Hurricane Katrina: Environmental Hazards in the Disaster Area

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Abstract

The flooding of New Orleans by Hurricane Katrina provides many lessons for the environmental and engineering communities and raises public policy questions about risk management. Although serious environmental and waste management issues were expected as a result of the flooding, extensive environmental sampling largely failed to substantiate them. The attention of those managing the emergency was diverted from critical issues to addressing this area of public apprehension. The potential environmental consequences were of concern because many chemical plants, petroleum facilities, and contaminated sites, including Superfund sites, in the area were covered by floodwaters. In addition, hundreds of commercial establishments, such as service stations, pest control businesses, and dry cleaners, use potentially hazardous chemicals that may have been released into the environment. The potential sources of toxics and environmental contaminants include metal-contaminated soils typical of old urban areas. Compounding these concerns is the presence of hazardous chemicals commonly stored in households and the fuel and motor oil in approximately 350,000 flooded automobiles. Uncontrolled biological wastes from human and animal sources also contributed to the pollutant burden. By and large, however, the environmental problems in the city are not significantly different now from environmental conditions before Hurricane Katrina. This discussion focuses on successes and failures in responding to the environmental concerns and on lessons learned for future disasters.

Introduction

Hurricane Katrina made landfall on August 29, 2005. The storm surge devastated the exposed coastline, including portions of the Louisiana and Mississippi coasts. In addition, failures in the hurricane protection system around New Orleans led to extreme flooding in portions of the city.

Much of the city was inundated by floodwaters 2 to 3 meters deep and, in some cases, 5 meters or more deep. New Orleans is a city at risk, with much of the city well below sea level. The city's protection against that risk includes levee structures that divide the city into a number of polders and large pumping stations that can be used to drain water from those tracts of reclaimed lowlands. When portions of the levee system failed, combined with the failure of or inability to activate the pumping systems, extensive flooding was the inevitable result. In some areas, near catastrophic failures of the levees were noted, and the ensuing rush of water destroyed homes and businesses immediately. In other areas, floodwaters overtopped and undermined levee systems and slowly flooded portions of the city. The flooding led to other infrastructure failures, such as the shutdown of power generation facilities necessary to operate the massive flood control pumping stations and the release of oil from a crude oil tank that led to further destruction in the community.

The flooding had a variety of effects beyond direct or indirect destruction of homes and property. When Hurricane Katrina flooded the city of New Orleans and adjacent areas, one of many concerns was whether widespread chemical contamination resulted from the flooding. In any city, many potential sources of toxic chemicals, such as hydrocarbon fuel storage and distribution facilities and commercial chemical storage, exist. Old inner-city neighborhoods often exhibit elevated levels of metals such as lead and arsenic. Homes and vehicles are also sources of toxic contaminants, with gasoline or diesel and crankcase oil from vehicles and toxic materials such as herbicides and pesticides that may be found in homes. In addition, several large chemical and petroleum production facilities operate in and around New Orleans, as well as old contaminated sites that have undergone or are currently undergoing remediation. Exhibit 1 shows the potential petroleum-related release points, including refineries, oil and gas wells, and service stations near the city. Exhibit 2 shows the major hazardous-material storage locations, Superfund sites, and Toxics Release Inventory reporting facilities.

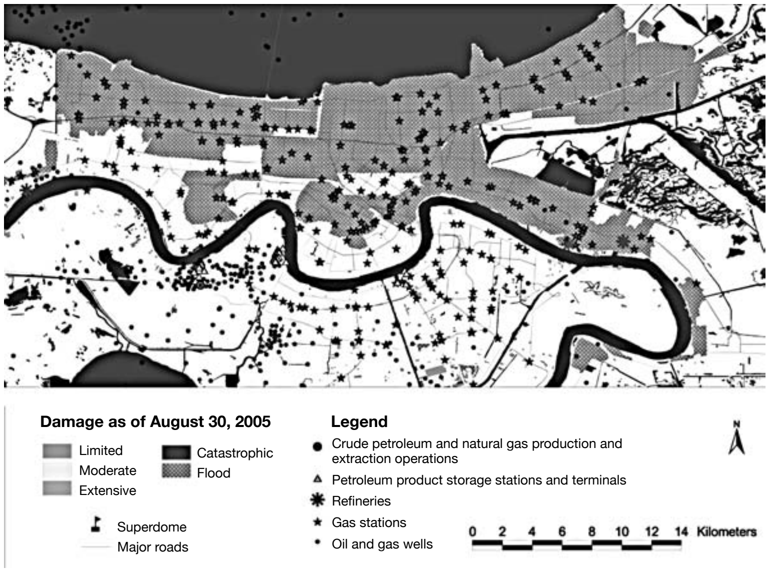
This combination of potential contamination sources led to concerns that the flooding produced a "toxic gumbo" that would significantly affect emergency response and both short- and long-term rehabitation by posing a risk to human health. A number of sampling efforts were initiated to understand and effectively respond to any potential concerns. In addition to concerns about the human health risks associated with floodwaters or any postflood residual, another environmental concern was the solid waste and debris left in Hurricane Katrina's wake. The extensive flooding resulted in significant amounts of solid waste that challenged the community's means of disposing of such waste. Given limited secure landfill space and a desire to avoid large-scale transportation of waste, much of the waste was disposed of in less-secure landfills, raising additional concerns about the long-term environmental hazards posed by the flooding.

