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Enhanced Tools and Techniques to Support Debris Management in Disaster Response Missions

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Abstract: Debris management is a critical function of disaster response activities. Debris can represent a serious health hazard in its own right, can hamper emergency response, and, by clogging streams and waterways, promote flooding. During an actual disaster, time is a limiting factor for the formulation and testing of improved debris management approaches. The time to improve management and technical approaches is before disasters strike. This report proposes that research can be effective in improving emergency response regarding debris management. This study investigated three aspects of debris management: debris management in stream beds, hazardous aspects of debris, and the use of geospatial measurements and techniques to improve management. The state of the practice for each was established. Areas of research opportunities were then identified and discussed. This document can serve as a framework for a debris management research focus area, which will provide guidance for emergency management organizations and professionals.

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Preface

This report stems from work conducted under the Flood and Coastal Storm Damage Reduction Research and Development Program, directed by Dr. Jack Davis and Dr. William Curtis of the Coastal and Hydrology Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC).

This research effort was directed by Dr. Victor F. Medina, Environmental Engineering Branch (EP-E), Environmental Processes and Engineering Division (EPED), Environmental Laboratory (EL), ERDC, who also prepared the section on hazardous materials in debris. Mike Channell (EP-E) and Mark Graves (Environmental Systems Branch, EE-C) produced the sections on debris in streams and the use of remote sensing in debris management, respectively. They were assisted by Agnes B. Morrow (EP-E) and Catherine C. Nestler, Applied Research Associates, Inc. The Mississippi Section of the American Society of Civil Engineers (MS-ASCE) provided their photo archive of Hurricane Katrina effects on the Mississippi Coast, photos taken within two weeks after the disaster. These pictures were collected by Chad Gartrell, Dr. Steven C. McCutcheon, Sarah Jersey, Shelly Tingle, and Jackie Pettway. Photos were also provided by the U.S. Army Corps of Engineers, Katrina Disaster Response Team. Dr. Dennis Brandon and Tom Borrowman provided in-house review. Dr. Brandon's contribution following his review was sufficient to include him as a co-author.

This study was conducted under the direct supervision of W. Andy Martin, Branch Chief, EP-E, and under the general supervision of Dr. Richard E. Price, Division Chief, EPED, and Dr. Elizabeth C. Fleming, Director, EL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Acronyms

ATSDR	Agency for Toxic Substances and Disease Registry
CAR	Clean Air Report
CCA	Chromated copper arsenate treated wood
CDC	Center for Disease Control
CRREL	Cold Regions Research and Engineering Laboratory
CRT	cathode ray tube
ERDC	Engineer Research and Development Center
FEMA	Federal Emergency Management Agency
GIS	geospatial information system
GPS	global positioning system
HAZUS-MH	Hazards U.S. - MultiHazard
HEC-RAS	Hydrologic Engineering Center-River Analysis System
HHW	household hazardous waste
HurDET	Hurricane Debris Estimation Tool
JALBTCX	Joint Airborne Lidar Bathymetry Technical Center
JPL	Jet Propulsion Laboratory
LDEQ	Louisiana Department of Environmental Quality
LIDAR	Light Detection and Ranging
LWD	large, woody debris
MDEQ	Mississippi Department of Environmental Quality
MS-ASCE	Mississippi Chapter, American Society of Chemical Engineers
NASA	National Aeronautics and Space Administration
NIBS	National Institute of Building Sciences
ppbv	part per billion by volume
PPE	personal protective equipment
ppmv	part per million by volume
RADAR	Radio Detection and Ranging
RCRA	Resource Conservation and Recovery Act

SAR	Synthetic Aperture RADAR
SWANA	Solid Waste Association of North America
TCEQ	Texas Commission on Environmental Quality
TEC	Topographic Engineering Center
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
pounds (mass)	0.45359237	kilograms

1 Introduction

Debris issues related to storms and natural disasters

Debris management is a critical issue in response to natural disasters (Federal Emergency Management Agency (FEMA) 2007; United States Environmental Protection Agency (USEPA) 2008). As part of the National Response Plan, the U.S. Army Corps of Engineers (USACE) is the Coordinator for Emergency Support Function (ESF) #3, Public Works and Engineering, in which the Corps is tasked with the restoration of essential public services and facilities (USACE 2006). Typical assignments under ESF#3 include debris management, which is usually the largest Corps mission in terms of both people involved and money expended. Debris management involves:

1. Predicting debris quantity and type through accurate modeling systems,
2. Pre-selecting debris staging/sorting areas and dump sites,
3. Clearing post-disaster debris from public roadways,
4. Hauling post-disaster, sorting, and proper disposal of post-disaster debris.

Debris can block roads, hampering movement of relief supplies and can clog rivers and streams, creating additional secondary flooding (Abbe and Montgomery 1996; Bilby and Likens 1980). Debris can contain hazardous and infectious agents, creating and spreading disease, or it can be composed of hazardous materials (Pardue 2006) and can serve as a haven for pests. Generally, there is a need to rapidly remove debris. Nonetheless, debris issues can persist for months, even years after the disaster (Public Broadcasting System (PBS) 2008). Developing new debris management practices and/or technologies during a response to a natural disaster is not practical as the focus during the emergency is on the immediate response. However, proactive planning ahead of time could yield effective new aproaches that can improve debris management and disaster response for future incidents (Reinhart and McCreanor 1999; Teaford 1998).

Objectives

This project had the following objectives:

1. Evaluate the current state of practice for three critical debris management areas:
   - Debris management in streams and waterways.
   - Contaminants in natural disaster debris.
   - Remote sensing to improve debris management.
2. Identify, for each of these focus areas, issues not currently addressed satisfactorily with current practices.
3. Develop recommendations based on these research gaps for additional research with the goal of improving disaster response.

2 Debris Management in Streams

Background and objectives

Debris in streams, mainly after high-flow events, has both beneficial and adverse effects on the stream and the riparian corridor adjacent to the stream. Large woody debris (LWD) has many benefits to the stream system but can also adversely affect the flow of the stream. During storm events not only can LWD accumulate in the stream but many other types of debris can be entrained in the flow of the stream, such as boulders, concrete, appliances, and household goods. All of these types of debris can cause significant morphological changes to the stream and increase risks of erosion and flooding, particularly if not cleared before another storm affects the stream. Debris management in streams following a natural disaster typically follows the pattern of immediate clearing of the stream channel followed by stream restoration at a later time, if at all. Rarely are these two activities coupled. This results in duplication of effort of personnel and equipment and higher project costs (Shields et al. 2004).

This section of the report will deal mainly with LWD and the removal and beneficial use of the material in restoring the stream to pre-storm event conditions. While other material, as mentioned above, can be included in the debris, these types of debris are usually removed and disposed of in a safe manner.

Importance of large, woody debris in stream systems

The importance of riparian trees in reducing bank erosion has been noted and relationships between channel width and riparian vegetation have been observed (Fischenich and McComas 2007). Naturally occurring LWD, defined as > 10 cm diameter and 2 m in length, is an important component of many lotic systems. It provides velocity refuge and overhead cover for fishes, substrate for aquatic invertebrates, and can be an important source of particulate organic matter adding to primary productivity of a stream (Fischenich and Morrow 1999).

