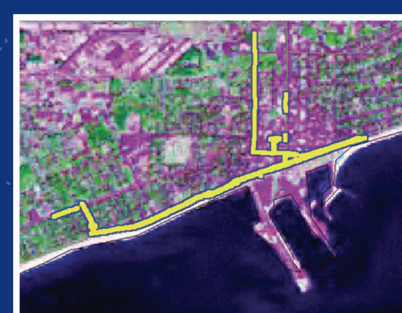
MCEER SPECIAL REPORT SERIES

Engineering and Organizational Issues Before, During and After Hurricane Katrina

HURRICANE KATRINA

Volume Two

REMOTE SENSING



Advanced Damage Detection for Hurricane Katrina: Integrating Remote Sensing and VIEWS™ Field Reconnaissance

J. Arn Womble, Shubharoop Ghosh, Beverley J. Adams and Carol J. Friedland

MCEER is a national center of excellence dedicated to establishing disaster-resilient communities through the application of multidisciplinary, multi-hazard research. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission has expanded from its original focus on earthquake engineering to address a variety of other hazards, both natural and man-made, and their impact on critical infrastructure and facilities. The Center's goal is to reduce losses through research and the application of advanced technologies that improve engineering, pre-event planning and post-event recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

Funded principally by NSF, the State of New York and the Federal Highway Administration (FHWA), the Center derives additional support from the Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

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Foreword

On August 29, 2005, Hurricane Katrina made landfall with sustained winds estimated at 125 mph, unprecedented storm surges approaching 30 feet and hurricane force winds extending 125 miles from its center. It resulted in over 1,300 lives lost, and caused major flooding and damage that spanned more than 200 miles along the Gulf Coast of the United States.

The extensive damage to the built environment far exceeded the expected damage for a storm of this size. Based on measured wind speeds and the Saffir-Simpson scale, Hurricane Katrina reached Category 5 strength while in the Gulf of Mexico, but quickly dissipated to a Category 3 storm before landfall. Although the wind speeds were substantially reduced before striking land, the storm surge apparently maintained the momentum associated with a Category 5 storm and appeared to be responsible for the majority of damage. It should be noted that early estimates ranked Hurricane Katrina as a Category 4 storm at landfall; the National Hurricane Center downgraded this ranking after revising wind speeds in December 2005.

Hurricane Katrina caused significant damage to engineered infrastructure including levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, waste water collection facilities, and vital communication networks. Damage to critical infrastructure such as hospitals and communication systems crippled the affected communities, and more importantly, the response and recovery efforts following the hurricane. In the aftermath of Hurricane Katrina, the important question now is: How can we better prepare ourselves to prevent or minimize the level of damage and the subsequent catastrophe in the next extreme event?

Funded by the National Science Foundation, a multidisciplinary team of investigators from the Multidisciplinary Center for Earthquake Engineering Research (MCEER), headquartered at the University at Buffalo, conducted post-disaster field reconnaissance to examine the impact of Hurricane Katrina on physical engineered systems and the response and recovery efforts that followed. Their objectives were to examine wind, storm surge and debris damage from a multi-hazard perspective. Implications of lessons learned from this reconnaissance effort are being examined to mitigate damage and improve response and recovery efforts not only from future hurricanes, but also from other extreme events such as earthquakes or terrorist attacks. By collecting this multi-hazard information, MCEER is seeking to develop engineering design strategies and organizational strategies that will make communities more resilient against any extreme event.

The MCEER special report series "Engineering and Organizational Issues Before, During and After Hurricane Katrina" was initiated to present the findings from the field reconnaissance mission. The topics addressed include advanced damage detection using remote sensing, damage to engineered structures, organizational decision making primarily in hospitals, and environmental and public health issues. The reports will contribute to the development of a better understanding of how to cost-effectively enhance the resilience of the nation's infrastructure against future extreme events.

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1.0 Introduction

1.1 Background

Hurricane Katrina first made landfall in the U.S. on August 23, 2005 in southern Florida as a Category 1 hurricane. After entering the warm waters of the Gulf of Mexico, it rapidly strengthened to a Category 3 hurricane and ultimately reached Category 5 status less than 12 hours later. On August 28, Katrina reached peak intensity with sustained winds exceeding 170 mph and a central pressure of 902 mb, (which at that time was the fourth-lowest central pressure recorded for an Atlantic Basin hurricane). The storm's intensity subsequently weakened in the 18 hours before its second landfall. Despite this weakening, the size of the hurricane continued to expand, with hurricane-level winds (exceeding 73 mph) extending more than 100 miles from the center and with tropical-storm-level winds (39-73 mph) extending more than 200 miles from the center. On the morning of August 29, 2005, Hurricane Katrina made landfall as a Category 3 hurricane (Knabb et al., 2005) near the Louisiana-Mississippi border (Figure 1-1).

As a natural disaster, Katrina was record-breaking – not when judged by standard criterion such as windspeed; rather, in terms of: (1) the *unique* convergence of multiple hazards within a single event, namely windstorm, storm surge, flooding, and levee breach, and (2) its status as the *costliest* U.S. hurricane on record.

The timing of Hurricane Katrina is also significant because it marks the first opportunity to study damage from multiple hazards using the "eye in the sky." Remote sensing platforms (including aircraft and satellite) provide a valuable perspective on disaster situations, particularly in instances where access is limited by law-enforcement agencies due to evacuation orders, or from the obstruction of roads by trees, flood waters, or bridge collapse. Important types of remote sensing images include: (a) optical, which shows the Earth's surface as it appears to the human eye; (b) radar, which can image at night and through clouds; and (c) lidar, which records the height of the terrain. Recently, public access to remote sensing data has significantly increased with the launch of the Internet-based Google Earth and MS Virtual Earth applications. For example, following Hurricane Katrina, evacuated residents with access to an Internet connection were able to view post-event images showing damage to their neighborhood and were thus able to gain an understanding of damage sustained by their property before returning home.

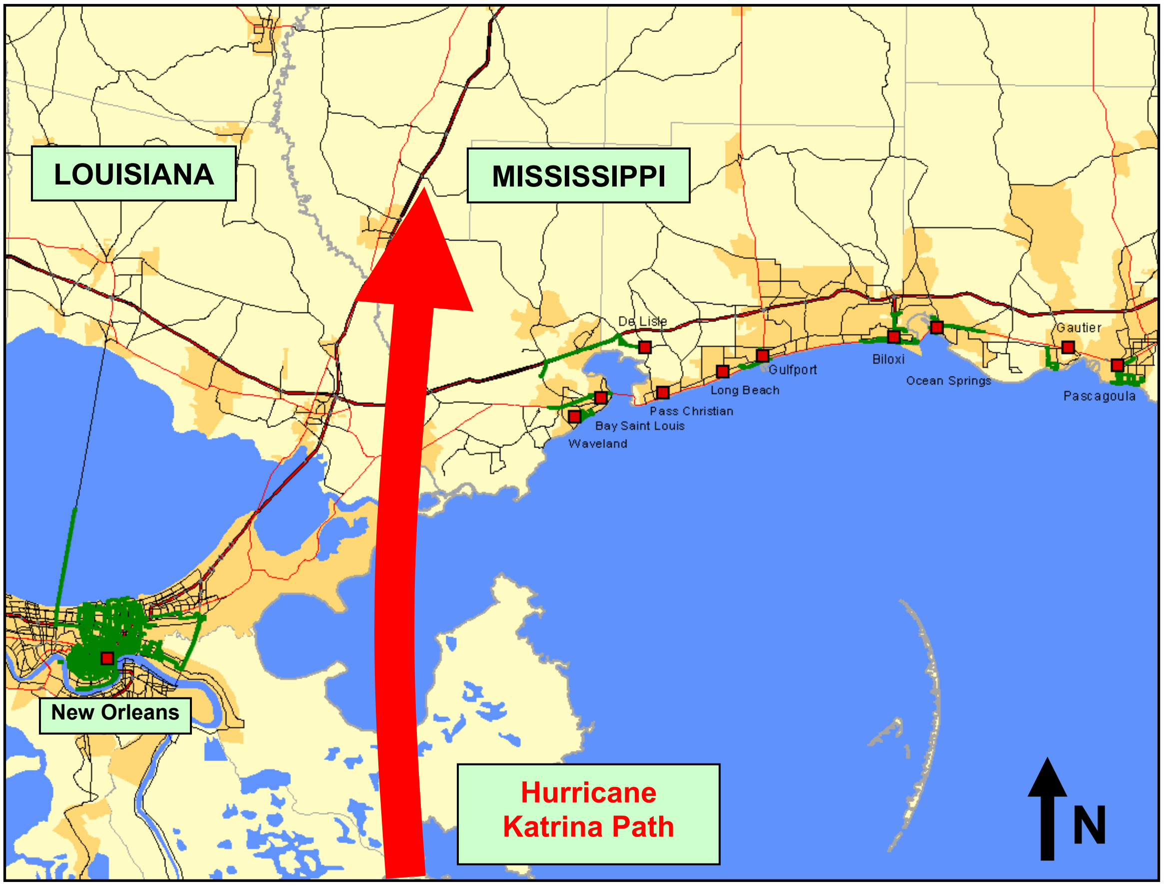


Figure 1-1. Orientation map showing approximate path of Hurricane Katrina, in relation to New Orleans and the Mississippi coast.

During the past few years, burgeoning technological innovations have led to significant improvements in methods used to collect and analyze post-disaster data. From a remote sensing perspective, information directly acquired from airborne and satellite imagery enables the rapid, thorough, and consistent assessment of damage. Indirect benefits arise from its integration into field survey tools such as the VIEWS™ system described in Section 5.1, through the streamlining and acceleration of reconnaissance activities. Initially employed for earthquake damage (Adams et al., 2004a), next for hurricane damage (Adams et al., 2004b; Womble et al., 2005; Womble 2005), and then for tsunami damage (Ghosh et al., 2005), the VIEWS™ system integrates pre- and post-disaster remote sensing data with in-field observations. It provides a permanent, geographically referenced record of the post-disaster scene, which can be used to support research activities and the development of new codes and standards in years to come.

1.2 Hurricane Damage

A majority of hurricane damage to the built environment consists of direct wind-induced failures (e.g., the removal of roofs, the launching of debris, and the breaking of doors and windows). In addition, these modes of damage typically allow rain to enter buildings and damage contents. Wind pressures acting directly on building surfaces to cause failures are considered a "primary" wind effect.

Direct wind pressures may also be accompanied by "secondary" effects, such as wind-driven storm surge and flooding, which are ultimately the result of water driven by hurricane winds or the swelling of rivers following intense rainfall. These secondary effects cause additional types of failure, for instance: the high-velocity wash-through of lower floors of buildings near the coast; and the inundation of buildings further inland by steadily rising floodwaters. Storm-surge effects can vary tremendously between hurricanes, depending on such factors as sea-surface pressure, distance from the hurricane center, local offshore (bathymetry) and onshore terrains, and tidal stages at landfall (Saffir 2003).

The wind velocity exerted by a hurricane reaches a maximum in the forward-right portion of the storm. Accordingly, wind-pressure and storm-surge effects are expected to be most severe on the "right" side of the storm (the east side of the storm, in the case of Hurricane Katrina moving north), with windspeeds generally dissipating with the distance from the eye. Similarly, wind-pressure and storm-surge effects are typically expected to be less on the "left" side of the storm (the west side in the case of Hurricane Katrina).

U.S. hurricanes are categorized by their windspeed according to the Saffir-Simpson Scale (summarized in Table 1-1). This scale classifies hurricanes in categories 1-5 according to sustained windspeeds (averaged over 1 minute, at a height of 10 m, over open water) and presents a general estimate of wind damage potential. The scale also presents estimated storm-surge levels and surge disaster potentials that may accompany the sustained windspeeds, but the official classification is based on the windspeed alone.

1.3 Hurricane Katrina: Unique Among Storms

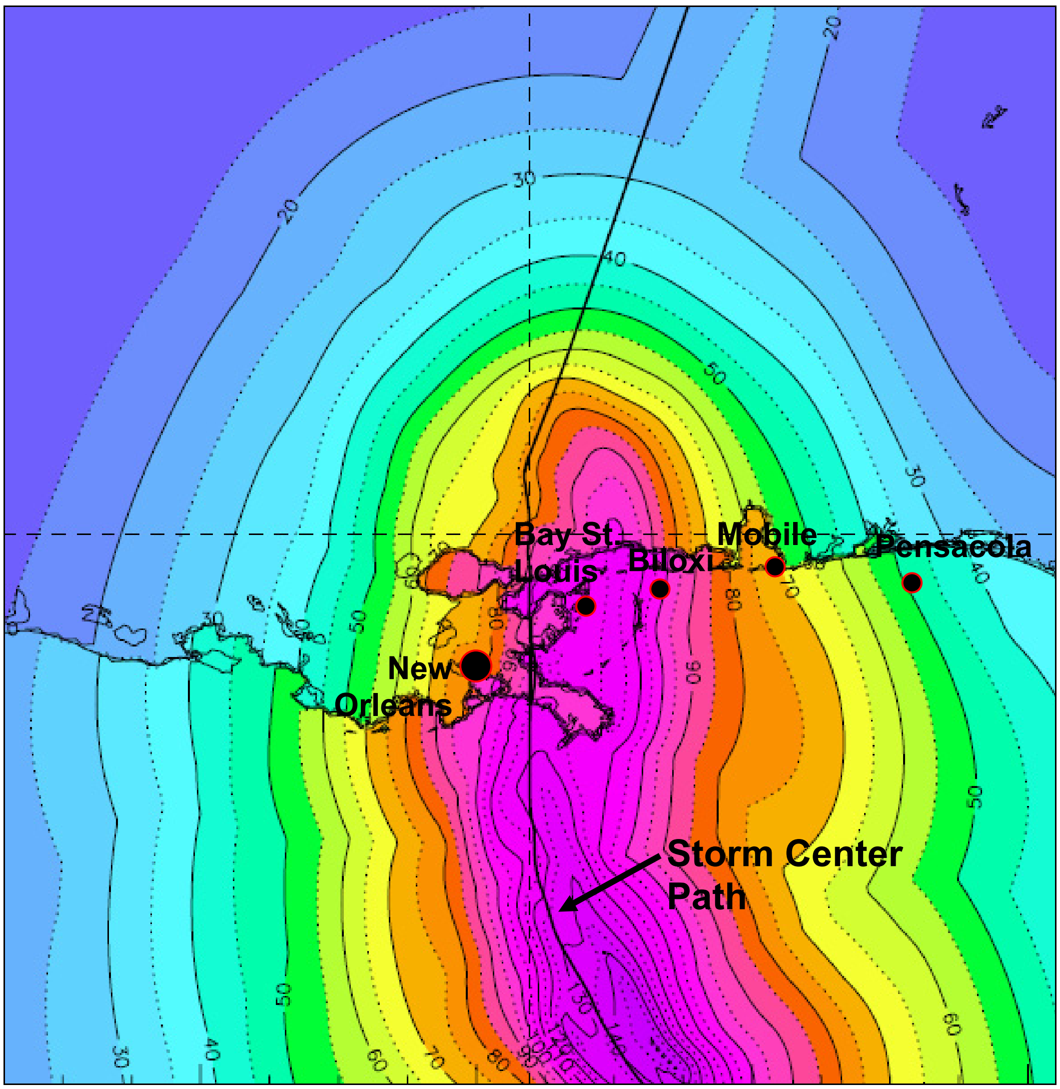
Figure 1-2 shows the estimated distribution of the maximum sustained windspeeds in Hurricane Katrina, assembled by NOAA (2005e). Although measurements made by NOAA's Hurricane Research Division prior to the

Table 1-1. Saffir-Simpson Scale of Potential Hurricane Damage

Category	Sustained Windspeed at 10 m Over Water (mph)	Maximum Expected Storm Surge	Potential Wind Damage	Potential Storm-Surge Damage
1	74-95	4-5 ft	No real damage to buildings. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs.	Low-lying coastal roads inundated. Minor pier damage.
2	96-110	6-8 ft	Some roofing material, door, and window damage of buildings. No major damage to buildings. Considerable damage to shrubbery and trees with some trees blown down. Major damage to exposed mobile homes.	Coastal roads and low-lying inland roads inundated. Considerable damage to piers.
3	111-130	9-12 ft	Some structural damage to small buildings with a minor amount of curtainwall failures. Damage to shrubbery and trees with foliage blown off trees and large trees blown down. Mobile homes destroyed.	Serious flooding at coast and many smaller structures near coast destroyed. Larger structures near coast damaged by battering waves and floating debris.
4	131-155	13-18 ft	Extensive damage to roofing materials, windows, and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. Shrubs and trees blown down. All signs down.	Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris.
5	> 155	> 18 ft	Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in doors and windows. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes.	Major damage to lower floors of all structures less than 15 ft above sea level within 500 yards of shore.

Saffir 2003

storm reaching land indicated maximum sustained winds exceeding 170 mph (Category 5), the storm weakened significantly in the 18 hours preceding landfall. Initially reported to be a Category 4 hurricane at landfall, detailed post-storm analysis later indicated that the storm was actually a Category 3 (based on sustained windspeeds), but with tremendous storm-surge capabilities held over from the storm's prior Category 5 status (Knabb et al., 2005). Figure 1-2 indicates that maximum sustained windspeeds in Mississippi likely did not exceed 120 mph.



NOAA: http://www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/wind.html

Figure 1-2. Spatial distribution of estimated maximum sustained windspeeds (mph) in Hurricane Katrina. Sustained windspeeds are averaged over 1 minute and measured at (or adjusted to) a standard height of 10 m above surface.

The spatial distribution of maximum windspeeds in Figure 1-2 shows them to be higher in Mississippi (to the east of the storm center) than in the New Orleans area, and also shows a lessening of windspeeds prior to landfall. Hurricane Katrina's landfall near the Louisiana-Mississippi border placed the Mississippi Coast in the classically vulnerable right side of the hurricane. The city of New Orleans falls in the (typically) less-vulnerable left side of the storm; indeed, Knabb et al., (2005) report that windspeeds in New Orleans likely did not exceed Category 1 or 2 levels. While the west side of the hurricane did experience lower windspeeds compared to the east (NOAA 2005e; WEMITE 2005; FCMP 2005), the particular location of Lake Pontchartrain to the north of the city resulted in water being pushed towards New Orleans, stressing the miles of levees constructed to hold back the lake and the network of canals. Coupled with the below-sea-level elevation of the city, this situation proved disastrous as floodwaters poured into the city, creating additional hazards.

In the case of Hurricane Katrina, overall primary wind effects were relatively minor compared to such major hurricanes as Andrew (1992) and Charley (2004); however, the horrific "secondary" storm-surge and flooding were responsible for an overwhelming majority of losses in both Mississippi and Louisiana, making this storm quite unique in terms of the number of hazards involved. Insurance industry officials estimate that Hurricane Katrina's insured losses could reach $40-55 billion, making it the most costly hurricane to strike the United States (*Insurance Journal* 2005) and possibly the world's most costly hurricane ever, according to the Swiss Reinsurance organization (*USA Today* 2005).

1.4 Importance of Post-disaster Reconnaissance

Reconnaissance activities aimed at documenting damage conditions following windstorms are important for rapidly assessing damage and losses, understanding the effect of these storms on the built environment, evaluating the effectiveness of mitigation measures (building codes and/or construction practices), and gauging the progress of windstorm mitigation over time. With proper analysis and implementation, such studies can help to lessen or eliminate the tragic consequences of future windstorms.

It is crucial that uniform and consistent assessments be made in the wake of windstorms such as Hurricane Katrina, because of their use in the long-term monitoring of progress in windstorm-resistant construction and reconstruction. However, a number of barriers to conducting complete and uniform surveys have emerged in engineering-oriented investigations of post-windstorm damage areas performed over the past four decades (Womble et al., 2005; Womble 2005). These most notably include: (1) the inability to document the damage states of all buildings in large areas both rapidly and in detail before cleanup efforts have commenced; (2) the inability to examine and document the "pristine" spread of windborne debris, which is frequently moved before investigators can arrive at the damage scene; (3) the inability to access damaged areas isolated by either law-enforcement agencies or by natural causes (e.g., fallen trees, washed-out roadways and bridges); (4) the inability to rapidly screen large areas for relative levels of damage, for use in the strategic planning of statistically sampled damage surveys, especially in unfamiliar areas; and (5) a lack of consistent (uniform) damage measures stemming from natural biases found to exist between investigators in assigning damaging-state rankings to damaged structures (WISE 2004). Such barriers can lead to costly time delays in the assessment of damage across a wide area and in the strategic deployment of emergency response personnel and supplies, together with the loss of valuable information for long-term research leading to improved understanding of severe wind effects on the built environment.

As a core component of the reconnaissance process, post-windstorm damage surveys have traditionally been undertaken through the detailed ground-based survey. However, the benefits of augmenting this conventional approach with advanced technology are increasingly recognized. The emergence of remote sensing as an accepted source of post-disaster information can be traced back to the September 11, 2001 attacks on the World Trade Center towers, where it was widely deployed at Ground Zero for situation assessment (Huyck and Adams, 2002). Within the wind-engineering arena, Hurricane Charley, which struck the Gulf Coast of Florida in August 2004, marked the initial deployment of satellite remote sensing combined with ground truthing for perishable damage assessment by the WISE (Wind Science and Engineering) Research Center at Texas Tech University, in collaboration with MCEER researchers at ImageCat, Inc. In this instance, pre- and post-hurricane satellite imagery was integrated within the technology-driven VIEWS™ field reconnaissance system and used to record the damage state of more than 10,000 buildings (Adams et al., 2004b; Womble et al., 2005; Womble 2005). The 2005 hurricane season has seen the implementation of information derived from remote sensing data by risk modeling companies such as Risk Management Solutions Inc. (RMS), to help generate initial loss estimates (RMS 2005; DigitalGlobe 2005).

As will be described in this report, in the case of Hurricane Katrina, MCEER researchers employed advanced technology to identify hard-hit areas, to guide the planning of field reconnaissance activities, and to provide in-field support. The MCEER field team deployed with the objectives of: (1) performing rapid and widespread assessments of damage at a per-building scale; and (2) preserving the perishable damage characteristics of this unique multi-hazard event for future research activities. Remote sensing data from optical and radar sensors, captured in the days following Hurricane Katrina, were analyzed using a spatially tiered framework, providing response teams, including MCEER, with a rapid and synoptic view of the affected areas. Through expert interpretation, these datasets went on to yield important information for disaster managers concerning the nature, severity and extent of building damage at regional and neighborhood scales. Ground truthing (by collecting georeferenced photographs and/or video using the VIEWS™ field reconnaissance system) provides a detailed perspective and serves to verify the remote sensing damage signatures. To ensure coverage of multi-hazard effects, these reconnaissance activities spanned two geographic areas:

- The Mississippi Coast, for investigation of damage to structures due to wind pressures and storm surge
- New Orleans, for investigation of damage to structures due to flood inundation and levee breach.

