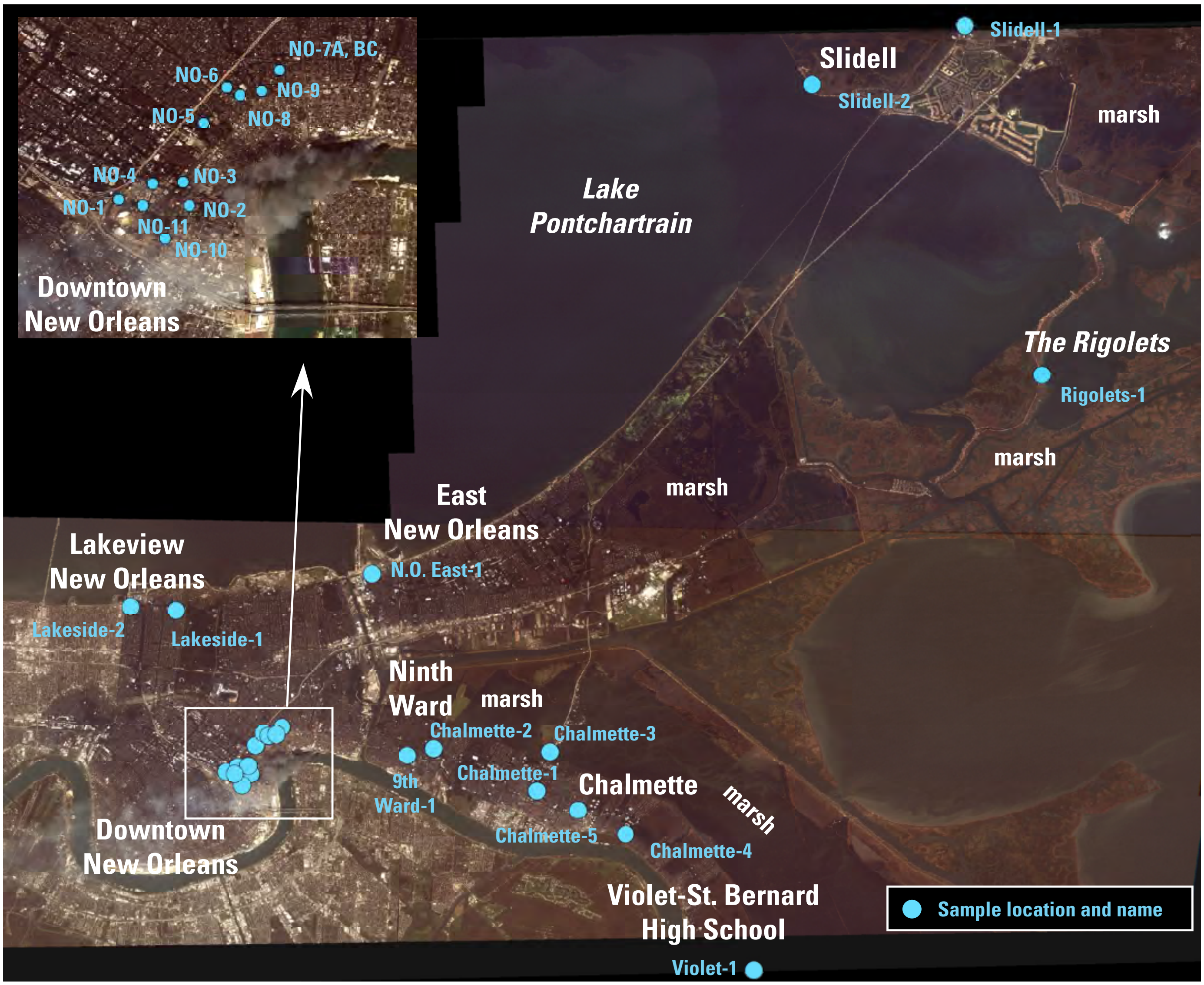

Figure 2. Locations of samples collected and analyzed in this study superimposed on top of satellite image of the New Orleans, La., area taken on August 31, 2005 (image courtesy of DigitalGlobe). Flooded portions of the urban area can be discerned from unflooded areas by their overall darker tone.