This article focuses on assessing the environmental challenges posed by Hurricane Katrina and the implications of those challenges for both short- and long-term risks to the community[1] (Reible et al., 2006). The primary focus, however, is not to detail the events of Hurricane Katrina but to provide

[1] The discussion here is largely excerpted from Reible et al. (2006). This discussion also was presented as part of the North Atlantic Treaty Organization Advanced Research Workshop on Decision Support for Natural Disasters and Intentional Threats to Water Security held April 2007 in Dbrovnik, Croatia, and was published in the proceedings of that workshop. For additional information, see Walsh et al., 2006, which further examines the legal and policy issues raised by the flooding of New Orleans.

Exhibit 1

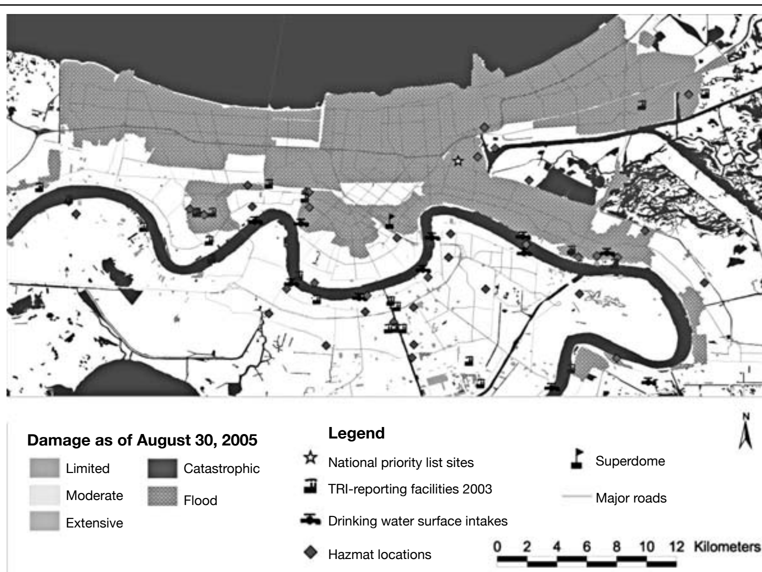
Map of New Orleans Showing Flooded Area and Petroleum and Natural Gas Extraction, Refining, and Distribution Facilities



Source: NIEHS (2005)

Exhibit 2

Map of New Orleans Showing Flooded Areas and Hazardous-Material Release, Storage, and Disposal Areas



TRI = Toxics Release Inventory.

Source: NIEHS (2005)

lessons for future similar disasters. This article raises questions that must be resolved when a community is appropriately responding to and recovering from such a calamity. In addition, this article addresses the failures that led to the human and economic disaster and the potential for more effectively avoiding such a disaster in the future.

Causes of the Disaster

Although Hurricane Katrina was certainly the instigating event for the disaster in New Orleans, only the catastrophic damages in the exposed Louisiana and Mississippi coasts can be considered largely unavoidable. The flooding in New Orleans has been found to be largely the result of a variety of human failures, including the following:

- Inadequate safety factors were used in the design of hurricane protection levees.
- Different political jurisdictions were responsible for constructing and maintaining the levees, leading to uneven design and levels of protection.
- The wetlands in the surrounding area, which could have acted as buffers and mitigated the effects of the hurricane, had been lost to development.
- The presence of potentially aggravating factors, including a navigational canal (the Mississippi River-Gulf Outlet Canal), allowed the full storm surge to penetrate deeply into the New Orleans area.