1.5 Report Organization

The purpose of this report is to document the integrated implementation of remote sensing and VIEWS™ field reconnaissance technologies for characterizing the multi-hazard impacts of Hurricane Katrina upon the built environment. Chapter 2 begins by reviewing the availability of remote sensing data for post-Hurricane Katrina reconnaissance in general, and specifically the assessment of hurricane-induced damage along the Mississippi Coast and in New Orleans. Chapter 3 goes on to present a theoretical framework for the use of remote sensing data to plan and support field reconnaissance in these areas. The operational implementation of remote sensing for post-Hurricane Katrina damage assessment is documented in Chapter 4, while Chapter 5 describes the collection of in-field observations using the VIEWS™ survey system. Chapter 6 presents new insights into the integration of remote sensing and VIEWS™ field-reconnaissance data for damage assessment, and Chapter 7 concludes this report with a summary of key findings and directions for future research.

This deployment for Hurricane Katrina serves as a part of MCEER's long-term Thrust Area 3 (Emergency Response and Recovery) research efforts into multi-hazard post-disaster response and recovery (MCEER, 2005a,b).

2.0 Remote Sensing Data

In the aftermath of Hurricane Katrina, remote sensing data from satellite and airborne platforms were collected rapidly and made available to support post-disaster situation assessment and response activities in Mississippi and Louisiana. While weather satellites provided constant monitoring of the storm track, given the limited ground access due to surge inundation and flooding, remote sensing imagery constituted one of the first available sources of information on damage conditions.

The following sections describe the remote sensing data available for assessment of post-disaster situations on the Mississippi Coast and in New Orleans, Louisiana. Specifications for the various types of remote-imaging sensors examined in this report are given in Table 2-1. Timelines for the collection of images are shown in Table 2-2 (Mississippi Coast) and Table 2-3 (New Orleans). These data cover a wide range of platforms and data types – including optical/radar, moderate/high-resolution, and satellite/airborne.

From Table 2-1, the available post-Hurricane Katrina remote sensing images span a wide variety of spatial resolutions (pixel size). The spatial resolution of an image determines the ability to view individual features such as buildings and bridges. It also affects the ability to monitor and assess damage conditions, and depends on the nature of the hazard itself (e.g., flooding, wind pressure, and storm surge). For instance, pixel sizes of approximately 10 m or smaller are necessary to discern the presence and location of individual buildings, while much smaller pixels (on the order of 1 m or less) are necessary to discern damage conditions of individual buildings (such as wind pressure damage to roofs). On the other hand, widespread flooding, such as in New Orleans following Hurricane Katrina, can be detected and monitored using less-detailed moderate-resolution imagery.

In addition to spatial factors, spectral resolution also influences the use and usefulness of the data. Materials have different reflectance values in different portions of the electromagnetic spectrum, and thus features of interest within the images (e.g., construction materials, water, and vegetation) can be identified by unique and distinguishing characteristics. The use of multispectral remote sensing systems (which measure the reflectance of materials in multiple portions of the electromagnetic spectrum) is therefore critical for the separation of constituent materials within an image, and for the interpretation of images for damage assessment.

Table 2-1. Specifications for Remote Sensing Data

Category	System	Spatial Resolution (Nominal)	Platform	Internet Sources
Low-Resolution Satellite	METEOSAT	2.5/5 km	Visible, Infrared, and Thermal Infrared Satellite	http://www.nottingham.ac.uk/meteosat/graphif.shtml
	GOES	1 km	Optical, Infrared, Microwave Satellite	http://rsd.gsfc.nasa.gov/rsd/images http://www.goes.noaa.gov/
	Terra-MODIS	250m - 1km	Optical Satellite	http://modis.gsfc.nasa.gov/
	Aqua-MODIS	250m - 1km	Optical Satellite	http://modis.gsfc.nasa.gov/
Moderate-Resolution Satellite	Landsat-5 TM	30 m	Optical Satellite	http://www.landsat.org
	Landsat-7 ETM	30 m	Optical Satellite	
	NigeriaSAT	32 m	Optical Satellite	http://www.nasrda.org/
	Terra-ASTER	15/30/90 m (Varies by band)	Thermal-Infrared Satellite	http://asterweb.jpl.nasa.gov/
	EO-1-ALI	10m/30 m (Varies by band)	Optical Satellite	http://eo1.usgs.gov/ali.php
	SPOT-2	20 m	Optical Satellite	http://www.spotimage.fr/
	SPOT-5	10 m	Optical Satellite	http://www.spotimage.fr/
	Radarsat Fine Beam (F)	8 m	Synthetic-Aperture Radar Satellite	http://www.rsi.ca/
	Radarsat Standard Beam (S1-7)	25 m	Synthetic-Aperture Radar Satellite	
	Radarsat Extended High Beam (EXTH-1-6)	25 m	Synthetic-Aperture Radar Satellite	
	Radarsat Wide Beam (W1-3)	30 m	Synthetic-Aperture Radar Satellite	
High-Resolution Satellite	QuickBird	61 cm	Optical Satellite	http://www.digitalglobe.com
	IKONOS	1 m	Optical Satellite	http://www.spaceimaging.com
	OrbView	1 m	Optical Satellite	http://www.orbimage.com
High-Resolution Aerial	VIEWS™ (HDV)	5-15 cm (varies with flight altitude)	Optical Aerial	http://www.imagecatinc.com
	NOAA Aerial Images	37 cm	Optical Aerial	http://ngs.woc.noaa.gov/katrina
	USACE Aerial Images	30 cm	Optical Aerial	http://www.tec.army.mil/Katrina

Table 2-2. Timeline Showing the Acquisition of Remote Sensing Data for the Mississippi Coast

Color Key:	Low-Resolution Satellite
	Moderate-Resolution Satellite
	High-Resolution Satellite
	High-Resolution Aerial

Date	System	Sensor Type	Comments
8/29/2005	***Hurricane Katrina Landfall in Louisiana/Mississippi***		
	QuickBird	Optical Satellite Images	Area extending from east of New Orleans, along Mississippi Coast, to Mobile Bay (urban areas obscured by heavy cloud cover)
8/30/2005	NOAA	Digital Aerial Images	Coastal (beachfront) areas from Bay St. Louis to Pascagoula, MS.
	OrbView	Optical Satellite Images	Cloud-covered area of western Mississippi Coast
	Terra-MODIS	Optical Satellite Images	Biloxi to Alabama
8/31/2005	NOAA	Digital Aerial Images	Coastal area near Bay St. Louis, MS (available online on Sept. 1)
	QuickBird	Optical Satellite Images	Coverage of coastal areas from Ocean Springs westward to Louisiana (heavy cloud cover, limited visibility for urban areas)
	Landsat-5 TM	Optical Satellite Images	Greater Mississippi Coast (partly cloudy)
	Aqua-MODIS	Optical Satellite Images	Louisiana to Biloxi
9/02/2005	OrbView	Optical Satellite Images	Cloud-free area covering majority of Mississippi Coast
	IKONOS	Optical Satellite Images	Mississippi Coast: Pass Christian to Mobile Bay
	Radarsat-S5	Radar Satellite Images	
	SPOT-5 (10m)	Optical Satellite Images	Biloxi, Ocean Springs
	NigeriaSAT (32 m)	Optical Satellite Images	Entire Mississippi Coast
9/03/2005	USACE	Digital Aerial Images	Aerial image collection by USACE Sept. 3–25
	QuickBird	Optical Satellite Images	Coverage of coastal areas from Gulfport to Pascagoula (most areas obscured by clouds)
9/04/2005	NOAA	Digital Aerial Images	Mississippi Coast (extending prior coverage further inland)
	Radarsat-EXTH-6	Radar Satellite Images	
	Radarsat-W1	Radar Satellite Images	

Table 2-2 (continued). Timeline Showing the Acquisition of Remote Sensing Data for the Mississippi Coast

Date	System	Sensor Type	Comments
9/05/2005	OrbView	Optical Satellite Images	Slightly inland area covering eastern portion of Mississippi Coast
9/06/2005	QuickBird	Optical Satellite Images	Entire Mississippi Coast
	Radarsat-EXTH-3	Radar Satellite Images	
9/07/2005	IKONOS	Optical Satellite Images	Mississippi barrier islands
9/08/2005	IKONOS	Optical Satellite Images	Majority of Mississippi Coast (covered with clouds)
	Landsat-7 ETM	Optical Satellite Images	Greater Mississippi Coast
9/13/2005	IKONOS	Optical Satellite Images	Bay St. Louis, Pass Christian, Pascagoula (partially cloudy)
9/16/2005	Landsat-5 TM	Optical Satellite Images	Greater Mississippi Coast
	Radarsat-S7	Radar Satellite Images	
9/19/2005	Radarsat-S3	Radar Satellite Images	
9/28/2005	Radarsat-W1	Radar Satellite Images	
10/02/2005	Landsat-5 TM	Optical Satellite Images	Greater Mississippi Coast (partly cloudy)
10/10/2005	Landsat-7 ETM	Optical Satellite Images	Greater Mississippi Coast
10/12/2005	QuickBird	Optical Satellite Images	Coverage of Gulfport and Biloxi
10/16/2005	IKONOS	Optical Satellite Images	Gulfport-Biloxi
10/24/2005	IKONOS	Optical Satellite Images	Pass Christian
10/26/2005	Landsat-7 ETM	Optical Satellite Images	Greater Mississippi Coast
10/27/2005	IKONOS	Optical Satellite Images	Bay St. Louis to Slidell, LA
10/31/2005	OrbView	Optical Satellite Images	Cloud-free area of Mississippi Coast from Waveland/Bay St. Louis to Gulfport
11/04/2005	IKONOS	Optical Satellite Images	Gulfport (covered by clouds)
11/10/2005	IKONOS	Optical Satellite Images	Gulfport
11/11/2005	Landsat-7 ETM	Optical Satellite Images	Greater Mississippi Coast
11/15/2005	IKONOS	Optical Satellite Images	Gulfport (covered by clouds)
11/18/2005	IKONOS	Optical Satellite Images	Gulfport
11/22/2005	QuickBird	Optical Satellite Images	Central Mississippi Coast – Biloxi

Table 2-3. Timeline Showing the Acquisition of Remote Sensing Data for New Orleans

Color Key:	
	Low-Resolution Satellite
	Moderate-Resolution Satellite
	High-Resolution Satellite
	High-Resolution Aerial

Date	Source	Type of Data	Comments
8/29/2005	***Hurricane Katrina Landfall in Louisiana/Mississippi***		
	QuickBird	Optical Satellite Images	Area extending from east of New Orleans, along Mississippi Coast, to Mobile Bay (urban areas obscured by clouds)
8/30/2005	VIEWS™	High-Definition Aerial Images	Greater New Orleans
	OrbView	Optical Satellite Images	Cloud-free area of central New Orleans (shows most of flooded area)
	Terra-MODIS	Optical Satellite Images	Shows flooded areas
	Landsat-7 ETM	Optical Satellite Images	Coverage of New Orleans and surrounding areas (partially obscured by clouds)
	SPOT-2	Optical Satellite Images	Greater New Orleans area
8/31/2005	NOAA	Digital Aerial Images	Greater New Orleans
	QuickBird	Optical Satellite Images	Coverage of greater New Orleans area. Shows water pouring through levee breach at Surekote Road. Also shows levee breach at 17th Street Canal.
	Aqua-MODIS	Optical Satellite Images	Shows flooded areas
9/01/2005	NOAA	Digital Aerial Images	Southern portions of New Orleans
	Radarsat-S6	Radar Satellite Images	
9/02/2005	NOAA	Digital Aerial Images	Selected areas of New Orleans bordering Lake Pontchartrain
	Radarsat-S5	Radar Satellite Images	
	SPOT-5	Optical Satellite Images	Greater New Orleans area
9/03/2005	USACE	Digital Aerial Images	Aerial image collection by U.S. Army Corps of Engineers Sept. 3–25
	QuickBird	Optical Satellite Images	Widespread coverage of greater New Orleans area (imagery purchased for field deployment)
9/05/2005	IKONOS	Optical Satellite Images	Western New Orleans
	Radarsat-W1	Radar Satellite Images	
9/06/2005	EO-1- ALI	Optical Satellite Images	
9/07/2005	Landsat-5 TM	Optical Satellite Images	Complete coverage of New Orleans and surroundings
	NOAA	Digital Aerial Images	Selected areas of New Orleans

Table 2-3 (continued). Timeline Showing the Acquisition of Remote Sensing Data for New Orleans

Date	System	Sensor Type	Comments
9/08/2005	QuickBird	Optical Satellite Images	Eastern portion of New Orleans and Lake Pontchartrain (Reveals eastward extent of flood inundation)
	IKONOS	Optical Satellite Images	Coverage for greater New Orleans (eastern portion covered with clouds)
	Radarsat-W2	Radar Satellite Images	
	EO-1- ALI	Optical Satellite Images	Shows some floodwaters have receded since Sept. 6
9/09/2005	Radarsat-F	Radar Satellite Images	Central New Orleans
9/13/2005	Terra-ASTER	Optical Satellite Images	Shows flooded areas
9/14/2005	Radarsat-S2	Radar Satellite Images	
9/15/2005	Landsat-7 ETM	Optical Satellite Images	New Orleans and surrounding areas
9/18/2005	Radarsat-S7	Radar Satellite Images	
9/19/2005	Radarsat-S3	Radar Satellite Images	
9/21/2005	QuickBird	Optical Satellite Images	Eastern portion of New Orleans and Lake Pontchartrain (Reveals eastward extent of flood inundation)
	Radarsat-S1	Radar Satellite Images	
9/25/2005	Radarsat-S6	Radar Satellite Images	
9/27/2005	OrbView	Optical Satellite Images	Cloud-free area of southeastern New Orleans
9/30/2005	OrbView	Optical Satellite Images	Partly cloudy area of eastern New Orleans
10/04/2005	QuickBird	Optical Satellite Images	Eastern portion of New Orleans and Lake Pontchartrain
10/05/2005	IKONOS	Optical Satellite Images	Eastern New Orleans
10/09/2005	Landsat-5 TM	Optical Satellite Images	Complete coverage of New Orleans and surroundings
10/11/2005	OrbView	Optical Satellite Images	Partly cloudy area of eastern New Orleans
10/14/2005	OrbView	Optical Satellite Images	Partly cloudy area of eastern New Orleans
10/17/2005	Landsat-7 ETM	Optical Satellite Images	Complete coverage of New Orleans and surroundings
10/22/2005	QuickBird	Optical Satellite Images	Central portion of New Orleans
10/31/2005	OrbView	Optical Satellite Images	Cloud-free area of central and eastern New Orleans
11/02/2005	Landsat-7 ETM	Optical Satellite Images	Complete coverage of New Orleans and surroundings
	IKONOS	Optical Satellite Images	West and Central New Orleans
11/07/2005	IKONOS	Optical Satellite Images	West and Central New Orleans
11/09/2005	QuickBird	Optical Satellite Images	Central portion of New Orleans (~50% clouds)
11/10/2005	IKONOS	Optical Satellite Images	Eastern New Orleans
11/18/2005	Landsat-7 ETM	Optical Satellite Images	Complete coverage of New Orleans and surroundings

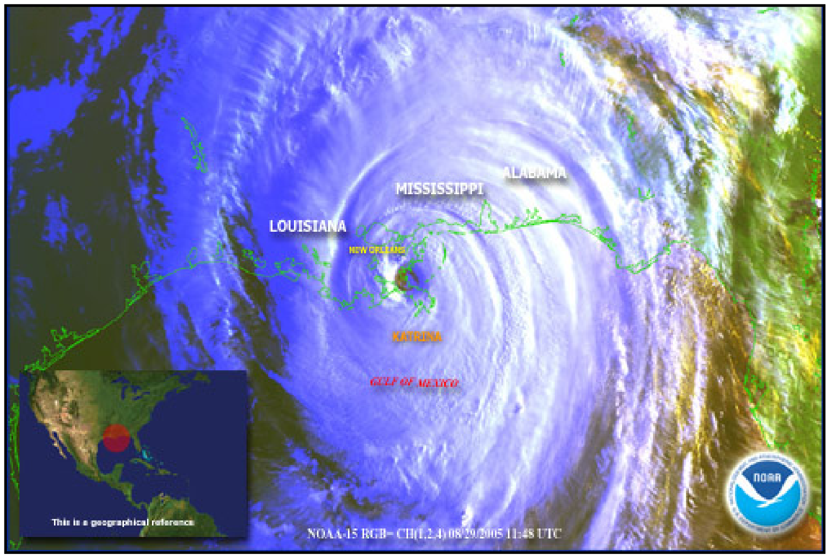
While post-disaster remote sensing images accurately capture damage caused by a disaster, previous studies suggest that pre-disaster coverage is extremely useful for establishing the normal (non-damaged) situation (e.g., Adams 2004; Ghosh et al., 2005; Womble et al., 2005). Serving as a benchmark for comparison, the use of pre-disaster imagery significantly increases confidence limits surrounding remote sensing-based damage evaluations, particularly for moderate damage states. The availability of recent remote sensing datasets captured prior to Hurricane Katrina is summarized in Section 2.3. Appendix A goes on to provide a listing of selected Internet resources related to both pre- and post-event remote sensing coverage for Hurricane Katrina.

2.1 Post-Hurricane Satellite Imagery

Earth-imaging satellites offer the advantage of providing overall (synoptic) views of the Earth's surface on a routine basis. The frequency with which a region of interest can be covered depends on the orbital characteristics of the individual satellites. Presently, satellite imagery is available commercially in a wide range of spatial resolutions (61 cm to >1 km). Application of the various imaging systems (Table 2-1) in disaster damage detection and assessment is largely driven by their spatial resolution. For purposes of this discussion, satellite imaging systems are classified by spatial resolution into low-resolution (≥100 m), moderate-resolution (5 to 100 m), and high-resolution systems (≤5 m).

2.1.1 Low-Resolution Satellite Imagery

Low-resolution earth-observing satellites such as METEOSAT, GOES, Terra-MODIS, and Aqua-MODIS, are commonly used for applications such as land-cover and land-use studies. As such, they are well-suited for the observation and monitoring of regional phenomena, including the tracking of overall weather patterns and providing views of the overall hurricane itself (Figure 2-1). The MODIS sensor onboard NASA's Terra satellite captured low-resolution images of coastal Mississippi areas on August 30, showing flooding in the rivers draining to the Gulf of Mexico (Figure 2-2). The Aqua-MODIS sensor captured images on August 31 clearly showing the flooding conditions in the City of New Orleans and in the land areas between Lake Pontchartrain and Lake Borgne (Figure 2-3).



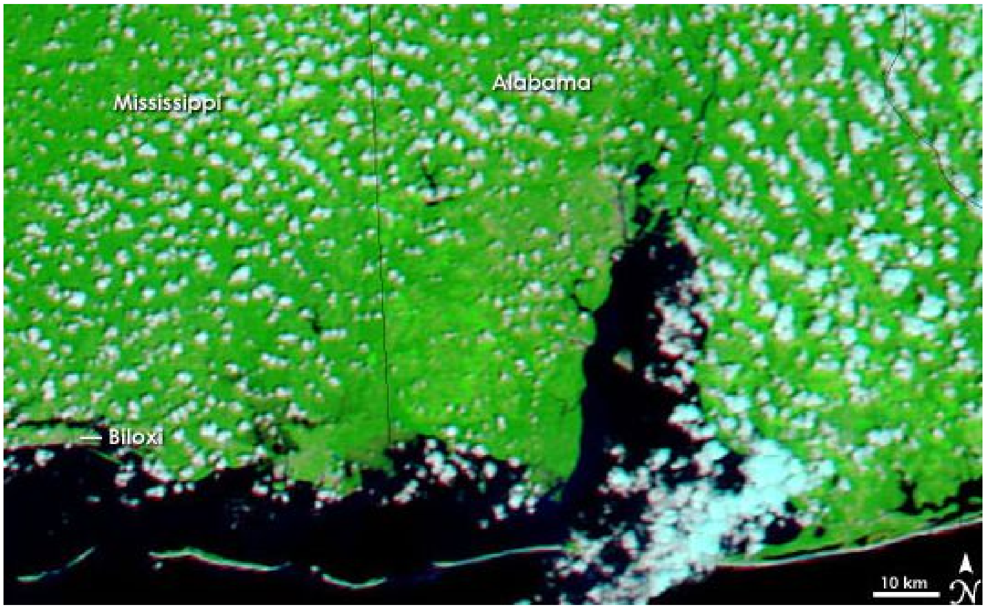
Satellite imagery from NOAA
http://www.osei.noaa.gov/Events/Tropical/Gulf_Mexico/2005/TRCkatrina241_N5L.jpg

Figure 2-1. NOAA'S GOES 1km-resolution weather satellite view of Hurricane Katrina making landfall in Louisiana on August 29, 2005.

2.1.2 Moderate-Resolution Satellite Imagery

A large number of earth-observing satellites capture imagery within the moderate-resolution range of approximately 5 to 100 m, including optical systems such as Landsat-5 Thematic Mapper (TM), SPOT, NigeriaSAT, and EO-1; thermal-infrared satellites such as Terra-ASTER; and synthetic-aperture radar (SAR) satellites such as Radarsat. The reasonable spatial resolution offered by these systems, together with the large area spanned by each scene, supports the observation of regional-scale phenomenon, such as the widespread flooding experienced by New Orleans following Hurricane Katrina. Systems such as Landsat also offer the ability to detect storm-surge scouring and debris transport. Moderate-resolution systems, however, are not generally able to detect damage to individual buildings (such as wind-pressure damage to building roofs).