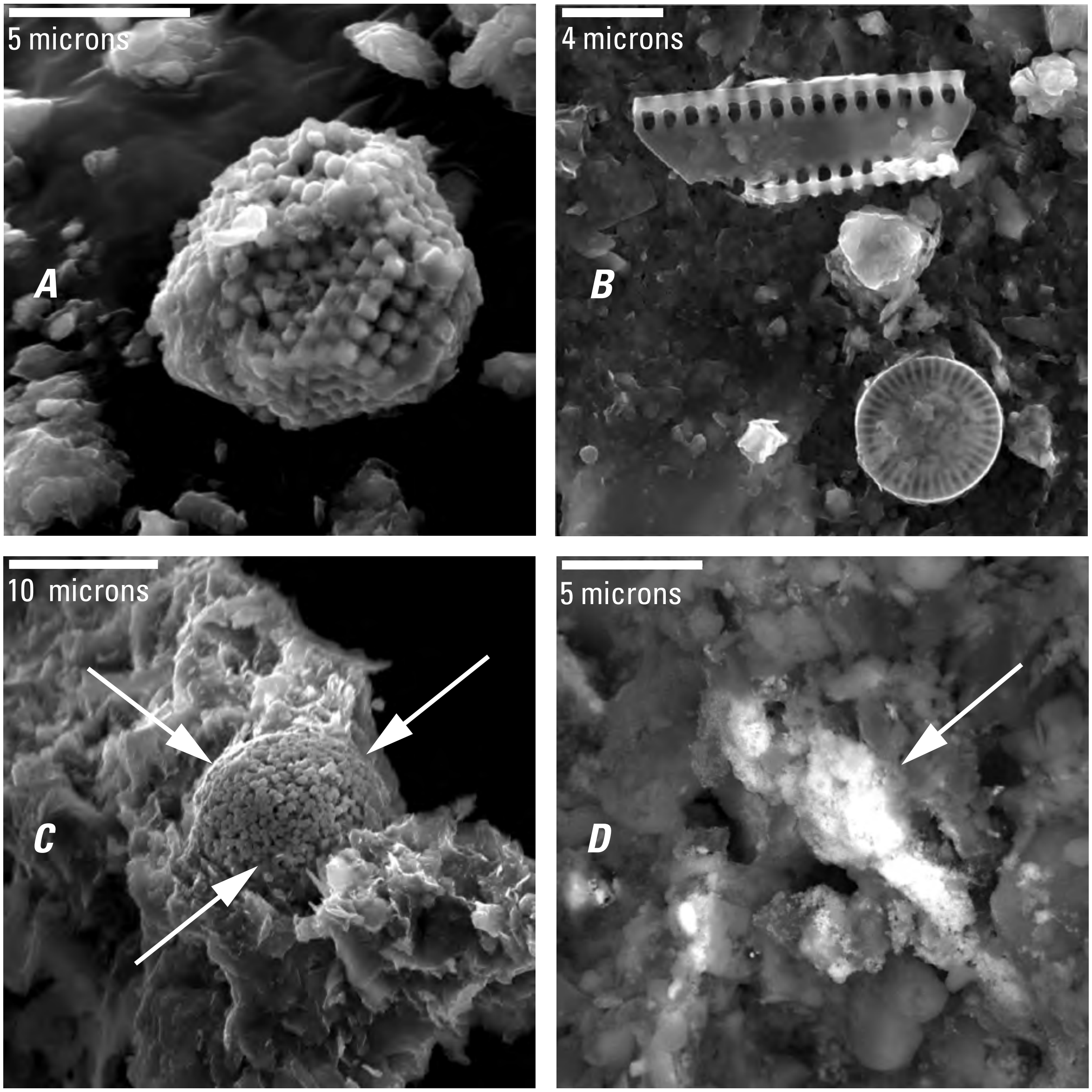

Figure 3. Scanning electron photomicrographs illustrate several diagnostic microscopic features of the Hurricane Katrina flood sediments used to help understand sources for the sediments. (*A*) Microscopic "framboidal" pyrite (an iron sulfide described by its name for its similarity in appearance to raspberries), indicated by the arrows in *C* and *D*, is common in the flood sediments from the Chalmette, Violet, and inland Slidell, La., areas. (*B*) Diatom frustules, which are microscopic silica skeletal remains of algae, are common in flood sediments collected from throughout the New Orleans, La., area. (*C*) Framboidal pyrite (indicated by the arrows) is also abundant in sediment cores from the marshes east of Chalmette and Violet. (*D*) Microscopic lead-rich particles, such as the light gray, metallic-lead or lead-oxide particles seen in this backscattered-electron scanning electron micrograph image, are commonly found in the flood-sediment samples collected from downtown New Orleans. No pyrite particles have been observed in the downtown New Orleans samples.