LWD also plays a major role in stream channel morphology, contributing to formation of pool habitat, increasing meandering, and increasing sediment capacity (Abbe and Montgomery 1996). LWD also dissipates

flow energy, resulting in improved fish migration and channel stability and provides basking and perching sites for reptiles and birds. Positive effects of LWD are documented in high gradient streams, and recent studies show that LWD is an important habitat component of low gradient streams with fine substrates (Shields et al. 2004; Smith et al. 1993).

Adverse impacts of LWD on stream systems

LWD and debris jams (Figure 1) can also have adverse impacts on stream systems. Fallen trees and debris jams can trigger bank erosion and channel migration in small and intermediate-order streams, and large debris jams have been observed to have significant effects on large rivers (Keown et al. 1981). Debris jams often result in widening of local channels, sediment deposition, and mid-channel bar formation immediately downstream of the debris pile. In some situations, the backwater effects, upstream from a jam, increase flooding and may facilitate meander cutoffs (Keller and Swanson 1979).

Figure 1. Large woody debris (LWD) jam located in a stream.

Factors controlling large, woody debris in stream systems

The amount of LWD in streams is significantly affected by anthropogenic factors. LWD is commonly removed from streams for a variety of reasons including improved navigation, reduction of flow resistance, flood control,

and perceived fish passage problems. LWD is also removed during channelization operations. When riparian vegetation is cleared, whether due to channelization operations, agriculture, forestry practices, or urbanization, LWD recruitment is reduced. Alternately, urbanization, channelization and other actions that lead to channel incision can initiate systemic channel instabilities that lead to a significant introduction of LWD into a stream. Major floods can have a similar effect.

Removal methods and effects

Clearing and snagging (i.e., the removal of woody vegetation and debris from stream channels and banks) is often undertaken to increase hydraulic capacity, prevent hazards to navigation, or reduce risks of jam formation on bridges. For flood control on small streams, snagging is the conventional practice that has been used to remove obstructions from the stream channel. Clearing refers to the removal of all significant vegetation within a specified width on both sides of the stream channel (Shields and Nunnally 1984). Clearing and snagging operations are often undertaken for the removal of debris jams that form following flood events.

Removal of LWD in the immediate aftermath of a flood is a natural response to reduce further risks, but can sometimes have unintended consequences. Removal of snags and debris jams reduces hydraulic resistance, increases current velocity next to the bank, and reduces resistance of banks to erosion (Nunnally 1978). Clearing and snagging typically result in acceleration of bank erosion and a wider channel. These effects are most pronounced for smaller streams. However, Strauser and Long (1976) attribute widening of the middle Mississippi River to bank clearing and channel changes on certain reaches of the lower Mississippi River. This upstream widening has been accelerated by land clearing between the levees for cultivation that has occurred on the lower Mississippi river.

The removal of snags and debris jams in a stream allows deposits of leaves, twigs, and sediments to be swept downstream. These deposits are key habitat components for many benthic species (Bilby and Likens 1980). In addition to the impact on fish food resources and habitat, snagging reduces cover and structures needed by fish. Studies have shown that clearing of streams may influence reproductive success of several fish species (Bilby and Likens 1980).

The conventional practice employed for flood control on small streams has been to remove all obstructions from the channel and to clear all vegetation within a specified width on both sides of the channel. Although clearing and snagging are usually done simultaneously, the two activities have varying ecological effects. Snagging removes debris and obstructions from the channel in order for water to free flow downstream. The removal of the debris in the channel can change the habitat conditions for aquatic animals, velocity in the stream, sediment load, and other characteristics of the channel. Clearing removes vegetation outside the stream channel, usually along the bank and adjacent flood plain. The removal of vegetation along the banks can cause more sediment to be entrained in the stream, bank erosion, and habitat. Clearing of the stream banks generally reduces shade and cover along the stream and can cause water quality problems within the stream system.

Improved understanding of the ecological importance of organic debris and riparian vegetations and concern over the undesirable effects of clearing and snagging has led to modifications of traditional clearing and removal practices (Gregory and Stokoe 1980). Instead of using the usual heavy equipment, adverse environmental effects may be reduced with little loss in flood control by using manual labor and construction methods that create only minimal disturbance. Negative environmental effects can also be minimized by limiting the type and amount of debris and vegetation removed. Revegetation of disturbed areas and control of future maintenance procedures ensures the long-term effectiveness of this modified approach of debris removal. Studies have shown that only debris that is a major flow obstruction need to be removed from the channel. Embedded logs that are aligned with the flow and minor debris are better left in the channel. Debris needs to be removed from the mouths of tributaries and from side channels. Major sediment deposits that have formed upstream or downstream of the debris jam should also be removed if it is determined removal of the jam will not flush them out.

Management and beneficial reuse of removed large, woody debris

Debris that is removed from streams is usually piled on the side of the channel and allowed to dry. In some cases, it is burned under the assumption that it will prevent the debris from being reintroduced into the stream. However, floods seldom reintroduce this material to the channel and actually tend to push the debris further outward on the floodplain. Some of the woody material can, and should, be used to restore the stream

to a more natural condition. For example, some of the debris can be used for erosion control if it is determined that bank erosion is occurring in the stream. Brush pile revetments can be created by positioning the debris parallel to eroding banks and anchoring it in place (Figure 2). Sedimentation induced by properly sited brush piles rapidly locks the piles in place. Once the brush piles have been established, cuttings of flood-tolerant woody species can be planted in the debris pile to provide long-term stability (Willeke 1981).

Figure 2. Large woody debris (LWD) removed from the stream bed and placed on the bank and mid-channel bar as a woody revetment to restore flow in the stream.

Whole trees or large debris can be placed perpendicular to eroding banks to deflect the current and help to “train” the channel to a desired position. Studies on a Vermont river (Edminster et al. 1949) showed that adequate erosion protection was obtained for 4-5 years by using whole trees that were 2 to 3 ft in diameter. However, the trees rotted and lost their effectiveness after 9 years. Bank slides along the Cumberland River have been repaired by interlocking debris that resulted from the slide along the bank toe and covering them with soil from the slide (Shields and Nunnally 1984). Also, tree barricades and log dams have been used to halt development of overflow secondary channels.

Cleared material from debris jams can also be placed in piles within the floodplain for terrestrial habitat. When used in this manner, material should be placed landward of existing woody vegetation that would prevent its re-introduction, or it should be anchored in place. This will reduce the possibility of the material reentering the stream in the event of a flood. The effects of debris piles placed in the floodplain should be evaluated to ensure that they do not adversely influence flood elevation due to increased flow resistance. Brush piles provide valuable wildlife habitat in predominantly cleared areas. Partial burying of debris piles anchors them in place and provides additional habitat for a diversity of animals and plants.

Research opportunities

Three opportunities have been identified for research and development in the area of integrating debris removal with stream restoration:

1. Develop a model that would compare combined restoration and removal operations with the more standard approach of simple debris removal followed by restoration at a later time.
   - Prepare a cost analysis to compare the two methods.
   - Conduct a controlled study using an actual flood site and compare the economics of both approaches.
2. Determine the ecological benefit of the restoration activities at the time of debris removal.
   - Begin by identifying actual situations that most closely resemble this approach and compare any ecological recovery data with that of sites in which the more standard approach of debris removal without restoration is deployed.
   - Conduct a controlled field study of restoration activity, for example, along the Wabash drainage system, which floods frequently.
3. Based on results of the previously mentioned research into stream restoration, and coupled with input from emergency management professionals, develop and prepare a guidance document on simultaneous debris removal and stream restoration. This document would also address funding and jurisdictional issues associated with combining these operations.