The causes of the catastrophe and the failure of the inadequate human response have been detailed in several studies and reports, including those of the Interagency Performance Evaluation Task Force (IPET, 2007), American Society of Civil Engineers External Review Panel (ASCE, 2007), and National Research Council Committee on New Orleans Regional Hurricane Protection Projects (NRC, 2006). In addition, both the coastal areas of Louisiana and Mississippi and the city of New Orleans suffered from inadequate evacuation efforts that certainly contributed to the loss of life. Evacuation problems included citizens' failure to heed the calls for evacuation and inadequate planning for citizens who had no practical means of evacuating.

Environmental Implications of the Flooding

The focus in this section is on the environmental consequences of the disaster during the event and long after floodwaters were removed from the city. Federal and state officials made several efforts during and after the flooding to monitor and quantify chemical and biological contamination and assess exposures to, and risks from, toxics and contaminants. Federal agencies, including the U.S. Environmental Protection Agency (EPA) and National Oceanographic and Atmospheric Administration, collected environmental samples both in New Orleans and from the surrounding area affected by Hurricane Katrina. Initial concerns in the city focused on acute exposures for stranded residents and relief workers. Subsequent efforts focused on acute exposures for returning residents and initial assessments of chronic exposures. Pardue et al. (2005), Presley et al. (2006), and the Natural Resources Defense Council (NRDC) (2005b) have reported the results of independent sampling.

Floodwaters were present in the city from the passage of the storm on August 29, 2005, until the U.S. Army Corps of Engineers (USACE) declared the city to be dewatered on October 11, 2005. Sampling showed elevated levels of inorganic and organic contaminants and biological constituents, including pathogens. The level of inorganic contaminants was generally low, even compared with drinking water standards. Presley et al. (2006) found no floodwater samples with concentrations higher than those designated for drinking water or acute and chronic threshold concentrations. Pardue et al. (2005) noted consistently high levels of arsenic in the floodwaters (a mean of 30 parts per billion, or micrograms per liter, compared with a maximum contaminant level of 10 micrograms per liter in drinking water). Drinking water standards, however, are not an appropriate indicator of water quality for floodwaters because exposure to floodwaters is expected to occur through contact, not ingestion. The standards do, however, provide at least a conservative (that is, protective) basis for comparison.

Organic constituents in floodwaters were also observed at relatively low concentrations. This observation was initially met with some surprise because of the evident oil and hydrocarbon fuel spills in many locations. Soluble petroleum oils and fuel constituents, such as benzene, however, are typically volatile, leading to rapid release to the air; less-soluble constituents would partition to sediments left behind by the floodwaters. EPA concluded that inorganic and organic chemical concentrations in the floodwaters were generally below levels of concern for short-term (90 days) dermal contact and incidental ingestion (EPA, 2005b).

Bacterial contamination in the floodwaters was a source of great concern. Both *most probable number* (MPN) and *colony forming units* (CFU) are measures of the number of bacteria. Median concentrations of fecal coliform of approximately 104 MPN per 100 milliliters were detected in the floodwaters (Pardue et al., 2005). This concentration can be compared to a water quality standard for primary contact of 200 MPN per 100 milliliters. The detection of human pathogens, such as *Aeromonas spp.*, at concentrations on the order of 107 CFU per milliliter at two locations in the downtown area raised even greater concern (Presley et al., 2006). Members of the genus *Aeromonas*, which has been associated with diarrhea and wound infections in humans, have also frequently been isolated from soils and fresh water.

Another major concern was the immediate and long-term effects of the discharge of floodwaters into Lake Pontchartrain. From September 6, 2005, to October 11, 2005, the floodwaters, which had largely originated in the lake, were returned to their source. Lake Pontchartrain is a brackish, shallow lake with a surface area of approximately 1,630 square kilometers and an average depth of about 4 meters; an active commercial fishery is on the lake. Pardue et al. (2005) detected low levels of dissolved oxygen in floodwaters and discharged water, which likely resulted in low oxygen levels in the immediate vicinity of the discharge point, but which had a minimal effect on the lake as a whole. Similarly, the generally low levels of inorganic and organic contaminants in the floodwaters were unlikely to have significant effects on Lake Pontchartrain. According to one estimate, 200 billion gallons of floodwaters (about 11 percent of the volume of Lake Pontchartrain) were pumped from New Orleans (Roper, Weiss, and Wheeler, n.d.).

The sediments at the mouths of the discharge canals contained some contaminants before the flooding due to normal wastewater and stormwater discharges from the city. The Hurricane Katrina floodwaters were similar in character, although significantly larger in volume, to the normal stormwaters discharged into the lake (EPA, 2005b). Bacterial contamination of the discharge waters was typically an order of magnitude greater than it was before they were discharged into the lake (as measured by fecal coliform concentration). Despite this contamination, in more than 100 samples collected by EPA in September and October 2005, bacterial levels in the lake were within recreational limits (EPA, 2005b).