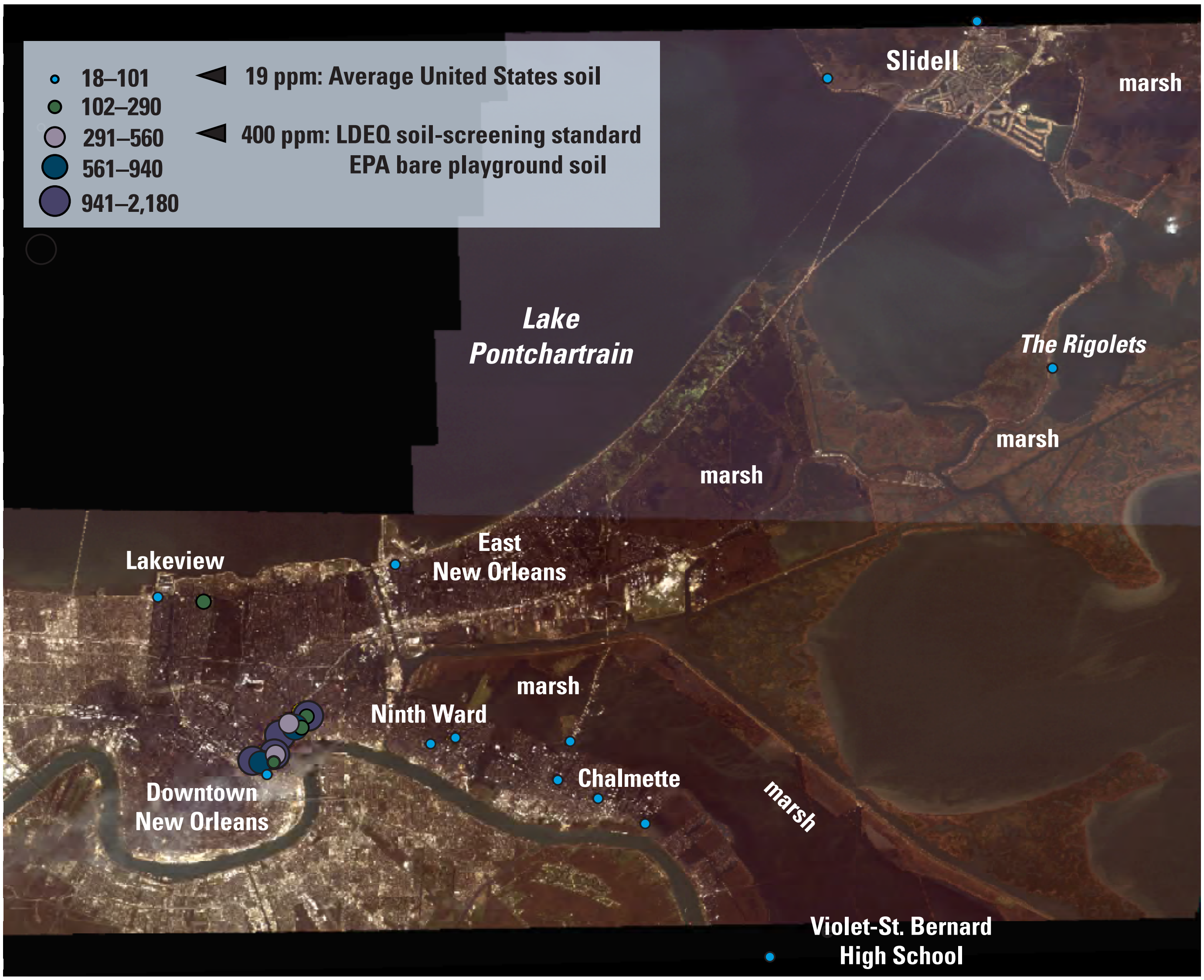

Figure 4. A map of lead concentrations in the flood sediments shows that downtown New Orleans, La., sediments generally have substantially higher lead levels than do flood sediments from areas closer to Lake Pontchartrain, the breached levees (near east New Orleans and the Ninth Ward), or the marshes (near Chalmette, Violet, The Rigolets, and inland Slidell, La.). Most of the downtown samples have lead concentrations well in excess of the 400 parts per million (ppm) residential soil-screening criterion used by the U.S. Environmental Protection Agency (EPA) (2005) and Louisiana Department of Environmental Quality (LDEQ) (2003).