Summary

During a storm event, many different types of material can accumulate in debris piles in a stream, including large, woody debris, appliances, tires, concrete, and other broken material. These materials are removed and disposed of in different ways. Large, woody debris that is removed from debris piles can be used for many restoration activities along the stream to prevent erosion and provide beneficial habitat along the stream. In many instances, the large, woody debris is removed from the stream and piled on the adjacent floodplain in order to restore the flow of the stream. However, restoration activities are usually not performed during the removal of debris. Instead, these are done at a later time, if at all, costing additional funds to complete.

Research opportunities that may improve stream restoration management include:

1. Studies to establish whether any cost savings are accrued from restoration activities performed during the debris removal.
2. Studies to determine the ecological benefit of the restoration activities at the time of debris removal.
3. Preparation of a guidance document on simultaneous debris removal and stream restoration activity following a natural disaster.

Numerous opportunities exist to improve the quality and cost-benefit analysis of stream restoration activities following storms and natural disasters.

3 Hazardous Materials in Natural Disaster Debris

Background and objectives

Natural and man-made disasters result in large volumes of debris that can overwhelm existing solid waste management systems (Harrington and Mabie 1997; Tandy 1996). One example was the 1995 Hyogen-Nambu Earthquake near Kobe Japan (Hayashi and Katsumi 1996). The solid waste generated was nearly 100 times larger than the average annual municipal solid waste generation of Kobe. It was also 150 percent larger than the average construction waste generated for the Kansai area, and was about 30 percent of the annual construction waste, on average, generated for Japan. The Northridge Earthquake in California (1994) generated 7 million yd^3 (Reinhart and McCreaner 1999) of debris. Hurricanes can generate quantities of debris on the order of years, perhaps decades, greater than the average annual solid waste levels in a given community (Solis et al. 1995). Hurricane Andrew (1992) for example, generated 43 million yd^3 of debris in Metro Dade County, FL (Reinhart and McCreaner 1999). Hurricane Inike in Hawaii generated 5 million yd^3. Hurricane Hugo generated 2 million yd^3 of plant waste, which was on the order of 5 to 15 times the annual solid waste produced in both North and South Carolina (Reinhart and McCreaner 1999). The 118 million yd^3 of debris produced by Hurricane Katrina makes it the largest debris cleanup project to date in the United States (Jadacki 2007). These large fluxes mean that even conventional waste streams can become severe environmental hazards due to their large volumes. Furthermore, the large volumes can overwhelm existing landfill space, particularly those for hazardous wastes and municipal wastes (Figure 3).

Debris removal typically focuses on clearing roads and right of ways that are critical for responding to the disaster, followed by removing debris that is impacting critical utilities. As a result, disaster plans focus on rapid removal of large volumes. The removal of these large volumes, however, frequently causes traffic congestion and may even further damage storm-damaged roads.

Figure 3. A landfill filled with storm debris in Southern Mississippi following Hurricane Katrina. Photo provided by USACE, Katrina Disaster Response Team.

The objective of this section is to briefly summarize debris forms resulting from large-scale disasters, then in more detail discuss particular components of the debris that have been identified as especially problematic. From that, the section will outline potential solutions to some of these troublesome sources and identify research opportunities.

Waste segregation

Debris from disasters can be categorized into the following types (Louisiana Department of Environmental Quality (LDEQ) 2005; State of Hawaii 2005; Solid Waste Association of North America (SWANA) 2005; Texas Commission on Environmental Quality (TCEQ) 2005):

1. Vegetative materials
2. Clean lumber
3. Inert materials
4. Building materials
5. Chromate copper arsenate (CCA)-treated wood
6. Putrescent wastes

7. Hazardous household wastes/materials (HHHW)
8. Others, as discussed below.

Vegetative materials consist of fallen trees, leaves, and yard wastes and these generally make up the bulk of storm wastes (Solis et al. 1995; Figure 4). These materials can create numerous problems, including blocking roads, clogging stream channels and storm water drains (and creating local flooding), and damaging electrical and communication lines (Emerson 2003; Sherman 2003; Figure 3). Because of these immediate issues, as well as the sheer volume of vegetative materials, most disaster response plans in storm-affected areas focus on these materials (Fairfax County, VA 2005; TCEQ 2005). Fortunately, vegetative wastes have little long-term negative environmental impact. They can be ground and/or burned to reduce volume (Gray 1998), and dried, ground material can even be mixed with coal to provide electricity. There are opportunities for beneficial use of these materials, including application of mulched materials for erosion control, and the use of logs for building materials and for stream stabilization (Chapter 2). Clean lumber can generally be handled the same way as vegetated materials.

Figure 4. A fallen tree on the Mississippi Coast following Hurricane Katrina. The tree knocked down a light pole (see bottom right). Photo provided by the Mississippi Section of the American Society of Civil Engineers. MS-ASCE.

Inert materials generally refer to clean soils, sediments, and sludges, which are often deposited by storms or flooding (Solis et al. 1995). These are usually considered environmentally harmless, but can be heavy (an issue in transportation) and can take up valuable landfill space. However, these materials can also be recycled as landfill cover material, clean fill material, or agricultural top soil.

Building materials are primarily generated from the destruction of flood- and wind-damaged buildings (Solis et al. 1995; Tansel et al. 1994). This waste consists of wood, cement/concrete, asphalt, bricks, rocks/gravel, roofing shingles, etc., in fact any material used in construction. They are also the bulk of wastes caused by earthquakes and from most terrorist attacks. Damaged buildings represent severe threats to the local community. However, the wastes associated with these buildings are generally benign from an environmental standpoint. Because most of these are relatively harmless, they can be placed into a construction and demolition waste landfill. These landfills are typically unlined and have limited or no surface water runoff and leachate control (TCEQ 2005). Much of the building material waste can also be recycled (Reinhart and McCreanor 1999). Often, the damaged areas need new building materials for buildings and roads. Concrete and building rock can be used as aggregate for new concrete or asphalt.

Complicating building waste issues are home and office furniture, appliances, and computer equipment that is typically mixed with these wastes (Solis et al. 1995). Furthermore, hazardous components can also be mixed in with the building material wastes, including asbestos (insulation in older homes, shingles and flooring), lead (in lead-based paints and old plumbing systems), polychlorinated biphenyls (electrical transformers), chemicals and petroleum products, and mercury from electrical switching equipment (Kurre 1997; Reinhart and McCreanor 1999).

CCA-treated wood contains hazardous metals including copper, chromate, and arsenic. It cannot be burned and it is typically disposed of in construction and demolition waste landfills (Pardue 2006). It is discussed in more detail below. Hazardous materials can come from demolished houses (HHHW), businesses, and from industrial spills. Disaster plans generally specify that the hazardous wastes be identified and separated (Reinhart and McCreanor 1999). The presumption is that they will be disposed of in

a secured hazardous waste landfill. These will also be discussed in more detail below.

Other waste materials mentioned in reports include night wastes (sewage and human waste) and electronic wastes (e-waste) (Hayashi and Katsumi 1996; Solis et al. 1995). Generally, these are managed with other waste streams, but in some cases, may require special attention.

Problem materials

Problem materials were determined from two sources. First, the literature was searched to determine materials that historically caused short- and long-term problems.