In summary, with the possible exception of biological pathogens, direct exposure to floodwaters either in the city or in Lake Pontchartrain appeared likely to have minimal toxic or contaminant effects. Although direct exposure to floodwaters appeared to have minimal long-term consequences, the long period of exposure to floodwaters led to extensive mold growth in homes. Airborne exposure to mold appears to be one of the most serious short-term issues residents faced during post-Hurricane Katrina reconstruction. Using respiratory protection during the removal of all mold-contaminated materials and reconstruction, however, can mitigate the risk of exposure to airborne mold.

Environmental Implications of Residual Sediment

Although floodwaters were removed from the city of New Orleans by October 11, 2005, their legacy of contaminated soils, sediments, debris, and houses remained. In addition, sediment mobilized from storm surge moving through Lake Pontchartrain and the Mississippi River-Gulf Outlet/Industrial Canal was deposited in the city. Additional sampling was done to assess the concentrations of chemical and biological contaminants in these media. Presley et al. (2006) found several inorganic constituents (arsenic, iron, and lead) and organic constituents in sediments from New Orleans that exceeded EPA Region 6 Human Health Medium-Specific Screening Levels for soils. The organic constituents of concern were mostly polycyclic aromatic hydrocarbons (PAHs), which are complex, high-molecular-weight compounds that result from the incomplete combustion of fossil fuels and are also present in natural sources. EPA Region 6 Human Health Medium-Specific Screening Levels are used to evaluate the "relative environmental concern for a site or set of environmental data. The values are not regulatory, but are derived using equations from EPA guidance and commonly used defaults" (EPA, 2005a).

The screening levels are not intended to represent action levels or cleanup levels but rather are intended as a technical tool for identifying potential hazards. The screening levels correspond to fixed levels of risk based on simplified assumptions of uniform lifetime exposures.

Of the 430 sediment samples that EPA collected between September 10, 2005, and October 14, 2005, a number exceeded the screening criteria of the local regulatory authority, the Louisiana Department of Environmental Quality (LDEQ), which developed the criteria in conjunction with its Risk Evaluation/Corrective Action Program (RECAP) (LDEQ, 2005). The criteria were developed to meet objectives similar to those of the EPA Region 6 Human Health Medium-Specific Screening Levels and were derived similarly. The constituents most often found to exceed the RECAP screening criteria were arsenic, lead, several PAHs (including benzo[a]pyrene, a carcinogen), and diesel range organics (diesel fuel and byproducts).

On November 19 and 20, 2005, EPA resampled areas where previous sampling had indicated contaminant concentrations in excess of screening criteria and where sediment depth equaled or exceeded 0.5 inch (EPA, 2005b). Because of the complex nature of the storm surge, levee breaches, and overtoppings, the amount of sediment deposited in flooded areas varied widely, and only 14 of the 145 locations resampled by EPA had sufficient sediment depth for testing. Three samples showed arsenic concentrations higher than 12 parts per million or milligrams per kilogram (14.4 to 17.6 milligrams per kilogram); one sample showed a benzo[a]pyrene concentration of 0.77 milligram per kilogram and one sample showed a concentration of diesel range organics of 2,100 milligrams per kilogram. Other samples were below applicable screening values.

The EPA also collected samples at specific sites where known or potential leaks of hazardous materials existed. Elevated concentrations of total petroleum hydrocarbons and a variety of crude oil-associated contaminants were observed in the vicinity of the Murphy Oil crude oil tank failure and spill; these chemicals and contaminants had a clearly identifiable source and could be easily differentiated from the general flooding-related contamination. The Murphy Oil-contaminated area is being managed separately from the rest of the flooded area and is not addressed further in this article.

EPA also collected 74 soil samples at the site of the Agriculture Street Landfill, a closed Superfund hazardous waste site that was flooded by Hurricane Katrina and that is still undergoing cleanup. The samples were collected immediately above the geotextile liner (12 to 24 inches below ground), which was installed as part of the site remedy. All samples were analyzed for lead, the contaminant of concern that defined the cleanup, but none showed concentrations that exceeded the lead cleanup standard or EPA screening standards for lead. EPA concluded that the flooding did not affect the effectiveness of the remedy (EPA, 2005c).

The NRDC analyzed samples from the Agriculture Street site for other contaminants and found arsenic at levels similar to those found at other New Orleans sites and a variety of high-molecular-weight PAHs at somewhat elevated levels (NRDC, 2005c). Although NRDC ascribed the presence of the high-molecular-weight PAHs to leachate from the landfill, due to the hydrophobic nature of these compounds, they more likely had been transported by resuspended soil from the site or elsewhere. Further assessment of the Agriculture Street area might be warranted.