The Landsat-7 and SPOT-2 satellites captured some of the earliest moderate-resolution images of New Orleans on August 30, showing the extensive flood areas within the city (Figure 2-4). However, in the case of Landsat-7, the imagery is subject to "no-data" issues due to failure of the scan line corrector in 2003 (resulting in a series of black streaks across the images). Subsequent



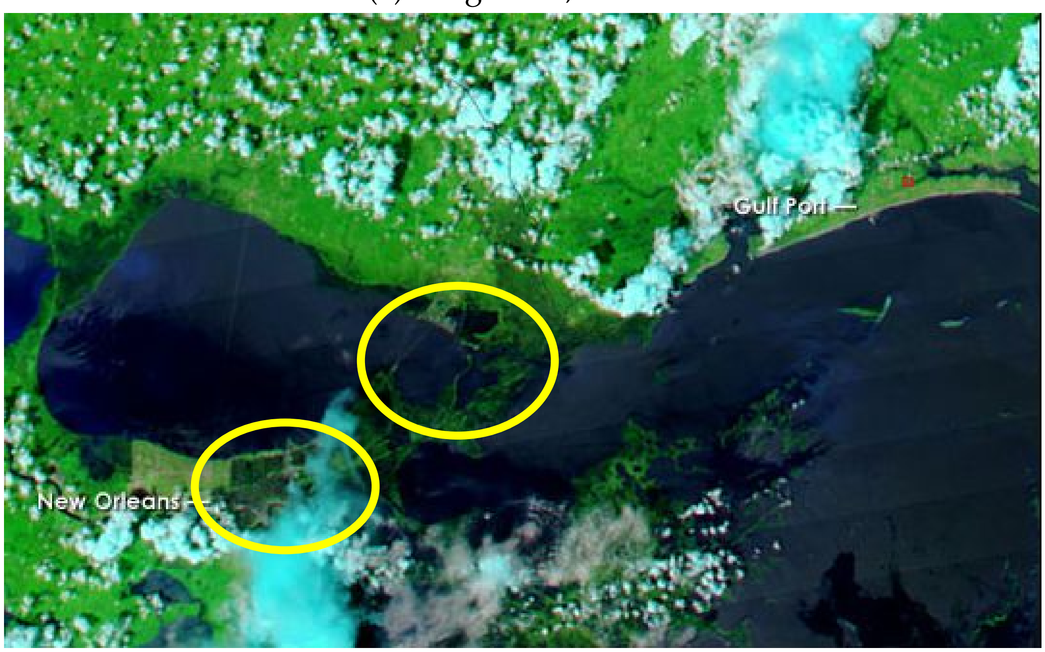
(a) August 27, 2005

(b) August 30, 2005

MODIS imagery from NASA, Jeff Schmaltz, MODIS Land Rapid Response Team, NASA GSFC
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13090

Figure 2-2. NASA's Terra-MODIS 250m-resolution sensor shows (a) pre-hurricane conditions in the rivers of southeast Mississippi and southwest Alabama on August 27, 2005 and (b) post-hurricane flood levels on August 30, 2005, one day after Hurricane Katrina's landfall in Louisiana.

(a) August 27, 2005



(b) August 31, 2005

NASA MODIS imagery from Jeff Schmaltz, MODIS Land Rapid Response Team, NASA GSFC
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13095

Figure 2-3. NASA's Aqua-MODIS 250-m imagery shows pre-hurricane conditions on August 27 and post-hurricane flooding extent in New Orleans and nearby areas on August 31.

(a) April 26, 2005

(b) August 30, 2005

NASA imagery from Jesse Allen with data provided by USGS EROS Data Center and Landsat Project Science Office at Goddard Space Flight Center http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13094

Figure 2-4. NASA's Landsat-7 30-m imagery reveals flooding extent in New Orleans on August 30, 2005.

image collections (Table 2-3) by moderate-resolution satellites including SPOT, Earth Oberserving-1 (EO-1), Terra-ASTER, and Landsat show the progression of rising and receding flood waters (Figure 2-5). Landsat-5 and Landsat-7 imagery was made available through the USGS public disaster ftp site (*ftp://edcftp.cr.usgs.gov/pub/data/disaster*).

Radarsat captured moderate-resolution radar coverage of both the Mississippi Coast and New Orleans using different imaging modes. The images collected include "fine" (8 m nominal resolution), "standard" (25 m), and "wide" (30 m). Radarsat captured early imagery of the hurricane system on August 28, as it approached land (Figure 2-6). The first Radarsat imagery for the Mississippi Coast following Hurricane Katrina's landfall was acquired on September 2. The first post-hurricane Radarsat coverage for New Orleans was also acquired on September 2, with subsequent collections on September 5 and September 9 (Figure 2-7). The SAR-based interpretation of flooded areas within urban settings is complex due to multiple reflections of the microwave signals from the water surface and surrounding buildings (CSA, 2005); research is ongoing to better understand urban flooding signatures within SAR imagery.

2.1.3 High-Resolution Satellite Imagery

The high-resolution satellites offer the newest innovations in earth-observing technology for disaster response. Available since 1999, this class of satellites is finding ever-growing usage in reconnaissance, because they offer enough detail to observe damage conditions of individual structures (Adams et al., 2004a,b,c; Womble 2005; Womble et al., 2005), while capturing a large geographic area within a single frame. While aerial imagery offers comparable or better resolution, many frames are required to achieve coverage, which typically increases data collection and processing times.

The current set of high-resolution optical satellites consists of QuickBird, which offers the highest resolution presently available from commercial satellites (61 cm), and the 1m-resolution IKONOS and OrbView satellites. Previous events such as the Bam earthquake (Adams et al., 2004a,d), and Hurricanes Charley and Ivan (Adams et al., 2004b; Womble et al., 2005) demonstrate the effectiveness of these high-resolution systems for detecting flood conditions, storm-surge debris, windborne debris, and wind-pressure damage to roofs.

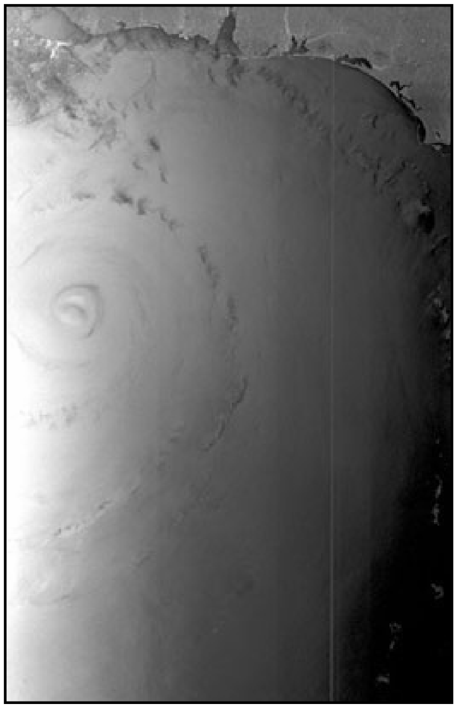
As is frequently the case in the immediate wake of a hurricane, collection of post-Hurricane Katrina remote sensing imagery was complicated by cloud

(a) September 6, 2005

(b) September 8, 2005

NASA image courtesy Lawrence Ong, EO-1 Mission Science Office, NASA GSFC. Annotations included based on graphic from the New York Times
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13133

Figure 2-5. NASA's EO-1 10-m imagery tracks the diminishing extent of flood waters in New Orleans on (a) September 6 and (b) September 8.



SAR imagery from MDA Corporation
http://gs.mdacorporation.com

Figure 2-6. Radarsat-1 SAR image of Hurricane Katrina approaching Louisiana and Mississippi on August 28, 2005. This image shows the surface of the sea within the hurricane.

SAR imagery from Canadian Space Agency
http://www.space.gc.ca/asc/eng/satellites/radarsat1/featured_north_america.asp and
MDA Corporation *http://gs.mdacorporation.com*

Figure 2-7. Radarsat-1 SAR image (Fine Beam – 8m resolution) of downtown New Orleans acquired on September 9, 2005.

cover remaining from the storm system, which obscured optical satellite views of the ground. For the Mississippi Coast, the QuickBird satellite encountered heavy clouds during its initial collection of images on August 29, within hours of the hurricane's landfall. In a subsequent acquisition on August 31, QuickBird again encountered mostly solid cloud cover, but was able to obtain high-resolution images of limited urban areas (Figure 2-8). OrbView also encountered heavy cloud conditions when obtaining high-resolution images of the western Mississippi Coast on August 30. Both the OrbView and IKONOS satellites were able to capture virtually cloudless, high-resolution-satellite images on September 2. The QuickBird satellite again encountered heavy clouds during a September 3 acquisition, but obtained low-cloud-cover images of the Mississippi Coast on September 6.

For New Orleans, high-resolution images were available to show the progress of flooding. Cloud-free OrbView images of August 30 show flood areas (Figure 2-9). QuickBird images from August 31 also show flooding, as well as water pouring through levee breaches at Surekote Road and at the 17th Street Canal (Figure 2-10). Subsequent image collections (Table 2-3) by IKONOS, OrbView, and QuickBird throughout September, October, and November continue to show the progression of flooding and receding flood waters.

2.2 Post-Hurricane Aerial Imagery

Digital aerial images offer a number of advantages in the remote sensing detection of damage. Aerial image acquisitions are not subject to the fixed-orbit patterns of satellites, and thus enjoy a more flexible schedule for timely image acquisition following a disaster. In many cases, aerial platforms may therefore offer the first available (as well as the highest-resolution) remote sensing imagery of post-disaster areas. Because of the low altitudes possible for aerial imaging, these systems can provide imagery with higher spatial resolutions than present satellite-imaging systems. These low altitudes, however, also necessitate the acquisition of numerous images to cover the same land area as a single satellite image, often causing the acquisition and processing times to increase.

(a) April 12, 2005

(b) August 31, 2005

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com and http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13104

Figure 2-8. QuickBird satellite imagery shows storm-surge damage and wind-pressure damage in Biloxi on August 31, compared to pre-storm (baseline) imagery from April 12, 2005. In this 61-cm high-resolution imagery, individual buildings are clearly evident.

(a) March 9, 2004

(b) August 31, 2005

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com and http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13096

Figure 2-9. QuickBird satellite imagery shows flood waters in New Orleans on August 31, compared to imagery from March 9, 2004. In this 61-cm high-resolution imagery, individual buildings are clearly evident.

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com and http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13101

Figure 2-10. QuickBird 61-cm high-resolution satellite imagery shows flood waters entering New Orleans through levee breaches on August 31.

2.2.1 VIEWS™ Aerial Imagery

One day after Hurricane Katrina made landfall in Louisiana, devastation to New Orleans and the Gulf Coast was recorded through rapid imagery capture under the ImageCat Post-disaster Damage Verification (PDV) program. GPS-referenced, 5-15 cm resolution imagery was acquired by airborne deployment of the VIEWS™ field data collection and visualization system, full details of which are provided in Chapter 5. Georeferenced high-definition video and still photographs recorded the initial storm flooding and subsequent overtopping of the levees surrounding New Orleans (Figure 2-11). Captured on August 29th, prior to either cloud-free post-storm satellite or NOAA airborne coverages, the information provided the earliest known remote sensing coverage of damage within New Orleans.

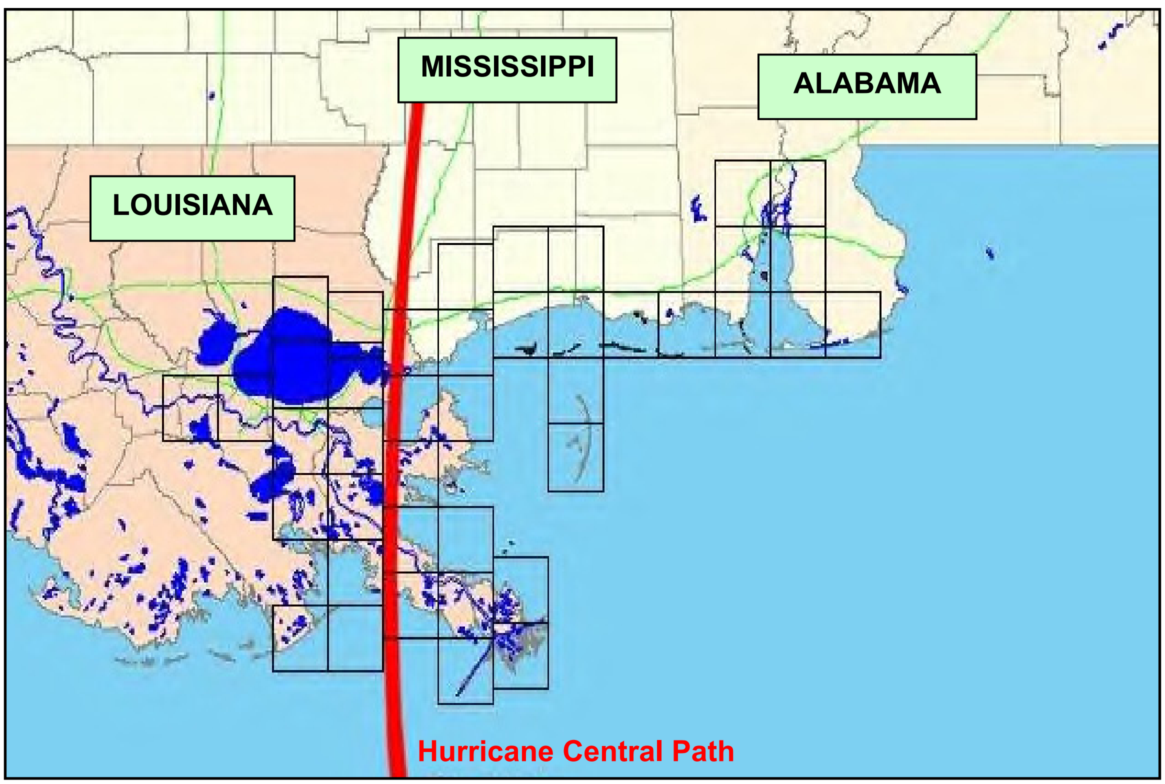
HDV imagery from ImageCat, Inc. www.imagecatinc.com

Figure 2-11. VIEWS™ high-definition aerial imagery acquired from an elevation of 5000 ft shows flooding as well as minor wind damage to roofs in New Orleans.

2.2.2 NOAA Aerial Imagery

On the day following Hurricane Katrina's landfall in Louisiana, NOAA began acquiring 37-cm digital aerial images of the Mississippi Coast (Figures 2-12 and 2-13), followed by the greater New Orleans area on August 31. Aerial photo coverage of the Mississippi Coast was extended inland on September 4, while areas surrounding New Orleans (St. Bernard Parish and the north side of Lake Pontchartrain) and the Mississippi River delta in southeast Louisiana were imaged during the period of September 1–8. In all, approximately 3,700 digital images were collected for Louisiana, Mississippi, and Alabama.

In most cases, these aerial images were made available online on the day following their collection. They were initially posted without geographic referencing. This information is needed to place the images in the correct location on the Earth's surface. However, applying it to the images takes time, and it was initially omitted to expedite public distribution of the imagery. The geographic information was made publicly available in the form of a camera data file, which enabled MCEER researchers at ImageCat to rapidly develop a custom correction algorithm to coarsely register the images



Base imagery from NOAA

Figure 2-12. General areas (noted by black boxes) of NOAA aerial-image coverage in Louisiana, Mississippi, and Alabama in September 2005, following Hurricane Katrina.

(a) September 2004 (b) August 30, 2005

Aerial imagery from NOAA

Figure 2-13. A comparison NOAA 37-cm aerial images acquired before and after Hurricane Katrina shows storm-surge and wind-pressure damage in Gulfport, Mississippi. Comparisons are from (a) September 2004 and (b) August 30, 2005.

for broadscale damage assessment. A coarsely registered set of images was also distributed via Google Earth (*http://earth.google.com and http://mceer.Buffalo.edu/research/Reconnaissance/Katrina8-28-05/views_dge.asp*). This was extensively used by evacuated homeowners to gauge the level of damage sustained by their properties. These NOAA scenes were among the earliest available remote sensing images, and as such, were also useful for damage assessment and reconnaissance planning. A fully registered and mosaiced version of the imagery was made available through the USGS website several months later.

2.2.3 USACE Aerial Imagery

The U.S. Army Corps of Engineers (USACE) obtained 30-cm digital aerial images of the storm-ravaged areas in Louisiana, Mississippi, and Alabama, beginning on September 3 and continuing for several weeks. The dense coverage area included 12,000 square miles, including New Orleans and surrounding areas, the southeastern tip of Louisiana (Mississippi River delta), the north side of Lake Pontchartrain, virtually all areas of the Mississippi Coast, and portions of southwestern Alabama (Mobile and surrounding areas). The USACE aerial images were made available for public use through the USGS disaster ftp site (see Appendix A) in a compressed MrSID file format. This reduced file sizes significantly compared with tif or jpeg formats, accelerating both the download process and availability of the data for operational use.

2.3 Pre-Hurricane Imagery

Pre-hurricane images also play a vital role in the detection and assessment of damage. Pre-storm images provide a "no-damage" baseline for change-detection operations, which compare pre- and post-storm images on a regional and/or per-building basis. From previous studies, the use of pre-event imagery significantly increases the confidence of damage assessment results, particularly for moderate damage levels.

For the investigation of Hurricane Katrina damage, pre-storm satellite imagery such as Landsat-5 and QuickBird, provided this important comparative baseline. Recent Landsat-5 imagery for the New Orleans area and Mississippi Coast was accessed through the USGS disaster website (see Appendix A), with an older scene dating back to 2000 obtained from the Stennis Space Center website (*https://zulu.ssc.nasa.gov/mrsid*).

In the case of airborne imagery, lidar coverage depicting coastal topography within many areas of the U.S. is available from NOAA (*http://ekman.csc.noaa.gov/TCM/*). In the aftermath of Hurricane Katrina, the lidar data were also posted on the USGS disaster website for use in flood-elevation mapping (see Sections 4.3 and 4.4). NOAA aerial images acquired in 2004 following Hurricane Ivan (NOAA 2004) were available for a few areas (e.g., Gulfport and Biloxi, Mississippi); as the effects of Hurricane Ivan on buildings in these locations was minimal, the post-event images also serve as a set of pre-storm data for Hurricane Katrina.

2.4 Summary of Key Findings

- Remote sensing imagery showing the unfolding situation in Mississippi and New Orleans was captured in the days and weeks following Hurricane Katrina by low-, moderate-, and high-resolution optical and radar sensors.

- For New Orleans, the VIEWS™ system, deployed on August 30 through the ImageCat PDV (Post-disaster Damage Verification) program, provided the first cloud-free high-resolution coverage showing flood and wind damage.

- For the Mississippi Coast, NOAA provided the first cloud-free coverage showing storm-surge and wind-pressure damage on August 30.

- NOAA imagery was initially made available online in a non-geographically referenced format (*http://ngs.woc.noaa.gov/katrina/*). The release of associated camera data files provided critical assistance, as it enabled MCEER researchers at ImageCat to coarsely georeference these data for damage assessment. Several days later, the imagery was distributed in coarsely processed format through Google Earth, and was used extensively by homeowners to gauge damage to their property.

- Although high-resolution satellites collected coverage of the disaster zones just one day after the event, it was affected by dense cloud cover. The first cloud-free, high-resolution satellite imagery of New Orleans was acquired by OrbView on August 30 and QuickBird on August 31. The first cloud-free high-resolution coverage of Mississippi was acquired by QuickBird on August 31 (limited area), followed by OrbView and IKONOS on September 2.

- Moderate-resolution sensors such as Landsat-5 are useful regional-scale damage assessment tools, showing the extent of flooding and storm-surge scour.

- Pre-event imagery provides a critical “no-damage” baseline for interpreting destruction as a function of changes between “before” and “after” coverages. The use of a pre-disaster scene significantly increases the confidence surrounding damage assessment results, particularly for moderate damage levels.

3.0 Remote Sensing for Reconnaissance Planning and Support: A Theoretical Framework

In the wake of disasters such as Hurricane Katrina, the gathering of situational information is a critical priority, since it provides decision support to guide immediate response and longer term recovery activities. Reconnaissance activities typically play a central role in information acquisition. The conceptualization in Figure 3-1, developed using experience from past hazard events including the 2003 Bam earthquake, 2004 Hurricanes Charley and Ivan, and the 2005 Indian Ocean tsunami, suggests that a holistic post-disaster reconnaissance process comprises three key components:

- Damage assessment for buildings, other infrastructure and lifelines;
- Hazard-specific technical observations related to the cause of the event (e.g., wind speed, hurricane central pressure, earthquake intensity); and
- Assessment of the socio-economic situation.

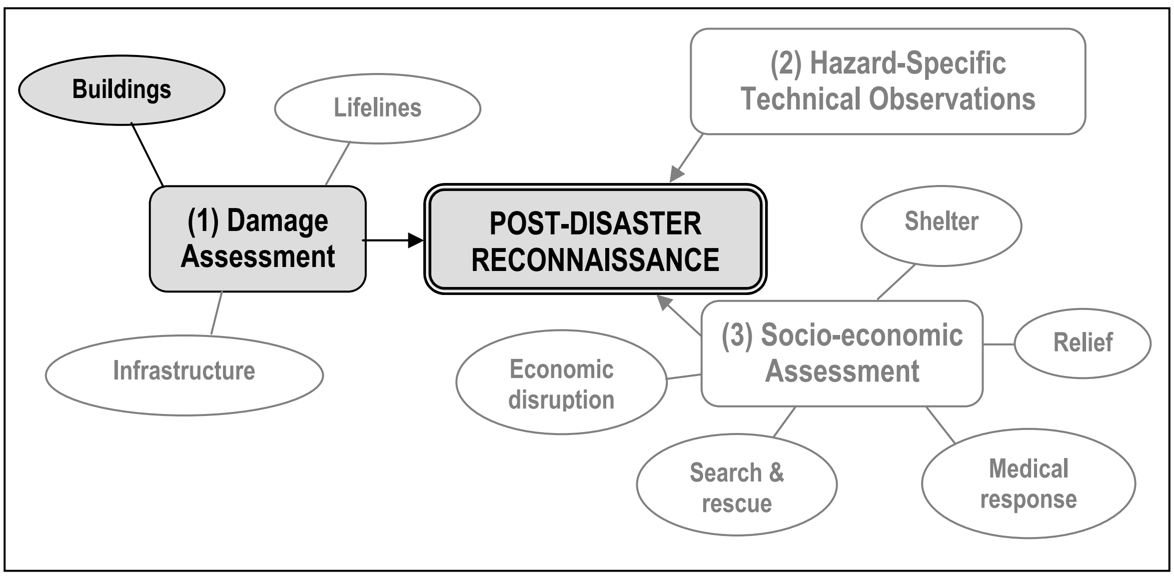


Figure 3-1. Conceptualization of key components within a holistic and multidisciplinary post-disaster reconnaissance program. Within this framework, damage assessment serves as one component of the overall reconnaissance program.