Household hazardous wastes (HHHW)

Managing HHHW is a problem in debris cleanup (Center for Disease Control (CDC) 2005; Pardue 2006; Simmons 1994). Generally, this waste stream comes from disasters that require the reclamation or destruction of damaged homes (Figure 5 and 6). The first issue is that these wastes are very diffuse in nature. They are found in most homes in relatively small quantities for each, but for a large disaster, the total quantities can be substantial. A second issue is that these materials can be very diverse in nature and include pesticides, paints, cleaning products, gasoline and oil (for lawn maintenance machines), and other materials. A third issue is that these wastes are generally not regulated as hazardous wastes, as the Resource Conservation and Recovery Act (RCRA) has an exemption for household wastes that would otherwise qualify as hazardous. Generally, the management approach is for people conducting demolition to separate out these wastes from the construction wastes (Figure 7). As a further safeguard, waste shipments into unlined landfills are visually inspected for obvious inclusions of HHHW. However, despite these safeguards, a study conducted at the Chef Menteur landfill in New Orleans indicated that this approach did not prevent appreciable quantities of HHHW from reaching that unlined construction waste landfill (Pardue 2006).

Figure 5. Completely destroyed homes near the Mississippi Coast following Hurricane Katrina. Photo provided by the MS-ASCE.

Figure 6. Household generated debris. Note the gasoline container in the middle of the view, illustrating issues of household hazardous waste. Photo provided by the MS-ASCE.

Figure 7. Hazardous household waste - segregated and accumulated curbside. Photos provided by USACE Katrina Disaster Response Team.

Sheetrock

Sheetrock is extensively used as a building material and is generally considered a stable and environmentally harmless material. However, recent problems at construction waste landfills have been traced to biological reactions involving these materials. O'Connell (2005) details odor issues traced back to sheetrock disposal found in landfills in Massachusetts, Ohio, and in New Hampshire – all involving normal waste loadings, not the heavy material influx expected from a disaster (Figure 8).

Figure 8. Damaged church near the Mississippi Coast following Hurricane Katrina. Damaged sheetrock is visible in the foreground. Photo provided by the MS-ASCE.

Reinhart et al. (2004) describe problems in Florida landfills. Gypsum found in these materials undergoes reductive reactions in anaerobic environments, creating hydrogen sulfide (H2S) gas. At best, H_2S generation is a nuisance, as it is a foul-smelling gas. Humans are extremely sensitive to H2S odors and can smell it at concentrations as low as 0.5 to 1 part per billion by volume (ppbv). Ambient air concentrations range from 0.11 to 0.33 ppbv (Agency for Toxic Substances and Disease Registry (ATSDR) 2006). According to information collected by the Connecticut Department of Health, the concentration of H2S in ambient air around a landfill is usually close to 15 ppbv (ATSDR 2006). At worst, if the gas accumulates in basements or in low-lying areas, it can conceivably reach toxic concentrations. Hydrogen sulfide is considered toxic at a concentration of 10 ppmv, and above 1000 ppmv can lead rapidly to death. Further, H_2S can be oxidized biologically to form sulfuric acid, promoting leaching of metals into surface water runoff or groundwater. Finally, H_2S can react with other materials and form other odorous reduced gases, including dimethyl sulfide, ethyl mercaptan, i-propyl mercaptan, t-butyl mercaptan, methyl n-propyl disulfide, dimethyl trisulfide, and thiophene. Generally, sheetrock from storm demolition is disposed of in construction and demolition landfills, which are not equipped to deal with gases or acid production (Pardue 2006).

CCA-treated wood

CCA-treated wood can be found in telephone poles, as well as in construction demolition wastes, particularly from outdoor decks and log cabin-type homes (Figure 9). Studies have indicated that arsenic can leach from these materials (Khan et al. 2006; Pardue 2006). The rate is low, but measurable in the laboratory. Making the situation potentially worse is that dissolved arsenic is generally in the form of arsenate, an anionic species that tends to migrate freely in the environment. The most cost-effective means of dealing with these wastes is disposal into a construction and demolition waste landfill. However, these types of landfills are typically not lined and do not have leachate control systems. There is concern that these wastes could result in arsenic contamination of groundwater or receiving surface waters.

Figure 9. Fallen telephone poles resulting from Hurricane Katrina. These damaged poles are a source of CCA-treated wood. Photo provided by USACE.

Putrescent wastes

Putrescent wastes come from dead animals and spoiled food (Figure 10). These wastes can quickly spoil and the resultant foul odors can affect relief workers. Generally, these wastes are either burned, or, more commonly, placed in a landfill. In general, these materials are not considered long-term environmental problems. However, there does not appear to be much information on the short-term effects (up to 2 years) of large-scale burial (landfill placement) of these wastes. There is the potential that large-scale burial of putrescent wastes would promote pathogen spikes in drinking water supplies.

Chemical spills

Disasters can create opportunities for chemical spills (Figure 11). Earthquakes can damage storage tanks and storm surges can tip tanks over, causing spills. Hurriedly conducted plant shutdowns can result in numerous spills (Ruckart et al. 2008). A review of the Hazardous Substances Emergency Events Surveillance System indicated 166 reportable spill events related to Hurricanes Katrina and Rita (Ruckart et al. 2008).

Figure 10. Removal of spoiled food from appliances (white goods) before disposal. Photo provided courtesy of USACE.

Figure 11. An exposed, excavated underground storage tank near the Mississippi Coast after Hurricane Katrina, illustrating the potential for chemical release. Photo provided by the MS-ASCE.

Generally, these spills are handled using conventional soil and water cleanup approaches. But the scope can be very large. For example, it was estimated that Hurricane Katrina resulted in 8 million gallons of spilled oil

in the New Orleans area (Perrow 2007). This is comparable to the oil spilled by the Exxon Valdez in 1989 (11 million gallons).

Particulate-forming wastes

It has been documented that fine particulate material in the air caused respiratory illness following both Hurricane Katrina and the terrorist attacks on the World Trade Center (Clean Air Report (CAR) 2005; CDC 2005, 2006; Farris 2005; Mattei 2003, 2004; Peterson et al. 2005; USEPA 2003; Yiin et al. 2004). Numerous sources of fine particulates follow a disaster, including fine sediments, smoke from fires (Dean 2008), mold spores from flood-damaged housing material, friable asbestos, pollen, and other fine plant material. This issue is a handling issue as opposed to a disposal issue; that is, once the wastes are in the landfill, there is no longer an issue with air particulates. However, during handling, and during the treatment process, there can be a problem with exposure to the particulates (Figure 12). Asbestos, for example, must be handled separately from other demolition wastes. Workers handling asbestos-containing material must wear personal protective equipment (PPE) to prevent dermal and inhalation exposure to the asbestos fibers (Figure 13). Hurricane-deposited sediments can become airborne with strong winds, vehicular traffic, or during their removal. These sediments could include organic and metallic contaminants (Suedel et al. 2008). Burning wastes, whether intentional or due to accidental combustion (Dean 2008, and Figure 17), and dusts produced by the application of landfill covers are two additional examples of treatments contributing to fine particulates in the atmosphere.