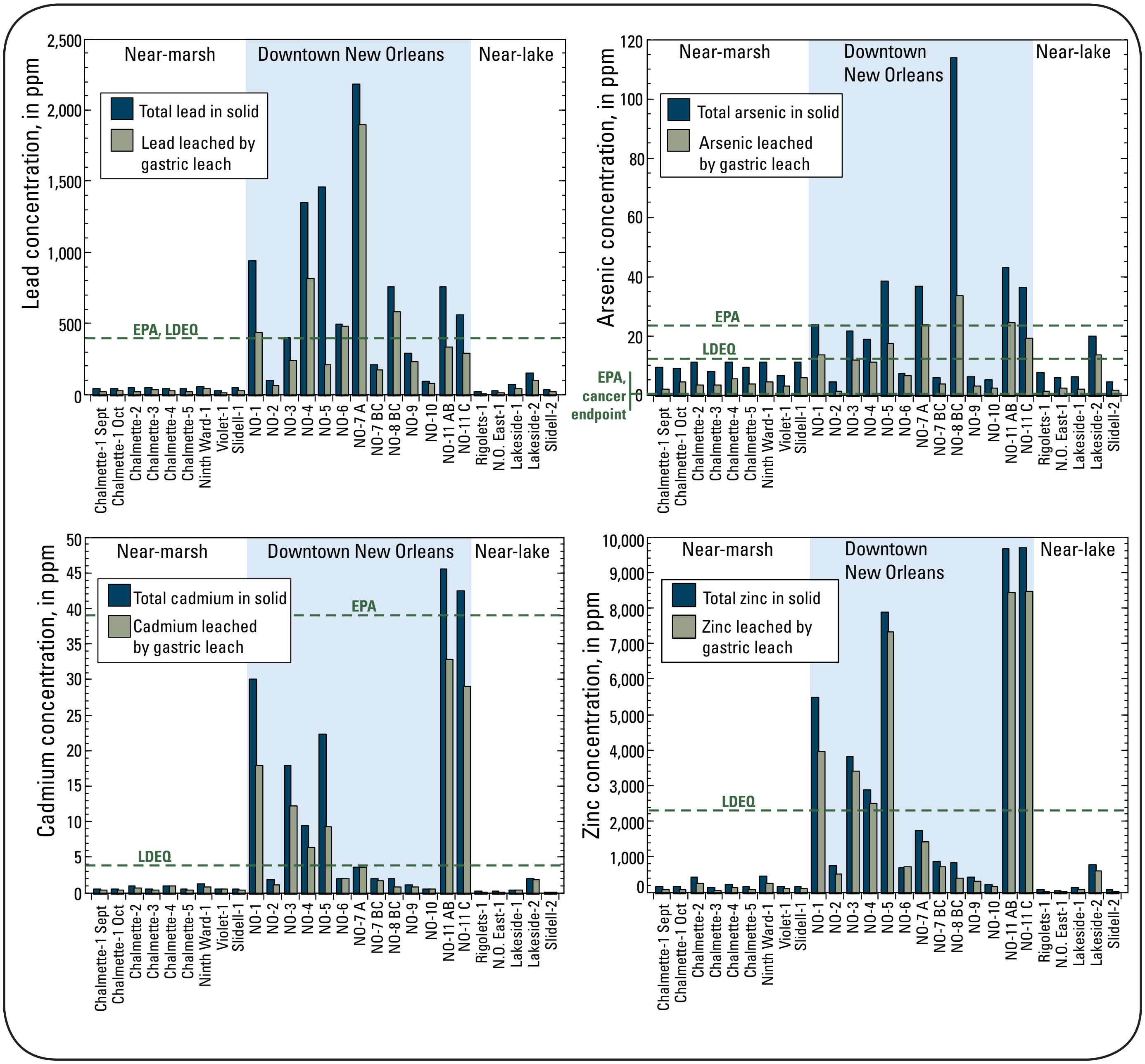

Figure 5. Total concentrations of selected metal contaminants in flood sediments compared to their concentrations leached by simulated gastric fluids. The near-marsh samples are dominated by marsh muds, and the near-lake samples include those from near Lake Pontchartrain or the breached canals. The dashed lines show U.S. Environmental Protection Agency (2005) Region 6 residential soil-screening levels and/or the Louisiana Department of Environental Quality (2003) nonindustrial soil-screening standard concentrations. Note that the scales of the concentration (y axes, in parts per million (ppm)) vary between the plots for the different elements. Similar plots for additional metals are shown in Plumlee and others (2006).

residential or nonindustrial soil-screening level used by EPA (U.S. Environmental Protection Agency, 2005) and LDEQ (Louisiana Department of Environmental Quality, 2003) (figs. 4 and 5).

Downtown New Orleans flood-sediment samples also are generally enriched in a variety of organic contaminants (such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and polychlorinated biphenyls (PCBs)) compared to the flood sediments dominated by lake-bottom or marsh muds; of the organic contaminants analyzed, the PAH benzo(a)pyrene (fig. 6) and to a lesser extent dieldrin (an organochlorine pesticide) were most consistently above EPA soil-screening criteria (U.S. Environmental Protection Agency, 2005) in the downtown samples. Similar spatial patterns of lead and PAH enrichments between the Katrina-Rita flood sediment samples and urban New Orleans soil samples collected and analyzed in the late 1990s and early 2000s by Mielke (1999) and Mielke and others (2004, 2006) suggest that the Katrina flood sediments in the downtown New Orleans area are likely dominated by reworked local soil material having pre-existing elevated metal and organic contaminant concentrations (fig. 7).

A limited number of USGS flood-sediment samples collected outside the downtown New Orleans area have elevated concentrations of some metal or organic contaminants, such as sample Lakeside-1 from the Lakeview neighborhood. The limited number of such samples, however, suggests that areas of contamination outside downtown New Orleans are rather restricted in occurrence and extent and most likely came from smaller local contamination sources.

Findings Pertinent to Human Health

Concerns have been expressed about the potential human health impacts that might have resulted from exposure to the flood sediments or dust generated from dried sediments during cleanup and rehabitation of flooded areas. The USGS characterization studies of the flood sediments provide useful insights into the physical, chemical, and microbiological components of the sediments that may be of interest from a human-health perspective.

When dry, the silt- and clay-rich flood sediments form hard, durable chunks (fig. 1) that require considerable effort to break apart. As a result, these sediments would likely only release appreciable dust or loose particles if they were extensively disturbed (such as by being driven upon or otherwise mechanically pulverized). This situation is fortunate, because particle-size analysis of disaggregated flood-sediment samples (fig. 8) indicates that a high proportion of the sediment is of the clay- to silt-size range that could be involuntarily ingested via hand-to-mouth contact (<250 µm), and a smaller but still substantial proportion (1–16 percent) of some sediment samples is in the respirable size range (less than 2–3 microns). Scanning electron microscopy (SEM) analysis of the lead-rich sediment samples indicates that the lead particles fall well within the ingestible size range (see particle in fig. 3*D*). Hence, cleanup procedures that minimize both physical breakup of the sediment chunks and dust generation from the sediments would help minimize exposure to any contaminants such as lead in the sediments.