Recognizing the importance of promoting rapid and accurate post-disaster reconnaissance, MCEER researchers have, for a number of years, worked to streamline information-gathering activities through the implementation of advanced technologies such as remote sensing (e.g., Eguchi et al., 2003; Adams et al., 2005a; Ghosh et al., 2005; Chang et al., in press). Within Thrust

Area 3 (Emergency Response and Recovery) of the MCEER research program, the application of remote sensing technology for reconnaissance has focused on two key areas, namely:

- Rapidly identifying impacted areas, to support reconnaissance planning
- Assessing multi-hazard damage to the built environment, as a reconnaissance information source

Hurricane Katrina heralded the benchmark deployment of remote sensing for reconnaissance planning and damage assessment support in a unique multi-hazard context. The aim of this chapter is to present the theoretical and conceptual backgrounds underpinning these advanced technology applications.

Section 3.1 commences with the conceptualization of a post-disaster geospatial framework referred to as the Tiered Reconnaissance System (TRS), within which remote sensing is used to identify the broadscale extent and severity of impacts. The information generated by the TRS provides a spatially tiered geographic focus for all aspects of the reconnaissance process, whether related to socio-economic assessment, technical observations, or urban damage assessment (as detailed in Chapter 4).

Section 3.2 further demonstrates how information from the TRS may also make a valuable contribution to the reconnaissance planning process. Initial inputs for the TRS occur through the development of site-selection protocols for multi-hazard situations. Having identified potential study sites, input then occurs in the form of a logistical framework (see also Huyck et al., 2004) or deployment plan for damage assessment, as a key reconnaissance component (see Figure 3-1).

Details of the operational deployment of advanced technology for damage assessment and reconnaissance planning are discussed in Chapters 4 and 5.

3.1 Tiered Reconnaissance System

The new millennium signified a major advance in the application of remote sensing technology for post-disaster reconnaissance. While moderate-resolution sensors such as Landsat and SPOT continue to offer a regional perspective on the unfolding scene, a new generation of very-high-resolution (61-cm to 1-m) imagery from commercial satellites, such as QuickBird, IKONOS, and OrbView (see Section 2.1.3), enables practitioners to focus in on the hardest hit areas at neighborhood and even per-building scales.

The implementation of moderate and very-high-resolution imagery for post-earthquake damage detection may be conceptualized within the three-stage Tiered Reconnaissance System in Figure 3-2. Regional information garnered from Tier 1 guides the identification of severely impacted areas for the focus of Tier 2. Tier 2 (neighborhood) findings offer guidance for detailed study-site selections undertaken at Tier 3.

In terms of advanced technology implementation, at Tier 1 moderate-resolution sensors such as Landsat-5 Thematic Mapper (TM) offer a "quick-look" region-wide perspective for establishing the broadscale extent of the event (Adams 2004; Adams et al., 2005a,b). At Tier 2, high-resolution imagery next distinguishes both the hardest-hit and lesser-affected neighborhoods (e.g., Adams et al., 2004a; Saito et al., 2004; Chiroiu et al., in press). At Tier 3, high-resolution imagery guides detailed site selection to the level of individual buildings. In the specific case of damage assessment, Tier 3 technology may further facilitate structural damage assessment through expert interpretation (Womble 2005) and its integration into field-reconnaissance tools such as VIEWS™ (Adams et al., 2006).

The comprehensive decision support offered by a spatially tiered approach to post-disaster reconnaissance is rapidly gaining widespread recognition. For example, the USGS Coastal and Marine Geology Program now employ a hierarchy of techniques including airborne survey and ground reconnaissance to investigate the extent and causes of coastal impacts of hurricanes and extreme storms (USGS 2005). In the following sections, the TRS framework is described in the context of post-Hurricane Katrina remote sensing activities undertaken by MCEER researchers, detailed descriptions of which are reserved for Chapter 4.

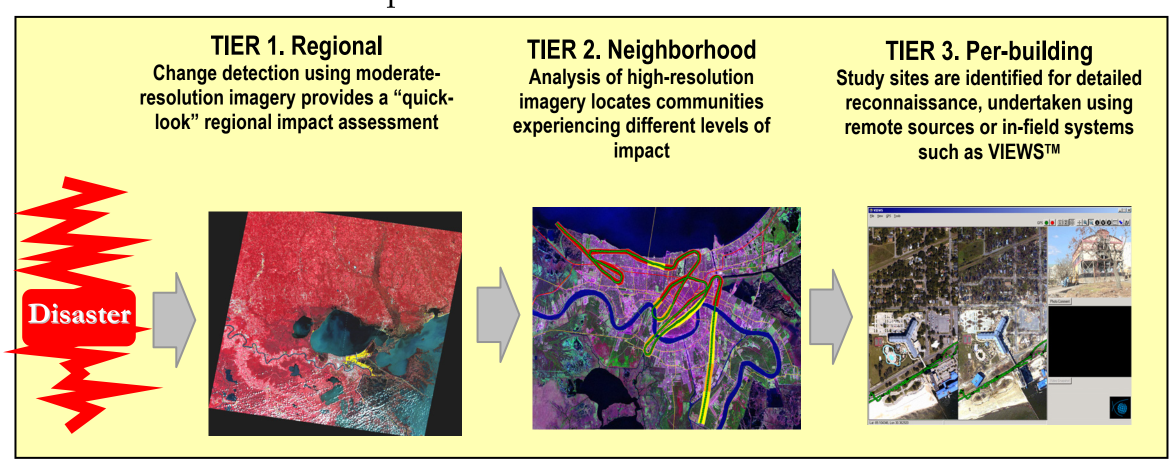


Figure 3-2. Tiered reconnaissance system, using remote sensing to identify impacted areas for multi-hazard reconnaissance planning and damage assessment.

3.1.1 Tier 1 (Regional Assessment)

In the present case of Hurricane Katrina, MCEER researchers utilized remote sensing at all 3 levels of the tiered reconnaissance system. From Table 3-1, Tier 1 impact-assessment activities focused on identifying regions of Mississippi and New Orleans experiencing extreme *change* between moderate-resolution pre- and post-hurricane Landsat-5 TM coverage (see Section 4.1.1 and Section 4.3.2). In this way, Tier 1 effectively identified the broadscale extent of areas impacted by storm surge and flooding. In the case of storm surge, significant changes were recorded along the Mississippi coastline between Pass Christian and Pascagoula. For flooding, extreme change was identified within Orleans and St. Bernard Parishes in New Orleans, which provided a focus for the identification of levee breaches at Tier 2. Tiers 1 and 2 provided limited insights into wind-pressure effects, due to their localized, rather than widespread, occurrence. As noted in Chapter 1, Hurricane Katrina was not a major event from the standpoint of direct *wind-pressure* damage alone, but rather in terms of *secondary* effects such as severe storm surge and flooding – hazards which ultimately have their roots in the intense hurricane. Accordingly, regional wind-pressure damage impact assessment employed inference-based, rather than deterministic, techniques to focus on areas that were likely to be hard hit (see Section 3.2.2).

Table 3-1. Organization of Post-Hurricane Katrina Remote Sensing-based Impact Assessment Activities Within the Three Levels of the Tiered Reconnaissance System (See also Figure 3-2)

Tier 1 (Regional)	Tier 2 (Neighborhood)	Tier 3 (Per-Building)
• Landsat evaluation of storm surge in Mississippi • Landsat evaluation of flood extent in New Orleans • Probabilistic evaluation of windstorm effects based on weather data (e.g., GOES satellite)	• NOAA aerial evaluation of storm surge line from Pascagoula to Pass Christian • NOAA aerial evaluation of windstorm damage within Waveland, Bay St. Louis, Gulfport, Biloxi, Ocean Springs, Gautier, and Pascagoula • PDV VIEWS™ overflight of flooding in New Orleans • QuickBird evaluation of flood boundary in New Orleans • QuickBird and NOAA evaluations of levee breaches and high-velocity flooding in New Orleans • NOAA per-scene severity ranking of windstorm damage • Lidar-based depth-of-flooding analysis for New Orleans	• VIEWS™ field survey of storm -surge damage in Waveland, Bay St. Louis, Gulfport, Biloxi, Ocean Springs, Gautier, and Pascagoula • NOAA per-building aerial evaluation and VIEWS™ field survey of wind damage in Waveland, Bay St. Louis, Gulfport, Biloxi, Ocean Springs, Gautier, and Pascagoula • VIEWS™ field survey of flood damage in New Orleans • VIEWS™ field survey of levee breach damage in New Orleans

3.1.2 Tier 2 (Neighborhood Assessment)

Having determined the severely impacted regions using Tier 1, subsequent Tier 2 activities focused on gauging the severity of multi-hazard impacts within affected neighborhoods. In the case of storm surge, high-resolution NOAA airborne imagery was used to delineate the position of the surge line within communities between Pass Christian and Pascagoula. For flooding, through the ImageCat PDV program, high-definition video (HDV) was captured in the immediate aftermath of the hurricane from an airborne platform, for locations throughout the New Orleans area. A transect-based impact evaluation was derived from the HDV data by classifying the degree of flooding within individual frames. A neighborhood flood impact map showing severely affected communities throughout New Orleans was also produced using high-resolution QuickBird satellite imagery. The same QuickBird coverage was used to identify the location of the levee breaches and probable extent of high-velocity flows. In the case of wind-pressures, areas sustaining extreme damage were identified through visually based ranking of NOAA aerial images.

3.1.3 Tier 3 (Per-building Assessment)

For Hurricane Katrina, Tier 2 effectively highlighted neighborhoods within affected regions that were severely impacted. This information serves as a valuable archive of perishable damage information and also guides detailed study-site selection for Tier 3 reconnaissance.

Tier 3 utilized advanced technology to guide and support detailed multi-hazard reconnaissance for individual structures. In the case of damage assessment, post-disaster survey on a manually intensive, per-building scale has typically been undertaken on foot, recording comments in a hard copy or (more recently) PDA format, accompanied with digital photographs. However, through advanced technology innovation, damage assessment may now be conducted directly from remote sensing sources and using GPS-based survey systems such as VIEWS™.

The work of Womble (2005) has made initial strides towards detailed damage detection at a Tier 3 level using high-resolution remote sensing imagery. Through this work, a remote sensing-based damage scale has been developed that categorizes building damage states based on characteristic modes of failure, identified through expert interpretation. Currently, no equivalent damage scales exist for flood, storm surge or levee breach.

Recognizing the importance of streamlining in-field activities to quickly and efficiently capture a permanent visual record of impacts in a georeferenced format that can be integrated with the outputs from Tiers 1 & 2, MCEER researchers at ImageCat have also developed an advanced technology-based reconnaissance data collection and visualization system called VIEWS™ (Adams et al., 2004b; Herring 2005; Womble et al., 2005). Described fully in Chapter 5, VIEWS™ is a portable laptop-based system that supports the rapid acquisition of georeferenced video, HDV stills and digital photographs from air, vehicle, boat, or on foot. To help guide reconnaissance activities, it incorporates a real-time GPS feed, which maps the field team's location on-the-fly onto GIS base layers including damage maps and street networks.

In the aftermath of Hurricane Katrina, the per-building Remote Sensing Damage Scale developed by Womble (2005) was implemented for detection of wind-pressure damage to buildings along the Mississippi Coast. Tier 3 VIEWS™ deployments captured detailed information about the location and characteristics of urban impacts caused by windstorm, storm surge, flooding, and levee breach. These datasets are, in their own right, a valuable source of damage information, and also serve a dual role as ground truth for the remote sensing analysis undertaken for Tiers 1 and 2.

3.2 Multi-hazard Reconnaissance Planning

Information generated using the advanced technology-based Tiered Reconnaissance System has duel applications within the reconnaissance process: first, for direct damage assessment (see Chapter 4); and second, to guide reconnaissance planning for the collection of per-building (Tier 3) information. From a planning perspective, outputs from Tiers 1 and 2 identify affected areas sustaining different levels of damage. As described in the following sections, these findings may usefully guide the destination for Tier 3 reconnaissance activities when formally integrated into post-disaster field-site selection protocols and deployment plans for damage assessment.

3.2.1 Multi-hazard Site-selection Protocols

Figure 3-3 conceptualizes the various sources of information that may be available to guide field reconnaissance teams for study-site selections in the aftermath of a disaster. In the case of Hurricane Katrina, the effects of four different hazards were juxtaposed. A comprehensive multi-hazard field reconnaissance campaign should consider various impacts (i.e., physical damage, socio-economic, and technical) resulting from each of the hazards, together with cases where the hazards co-occur to produce a combined effect.

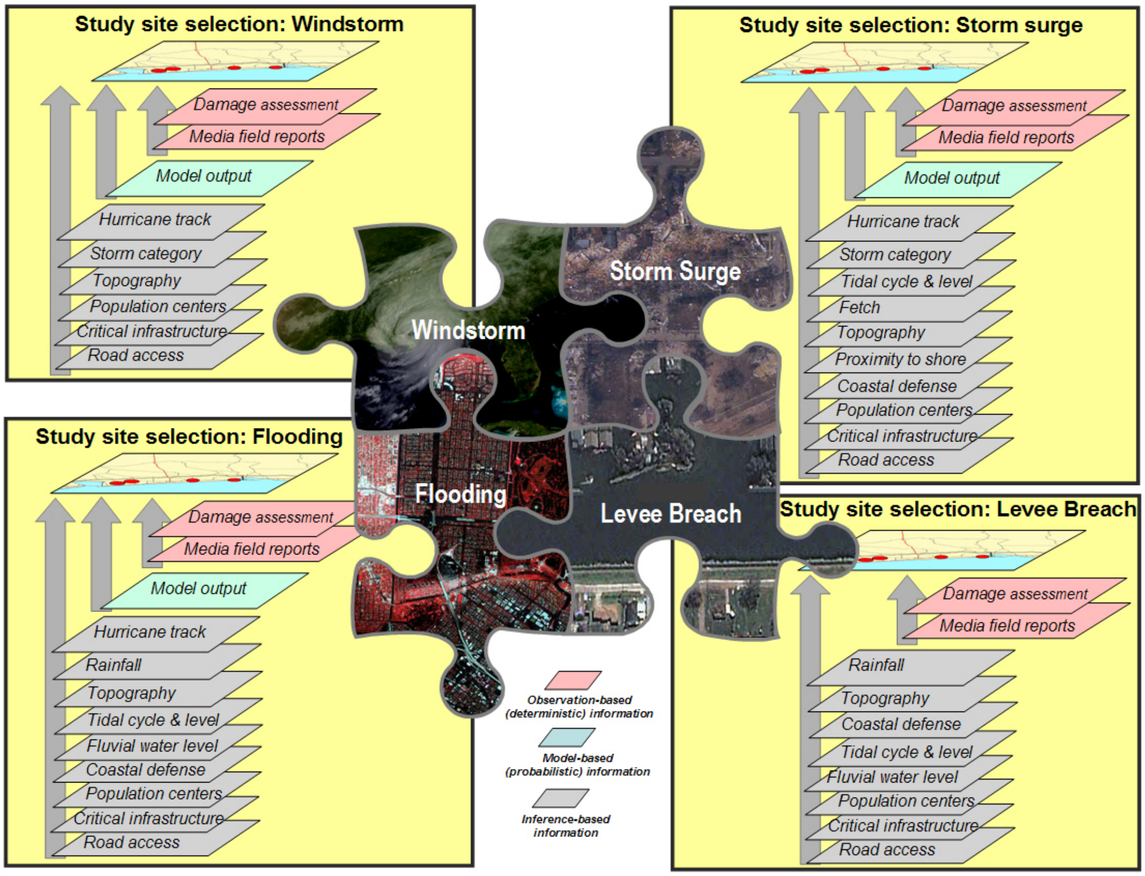


Figure 3-3. Conceptualization of information sources typically available in the aftermath of a multi-hazard disaster to guide the selection of field sites for detailed (Tier 3) reconnaissance.

Information used to guide the selection of sites for detailed reconnaissance is generated by different sources, which may be categorized as:

- *Deterministic* – based on bona-fide observations;
- *Probabilistic* – based on the output from predictive models; and
- *Inferential* – based on the integration of biophysical and socio-economic factors.

The results from Tier 1 and Tier 2 damage assessment activities are a key deterministic source guiding Tier 3 study-site selection. Damage information derived from remote sensing is typically generated through a combination of objective and subjective techniques (see Chapter 4). At a regional scale, objective change-detection indices are based on statistical differences between "before" and "after" imagery. In contrast, much of the hurricane-based research conducted to date at a neighborhood scale has employed subjective methodologies, where the level of impact is identified through expert interpretation. Although objective object-oriented methodologies are being developed for the earthquake hazard (Gusella et al., 2004, 2005; Vu 2005), such methodologies have yet to be implemented for windstorm, flooding, or storm-surge damage assessment.

Another important deterministic source is that of field-based observations reported by the media through television, radio, and Internet news reports. Experience from past disasters suggests that information from these sources is highly subjective, and tends to converge on a subset of hard-hit locations. Lesser-damaged or lesser-known locations may receive little attention, and as such may not be identified as a high priority for assistance. To combat this effect, researchers at the California Institute for Telecommunications and Information Technology have begun working on a disaster portal, with web crawlers that track online reports made through a variety of forums including media sites, blogs, and maps (Calit2, 2005).

Probabilistic post-disaster information about the spatial distribution and severity of losses may also be available from publicly available and commercial predictive models. In the case of windstorm, the FEMA-sponsored HAZUS-Hurricane model provides an estimate of building, infrastructure and socio-economic impacts, based on characteristics of the windstorm event. Commercial models developed for the insurance and reinsurance industry (e.g., RMS 2005; AIR 2005; and EQECAT 2005) perform a similar prediction, generating losses based on the occurrence of a comparable hazard scenario. For the case of the storm-surge hazard, the SLOSH (Sea, Lake and Overland Surges from Hurricanes) model (NOAA 2005c) is available to government and state agencies for estimating the height and inland extent of inundation. A major advantage of information obtained from probabilistic sources is that impacts can be computed within minutes of the event and do not rely on access to affected areas. However, the accuracy and reliability of model outputs are dependent on the degree to which the model represents the real-world situation.

Wind engineers have traditionally employed a combined inference- and deterministic-based approach to site selection for detailed damage studies in potentially impacted areas and involves the examination of key datasets – including storm tracks, field windspeed measurements (e.g., WEMITE 2005; FCMP 2005), some media reports, and prior knowledge of local building patterns. Once in the field, an exploratory drive-through is used to finalize a suite of study locales for detailed impact assessment.

Datasets for the inference process span bio-physical, socio-economic and operational factors. Biophysical data include the hurricane path and windstorm category, with the level of impact decreasing outwards the center of the track, with a bias towards more extreme impacts to the right of the eye-wall. Topography is another important physical consideration for multi-hazard site selection, as it influences the vulnerability of populated areas to wind exposure, flood inundation, storm-surge damage, and submergence (e.g., following a levee breach). For flooding, surge, and levee breach, tidal and riverine factors are a further concern. The likelihood of damaging high-velocity flows is a function of the fetch over which the hurricane has gained momentum, local topography, and the tidal level at the time of landfall. Taken in combination with incident rainfall, the water level within riverine systems is also a key factor affecting localized and downstream flooding. From a socio-economic standpoint, post-disaster reconnaissance activities typically focus on areas of urban development, identified as population centers. The location of critical infrastructure is another important factor, spanning both land-based structures and off-shore facilities, such as oil drilling platforms. From an operational standpoint, accessibility is a final concern, since reconnaissance teams often wish to acquire Tier 3 information through site visits, and accordingly require reasonable access to the site.

Based on the above review of information sources, it is recommended that a multi-hazard site selection protocol employ an integrated approach. Although no formal site selection system currently exists, it may be envisaged how this could take the form of a GIS application. The spatially-based tool would integrate available information layers from deterministic, probabilistic and inferential sources, and use these to generate a series of maps depicting the nature of impacts (flooding, storm surge, etc.) and ranking their severity.

3.2.2 Deployment Plan for Damage Assessment

Having employed the site-selection protocol (Section 3.2.1) to select a series of field locations for detailed Tier 3 reconnaissance, MCEER's advanced technology field teams typically develop a *deployment plan* to formalize operational considerations. The aim of the deployment plan is to provide a blueprint for in-field operations, which will, amidst the chaotic and often rapidly changing field situation, serve to streamline and prioritize activities and ensure that all objectives are achieved.

Table 3-2 provides a sample deployment plan for multi-hazard Tier 3 reconnaissance, which has the stated aim of *using advanced technologies to rapidly assess damage in multi-hazard disaster situations*. The deployment plan summarizes key operational considerations, to help ensure that the methodology used to achieve them is logical and consistent with the expected results and findings.

First, the deployment objectives are identified, which in this case involved the acquisition of perishable damage information for windstorm, flooding, and storm surge. Next, the geographic extent of the deployment is identified. *Extensive* implies that a diverse series of structures will be covered within a broad geographic region, compared with *intensive* – where the deployment will concentrate only on one or two structures. Study sites are then identified, as a function of the site selection protocol. The *General approach* details the methodology that will be employed to achieve the deployment aim and objectives. For Hurricane Katrina, this entailed deployment of the VIEWS™ system to collect damage data, and its subsequent interpretation as a function of hazard-specific damage scales. Base data for the VIEWS™ deployment supply critical information for the site-selection process and subsequently guide in-field activities. These datasets range from satellite images (for highlighting urban areas) to GIS street-network layers (for tracking survey routes and monitoring progress). Finally, the anticipated end products are identified. These should satisfy the deployment aims and objectives, and in this case comprise a catalogue of damage observations and damage maps produced using pre-determined remote sensing-based damage scales.

Chapter 5 includes a modified version of the deployment plan, which follows the overarching framework in Table 3-2. This serves to illustrate its operational deployment for guiding and streamlining the post-Hurricane Katrina Tier 3 reconnaissance activities of the MCEER advanced technology field teams for sites in Mississippi and New Orleans.

3.3 Summary of Key Findings

- A TRS (Tiered Reconnaissance System) framework is proposed within which multi-resolution imagery acquired from satellite and airborne platforms is used to guide and inform reconnaissance activities.

- Tier 1 of the TRS performs a "regional" assessment of damage extent. Tier 2 establishes the severity of damage at a "neighborhood" scale, and offers guidance for detailed study site selection for Tier 3 "per-building" studies. At Tier 3, detailed reconnaissance is undertaken using in-field systems such as VIEWS™ or by using high-resolution imagery acquired through the PDV (Post-disaster Damage Verification) program or by high-resolution satellite or airborne sensors.

Table 3-2. Advanced Technology-based Deployment Plan for Tier 3 Damage Assessment
(This table serves as a guiding framework for operational multi-hazard reconnaissance.)