Vehicles

Vehicles (cars, trucks, campers, boats, etc.) are often moved great distances by water, wind, and mud during disasters (Figures 14 and 15). These items are bulky and may block roads and access points needed by recovery teams. In addition, they leak gasoline, diesel fuel, and other hazardous chemicals. Tires can be a considered a problem-causing substance and are often cited as the cause of landfill fires. Removal and disposal are complicated by ownership and insurance issues, which slows down cleanup and recovery efforts.

Figure 12. Removed asbestos-containing material resulting from Hurricane Katrina. Material was marked so it would not be picked up by hauling crews. Photo provided by USACE.

Figure 13. Safe handling of asbestos debris during disaster recovery requires respiratory protection and protective clothing. This protective equipment can stress relief workers, especially since most severe storms occur during hot times of the year.

Electronic wastes (e-waste)

The Louisiana Department of Environmental Quality (LDEQ) reported that the Environmental Protection Agency collected 602,711 electronic goods units (Figure 16) from nine Parishes in Louisiana as of August 2006 as a result of Hurricanes Katrina and Rita (LDEQ 2008).

Figure 14. Vehicles staged for disposal in southern Mississippi following Hurricane Katrina. Photo provided by USACE.

Figure 15. Damaged boats pushed ashore in Gulfport, MS area during Hurricane Gustav (2008). Photo provided by USACE.

Many computers and electronics contain components that can be hazardous to the environment. Some of these components include:

1. Cathode ray tubes (CRT) - the glass picture tubes found in computer monitors and TVs contain lead, while the flat screen monitors contain small quantities of mercury. The amount of lead varies from 4 to 6 lb per unit.
2. Printed circuit boards contain hazardous metals including chromium, cadmium, lead and mercury (MDEQ 2008; Thibodeau 2002).
3. Batteries in electronics and computers may contain lead, mercury, nickel and cadmium.

Appliances

Appliances are a problem mainly due to their large size, creating issues with loading, hauling, and landfill space. Generally, appliances are made of relatively harmless materials. However, refrigerators can contain putrescent wastes (see above) and freon chemicals that should be removed prior to disposal.

Debris pile fires

As mentioned above, woody debris is often intentionally burned to reduce volume. However, the Katrina experience indicated that debris can also inadvertently catch fire, creating problems. In many cases, vegetative material was segregated and finely mulched. In this form, it became a valuable resource, which could be given or sold to residents as a compost material, used as a landfill or slope stabilizing substrate, or used by paper mills as a feedstock material. A pile of this finely ground material is susceptible to spontaneous combustion during dry, hot days. Lightning strikes also could cause fires in debris materials. These fires could threaten nearby structures or forests with fire from airborne embers and represented a source of particulate air contaminants (Figure 17).

Figure 16. Collection of electronic waste in Louisiana following Hurricanes Katrina and Rita. Picture provided courtesy of USACE.

Figure 17. Fires in piles of debris and/or at landfills may result from spontaneous ignition or lightning. They contribute hazardous fine particulates to the air. This fire occurred in a debris pile in Southern Mississippi following Hurricane Katrina. Photo provided by USACE.

Swimming pool issues

Swimming pools (Figure 18) often fill with potentially hazardous debris during a natural disaster. The debris hides the swimming pool from recovery teams, making the pool a work hazard. During recovery, water and debris must be removed from the pool, wastes must be segregated, and the pool must be filled with sand so it does not become a health hazard.

Research opportunities

Cone penetrometer sensor for HHHW

Keeping HHHW out of construction and demolition landfills is imperative, as these landfills do not have the systems to prevent their migration. Currently, inspectors can only visually inspect the surfaces of shipments entering these landfills. In this way, substantial quantities are believed to have entered New Orleans construction and demolition landfills in the aftermath of Hurricane Katrina.

It is clear that a better means of assessment is needed for these materials. One option is penetrometer sensors (Figure 19), which are used commonly for soil gas and hydropunch surveys (Grunwald et al. 2001;

Figure 18. Swimming pools filled with debris can rapidly become health hazards to the community. This is a pool in Southern Mississippi following Hurricane Katrina. Photo provided by USACE.

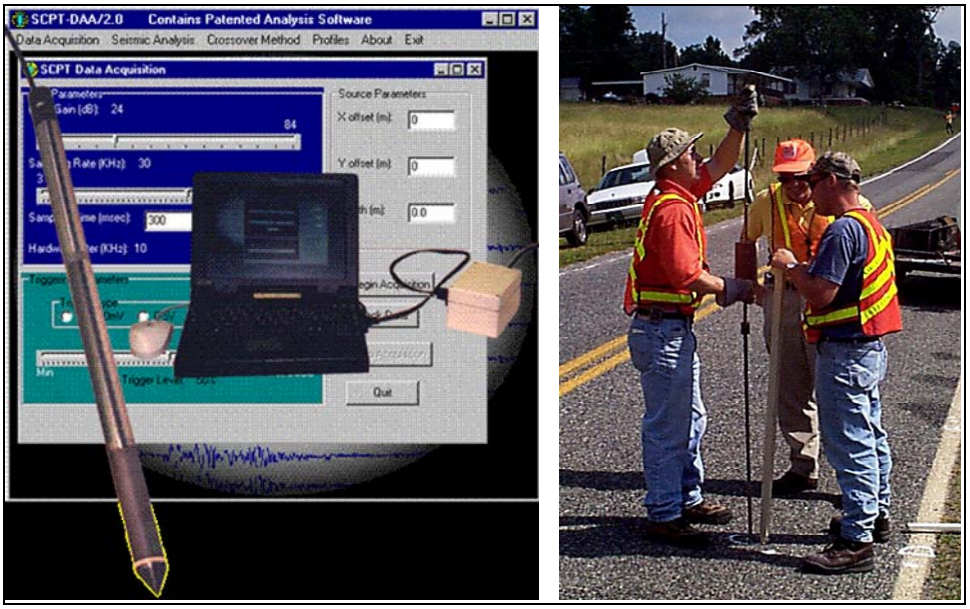

Figure 19. Commercially available cone penetrometer and software system and its use in the field.

Robbins et al. 1995). These are based on cone penetrometers, which are steel tubes that can be pressed or hammered into the media of interest. Simple gas sensors could be developed to detect volatile compounds found in many HHHWs. The gas sensors would be inserted, via the cone penetrometer, into debris in the waste-hauling vehicles prior to disposal. The penetrometer would be pushed or hammered into the wastes. Then, a vacuum would be pulled through some sampling holes. The gas would be analyzed for the volatile components of interest. This could reduce the amount of HHHW accidentally reaching inappropriate landfills.

Studies on H_2S generation from sheetrock materials

Simulated landfill chambers could be used to study H_2S generation from sheetrock materials in different landfill settings (i.e., construction versus municipal). This would improve understanding of conditions that cause H_2S production. One possible treatment involves mixing the sheetrock with fly ash, which appears to hamper the H_2S forming reaction (Pardue 2006). Another approach is the use of specialized landfill cover materials that may attenuate H_2S passing through them (Plaza et al. 2007). Mixing pH basic materials (lime or crushed concrete) with fine sand may also have beneficial effects. Studies can also be conducted to investigate retrofit approaches to deal with disaster waste landfills currently experiencing problems.

Effects and treatment for putrescent wastes

Simulated landfills could be used to determine if buried putrescent wastes can cause short-term water quality issues through increased organic content, pathogenic organisms, etc. “In the box” treatment approaches can be developed to treat spoiled food in refrigerators. Lime would be an attractive material because it is inexpensive, has dewatering capabilities, and can inhibit microbial activity.