Bioaccessibility leaching experiments using simulated gastric fluids were conducted on the flood sediments to test how readily heavy metals such as lead might leach from the sediments should they be involuntarily ingested (such as by children via hand-to-mouth contact). The simulated gastric fluids generally leached relatively high concentrations of lead, zinc, cobalt, cadmium, manganese, arsenic, and nickel from the downtown New Orleans samples compared to samples collected elsewhere; leach test results for lead arsenic, cadmium, and zinc are shown in figure 5. These results suggest that both the metal-rich downtown flood sediments and the metal-rich prehurricane soils from which they were derived are potentially important exposure sources for bioaccessible lead and other metals to long-term inhabitants of the downtown area.

The USGS results are consistent with the findings of pre-Katrina soil surveys in New Orleans (Mielke, 1999; Mielke and others, 2004, 2006), which indicated that 20–30 percent of the children living in inner-city New Orleans prior to Hurricane Katrina had elevated blood-lead levels (>10 µg per dL) and that there was a direct correlation between child blood-lead levels and residence in New Orleans locations with elevated soil lead. The USGS results also are consistent with results of the EPA-LDEQ New Orleans flood-sediment analysis program (U.S. Environmental Protection Agency, 2006), which listed a number of recommendations for local residents to follow to help prevent exposure to the lead, particularly for young children. Mielke and others (2006) also summarized results of a pilot program to remediate high lead concentrations in New Orleans soils.

Using DNA-based polymerase chain reaction (PCR) testing techniques, USGS microbiologists found that human enteroviruses (those associated with untreated sewage) and at least one type of bacterial pathogen commonly found in soils had been present in some of the flood-sediment samples; however, these tests do not indicate whether the microbes were still alive and viable at the time that the sediment samples were collected. Our colleagues at SUNY–Stonybrook were able to culture a variety of bacterial and other types of microbial colonies from the dried flood-sediment samples collected by the USGS, indicating that a number of microbe species were viable in the samples studied. In general, the microbial findings are consistent with those that would be expected to be encountered in flooded (and redried) soils under the direct influence of untreated sewage.