Another phase of focused sampling of soil and sediment ended February 22, 2006. This phase involved taking 147 composite samples in 43 specific flood-affected residential areas where previous sampling found concentrations of arsenic, lead, or petroleum indicators in excess of risk management screening levels. The purpose of this sampling effort was to determine whether the locations with elevated levels of these chemicals were isolated or whether they were representative of a larger contaminated area.

Arsenic levels did not exceed EPA's safe risk management level, although apparently elevated concentrations were often noted. The concentrations of arsenic throughout the Mississippi River Delta region of south Louisiana is on the order of 10 milligrams per kilogram (Gustavsson et al., 2001), and LDEQ has reported a background arsenic concentration of 7 milligrams per kilogram. Pre-Hurricane Katrina concentrations of arsenic could be even higher in residential areas because of arsenic in lawn fertilizers (WSDA, 2001).

The only area with a PAH contamination in excess of risk screening levels was an area near the Agriculture Street Landfill. Lead concentrations exceeded 400 milligrams per kilogram (the screening level) in 57 of 147 composite samples (38.1 percent). The level of exceedances is similar to a pre-

Hurricane Katrina study of New Orleans that indicated that about 40 percent of nearly 5,000 soil samples had lead levels in excess of 400 milligrams per kilogram (Mielke et al., 2004; Pelley, 2006). Nationwide, approximately 23 percent of privately owned homes in the United States built before 1978 are estimated by EPA to contain soil-lead levels above 400 milligrams per kilogram. In 2000, 14 percent of the children tested in the vicinity of the city of New Orleans had lead levels in excess of the federal advisory level of 10 micrograms per deciliter of blood.

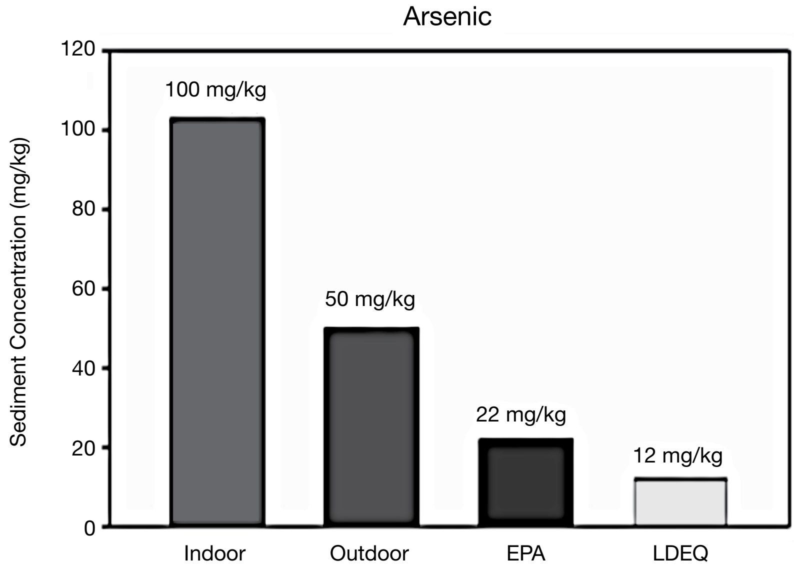
A fourth phase of sediment sampling (also conducted in February 2006) in flood-affected areas involved taking 712 samples from 586 locations in Orleans and St. Bernard Parishes based on a 200-foot grid. EPA was unable to collect samples at another 1,090 locations because either insufficient or no sediment was present to sample or the location was in a commercial area; only 35 percent of the locations had sufficient sediment or were residential. In only one sample, arsenic, lead, and benzo[a]pyrene each were detected in concentrations exceeding the risk management screening level (that is, the one-in-one hundred thousand excess lifetime cancer risk level for arsenic and benzo[a]pyrene or the 400-milligrams-per-kilogram risk management screening level for lead), which equates to roughly 0.4 percent of the samples. The reduced frequency of elevated contaminant levels was associated with the random sampling rather than biased sampling toward areas that had previously exhibited elevated levels as in the third phase of sampling.

The conclusion from the residual sediment sampling was that, on the whole, post-Hurricane Katrina sediment contaminant levels did not differ significantly from pre-Hurricane Katrina levels. Contaminant levels in specific areas, such as the vicinity of the Murphy Oil crude oil spill, were significantly affected by the flooding, but generally the flooding and deposition of residual sediments appeared to have little effect on exposure to contaminants. This observation does not suggest, however, that the contaminant exposures were of no concern or were inconsequential. Significant concern about chronic contaminant exposures in the city of New Orleans was present before Hurricane Katrina occurred, and this concern persisted after the hurricane affected the area.