Reduction of fine particulates in debris management

Fixatives can be developed from plant resins and/or asphaltic materials to hold fine particulates in place. A logical starting point would be to focus on treatment of mold spores, which have documented negative health effects (Mazur and Kim 2007; Seltzer and Fedoruk 2007) and which created numerous health problems during the cleanup of flood-damaged homes in New Orleans and Mississippi in the aftermath of Hurricane Katrina (CDC 2006; Farris 2005; Monacelli 2006).

Guidance and best management practices for debris recycling/reuse

Managing debris is a challenge for a disaster-impacted area. At the same time, the debris, following separation/removal of any hazardous components, can also be a resource for the area to rebuild roads, buildings, and landfills. Inert soils and sediments, ground concrete, and mulched vegetative materials can be used for landfill covers, which are generally needed in large quantities. Concrete, asphalt road base, inert rocks, petroleum-contaminated soils, and ground asphalt shingles can be used by asphalt plants to repair or replace damaged roads (Brickner 1995). Similarly, ground concrete, rocks, sand, and other materials can be used as aggregate for the new concrete needed for construction. Plant material can be composted and reused as fertilizer to promote new growth at damaged parks. Logs can be used to stabilize slopes. Gypsum recovered from sheetrock can be utilized for stabilizing soil pH and can be used as a soil fertilizer (URS Corporation 2005; Zublena et al. 1995; McPhee 1997).

Two factors inhibit effective recycling: the need for rapid deployment following a disaster and space for staging areas. Still, with forethought, these issues can be dealt with to increase recycling (Reinhart and McCreanor 1999). A project could be developed to study successful recycling efforts and to develop best management practices. Modeling

projects can be developed to assist affected communities in better staging of materials for recycling. The important aspect of these projects is the forward planning required for coping with the aftermath of a disaster.

Guidance and best management practices for damaged building assessment/demolition

While building demolition can cause major problems, the resulting building debris offers a tremendous opportunity for recycling. By assessing a building, before dismantling it, better results can be obtained regarding separation of hazardous and problem wastes and materials can be better recycled (Kurre 1997). A program to develop guidance to rapidly assess buildings would be useful. Training programs could be developed to quickly train personnel in these techniques.

Summary

Several hazardous materials commonly found in debris from a natural disaster have been identified. These range from toxic air particulates to animal carcasses and rotten food, to construction and demolition debris. Several research opportunities that may improve the management of these problem materials include:

1. Basic research on chemistry of complex landfill wastes in order to reduce odors and toxic leachates.
2. Reduction of fine air particulates through engineering practices.
3. Sensors to improve waste assessment.
4. Production and dissemination of training materials, guidance documents, and best management practices in order to coordinate USACE disaster response on a nationwide level.

Numerous opportunities exist to improve debris management via practices and technologies that support future disaster response.

4 Application of Geospatial Technologies for Improved Debris Management

Background and objectives

The term "geospatial" in its widest context is used to describe the combination of spatial software and analytical methods with terrestrial or geographic datasets. Geospatial technologies usually include three principal technical areas: geographic information systems (GIS), remote sensing, and global positioning systems (GPS). Each of these technologies plays an important role in the development of accurate and timely geographic datasets and the extraction of information from those datasets. The USACE ESF #3 of the National Response Plan depends on the support services provided by the Mission Modeling Assistance Team (USACE 2006). The models provide support for pre-disaster planning and are updated with ground truth data provided by satellite and /or airborne imagery. GIS is used during both the response and recovery periods.

In their recently published update of the 1995 document "Planning for Disaster Debris," the USEPA (2008) and a wide range of other federal, state and local agencies, present lessons learned from past disaster responses and provide recommendations for the development of debris management plans. While this report stresses the importance of GIS for pre-event planning, such as for predicting volumes of debris which would likely be generated by major disaster events (using, for example, Hazards U.S. - MultiHazard (HAZUS-MH) or the Hurricane Debris Estimation Tool (HurDET), geospatial technologies, unfortunately, are not specifically addressed in this document. Furthermore, guidelines and suggestions for the use of remote sensing technology are not addressed at all in the USEPA (2008) document.

In the FEMA publication "Public Assistance Debris Management Guide" (2007), remote sensing technologies are specifically addressed as an important tool for forecasting the amount, mix, and extent of debris. In this report (FEMA 2007), GIS technology is recognized for being beneficial in mapping and, again, in forecasting the quantity of debris likely to be generated by various disaster events.

Overview of remote sensing

Remote sensing has been defined by Lillesand and Kiefer (2000) as the "science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation." Most commonly, in a modern, large-scale mapping context, remote sensing involves the use of digital airborne or space-borne sensors, which image the earth's surface in different portions of the electromagnetic spectrum.

In a post-flood situation, emergency managers need quick access to information which is timely, easily understandable, and is of the right space and time scales. Remote sensing imagery is often used in such disaster situations since imagery can provide rapid assessment of large areas, is not constrained by the site access issues that are often associated with disaster situations, and can provide an overview perspective of ground conditions.

Remotely sensed imagery can be classified into two broad categories: passive or active. Passive systems measure reflected or emitted (thermal) information in discrete parts of the electromagnetic spectrum. The number of portions (or bands) of the electromagnetic spectrum measured represents the spectral resolution of a sensor, while the dimensions of each discrete element of the ground measured represents the spatial resolution of a sensor. For example, the Landsat Thematic Mapper sensor has seven bands (spectral resolution) with a spatial resolution of 30 m (each cell, or pixel, represents 30 m on the ground).

A vast array of airborne and satellite imaging sensors exist and each of these possess different spatial and spectral characteristics. Part of the art of remote sensing is sensor selection: ensuring that the proper system is used for the application at hand. For example, for a simple image of the ground, spatial resolution is much more important than spectral resolution, as only three bands are required for a color image. However, to map vegetation or materials on the ground, spectral resolution is critical - since it is necessary to have many narrow portions of the electromagnetic spectrum imaged to classify surface materials.

Most systems are passive, in that they only measure emitted or reflected electromagnetic energy from surface features. Others, such as LIDAR (Light Detection and Ranging) or Synthetic Aperture RADAR (Radio Detection and Ranging) (SAR), emit a signal and measure returned energy

to characterize features of interest. LIDAR systems, in particular, are experiencing a rapid rise in use and applications for their ability to create a three-dimensional model of the ground surface. The vast quantity of data collected by such systems presents some challenges for processing, but these systems are quickly replacing traditional methods of surface generation, which required stereo photography.

Applications of remote sensing technology for debris management

Remotely sensed data currently have a wide array of applications in debris management situations and the potential applications of these technologies are rapidly growing. This is due to constantly improving spatial resolution and the growing availability of active LIDAR systems. Passive imagery can be quickly gathered to assess debris location and assist in map generation. Multi- or hyperspectral imagery can be analyzed in more detail to determine the content of debris piles. Finally, active LIDAR systems can be employed to determine the volume of debris piles in streams. This type of data can be very helpful in planning for debris removal or in determining changes in stream morphology for hydrographic modeling purposes. This can be useful for determining any impacts of the debris such as secondary flooding or bank erosion.