GENERAL AIM	***Use advanced technologies to rapidly assess damage in multi-hazard disaster situations***		
SPECIFIC OBJECTIVE	1. To collect *perishable storm-surge damage data* for buildings, transportation and utility lifelines, essential facilities	2. To collect *perishable wind damage data* for buildings, transportation and utility lifelines, essential facilities	3. To collect *perishable flood damage data* for buildings, transportation and utility lifelines, essential facilities
GEOGRAPHIC EXTENT & SITE SELECTION PROCESS	Extensive Site locations determined based on remote sensing surge-extent evaluation and media reports	Extensive Site locations determined based on windspeed estimate maps, design wind load provisions in building codes for specific region, and media reports	Extensive Site locations determined based on remote sensing flooding extent, depth evaluation, and media reports
GENERAL APPROACH	Deploy VIEWS™ from a moving vehicle to conduct an area-wide damage assessment, spanning all levels of impact. Use storm surge damage scale for buildings, lifelines, etc. to classify damage on a building-by-building or neighborhood basis.	Deploy VIEWS™ from a moving vehicle to conduct an area-wide damage assessment, spanning all levels of impact. Use wind damage scale for buildings, lifelines, etc. to classify damage on a building-by-building or neighborhood basis.	Deploy VIEWS™ from a moving vehicle to conduct an area-wide damage assessment, spanning all levels of impact. Use flood damage scale for buildings, lifelines etc. to classify damage on a building-by-building or neighborhood basis.
BASE DATA	• Satellite imagery • Streets, zip codes, counties layers • Potential study sites/ critical areas	• Satellite imagery • Streets, zip codes, counties layers • Potential study sites/ critical areas	• Satellite imagery • Streets, zip codes, counties layers • Potential study sites/ critical areas
POTENTIAL END PRODUCT	1) Storm surge damage observation catalogue for different occupancy classes and lifelines 2) Storm surge damage map using remote sensing-based damage scale	1) Wind damage observation catalogue for different occupancy classes and lifelines 2) Wind damage map using remote sensing-based damage scale	1) Flood damage observation catalogue for different occupancy classes and lifelines 2) Flood damage map using remote sensing-based damage scale

- Following Hurricane Katrina, damage assessment and reconnaissance activities conducted by MCEER researchers at ImageCat and MCEER advanced technology field teams spanned all three levels of the TRS.

- A site selection protocol is introduced for multi-hazard reconnaissance, to guide Tier 3 field investigators to key areas of interest.

- It is recommended that a multi-hazard site selection protocol employ an integrated approach, combining deterministic, probabilistic and inferential information sources. Although no formal site selection system currently exists, it may be envisioned how this could take the form of a GIS application, integrating available information layers to identify the nature of impacts (flooding, storm surge, etc.) and rank their severity.

- A deployment plan is developed based on the logistical framework organizational concept. The plan provides a roadmap for in-field operations, serving to streamline and prioritize activities and ensure that all objectives are achieved. The deployment plan summarizes key operational considerations, to help ensure that the methodology used to achieve them is logical and consistent with the expected results and findings.

4.0 Damage Detection Using Remote Sensing

In the aftermath of extreme events such as Hurricane Katrina, the rapid and accurate characterization of the extent and severity of urban damage is a high priority. Timely damage data generated through reconnaissance activities (detailed in Figure 3-1), provide critical decision support for numerous applications, ranging from emergency response to loss estimation. It is increasingly recognized that advanced technologies such as remote sensing and geographic information systems (GIS) have key roles to play in rapid damage assessment, providing a holistic perspective of damage sustained in locations that are often inaccessible for a number of days after the event.

Researchers working under MCEER's Thrust Area 3 (Emergency Response and Recovery) have made significant progress with the development of remote sensing-based damage detection methodologies. The 1999 Marmara (Turkey) earthquake constituted the initial implementation of moderate-resolution imagery (Section 2.1.2) for detecting urban damage within the cities of Golcuk and Adapazari (Eguchi et al., 2000; Adams 2004; and Huyck et al., 2004). The 2003 Boumerdes (Algeria) and Bam (Iran) earthquakes in turn marked the primary deployment of high-resolution imagery (Section 2.1.3) for building damage assessment (Adams 2004; Adams et al., 2004a; Gusella et al., 2004). From a multi-hazard standpoint, the 2004 U.S. hurricane season saw the first utilization of high-resolution QuickBird and IKONOS satellite imagery for assessment of windstorm damage (Adams et al., 2004b,c; Womble et al., 2005; Womble 2005) and for mapping effects of the Indian Ocean tsunami (Adams et al., 2005a,b; Chang et al., in press; Ghosh et al., 2005).

Hurricane Katrina presented a unique opportunity to apply previous damage-detection research findings in a multi-hazard context. This chapter describes the implementation of selected remote sensing datasets from Chapter 2 for identifying urban damage caused by:

1. Storm surge
2. Wind pressure
3. Flood inundation
4. Levee breach

From an operational standpoint, storm-surge and flooding information was used by Risk Management Solutions, Ltd. for verifying loss estimates

(ImageCat 2005). As described in Chapter 3, multi-hazard damage data were also used by MCEER advanced technology reconnaissance teams within a tiered reconnaissance framework for deployment planning and support.

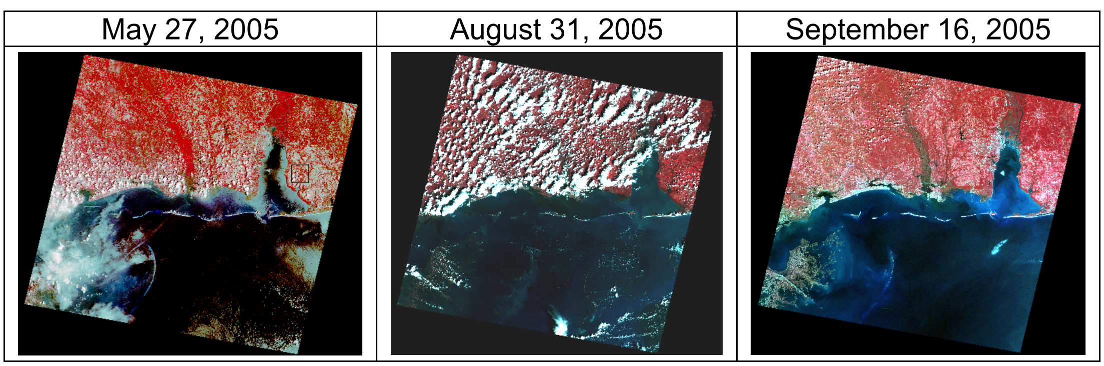
4.1 Storm Surge (Mississippi Coast)

From the suite of remote sensing datasets described in Chapter 2, a combination of moderate and high-resolution imagery was used to provide first a *region-wide* and then a more detailed *neighborhood-scale* perspective on storm surge damage.

4.1.1 Region-wide Damage Detection Using Landsat-5 Imagery

As noted in Section 2.1.2, the moderate spatial resolution and extensive geographic coverage afforded by Landsat-5 Thematic Mapper (TM) imagery provides a holistic perspective of post-disaster damage. Although Landsat-7 ETM imagery offers greater detail for the same extent, failure of the scan line corrector in 2003 limits the use of this data, due to the presence of "no-data" gaps (appearing as black lines in the imagery).

As shown in Table 2-2, Landsat-5 TM imagery was captured rapidly after Hurricane Katrina on August 31. However, as shown by Figure 4-1, the coverage from August 31 was subject to considerable cloud cover, and as such proved to be of limited value for storm-surge damage detection. The analysis instead employed the next available dataset (September 16, 2005), together with pre-storm imagery dating from May 27, 2005.



Landsat imagery from USGS and NASA

Figure 4-1. Pre- and post-Hurricane Katrina Landsat-5 TM Imagery (Path 21 Row 39) used to detect storm surge damage in Mississippi.

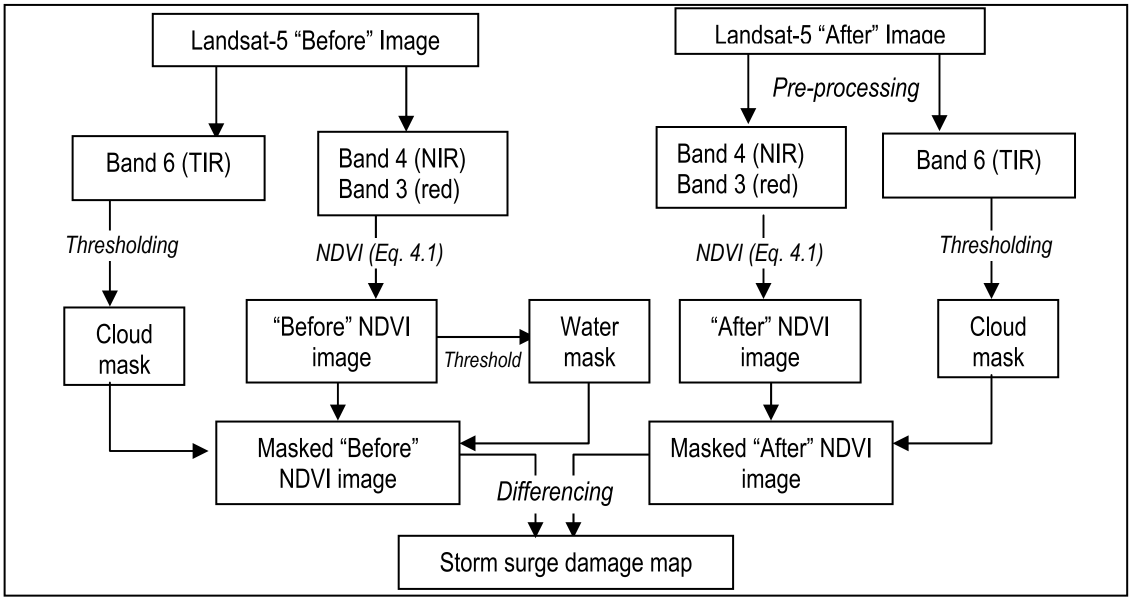


Figure 4-2. Methodology employed for region-wide storm surge damage detection.

From a methodological standpoint, Figure 4-2 outlines the multi-temporal change detection algorithm used to locate the hardest-hit areas. Originally developed to detect inundated coastal tracts in the aftermath of the December 2005 Indian Ocean tsunami (Adams et al., 2005b, Chang et al., in press), the algorithm identifies urban damage as a function of changes in land surface cover between the pre- and post-disaster images.

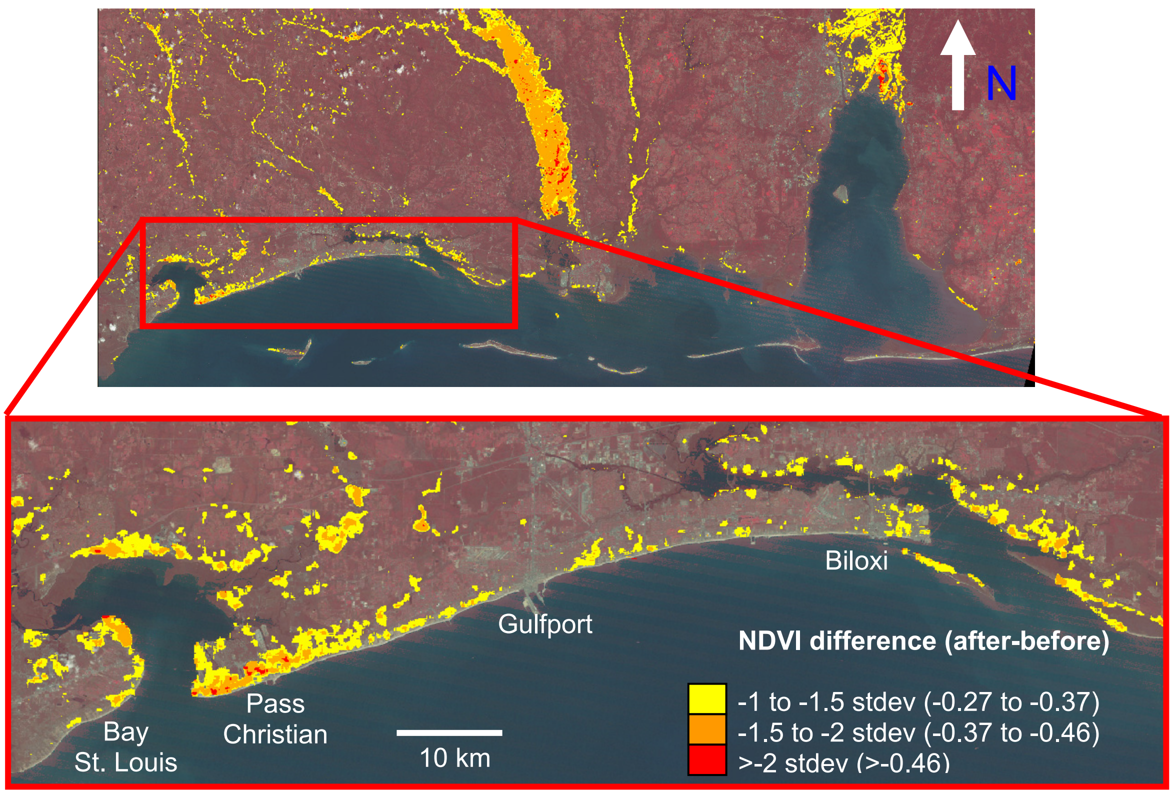
Following an initial pre-processing registration step to ensure spatial alignment of the pre- and post-storm images, landcover is effectively quantified using the Normalized Difference Vegetation Index (NDVI). From Equation 4.1, the NDVI is defined as the ratio between spectral information contained in Landsat-5 TM near-infrared and red bands.

$$\text{NDVI} = \frac{(\text{Near-infrared}) - (\text{Red})}{(\text{Near-infrared}) + (\text{Red})} \qquad [4.1a]$$

$$\text{NDVI} = \frac{(\text{Landsat-5 TM Band 4}) - (\text{Landsat-5 TM Band 3})}{(\text{Landsat-5 TM Band 4}) + (\text{Landsat-5 TM Band 3})} \qquad [4.1b]$$

To minimize the occurrence of false positives, potential non-damage-related sources of change were eliminated by masking. A cloud mask was obtained by thresholding Landsat-5 TM Band 6, which records thermal-infrared (TIR) emissions. Clouds have a distinctive signature within TIR imagery, recording a characteristically low value, as they are cold compared with the earth’s surface. Water surfaces are another potential source of change, due to differences in tidal height, surface illumination and roughness. A water surface mask was obtained by thresholding the "before" NDVI image. Since flooding can be a bonafide source of damage in hurricane affected areas, the water mask was not applied to the "after" images. Adjusted "before" and "after" NDVI images were produced by applying the respective masks. The extent of damage created by the storm surge was finally determined as a function of the difference (computed as "after" minus "before") between the adjusted NDVI scenes.

Figure 4-3 summarizes the results obtained. Measured in terms of standard deviation about the image-wide mean, extreme changes in NDVI are evident along the Mississippi coastline between Biloxi and Bay St. Louis. The negative difference indicates that NDVI readings are lower in the "after" than



Landsat imagery from USGS

Figure 4-3. Region-wide storm surge damage map for the Mississippi Coast. Damage is measured in terms of change in NDVI between pre- and post-hurricane Landsat-5 TM images. Extreme changes are evident within a narrow coastal strip between Biloxi and Bay St. Louis where coastal development has been replaced by bare soil and debris.

in the “before” image. This finding suggests that the surface has experienced extreme scouring, with the urbanized environment of buildings, roads, and vegetation replaced by bare soil and debris. A similar reduction in NDVI was observed along the tsunami-affected coast of Thailand where the land surface was scoured and buildings were destroyed by the high-velocity tidal wave (Adams et al., 2005a).

Despite the application of cloud and water masks to the NDVI scenes, other sources of significant change are also apparent. The waterways of the Pascagoula, Mobile, and Tensaw Rivers also exhibit a major reduction in NDVI between the pre- and post-hurricane images. From visual inspection, these areas comprise wetland vegetation rather than urban land use. According to experts at the Mississippi Department of Marine Resources (G. Larsen, personal communication), this reduction in spectral response from the wetland vegetation may be attributable to a combination of browning and leaf loss induced by the windstorm and to blanketing debris. To minimize the effect of this ecologically-based source of change, MCEER researchers at ImageCat surmised that an additional non-urban mask should be applied to subsequent analyses.

4.1.2 Neighborhood Damage Detection Using NOAA Aerial Imagery

High-resolution aerial photography captured by NOAA in the days following the hurricane provides a valuable neighborhood-scale perspective on damage within the storm-surge affected regions stretching from Waveland/Bay St. Louis to Biloxi. As noted in Section 2.2.2, this imagery was rapidly posted on the NOAA website in non-georeferenced format. Figure 4-4 includes a sample of the NOAA coverage for Biloxi. From visual inspection, the surge-affected region is characterized by a significant increase in exposure of the underlying ground surface, where features of the urban landscape ranging from buildings to roads and vegetation have been removed. This serves to verify findings from the NDVI region-based analysis that scouring by the incoming wave replaced coastal developments with little more than bare soil and debris.

Figure 4-5 summarizes the methodology employed for damage assessment. To delineate the position of the surge line, and thereby identify neighborhoods experiencing a high proportion of collapsed structures, MCEER researchers at ImageCat began by downloading and archiving the online NOAA database, which initially comprised ~350 (and was subsequently expanded to several thousand) images, using a proprietary

Figure 4-4. Sample of NOAA aerial imagery (ID 24330689) at Gulfport, Mississippi.

routine. The archived images were then georeferenced using an accompanying file comprising limited geospatial information for each scene. Since these data lacked "header" information to perform standard registration, warping, and georeferencing procedures, a custom algorithm was developed to generate new positional information. Due to file-size issues, the registered output images were then compressed to enable multiple scenes to be efficiently viewed within a GIS environment.

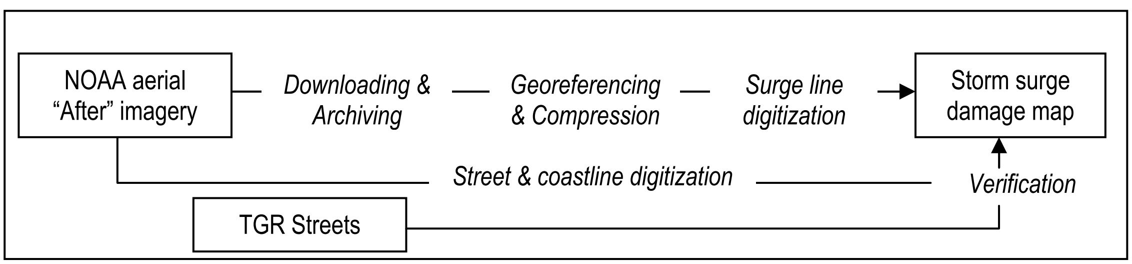


Figure 4-5. Methodology employed for neighborhood-scale storm-surge damage detection.

A high-confidence surge line was delineated within coastal communities, based on expert interpretation of the georeferenced NOAA imagery on a frame-by-frame basis. Figure 4-6 shows that the Mississippi Coast was divided into seven tracts comprising multiple frames of NOAA data, running from Biloxi in the east through to Pass Christian in the west. This division was necessary to maintain efficiency of the digitization process, given the large number of images involved. Finally, the surge lines for the respective frames within the seven tracts were fused together using GIS-based integration functions.

During the surge-line delineation, a series of quality-control features were identified within each frame, including the coastline and street networks (as shown in Figure 4-7). To serve as independent verification that the NOAA coverage and surge line were correctly scaled and positioned, these control features were compared against the TIGER® street network database (U.S. Census Bureau 2002).

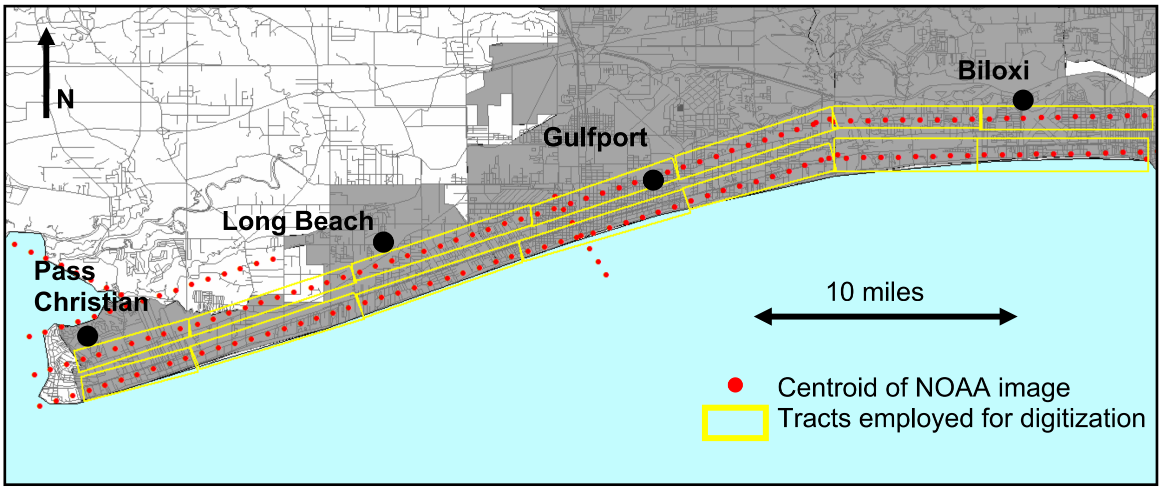
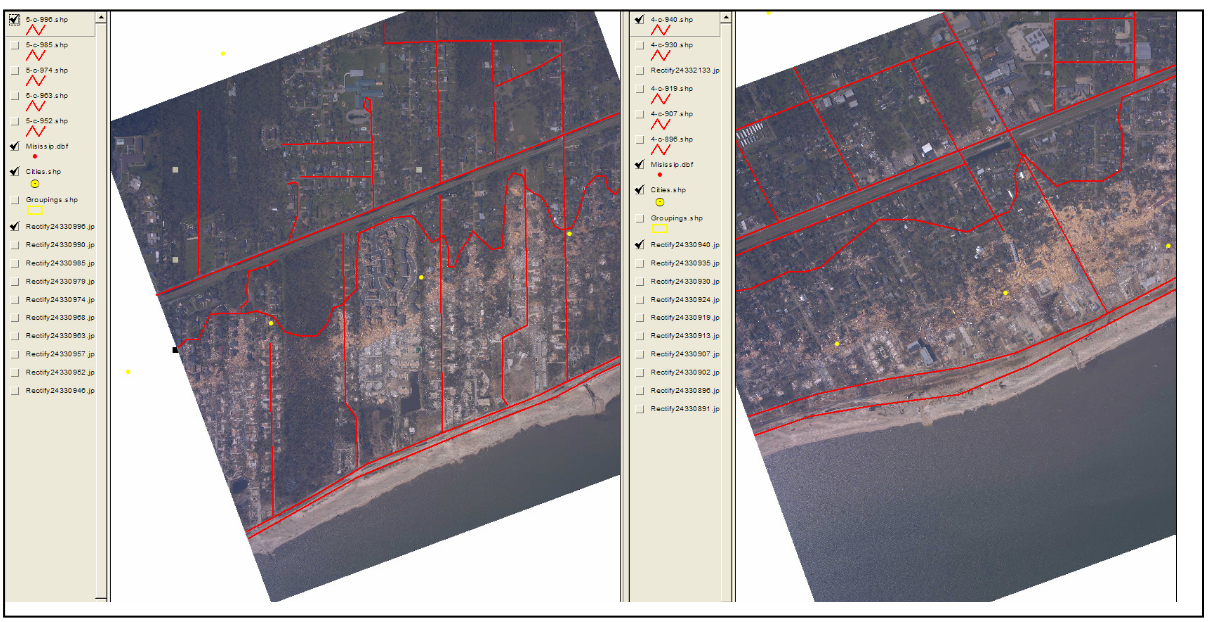


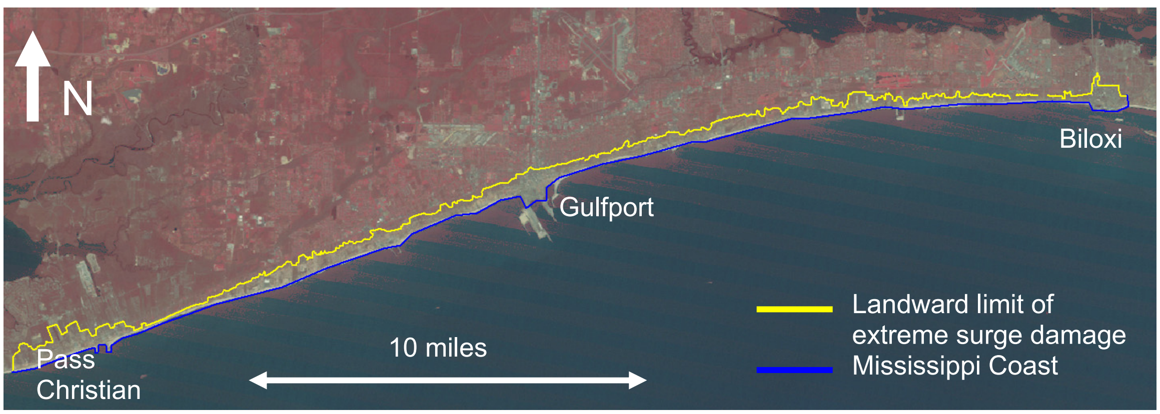
Figure 4-6. NOAA aerial coverage for the Mississippi Coast, divided into seven tracts for efficient digitization of the storm surge line.