Of special concern is the limited evidence that indoor biological and chemical hazards may be far greater than suggested by generalized outdoor sampling and assessments. The sheltered environment indoors provides an opportunity for the growth of biological hazards, including bacteria and mold, but also is a source area for chemical hazards as a result of the storage of household hazardous materials. Furthermore, as shown in exhibit 3, for arsenic, limited sampling of residual sediments indoors has suggested that these sediments may be significantly concentrated with respect to contaminants relative to outdoor soils and sediments (Ashley, Valsaraj, and Thibodeaux, 2007). These elevated concentrations may be the result of the low-energy indoor environment leading to the deposition of fine-grained particles that are dispersed more widely outside. Fundamental research is needed to better understand the relationships between regional assessments of environmental exposure and local and individual exposures.

Exhibit 3

Indoor and Outdoor Arsenic Concentrations in Post-Hurricane Katrina New Orleans and Comparison to EPA and LDEQ Screening Levels.



EPA = U.S. Environmental Protection Agency.
LDEQ = Louisiana Department of Environmental Quality.
Source: Ashley, Valsaraj, and Thibodeaux (2007)

Environmental Implications of Waste and Debris

Although most portions of the city did not exhibit substantially different soil or sediment contamination levels after the hurricane occurred, an unprecedented legacy of waste and debris was present. An estimated 120 million cubic yards of construction and demolition debris were generated by the storm and the subsequent flooding. In addition, the flooding destroyed approximately 350,000 automobiles and some 750,000 white goods (washers, dryers, and refrigerators). The volume of solid waste was unprecedented, and the removal and disposal of this waste significantly delayed recovery and reconstruction.

Problems associated with managing the waste included both the inability to marshal sufficient resources to pick up and transport the waste to disposal sites and the insufficient capacity at appropriate disposal sites. As with many other tasks in New Orleans, the unavailability of workers significantly constrained progress. Although no contractor could be expected to have the readily available capacity to address the volume of waste, some firms that initially contracted to assist in the effort proved incapable of developing that capacity. Automobiles rendered worthless by the flooding, for example, sat for many months awaiting removal of crankcase oil and fuel and then destruction. Additional delays in managing the solid waste were associated with the failure of many residents to return in a timely manner to conduct demolition. Waste and construction debris on private property generally could not be transported for disposal.

Disposal of this waste posed other problems. The shear volume of waste required alternative disposal sites. Transportation of the waste to disposal sites out of the area was not available, partially as a result of concerns about Formosan subterranean termites that are quite common in the New Orleans area. Initial interest in open-air burning of combustible debris was abandoned due to air quality concerns. Ultimately, much of the waste was disposed of under the presumption that the waste was solely construction and demolition waste. Closed, insecure landfills not meeting current design standards for household waste, such as the Chef Menteur Landfill in eastern New Orleans, were opened and used as disposal sites for the flood debris. The use of such landfills, however, depends on the ability to adequately separate household and commercial hazardous waste, and evidence shows that that separation of the flood debris was inefficient (Pardue, 2006). Concerns have been raised about the future environmental consequences of such disposal (Pardue, 2006). Even if household hazardous waste was effectively separated from the other waste, components of construction and demolition waste have also generated concerns about problems such as arsenic leaching from treated wood (Khan et al., 2006). Recognition and management of those problems will be an important role for city and regional managers in the years ahead.

Building a More Resilient New Orleans

Recognition of the consequences of Hurricane Katrina and the subsequent flooding in New Orleans leads to obvious interest in avoiding a repetition of the events. A variety of preventive measures are available depending on the primary objective of any mitigation efforts. Perhaps the most obvious effort would be improving the hurricane protection system to ensure its protectiveness in the face of likely hurricane events. This improvement would help prevent the loss of human life and help protect property. Clearly, significant gains in protectiveness could be achieved by relatively modest improvements in the design, construction, and integration of the hurricane protection systems. A variety of recommendations for such improvements can be found in the report of the USACE's Interagency Performance Evaluation Taskforce (IPET, 2007). At the same time, it is important to note that the standard for protection against dam failure in the United States (USBR, 2003) is that risks that might lead to fewer than 1,000 deaths in a million years provide "diminishing justification to take action to reduce risk." Conversely, risks that might lead to more than 1,000 deaths more often than once in 10,000 years provide "justification to take expedited action to reduce risk." By such a standard, the loss of 1,000 lives as the result of a storm that has an expected return frequency of less than once per 100 years is clearly unacceptable.