While the usefulness of aerial photography for post-flood events has been long accepted, the usefulness of digital imagery for post-flood analyses is quickly becoming mainstream as well. Imagery in a digital format lends itself to being easily incorporated into a GIS system for generation of map products that can be quickly put into the hands of field teams. Multispectral or hyperspectral data, in the hands of trained image analysts, can be used to determine the composition of debris piles or other stream features. Leckie et al. (2005), for example, used multispectral data to develop automated techniques to map stream features, including woody debris, and other materials. Through the use of hyperspectral data, it should be possible to quickly determine the presence of man-made materials in channel debris, such as possible sources of contamination.

One of the most comprehensive applications of a broad range of remote sensors for debris management occurred in the aftermath of the September 11, 2001 terrorist attacks in New York City. A wide array of sensors was employed representing almost the entire gamut of remote sensing platforms (both airborne and space-based active and passive systems). For example:

1. High-resolution satellite imagery was used to create base-maps of the area.
2. LIDAR was used to characterize the debris volume.
3. Thermal imagery was used to map heat plumes in the rubble.
4. Hyperspectral systems were used by the Jet Propulsion Laboratory (JPL) and the National Aeronautics and Space Administration (NASA) after this event to map possible asbestiform minerals and particulate asbestos over the World Trade Center and surrounding areas (United States Geological Survey (USGS) 2001).
5. Many of the lessons learned during this event were documented by Huyck and Adams (2002). Several key items noted in the application of remote sensing data would also be applicable to debris management activities. These include:
   - Remote sensing data need to be used as more than just a background picture or imagery backdrop within a GIS system. Much of the data regarding targets of interest are contained in the digital values of the imagery and within the spectral content of the imagery. Therefore, wider use should be made of programs specifically designed for image analysis.
   - Fusion of datasets often results in much more information than examining single datasets alone. During the 911 effort, fusion of remotely sensed imagery was largely overlooked.

GIS analysts who are the primary responders need to be adequately trained on how to fuse vector and raster datasets to produce meaningful statistical results – and remote sensing experts should be aware of the applicability of GIS to expand the usefulness of their datasets. As it is difficult to learn new approaches and ideas during an emergency, the emergency managers need to be better educated on the capabilities of GIS, remote sensing, and related modeling technologies prior to an actual disaster.

Applications of LIDAR

While passive remote sensing systems can be used to locate and characterize the composition of debris in stream channels, airborne LIDAR technology provides a method to rapidly assess the volume and shape of the debris piles. LIDAR technology employs a scanning system to rapidly point a laser at the ground. The laser light strikes a surface, and a portion of the reflected energy is directed back at the instrument where it is measured. The time that elapsed during this process is then measured, and is used, along with accurate GPS measurements, to compute the altitude of

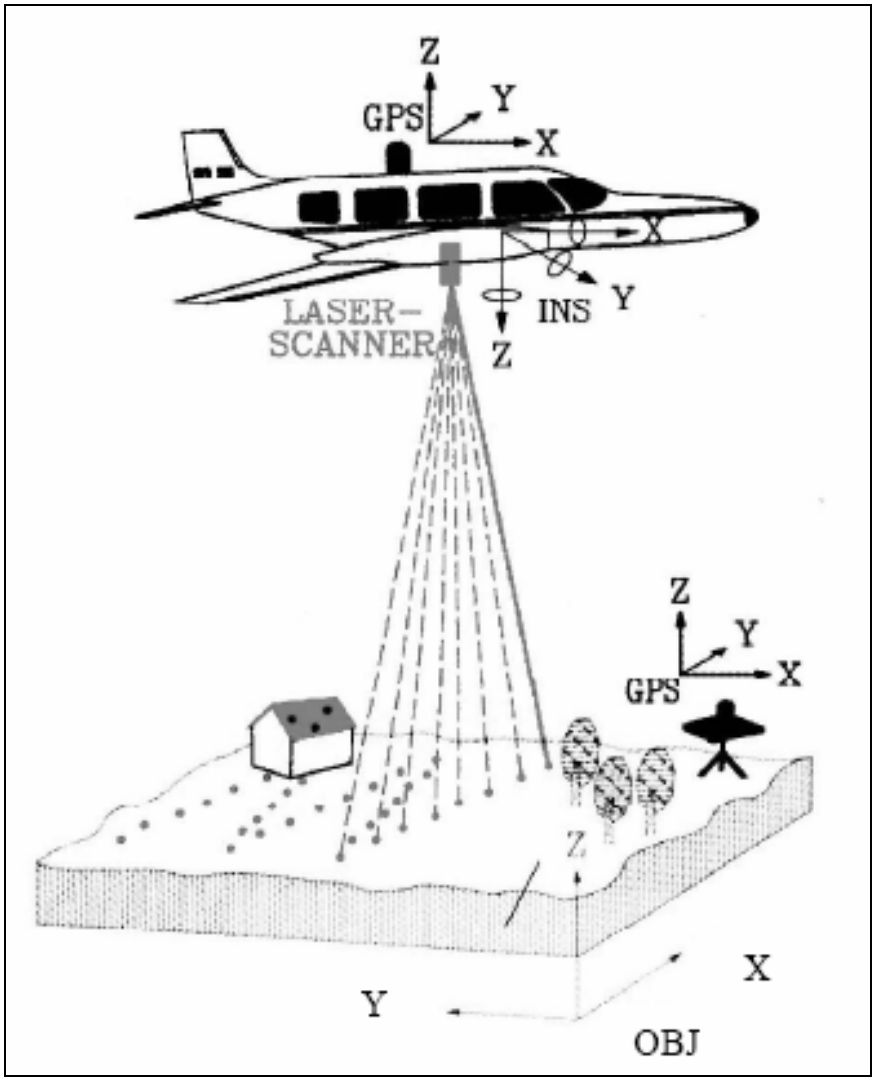

Figure 20. The use of LIDAR for surface mapping
(based on Fleece 2002).

the surface (Figure 20). Airborne instruments are capable of generating tens of thousands of pulses per second.

In a damage evaluation of the 2005 Taum Sauk Reservoir failure in southeast Missouri (Figure 21), LIDAR data proved instrumental in evaluating channel deposits and debris dams and scour features (Luna et al. 2007). Volumetric and morphologic data obtained from LIDAR technology proved invaluable in modeling future changes to the stream features and in assisting in stream rehabilitation.

Figure 21. High-resolution imagery overlain on LIDAR-derived surface. The wall failure and stream scour are quite visible even in this overview of the area (Luna et al. 2007).

The rapid commercialization of LIDAR technology means that it is readily available over any part of the United States. Vendors can obtain information after a major flood event and, unlike most passive remote sensing systems, LIDAR data are not dependent upon cloud-free weather conditions. By combining surfaces derived from LIDAR data with pre-event digital elevation models in a GIS, a simple subtraction of one surface from the other can quickly highlight areas of erosion or deposition. These features can then be fed to raster hydrologic modeling systems, such as the Hydrologic Engineering Center-River Analysis System (HEC-RAS), to determine any impacts of secondary flooding caused by debris dams or constrictions in the stream channel. This type of information, combined with other GIS layers, can be used in stream-clearing operations to prioritize channel debris removal operations.

LIDAR data may also be used in pre-event situations to assess the characteristics of the forest and bank structure of streams. Fleece (2002) used LIDAR data to characterize streamside forest structure to feed to models to predict the rate delivery of large woody materials to streams.