Base images from NOAA

Figure 4-7. Extraction of quality-control features within surge-affected regions to verify the geographic accuracy of the surge line.

The damage assessment results shown in Figure 4-8 indicate that the entire coastal strip between Pass Christian and Biloxi was affected by the storm surge. On average, the most extreme damage where 90-100% of buildings were completely destroyed occurred within about ½ to 1 mile of the shore. In many locations, the landward limit of this devastation zone is demarcated by a wide debris line comprising housing materials and scoured vegetation. From visual inspection during the digitization process, particular land surface features served to mitigate the effect of the surge. For example, the debris line fell seaward of the average position where densely vegetated areas such as woodland were encountered. Also, large buildings such as factories and warehouses appeared to partially divert the incident surge, affording some protection to other buildings situated in their wake.



Landsat imagery from USGS

Figure 4-8. Mississippi coastal zone between Pass Christian and Biloxi experiencing extreme storm surge damage. The digitized surge line is overlaid with a false-color composite Landsat-5 TM image acquired on September 16, 2005.

4.2 Wind Pressures (Mississippi)

For the detection of damage due to wind pressure, exploratory investigations suggested that available moderate-resolution remote sensing imagery was of limited value for the region-wide assessment of the hardest-hit areas, due to the distributed occurrences of wind damage. Furthermore, in many cases, wind effects were juxtaposed with other damages, such as storm surge. Given the comparative dominance of these "secondary" factors, isolating wind damage at a geographically extensive scale proved to be problematic.

As described in the following section, the assessment of wind damage effects instead focused on neighborhood and per-building scales, and the identification of hard-hit communities to guide the planning of in-field reconnaissance activities. Damage detection is described for both wind pressure alone and for wind pressure integrated with storm surge situations, since as mentioned above, these were often juxtaposed along the affected coastline. For this investigation, the detection of wind damage is based on expert interpretation and builds on remote sensing-based damage scales developed by Womble (2005) in the aftermath of Hurricanes Charley and Ivan.

4.2.1 Neighborhood Damage Detection Using NOAA Aerial Imagery

Of primary importance for the remote sensing assessment of windstorm damage is the acquisition of high-resolution remote sensing imagery as soon as possible following a windstorm. Such post-storm images form the basis for visual interpretation of damage states, offer guidance for strategic ground-truthing surveys, and provide a permanent record of damage conditions for future reference and analysis.

In the case of Hurricane Katrina, NOAA provided one of the first-available sources of high-resolution data (discussed in Section 2.2.2). Comprising approximately 3,700 digital aerial images, this library offered a timely record of damage conditions, with rapid online availability (in a non-georeferenced form), relatively high spatial resolution, and extensive coverage of the Mississippi Coast.

To identify hard-hit areas along the Mississippi Coast, MCEER researchers at ImageCat applied a *severity ranking system* to the archive of images. Following the simple methodology outlined in Figure 4-9, the full set of images was subdivided into four categories, based on the interpreted severity of wind damage within the scene, where:

Level 3 – High damage: Wind damage evident throughout the scene. Damage is severe in some locations.
Level 2 – Moderate damage: Some damage within the scene. Isolated occurrences of severe damage.
Level 1 – Low damage: Wind damage isolated or absent.
Level 0 – Obscured: Wind damage extent obscured because of obliterating storm-surge damage to buildings.

Figure 4-9. Methodology employed for neighborhood-scale wind damage detection.

As shown in Figure 4-10, small areas of "high damage" were found primarily in Bay St. Louis, Pass Christian, Gulfport, and Biloxi. These Level 3 locations were identified as a high priority for detailed inspection on a per-building scale through image interpretation (Section 4.2.2) and in-field survey (Section 5.2.2). A sample of Level 2 and Level 1 scenes from further east in Ocean Springs, Gautier, and Pascagoula were also included in subsequent per-building studies to ensure that the full range of damage states was observed.

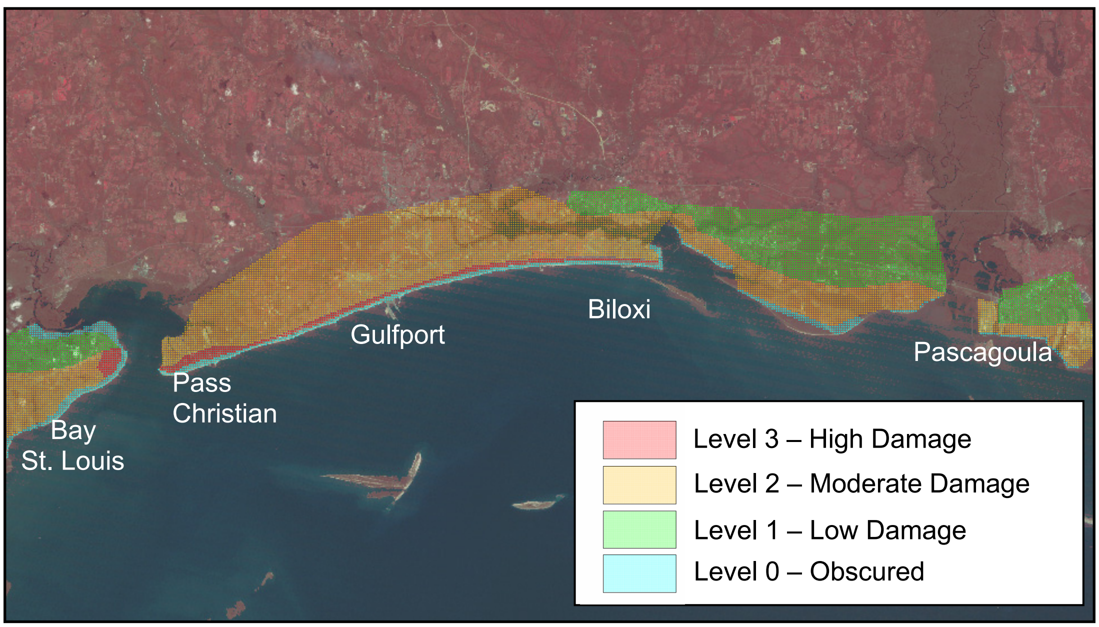


Figure 4-10. Wind damage severity ranking for the library of NOAA images acquired for the Mississippi coast.

4.2.2 Per-building Damage Detection Using NOAA Aerial Imagery

The use of remote sensing technology for the detection of windstorm damage to individual buildings is a relatively young endeavor, having been largely accelerated by the availability of high-resolution pre- and post-storm satellite imagery from Hurricanes Charley and Ivan in 2004, along with rapid post-disaster field data collection (Adams et al., 2004; Womble et al., 2005). Womble (2005) describes the state-of-the art in the application of remote sensing technology for the assessment of structural windstorm damage, and provides a foundation for continued research in this field. The approach is generally modeled after that of earthquake damage assessment using advanced technology, but integrated with particular nuances of windstorm damage, i.e., the different physical appearance of windstorm damage – both in the field and within remote sensing imagery.

MCEER researchers at ImageCat utilized NOAA digital aerial images captured immediately after the event (Section 2.2.2), together with expert interpretation, to visually assess wind-pressure damage to buildings at a per-building scale and to identify target areas for field data collection (as discussed in Section 5). Figure 4-11 summarizes the methodological process used to categorize wind-pressure damage on a per-building scale for the subset of scenes conducted through the neighborhood evaluation in Section 4.2.1. Following pre-processing operations, an expert interpretation of damage was conducted using the Remote Sensing Damage Scale for Residential Buildings in Table 4-1 (see also Womble 2005), which is an initial attempt to describe wind-pressure damage from the remote sensing perspective on a per-building basis for a particular construction category. The damage categories are generally consistent with those employed in the FEMA HAZUS-Hurricane model (Section 5.2.3), but are specifically tailored for use with remote sensing technology. Individual roof facets are labeled with colored symbols indicating the damage state assigned by visual inspection, ranging from RS-A (least damage) to RS-D (most damage). Ongoing complementary research is targeted on the development of automated algorithms that utilize quantifiable damage metrics to perform rapid windstorm-damage assessments.

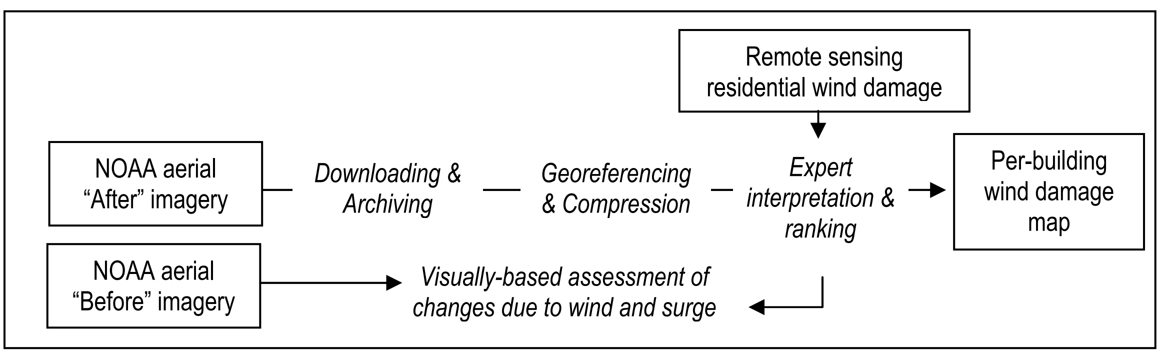


Figure 4-11. Methodology employed for per-building wind damage detection.

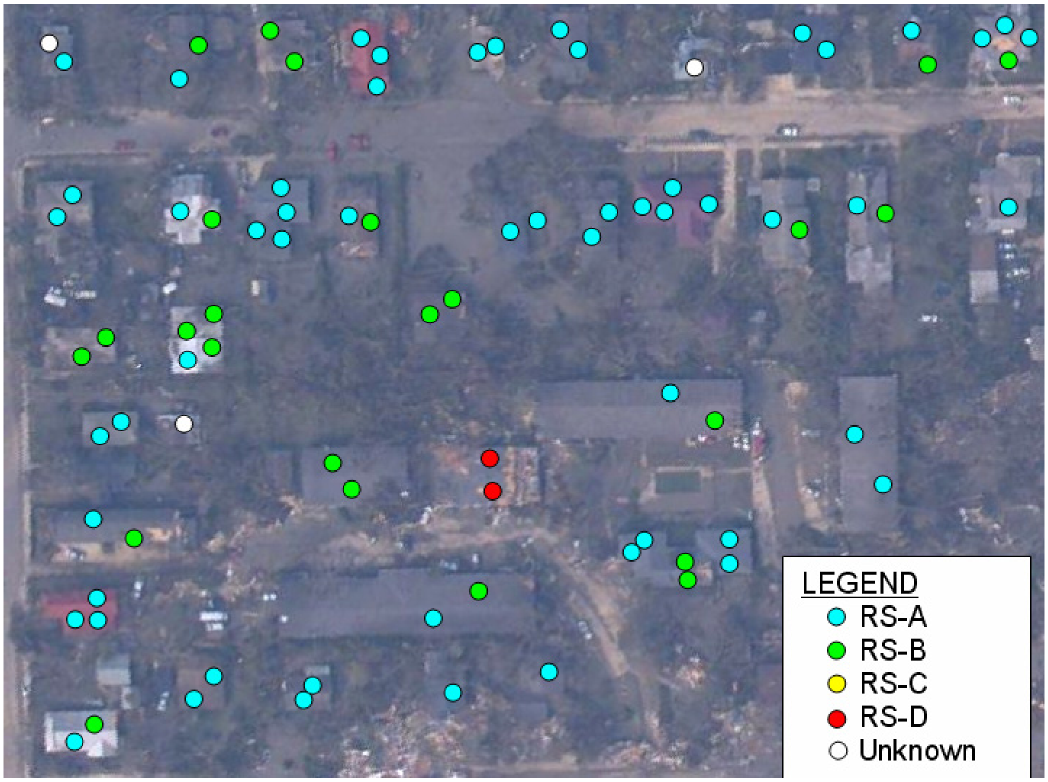
Figure 4-12 exemplifies the results from the damage assessment, for a community that experienced various degrees of wind-pressure damage from Hurricane Katrina.

Table 4-1. Remote Sensing Damage Scale for Residential Construction

Damage Rating	Most Severe Physical Damage	Remote Sensing Appearance
RS-A	No Apparent Damage	• No significant change in texture, color, or edges. • Edges are well-defined and linear. • Roof texture is uniform. • Larger area of roof (and more external edges) may be visible than in pre-storm imagery if overhanging vegetation has been removed. • No change in roof-surface elevation.
RS-B	Shingles/tiles removed, leaving decking exposed	• Nonlinear, internal edges appear (new material boundary with difference in spectral or textural measures). • Newly visible material (decking) gives strong spectral return. • Original outside roof edges are still intact. • No change in roof-surface elevation.
RS-C	Decking removed, leaving roof structure exposed	• Nonlinear, internal edges appear (new material boundaries with difference in spectral or textural measures). • Holes in roof (roof cavity) may not give strong spectral return. • Original outside edges usually intact. • Change in roof-surface elevation. • Debris typically present nearby.
RS-D	Roof structure collapsed or removed. Walls may have collapsed.	• Original roof edges are not intact. • Texture and uniformity may or may not experience significant changes. • Change in roof-surface elevation. • Debris typically present nearby.

Notes: *Womble 2005*

- *Damage states apply to individual roof facets, rather than the full roof.*
- *For all damage states, the presence of debris can indicate damage to walls, doors, and windows, which is not directly visible via vertical, optical imagery. Independent verification is necessary for such damage.*

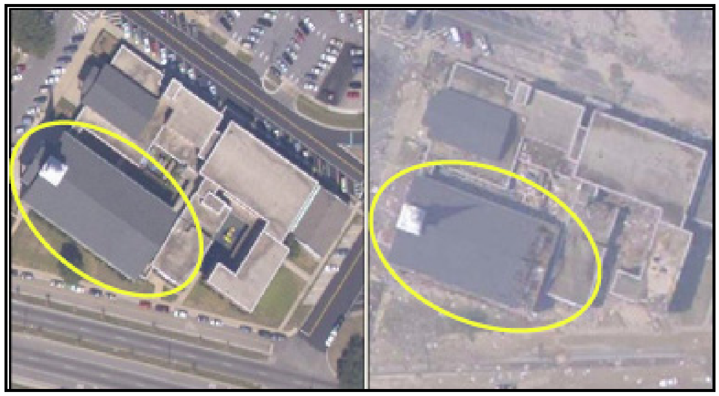


Base image from NOAA

Figure 4-12. Example of per-building visual assessment of wind-pressure damage. Colored symbols are superimposed on a NOAA aerial image, indicating the damage states of individual roof facets according to the Remote Sensing Damage Scale (Table 4-1).

In addition to the expert-interpretation-based damage map in Figure 4-10, a detailed visual assessment was also made of the damage sustained by buildings in the area. While this investigation focused on wind damage, for buildings where wind damage was juxtaposed with storm–surge damage, both sets of effects were identified, compared, and contrasted.

This detailed visual assessment revealed that structures situated inland - typically more than ½ to 1 mile from the shore - were affected by the *wind pressures acting alone*, and as such, serve as an example of "pure" wind-pressure damage. For most portions of the Mississippi Coast, wind damage to individual structures consisted of the removal of roof coverings (Figures 4-13 to 4-16) – particularly near the edges, where wind pressures are highest, with occasional removal of roof decking and partial collapse of the roof structure (Figure 4-17). In addition to removal of roof-cladding elements, areas of wind-pressure damage are distinguishable from storm-surge damage by the low-density appearance of windborne debris nearby (Figure 4-17).



Aerial imagery from NOAA

Figure 4-13. Aerial photo of this Gulfport church reveals wind-pressure damage to the roof, but not the fact that the exterior walls of the building were demolished, leaving only the structural steel frame and roof.

Aerial imagery from NOAA

Figure 4-14. Aerial photo reveals wind-pressure damage to the roof cladding, and low-density debris nearby. This portion of Bay St. Louis was not affected by storm surge.

Aerial imagery from NOAA

Figure 4-15. Before-and-after aerial photos reveal wind-pressure damage to the roof cladding, and low-density debris nearby. This building was not noticeably damaged by storm surge.

Aerial imagery from NOAA

Figure 4-16. Aerial photo reveals wind-pressure damage to the roof cladding, and low-density debris nearby. This portion of Waveland was not affected by storm surge.

Aerial imagery from NOAA

Figure 4-17. Aerial photo reveals wind-pressure damage to roof cladding, and low-density debris nearby. This portion of Waveland was not affected by storm surge.

While the Remote Sensing Damage Scale in Table 4-1 has been developed for residential structures, continuing research is focused on the development of formal damage scales for other building categories (e.g., commercial and industrial). Within affected areas along the Mississippi Coast, wind-pressure damage to tall buildings generally has a different appearance to that of low-rise buildings, in that wall surfaces often sustained more damage than roof surfaces for these buildings. While damage to roof coverings is still readily detectable via remote sensing imagery (Figure 4-18), damage to cladding elements on exterior walls is difficult to observe in vertical overhead imagery. Oblique images are preferred for the detection and assessment of such damage. In the absence of oblique imagery, ground-based observations may be necessary to confirm damage extent.

Aerial imagery from NOAA

Figure 4-18. Aerial photo reveals wind-pressure damage to roof cladding of high-rise hotel.

An expert examination of the NOAA aerial images stretching from Waveland/Bay St. Louis to Biloxi shows that buildings close to the waterfront were generally subject to a mixture of *wind-pressure and storm-surge* damage. In such cases, visual interpretation of the remote sensing images sought to differentiate between the visual signatures of wind-pressure and storm-surge damage, in order to assess the extent of damage due to each particular hazard. In addition to the roof-based remote sensing damage indicators in Table 4-1, these visual signatures utilized the distribution and density of debris as well as the orientation of buildings relative to their pre-storm positions.

For most waterfront areas in Mississippi, storm surge proved far more damaging than wind pressures. The NOAA aerial images reveal numerous instances in which roofs experienced minimal wind damage, yet the portions of the buildings beneath were washed away. In several areas, roof assemblies were found virtually intact but detached from the building beneath and washed some distance away. As such, roofs that appeared intact in the remote sensing imagery but were surrounded by areas of dense debris and/or displaced from their original locations were indicative of destruction by storm surge (Figures 4-19 and 4-20).

Aerial imagery from NOAA

Figure 4-19. NOAA aerial images, acquired before and after Hurricane Katrina, show a residential neighborhood in Pascagoula subjected to severe storm surge. Dense areas of debris and skewed rooftops show evidence of severe storm-surge damage but little wind-pressure damage to the roofs.

Aerial imagery from NOAA

Figure 4-20. NOAA aerial image of a Bay St. Louis neighborhood indicates storm-surge damage (presence of dense debris), but intact roofs show there is little wind-pressure damage.

4.3 Flood Inundation (New Orleans)

In the days following Hurricane Katrina, it became apparent that rather than a single event, this was in fact a series of disasters. After the initial impact of wind pressure and storm surge, additional disasters unfolded as levees breached and floodwaters poured into New Orleans. With access to the city severely restricted as major highways were submerged, remote sensing played a central role in reconnaissance activities. MCEER researchers at ImageCat initially used imagery to *rapidly* assess the severity of flooding effects and subsequently to provide *regional* and detailed *city-wide* perspectives on the damage extent.

4.3.1 Rapid Post-disaster Damage Verification (PDV)

In response to increasing demand for damage information in the hours following a disaster, ImageCat launched a rapid Post-disaster Damage Verification (PDV) initiative for the 2005 hurricane season. The aim of the PDV program is to acquire and distribute high-resolution aerial imagery *within 24-48 hours of the event*. The data-collection system comprises a high-definition video (HDV) camera, controlled through the VIEWS™ reconnaissance system (described in Chapter 5). Acquired along a linear flight path with a spatial resolution ranging from 5-15 cm (depending on the altitude of the aircraft), the imagery provides extremely detailed coverage of damage conditions. Notably, the PDV program offers a transect-based perspective on damage, compared with the regional coverage offered by satellite platforms. However, the data can be acquired more quickly and are more resilient to limitations affecting optical satellite systems, such as cloud cover.