On the basis of protection systems alone, can New Orleans be protected sufficiently to avoid repeating the events stemming from Hurricane Katrina? A number of factors suggest that this degree of protection is not possible or is not a wise use of resources.

First, New Orleans has a variety of risk factors that cause the city to be more vulnerable to hurricanes. Much of the city is well below sea level and is built in areas that are not possible to protect without extraordinary efforts such as massive pumping systems that are currently in use in the city. Making protection more difficult is the specter of global sea level rise and, more significantly, relatively rapid subsidence in and around the city of New Orleans. Sea level rise is currently on the order of 1 millimeter a year, but subsidence in New Orleans is 5 to 10 times greater (Dokka, 2006).

Subsidence is likely caused by a combination of regional oil, gas, and water extraction and the normal consolidation of south Louisiana sediments, especially because channelization of the Mississippi River limits the introduction of new sediment to the area. It was, in fact, the deposition of these sediments that lead to the existence of south Louisiana. The levees and other flood control structures along the river, however, discharge most of this sediment to the Gulf of Mexico, leading to severe declines in land mass and protective wetlands along the coast. Although efforts are under way to partially restore the natural flow of sediment, complete restoration without loss of flood protection function is unlikely.

Equally challenging is the fact that the variability of storm events in the Gulf of Mexico is quite high. The extensive flood control systems of the Netherlands have often been cited as a model for protecting New Orleans, but the storms of the North Sea are, by some measures, less intense than those of the Gulf of Mexico. The ratio of wave height in a 10,000-year storm to that of a 100-year storm in the North Sea is about the same as that expected in a 1,000-year storm in the Gulf of Mexico. In addition, the Netherlands can be protected by the construction of storm control structures between peninsulas that limit the size of the structures relative to the area being protected. This type of storm protection is much more difficult to construct in the "convex" coastline of the Mississippi River Delta. Finally, a large fraction of the Netherlands' gross national product depends on the storm control structures put in place subsequent to the 1953 floods. In comparison, both the total economic impact and the proportion of the U.S. economy that depends on New Orleans are relatively small. It may not be possible to marshal the will and resources to adequately protect New Orleans to meet the "1,000 lives, million years" risk standard currently in place.

Alternatively, planning to more effectively respond to the consequences of a major storm and flooding may be more fruitful. This response could take the form of improved evacuation planning to reduce the loss of human life or rebuilding a more resilient city that could better weather the storm and flooding and recover more quickly. Resiliency could be implemented by better land use restrictions that could discourage building in the most hazardous areas and improve design or construction in other areas. Especially important infrastructure (bridges, communication, or other critical services infrastructure) could be designed and constructed for survivability in much the same way that such structures are designed and constructed in earthquake-prone areas.

Regardless of any efforts to improve the effectiveness of the hurricane protection infrastructure or the resiliency and survivability of the critical infrastructure, improved planning for recovery from the inevitable catastrophic storm and flood must be implemented. An examination of the aftermath of Hurricane Katrina and the slow and still incomplete recovery from that catastrophe provides a number of recommendations that could help guide future recovery efforts.

First, it must be recognized that the problems associated with a major natural disaster are not uniformly distributed throughout the community. Problems, of course, arise in that individuals have different capacities to respond to the destruction caused by such a disaster. Decisions to equitably support reconstruction in the face of this uneven capacity should be made openly and adequately reflect the values of the community.

Although environmental contamination, which involves the consideration of chemical and biological contamination, mold issues, and the potential for future floods, influences habitability and reconstruction decisions, it is likely that other factors, such as the potential for future floods, will control these decisions. As indicated previously, contaminant concentrations in soils in New Orleans are generally similar to those recorded before Hurricane Katrina occurred. Elevated concentrations, however, may be found in specific areas. The ability to translate communitywide effects of exposure and risks to the individual homeowner should be improved.

Where these elevated concentrations are associated with a recognized source, identification of both the contamination and liability is relatively easy. More difficult are those situations leading to isolated areas of contamination. How can a homeowner be confident that his or her home and yard do not exhibit elevated contaminant levels? In the absence of assistance programs, the cost of testing and cleanup would fall to the homeowner. Because reconstruction or other recovery efforts would likely be more important to the homeowner, environmental remediation and restoration may never be conducted. Should an event such as Hurricane Katrina be viewed as an opportunity to improve environmental conditions in the city? It is clear that the flexible sampling and expedited analyses that EPA and LDEQ used in the New Orleans area were effective in characterizing the general contamination characteristics, but these tools may need to be supplemented with low-cost screening for individual properties. Moreover, future catastrophic events of a similar nature will likely result in similar needs, suggesting that a national program of environmental screening analysis would be worthwhile. Such a program could be built on the model used for routine low-cost screening of physical and chemical properties of soil for agricultural purposes. The extensive quality assurance and quality control programs that drive much of the cost of environmental analysis could be relaxed for such a screening program.