Applications of GIS technology in debris response

Most stream debris management applications use at least a basic level of GIS. During post-Katrina response and after most major flood events, GIS technology was used to produce base maps to serve field teams and to portray data collected in the field using GPS technology. Often, imagery from remote sensing systems are displayed within a GIS to further convey status information to response teams.

More advanced applications of GIS technology come from modeling or geoprocessing applications, which take data from existing geodatabases and feed hydrologic models or simple geoprocessing models, which analyze data in a geographic context. For example, presented with a large amount of debris in a stream channel and a polygon representing the flooded area, a simple query could be performed against a GIS layer, such as the EPA's Toxic Release Inventory (USEPA 2007), to determine what potential upstream contaminants may be present in the stream debris. Information on changed stream morphology, derived from before and after comparisons of digital elevation models and post-event LIDAR data, can be fed to hydrologic modeling software, such as HEC-RAS (Brunner 2008), to determine the effects of the changed system status on secondary flooding.

A number of models designed to predict the types and amounts of debris caused by various events interface or link to GIS platforms. Among these are the HAZUS-MH program developed by FEMA under contract with the National Institute of Building Sciences (NIBS). The Corps of Engineers has its own model, called the "U.S. Army Corps of Engineers (USACE) Debris Estimation Model" which makes cursory use of GIS technology to estimate possible debris volumes (USEPA 2008).

Research opportunities

A number of areas need to be explored to improve the usefulness of geospatial technologies for debris management activities. During the time immediately following a major flood event, the processes for data acquisition and analysis of the appropriate remote sensing data need to be better integrated into the response planning process. Too often, the application of remote sensing data is a side-venture, with GIS specialists leading the way. While GIS specialists are well aware of the requirements for displaying imagery in a GIS context and for rudimentary image analysis – such as

mapping features by on-screen digitizing – often they do not possess the more advanced skills required for analysis of multispectral or hyperspectral imagery. Therefore, the potential of remote sensing platforms to determine the composition of debris, or to determine the morphology and volume of debris or stream scour (and for use in subsequent modeling of induced-hydrologic changes) is often not realized.

While tools such as HAZUS-MH and the Corps' own debris estimation models exist, these tools need to be further used and tuned to improve their ability to accurately predict the volumes and character of debris likely to be present in stream channels. Further work needs to be conducted to produce GIS-based tools that, given the location of debris in stream channels, can predict the presence of potential contaminants based on queries of existing spatial databases maintained by federal and local agencies. In addition, information on stream-channel debris location and volume should be quickly analyzed in modeling tools that link with a GIS (such as HEC-RAS) to determine any impacts of secondary flooding.

Remote sensing imagery needs to be more fully integrated into the pre-disaster planning and post-disaster response protocols. While the Corps maintains a list of GIS specialists who can be called upon in the event of a disaster response, the same type of list needs to be maintained for trained image analysts – and care needs to be taken to make sure the Corps has an adequate resource of image analysts who can fully exploit state-of-the-art active and passive systems. It is a mistake to assume that GIS specialists also possess the skills needed to effectively process imagery and LIDAR data for advanced feature extraction applications. Further research needs to be conducted on assessing the utility of existing and future high-resolution satellite imagery, radar systems, and new LIDAR processing techniques, and the fusion of data from multiple platforms for stream debris response and subsequent channel restoration activities.

The Corps' Imagery Office at the ERDC Topographic Engineering Center (TEC), the Joint Airborne Lidar Bathymetry Technical Center (JALBTCX) based at Stennis Space Center in Mississippi, and the ERDC Remote Sensing/Geographic Information Systems Center at the Cold Regions Research and Engineering Laboratory (CRREL) each represent specific resources that need to be incorporated fully into the development of refined procedures and approaches for the proper use of geospatial technologies in the pre- and post-disaster environment. Similarly,

environmental and stream channel specialists should incorporate geospatial technologies fully in restoration efforts.

Summary

The lack of coordination between geospatial technologies and stream channel debris management and restoration planning processes has been identified as a major difficulty in natural disaster recovery efforts. Emergency responses are not ideal times to try new approaches or attempt to integrate new technologies into recovery and restoration activities. Therefore, research to improve the coordination between the two disciplines is recommended, including:

1. Develop measurement and analytical techniques that can
   - identify accumulations.
   - prioritize for removal.
2. Improve the integration of remote sensing and GIS technologies during stream debris response and subsequent channel restoration.
3. Develop and test new guidelines and procedures to
   - specifically address flood-deposited channel debris and subsequent restoration.
   - integrate these procedures into existing Corps training programs.

Numerous opportunities exist to improve the response and recovery to a natural disaster by combining these two technologies - GIS and remote sensing.

5 Conclusions

Three critical areas of disaster debris management are discussed in this report:

1. Debris management in streams and waterways.
2. Contaminants in natural disaster debris.
3. Use of geospatial technology and remote sensing to improve debris management.

The current state of practice was defined for each of these areas and research opportunities were identified. For example, there are two major classes of debris that accumulate in waterways following a storm event, natural (LWD) and anthropogenic debris. This debris can block stream flow and contribute to bank erosion. While the anthropogenic debris is generally removed promptly, removal of LWD and stream restoration is often performed at a later date. There is a need for research on the ways, means, and benefits of reusing LWD to restore ecological functioning of the stream ecosystem. Little research has been done on either the ecological effects of delayed debris removal and stream restoration or the cost-benefit ratio of immediate removal vs. delayed removal.

Immediately following a disaster, and often for an extended period of time after, cleaning up debris is an important component of disaster response. A number of different classes of hazardous materials are found in disaster debris, ranging from toxic chemicals in household and industrial waste to animal carcasses and spoiled food to demolition debris. Currently, there is no uniform nationwide guidance or training in disaster response for the USACE, particularly in the area of handling possibly toxic debris.

The third area discussed was the use of geospatial technology in handling disaster debris. The two arms of this technology, GIS software and remote sensing capabilities, have each achieved maturity in their own right. Issues not currently being addressed are improved integration between:

1. GIS and remote sensors, yielding more precise geospatial information.
2. Geospatial information and disaster response plans.
3. Geospatial information and ecological restoration activities.

Research in the areas mentioned above should improve the coordination of efforts in disaster response, reduce the associated costs, and increase the ecological and human health benefits derived from prompt and correct response to disaster debris. The theme that emerged was the need for a common nationwide plan, guidance documents, and training to enhance coordination among disaster response teams dealing with the tremendous problem of disaster debris. Improvements in these areas will aid communities in achieving rapid recovery following disasters (Figure 22).

Figure 22. Rainbow near the Mississippi Coast in the days following Hurricane Katrina. Photo provided by the MS-ASCE.

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14. ABSTRACT

Debris management is a critical function of disaster response activities. Debris can represent a serious health hazard in its own right, can hamper emergency response, and, by clogging streams and waterways, promote flooding. During an actual disaster, time is a limiting factor for the formulation and testing of improved debris management approaches. The time to improve management and technical approaches is before disasters strike. This report proposes that research can be effective in improving emergency response regarding debris management. This study investigated three aspects of debris management: debris management in stream beds, hazardous aspects of debris, and the use of geospatial measurements and techniques to improve management. The state of the practice for each was established. Areas of research opportunities were then identified and discussed. This document can serve as a framework for a debris management research focus area, which will provide guidance for emergency management organizations and professionals.

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