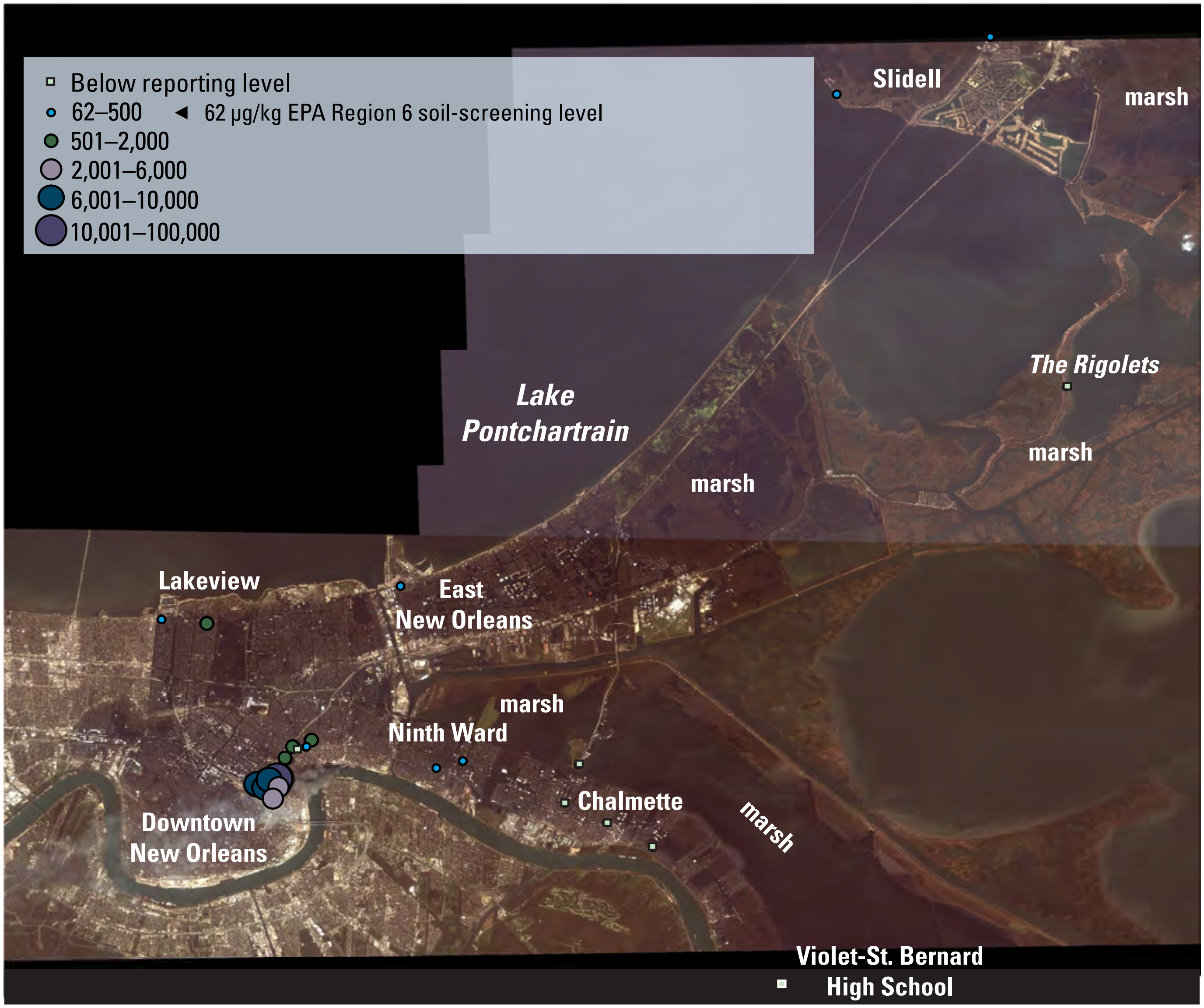

Figure 6. A map of benzo(a)pyrene in the flood sediments also shows an overall enrichment in most downtown samples compared to those of the surrounding areas, with most downtown samples having concentrations that substantially exceed the U.S. Environmental Protection Agency (2005) residential soil screening standard of 62 µg/kg (micrograms per kilogram, or parts per billion).

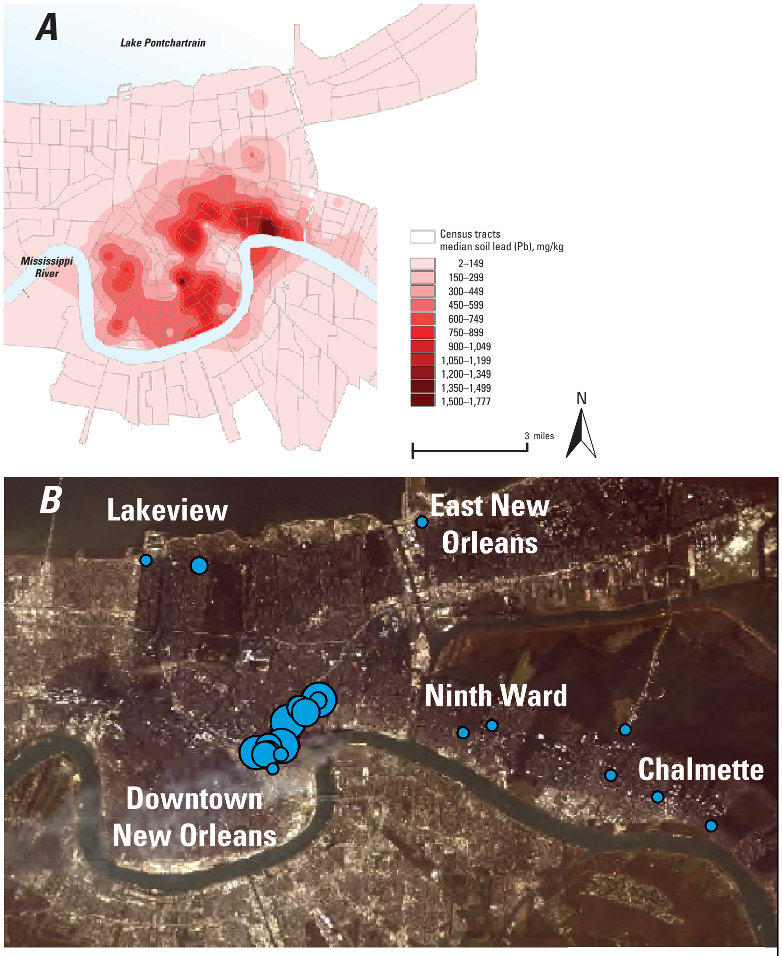

Figure 7. Map showing patterns of lead concentration in pre-Hurricane Katrina soils in New Orleans, La. (high in the downtown area, generally low in the surrounding areas), collected in the 1990s by Mielke (1999) and by Mielke and others (2004) (*A*). Lead concentrations in flood sediments in New Orleans, La., after Hurricanes Katrina and Rita are generally similar to those in *A* (larger dots represent higher soil lead concentrations) (this study; U.S. Environmental Protection Agency, 2006) (*B*). Note that the mg/kg (milligrams per kilogram) concentration unit used by Mielke in *A* is equivalent to the parts per million (ppm) concentration unit used in this study.

Environmental Findings

USGS scientists and their collaborators have carried out a number of tests to assess potential metal leaching from the flood sediments into the environment. Tests that leached both wet and dry sediments with simulated rainfall and simulated dilute sea water (such as that found in the brackish Lake Pontchartrain) indicate that there should be relatively little release of metals from the sediments over the short term into onland and lake environments. Tests designed to model the interactions of materials with waters present in landfills indicate that some metals, including lead and zinc, may be mobilized in low concentrations from wet marsh-derived sediments disposed in landfills.

Other USGS tests indicate that the long-term weathering of exposed flood sediments with greater than about 2–5 percent pyrite may eventually lead to the formation of acidic pore and runoff waters with elevated concentrations of acid and sulfate (in the form of moderately concentrated sulfuric acid), along with iron, aluminum, manganese, copper, and several other metals. These net acid production (NAP) tests (results shown in fig. 9) indicate that the most pyrite-rich flood-sediment samples are potentially more acid generating than are many mine waste piles found at a variety of metal mines (e.g., Fey and others, 2000). The acid drainage could be somewhat corrosive to concrete and metals with which the sediments remain in contact and might be detrimental to any vegetation and aquatic life exposed to the drainage. Sediments containing high concentrations of iron sulfides and low concentrations of carbonate minerals (carbonates help neutralize acid drainage) should therefore best be considered as candidates for disposal into water-covered disposal areas or disposal facilities isolated from the atmosphere and rainfall.