In some areas, general environmental assessment efforts after Hurricane Katrina were lacking. The habitability assessment should also address potential concerns posed by the presence of mold and airborne mold spores in homes and concerns about indoor sediment and dust. Unlike air, water, and soil contamination, currently little scientific basis exists for evaluating the potential effects of mold and indoor dust on human health or for developing risk-based action or cleanup standards. Airborne mold counts of 50,000 spores per cubic meter are considered very high, yet mold counts as high as 650,000 spores per cubic meter were observed by NRDC in one home in mid-city New Orleans after Hurricane Katrina (NRDC, 2005a). Because no standards have been developed to which these mold counts can be compared, little guidance is available regarding how to appropriately respond to such high mold counts. In addition, no clear regulatory responsibility has been delegated among federal agencies for indoor air quality. High mold counts are cause for concern, however; both NRDC and EPA recommended that returning residents remove all porous construction materials, including carpets and drywall, from flooded homes and use respiratory protection while removing such debris. The pervasive nature of mold contamination in New Orleans in the aftermath of Hurricane Katrina and the lack of knowledge about the risks of mold and airborne mold spores suggest that additional research is needed to improve the ability to respond to this problem.

The precise processes used to integrate the best scientific understanding of future flood risk, the risk of levee failure, the risk of mold contamination, and what, if any, chemical contamination in the redevelopment and habitability decisions is beyond the expertise of the author or the scope of this article; however, master reconstruction plans, zoning, and other mechanisms exist to integrate the actions of federal, state, and local governmental entities and the private sector. The existing data suggest that the level of chemical contamination in New Orleans may be of lesser concern than other reconstruction issues.

Future habitability decisions after events such as Hurricane Katrina and the subsequent flooding are likely to require input from a wide range of stakeholders. The criteria by which decisions are made should be uniform, transparent, and consistent with existing hazardous waste and natural disaster cleanup criteria. Fortunately, the sampling to date suggests that only a very small number of locations, if any, contain chemical concentrations in the soil that warrant remedial action.

The critical test of a legal process is not whether an agency chooses the alternative preferred by the public but whether the public perceives the process as fair. A necessary predicate to fairness is communication of the nature of such a process. The discrepancy between some of the concerns expressed by local residents and environmental groups and the results of the EPA and LDEQ sampling efforts suggests that, despite the unprecedented public involvement efforts (and challenges), more extensive efforts to maintain a dialogue with the public may be needed. The experience in New Orleans once again reflects the difficulty associated with calculating risks, communicating with the public about such risks, and building trust about risk, particularly in the midst and aftermath of an emergency.

A key policy issue facing New Orleans, and likely to recur in other communities faced with major flooding, is whether reconstruction should include cleanup of preflooding contamination. EPA and LDEQ repeatedly note that the level of some isolated contaminants is the same as it was before Hurricane Katrina came ashore. Clearly, these levels were not caused by the storm. Not surprisingly, however, local residents and other groups demand that the soil be safe regardless of the cause or who pays for the remediation. Thus, the question arises as to whether individuals might be willing to delay their return and support governmental decisions about which neighborhoods might be rebuilt, based on the levels of chemicals in the sediment or soil, even if these levels are the same as or even reduced from the levels that existed before Hurricane Katrina occurred.

The ongoing cleanup decisionmaking process might also be an opportunity to reduce exposure to toxics and other contaminants (for example, ensuring that any soil contaminated from lead-based paint or lead-based paint remaining in homes is removed), regardless of whether the contamination was present before or after Hurricane Katrina. As a practical matter, such an approach is likely to require that the citizens of New Orleans accept a diversion of reconstruction funds to environmental cleanup.

Every effort should be made to put aside partisan concerns to solve real, significant problems concerning the way we process information in emergencies and to make sensible, safe, and equitable cleanup and habitability decisions in an environment of great uncertainty. Because existing institutions were largely unprepared for a disaster the scale of Hurricane Katrina, it may not be possible to implement these principles in New Orleans. Nevertheless, we can learn from Hurricane Katrina and implement more effective responses to future catastrophes.

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