Figure 4-21 summarizes the extent of HDV imagery collected throughout New Orleans and surrounding districts. In line with PDV program objectives, data acquisition began the day following Hurricane Katrina's landfall and continued for three days.

To provide a "quick-look" assessment of flooding extent, the HDV imagery was analyzed on a frame-by-frame basis through expert interpretation. Figure 4-22 shows the New Orleans flight line, color-coded according to flood severity. As of August 30, extreme flooding was evident throughout central areas of New Orleans. Western portions of the city were also inundated at this time, which is an important finding given that analyses conduced one week later (see Section 4.3.2) observed little flooding within this area, suggesting that methods for floodwater extraction were effective.

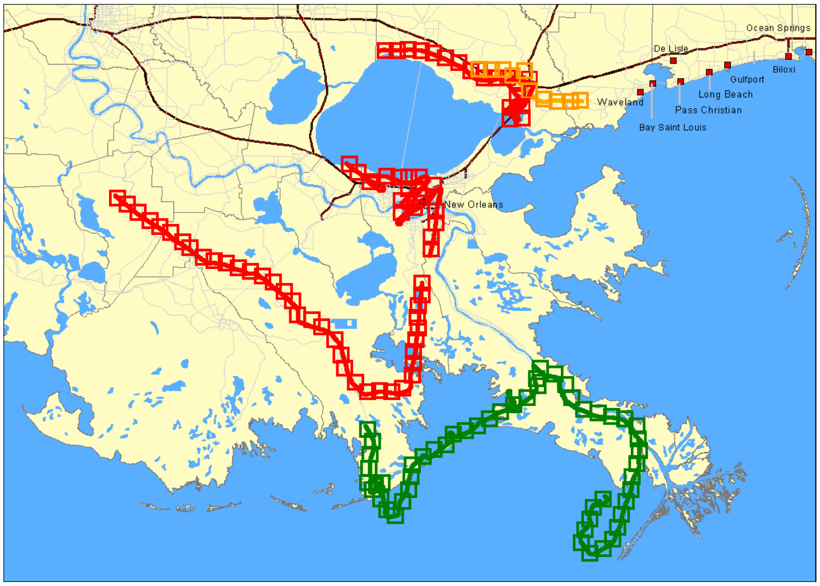
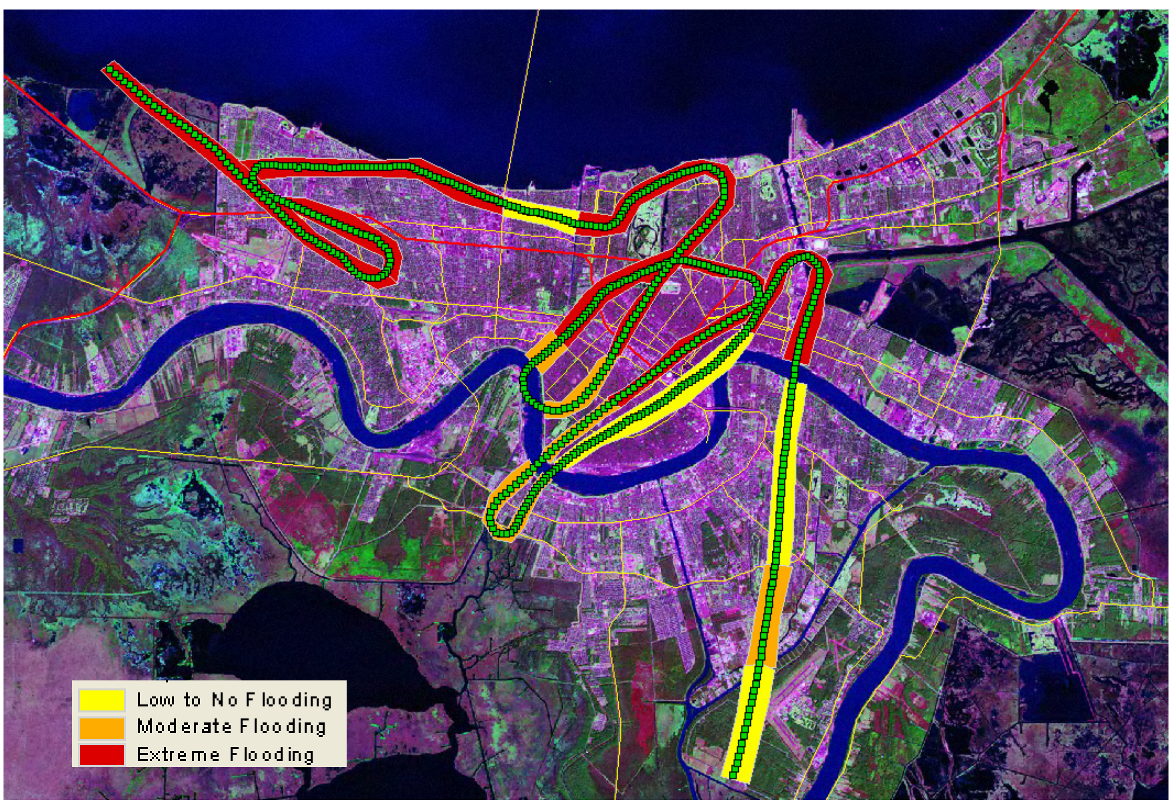


Figure 4-21. Locations of PDV aerial surveys of flood damage conducted within New Orleans and surrounding areas in the aftermath of Hurricane Katrina. Damage information was distributed within 24-48 hours of the event.



Landsat base image from USGS

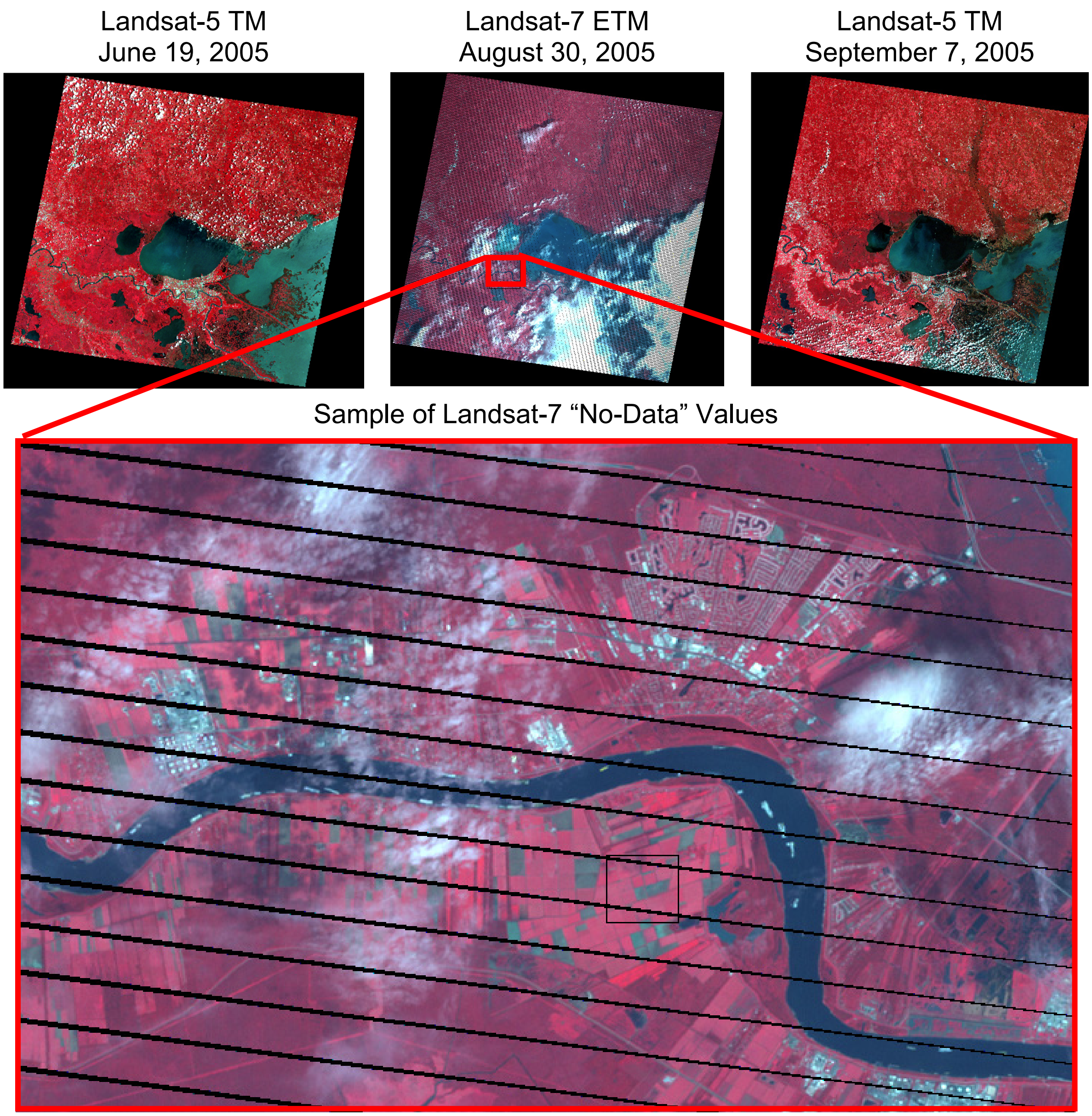
Figure 4-22. Damage assessment of flooding severity on August 30, based on expert interpretation of PDV VIEWS™ footage.

4.3.2 Region-wide Damage Detection Using Landsat Imagery

As previously observed in the case of storm-surge damage (Section 4.1.1), the moderate spatial resolution and extensive geographic coverage afforded by Landsat imagery provide a region-wide perspective of post-disaster damage. In terms of flood damage detection, Table 2-3 shows that Landsat-7 ETM imagery was collected on August 30. Although this dataset provides reasonable coverage for downtown New Orleans (see Section 4.3.3), it is of limited value on a region-wide scale due to the no-data gaps (black lines) radiating outward from the center of the scene (Figure 4-23), caused by failure of the scan line corrector in 2003. The present analysis instead employed the first set of Landsat-5 TM imagery captured after Hurricane Katrina on September 7, together with pre-storm imagery from June 19, 2005.

Figure 4-24 summarizes the methodology used to assess urban damage on a region-wide basis. For the storm-surge analysis, an initial pre-processing step involved registering the pre-and post-storm imagery to ensure spatial alignment. Landcover within the co-registered pre-and post-disaster scenes was quantified using the NDVI defined in Equation 4.1. A set of masks was then applied to minimize the occurrence of false positives commensurate with non-damage-related sources of change. A cloud mask was obtained for each image by thresholding the Landsat-5 TM Band 6 coverage to identify their characteristically cold signature. The water surface mask was obtained by thresholding the pre-storm NDVI image.

Learning from the storm-surge analysis in Section 4.1.1, an additional non-urban mask was also applied to eliminate potential ecologically based changes where the hurricane caused vegetation browning or leaf loss. A supervised classification of the pre-storm image was used to create the mask. Training sites were selected for eight dominant classes: (1) urban; (2) vegetated land; (3) wetland; (4) cleared agricultural land; (5) river/ocean; (6) cloud; (7) shadow; and (8) unclassified. For a sample of landcover classes, Figure 4-25 shows (a) the input image and (b) classified output image following application of a 9x9-pixel majority filter used to minimize isolated pixels within an otherwise homogenous class.



Landsat imagery from USGS and NASA

Figure 4-23. Pre- and post-Hurricane Katrina Landsat-7 ETM imagery (Path 22 Row 39) used to detect flood damage in Louisiana. The Landsat-7 ETM imagery captured on August 30 illustrates the "no-data" values (black lines) that precluded use of this imagery for region-wide change detection.

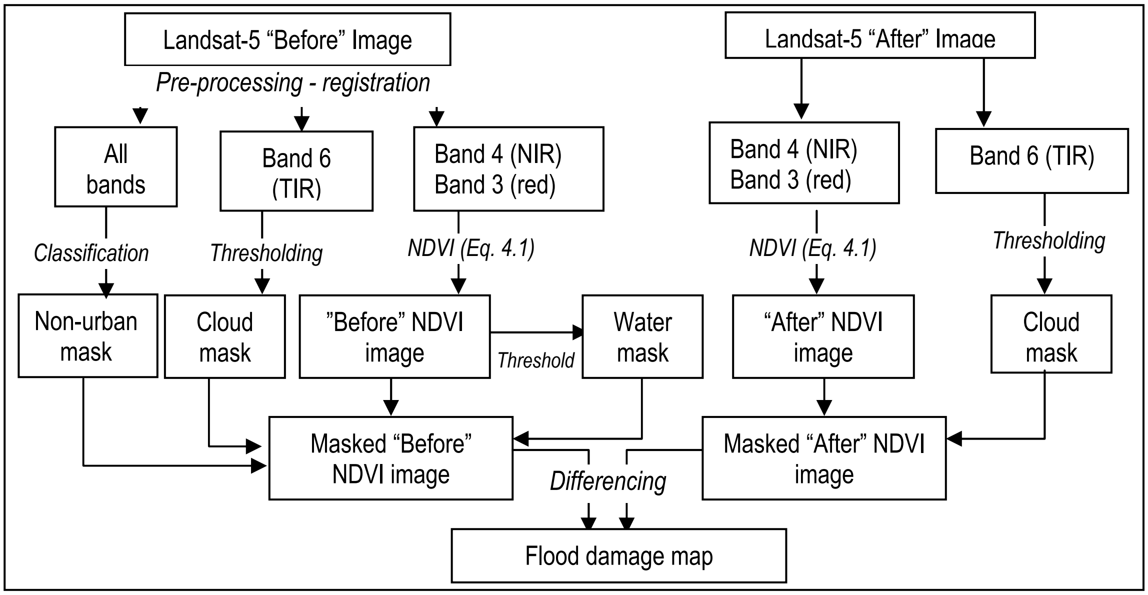
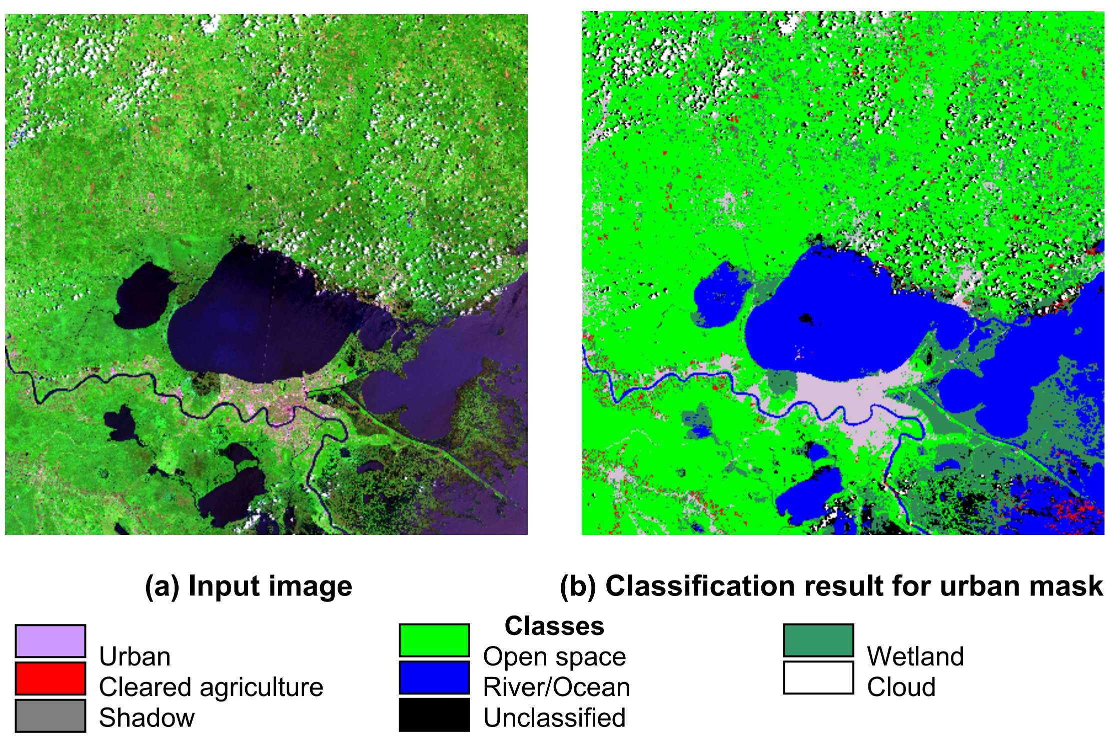


Figure 4-24. Methodology employed for region-wide flood damage detection.



Landsat base images from USGS

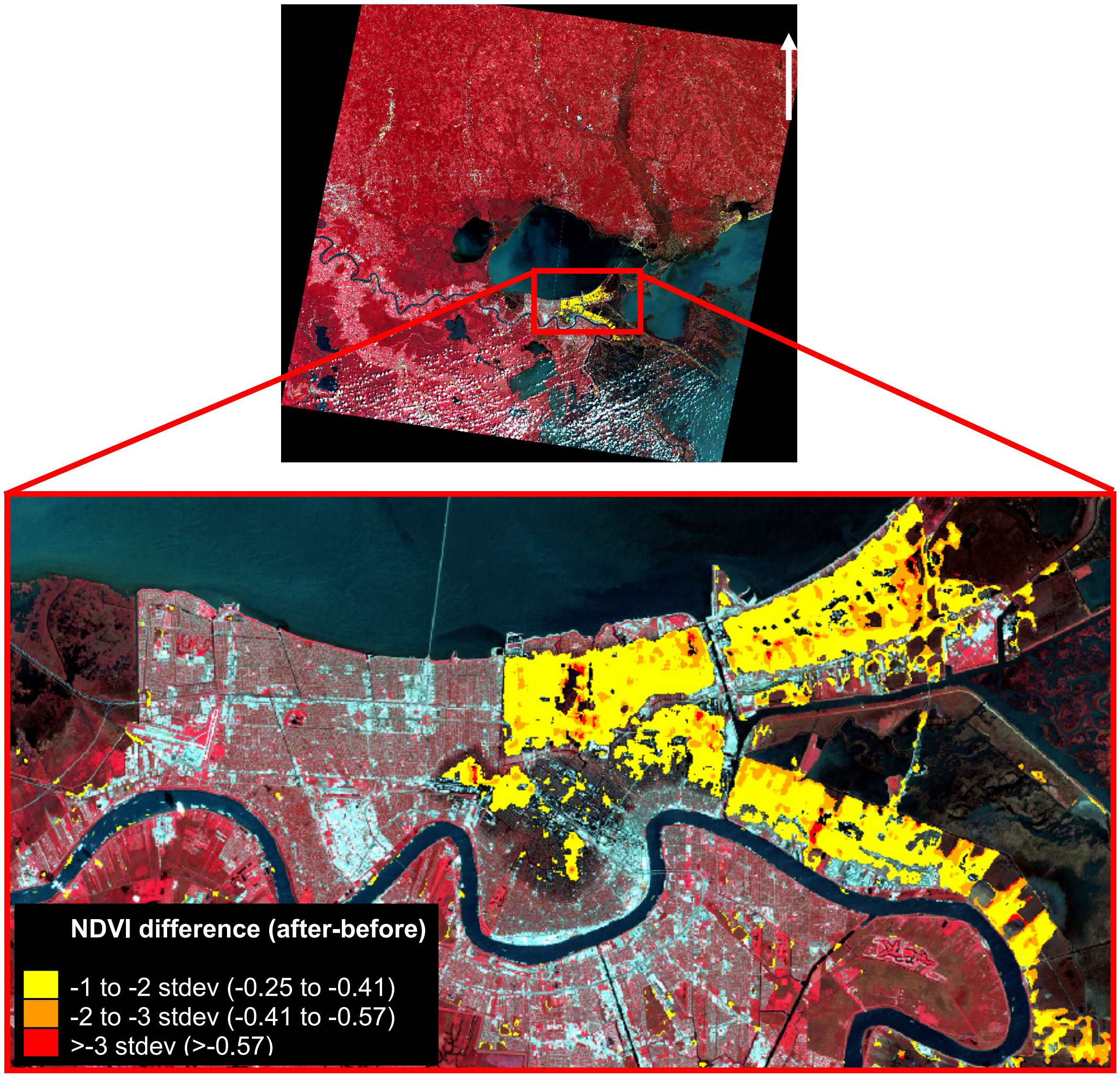
Figure 4-25. (a) Input Landsat-5 TM image (Bands 7,4,2) for New Orleans area, and (b) output classification result, subject to a 9x9 majority filter to mitigate the effect of isolated pixel classes. The "urban" class was used to create a mask in order to eliminate ecologically-based changes.

Adjusted "before" and "after" NDVI images were produced by applying the cloud, water, and urban masks to the "before" image and the cloud mask to the "after" image. The extent of flooding caused by the hurricane and levee breach was finally determined as a function of the difference (computed as "after" – "before") between the adjusted NDVI scenes, also expressed as a measure of standard deviation about the image-wide mean.

Figure 4-26 shows the flood inundation map for Louisiana, as of September 7, 2005. Areas within Orleans and St. Bernard Parishes exhibit a significant change between the pre- and post-hurricane coverage, synonymous with inundation caused by flooding. The negative difference in NDVI indicates a reduction in spectral response in the red and near-infrared bands within the "after" scene. Whereas a similar reduction along the Mississippi Coast was attributed to surface scour by the storm-surge wave, in this instance the relatively bright reflection from buildings and vegetation comprising urbanized surfaces is replaced by the comparatively dark reflection from floodwaters.

The study of Hurricane Katrina damage from a remote sensing perspective reinforces the value of an integrated approach to damage assessment, which combines rapid survey with regular monitoring (i.e., situation assessment) during the following days and weeks. Figure 4-27 shows a temporal comparison of New Orleans images captured before and after the hurricane, from June to October 2005.