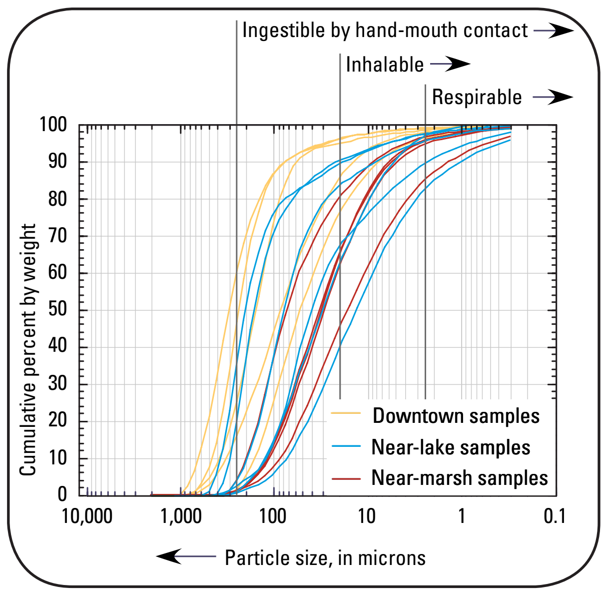

Figure 8. Cumulative particle-size distribution of flood-sediment samples determined on sample splits that had been physically disaggregated and then placed in an ultrasonic bath for 10 minutes to disaggregate larger clumps. The samples are grouped by line color according to their location or source. Downtown samples generally have a greater proportion of coarser material than do the near-lake or near-marsh samples. The sizes of particles that fall within approximate ingestible, inhalable, and respirable (deep lung particle penetration) ranges also are shown.

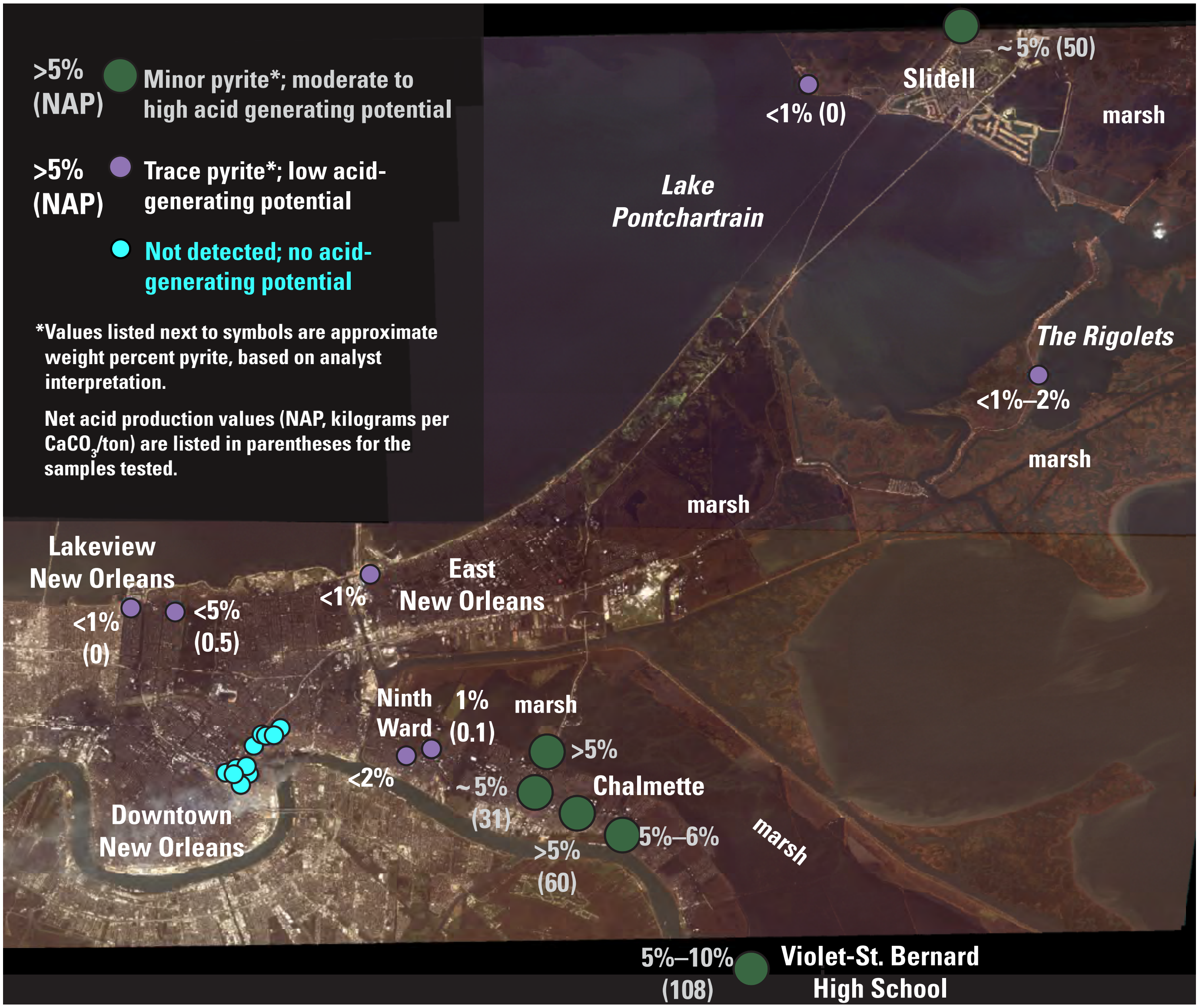

Figure 9. Map of estimated pyrite contents in the flood-sediment samples collected from the New Orleans, Chalmette, Violet, The Rigolets, and Slidell areas in Louisiana, as determined by x-ray diffraction (XRD) analysis. Flood-sediment samples from neighborhoods closest to the marshes have the highest pyrite concentrations, suggesting that the sediments in these neighborhoods are primarily composed of muds transported from the marshes by Hurricane Katrina's storm surge. Net acid production (NAP) tests were run on a subset of the samples, and the results illustrate that samples with the most abundant pyrite have the highest potential to generate acid drainage as the pyrite weathers in the sediments. For comparison, the flood-sediment NAP values are generally similar to those measured on pyrite-rich mine waste piles from a number of historical Rocky Mountain metal mine sites in Colorado (Fey and others, 2000).

Cleanup managers from LDEQ used these USGS results as a validation of their decisions regarding disposal of the flood sediments from the different New Orleans neighborhoods. In contrast to the higher pyrite flood sediments from Chalmette, Violet, and inland Slidell (fig. 9), the NAP tests indicate that downtown New Orleans flood sediments and the flood sediments dominated by lake-bottom mud, canal-bottom materials, and levee materials do not appear to pose a similar problem for generation of acid drainage.

Comparison of analytical results for organic contaminants in samples collected from the Chalmette-1 locality (fig. 2) in September and October 2005 indicates that many of the organic contaminants decreased in concentration over time. This finding suggests that continued exposure of flood sediments to sunlight, the atmosphere, and rainfall may help reduce concentrations of many of the semivolatile organic contaminants examined though abiotic (photolytic, hydrolysis, oxidation reactions) and biotic degradation processes or by physical mechanisms such as volatilization and water washing. Of these processes, water washing may have the greatest potential to affect the local environment, by releasing organic contaminants from the sediments into nearby water bodies.

Summary

The USGS characterization studies of flood sediments produced by Katrina and Rita show that the sediments were derived from a variety of sources, including marsh muds, lake- and canal-bottom sediments, levee-construction materials, material eroded from beneath the canals, and urban soils and debris. Several lines of evidence indicate that flood sediments in the downtown New Orleans area were derived primarily by reworking of older, highly contaminated urban soils, with elevated concentrations of lead, arsenic, other heavy metals, and PAHs (e.g., benzo(a)pyrene). Lead and some other metal contaminants in the downtown soils and flood sediments are likely to be quite bioaccessible, and therefore the downtown soils and their derived sediments pose a potential long-term exposure risk to residents.

In contrast, flood sediments derived from marshes and Lake Pontchartrain bottom sediments generally have, apart from localized areas of contamination, substantially lower metal and organic contaminant concentrations than do the downtown sediments. Instead, the marsh sediments pose a greater risk for the eventual development of environmentally deleterious acidic, metalliferous drainage should the sediments remain in contact with both air and water for an extended period of time. Several species of bacteria and viruses commonly found in natural soils or soils contaminated by untreated sewage, or both, also were indicated to be present in flood-sediment samples from throughout the area sampled. As with any material that has the potential to generate dust, cleanup of the flood sediments should be carried out with appropriate respiratory protection and should be done following appropriate procedures to minimize dust generation and exposure.

The USGS study results have been used by cleanup managers and scientists assessing environmental impacts of the hurricanes and subsequent cleanup activities. The results also show that earth science characterization methods focused on environmental processes can be a valuable component of interdisciplinary scientific studies that help emergency responders, public health officials, and other stakeholders to better understand the potential health and environmental implications of natural disasters such as Katrina and Rita.

Acknowledgments

A large number of scientists participated in the sampling, sample preparation, and sample analysis for this study. These include George Breit, Steve Sutley, Paul Lamothe, Suzette Morman, Phil Hageman, Harland Goldstein, Ed Furlong, Bob Rosenbauer, Carl Orazio, Monique Adams, Murray Beasley, Mark Burkhardt, Zoe Ann Brown, Roger Clark, Jim Crock, Bob Eganhouse, Tammy Hannah, Todd Hoefen, JoAnn Holloway, Chris Ingersoll, Eric Livo, Elena Nielsen, Jim Ranville (CSM), Liz Roemer (SUNY–Stony Brook), Rick Sanzolone, Gregg Swayze, Joe Taggart, Dave Walters, Steve Werner, Tom Wildeman (CSM), and Steve Zaugg.

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