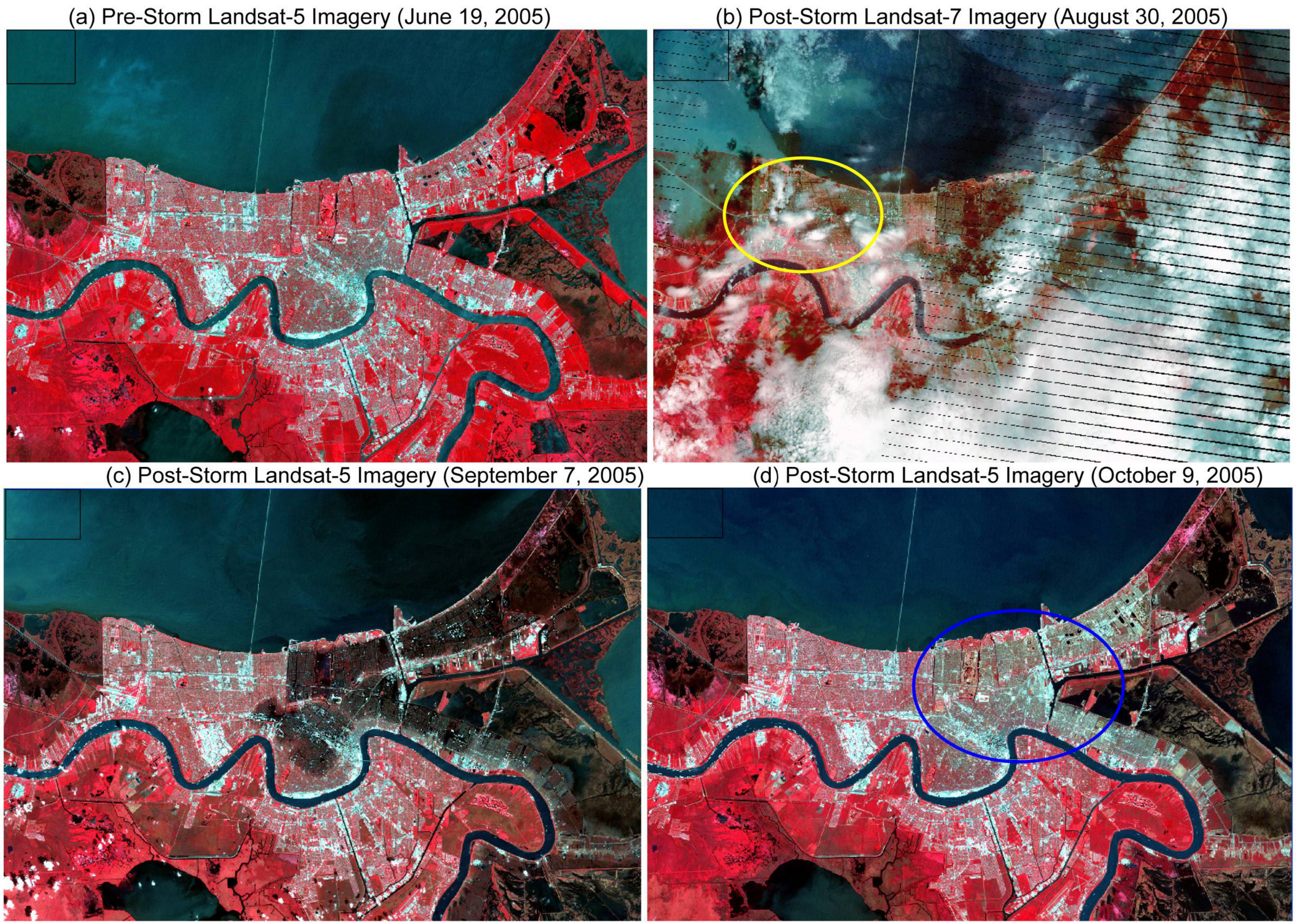
Comparison of the pre-storm Landsat imagery from June 2005 (Figure 4-27a) with post-event Landsat imagery from August 30, 2005 (Figure 4-27b) suggests that in the immediate aftermath of Hurricane Katrina, flooding occurred throughout western, eastern, and central districts of New Orleans. Multi-temporal analyses are also useful for monitoring the evolving disaster situation. For example, while flooding remains evident throughout central and eastern districts in the September 7 Landsat-5 imagery (Figure 4-27c), inundation that was observed during the PDV survey (Section 4.3.1) and Landsat coverage of August 30 (noted in yellow in Figure 4-27b) is no longer apparent. This finding suggests that flood waters retreated at different rates throughout the city, which may in turn be linked to the source of flood water (overtopping versus levee breach).



Landsat imagery from USGS

Figure 4-26. Region-wide flood damage map for the New Orleans area overlaid on the Landsat-5 TM image of September 7. Damage is measured in terms of change in NDVI between pre- and post-hurricane images. Extreme changes are evident within Orleans and St. Bernard Parishes in the eastern portion of the image.

The September 7 Landsat coverage in Figure 4-27c clearly depicts widespread inundation within central and eastern districts; due to dense cloud cover and no-data values, it is difficult to determine if these areas are also inundated in the August 30 Landsat-7 scene. Within the false-color composite comprising near-infrared, red, and green bands, flooding is characterized by a low spectral return (dark reflection). From detailed visual inspection, this low return can be traced to the location of levee breaches (see Section 4.3.3).



Landsat base images from USGS

Figure 4-27. Temporal sequence of false-color composite images (Landsat-5 Bands 4, 3, 2) for New Orleans, acquired before and after Hurricane Katrina. Flooding that is evident in western districts on August 30 (see yellow annotation) is no longer apparent on September 7. Extensive flooding within central and eastern districts has subsided by October 9, leaving a distinctive spectral signature (see blue annotation).

By October 9, when the fourth image in the sequence was acquired (Figure 4.27d), the floodwaters have subsided, and the inundated region exhibits a new signature. Compared with the pre-storm scene, spectral return is markedly lower at near infrared wavelengths, resulting in a blue/grey appearance. Judging from experience garnered following the Indian Ocean tsunami (Adams et al., 2005b) and through analysis of the Hurricane Katrina surge line in Mississippi (Section 4.1.1), this effect is likely due to the die-back of surface vegetation, together with the deposition of waterborne sediments and debris.

In an applied context, this evaluation of temporal changes in flooding extent and severity has far-reaching implications for loss assessment within affected communities. During the days and weeks following the event, usual ground-based routes of access employed by insurance companies to assess the severity of damage were unavailable. The remote access offered by satellite and aerial imagery provides an accurate and holistic picture of the unfolding scene. Such data could serve as key benchmarks from which claims assessors could identify the probable degree of damage and prioritize post-disaster business activities.

4.3.3 Neighborhood Damage Detection Using QuickBird Imagery

In addition to the swift identification of hurricane-affected areas through transect-based rapid PDV visualization and the broad-scale extent of damage using moderate-resolution Landsat-5 coverage, high-resolution QuickBird satellite imagery offers a detailed neighborhood-based flood damage assessment for the entire city of New Orleans. This neighborhood evaluation serves as an exemplary case for the way in which the collection, ordering, delivery, and processing of satellite imagery can be streamlined to facilitate rapid response activities.

Figure 4-28 summarizes the methodology used to determine the status of communities in New Orleans as of Saturday September 3, 2005. High-resolution near-nadir (vertical) QuickBird imagery was acquired by DigitalGlobe during the afternoon of September 3 and made available for ordering the same afternoon. An imagery order for a 618-km^2 area was placed on the night of Saturday September 3, as a "Rush-Archive" request, which promotes the order to the head of DigitalGlobe's processing schedule. The processed imagery became available less than 24 hours later and was downloaded overnight via the Internet (ftp) to make the data available for analysis on Monday morning, September 5.

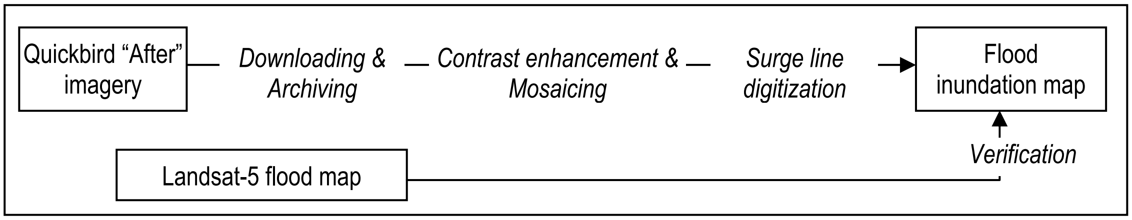
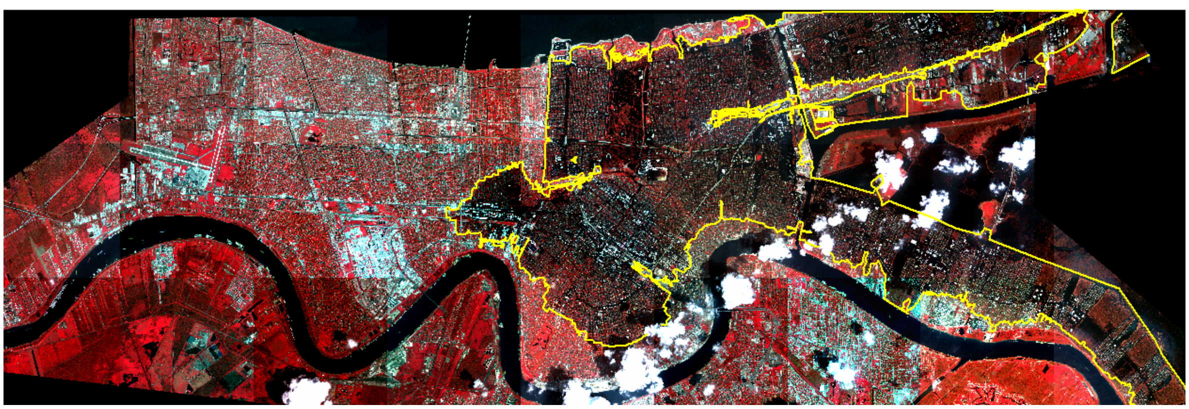


Figure 4-28. Methodology employed for neighborhood flood damage detection.

The post-hurricane QuickBird imagery covering the New Orleans area was delivered as a series of 34 individual tiles in order to streamline the processing activities and to avoid large file size issues. To highlight the flood area in preparation for expert interpretation, a series of processing steps were performed. First, a contrast-enhanced false-color composite comprising near-infrared, red, and green bands was produced for each image tile in an attempt to capitalize on the distinctive signature (dark reflection) of the inundation zone and to minimize the effect of cloud and shadow. Next, the image tiles were converted to a GIS-compatible format in preparation for flood-line digitization. Finally, as shown in Figure 4-29, the tiles were mosaiced together within a GIS environment.

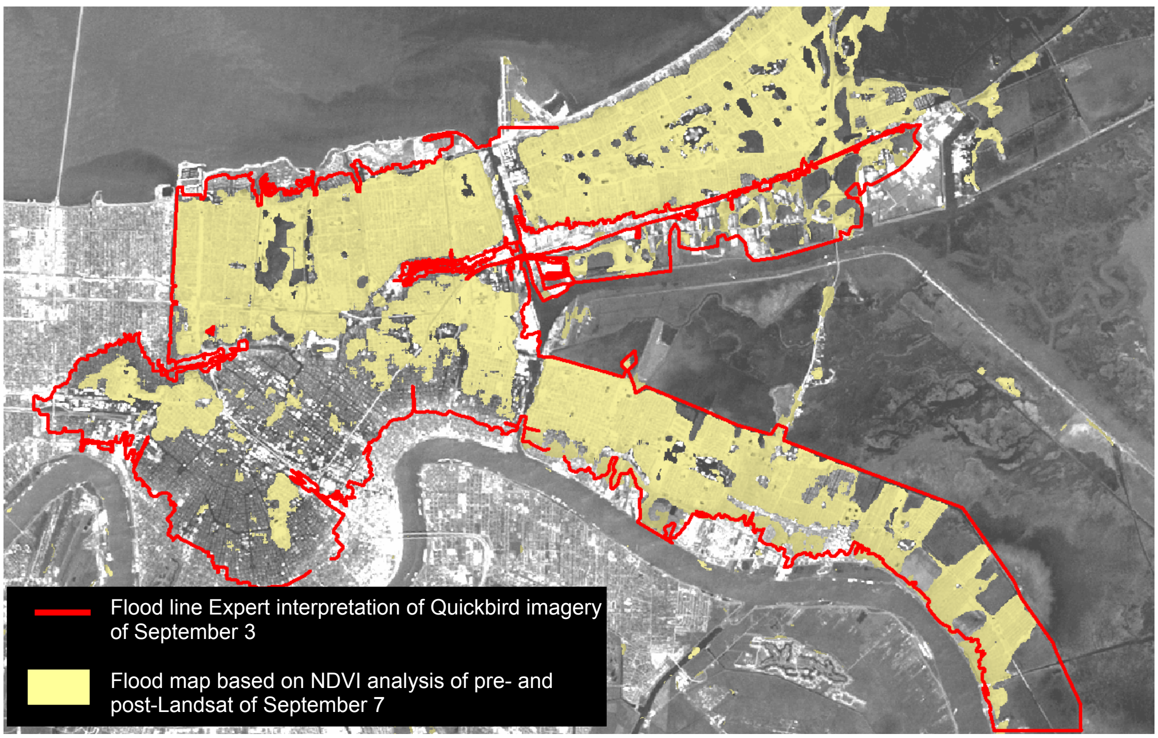


QuickBird Imagery from DigitalGlobe, Inc., www.digitalglobe.com

Figure 4-29. Expert-interpretation-based flood limit (delineated in yellow) overlaid with the QuickBird false-color composite image of New Orleans for September 3, 2005 (from which the flood zone was derived), comprising 34-contrast enhanced and mosaiced tiles.

The boundary of inundation was delineated for New Orleans as a series of polygons, based on expert interpretation of the spectrally enhanced September 3 QuickBird coverage. For the Landsat-5 coverage (see Figure 4-27), the flooded area was identified based on the lower reflectance of water as compared with non-flooded ground-surface features. Given the high spatial resolution of the imagery, it was possible to distinguish inundated areas to within the nearest city block. There were several isolated areas surrounded by flooding, for which polygons appear as "non-flooded islands."

The expert-defined flood boundary for September 3 was visually compared with the NDVI-based flood map developed using Landsat-5 TM coverage for September 7 (see Section 4.3.2 and Figure 4-30). There is a close correspondence between the two extents, with flooding concentrated in the central and eastern districts of the city. An area of discrepancy is present within southern districts, where the NDVI analysis did not identify significant flooding. This discrepancy may be a function of the flooding severity.



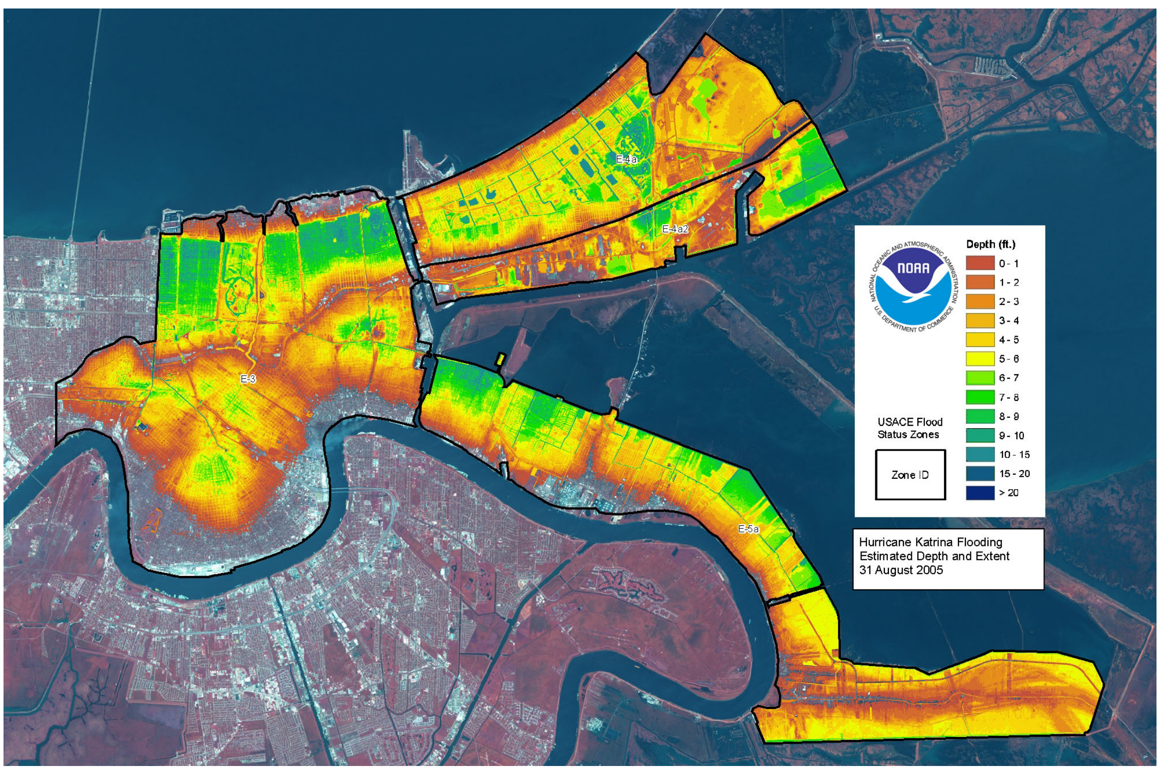
QuickBird Imagery from DigitalGlobe, Inc., www.digitalglobe.com

Figure 4-30. Independent verification of the QuickBird flood line, using the NDVI flood map developed with pre-hurricane Landsat-5 TM imagery and post-coverage for September 7.

4.3.4 Neighborhood Flood-Depth Analysis

Flood-depth information is a key factor in determining urban damage and losses from floodwaters that lack significant velocity. Following Hurricane Katrina, MCEER researchers at ImageCat employed a range of publicly available sources to define areas of greatest flood depth.

Flood-depth maps produced by government agencies including NOAA and the U.S. Army Corps of Engineers (USACE) were used to create preliminary estimates of flood inundation damage. NOAA's flood depth estimation map for August 31, 2005 is shown in Figure 4-31, and is based on lidar (Light Detection and Ranging) data from Louisiana State University and the State of Louisiana combined with optical imagery from the Department of Defense National Geospatial-Intelligence Agency (NGA). Additional flood-depth information was provided by USACE daily flood elevation readings, combined with topographic base data. Flood elevation data were collected throughout New Orleans using in-situ gauging devices. By interpolating a surface between measurements, these flood elevations were used to create a flood elevation surface. Lidar elevations (corrected for buildings) for New Orleans were subtracted from the flood elevation surface, producing daily values of flood depth throughout New Orleans.



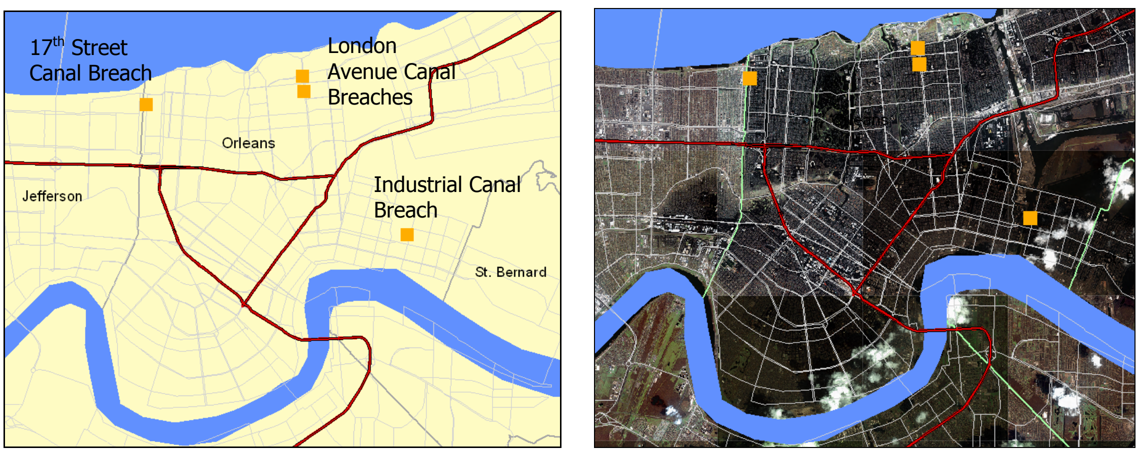
NOAA http://www.noaanews.noaa.gov/stories2005/s2503.htm

Figure 4-31. Flood depth estimation August 31, 2005.

While flood-depth information provided by remote sensing was valuable in assessing regional impacts of floodwaters and critical in identifying areas that may be most affected by the flood event, there was also a pressing demand for in-field reconnaissance. Accurate assessment of flood damage and full understanding of the associated impacts demands additional information about building floor elevations. As observed in New Orleans, many homes exhibit a traditional, elevated architectural style, which evolved in response to frequent flooding of the area. A Tier 3 assessment (see Section 3.1) of the prevalence of this construction technique throughout New Orleans is central to understanding the extent to which these local architectural and construction practices were successful in the mitigation of flood damage.

4.4 High-Velocity Flooding (Levee Breach)

One day after Hurricane Katrina made landfall, sections of levees along the 17th Street Canal, the London Avenue Canal, and the Industrial Canal collapsed (Figure 4-32), leaving almost 80% of the city under water (NOAA, 2005d). In addition to the flood assessment described in Section 4.3, a combination of high-resolution satellite and aerial imagery (see Chapter 2) was used to provide a neighborhood-scale perspective of high-velocity flooding damage stemming from the levee breaches.



QuickBird images from DigitalGlobe, Inc., www.digitalglobe.com

Figure 4-32. Levee-breach locations on the 17th Street Canal, London Avenue Canal, and the Industrial Canal in New Orleans. (a) Area map showing the levee-breach locations; (b) QuickBird imagery showing the levee-breach locations.

4.4.1 Neighborhood Damage Detection Using QuickBird Imagery

As discussed in Chapter 2, DigitalGlobe's high-resolution QuickBird imagery of New Orleans became available for analysis within days of the disaster. High-resolution imagery was acquired by DigitalGlobe on Saturday, September 3, and distributed to MCEER researchers at ImageCat on Sunday, September 4. A neighborhood-based, high-velocity flood damage assessment for areas near the levee breaches was performed using this QuickBird dataset.

Each of the levee-failure locations was identified using expert interpretation of a pansharpened natural-color composite of the QuickBird imagery. Figure 4-33 shows a visually based interpretation of the levee-breach sites. Areas surrounding the levee failures were inspected using the composite image to extract information concerning:

- Extent of the breaches (approximate lengths).
- Location of flooded areas associated with the breaches. For example, the east side of the 17th Street Canal bordering Jefferson and Orleans Parishes failed, causing high-velocity flooding in Orleans Parish on the east side of the canal, while Jefferson Parish to the west was not similarly affected.
- Major changes in building configurations due to high-velocity floodwaters removing buildings from their foundations.
- Changes in urban vegetation (e.g., uprooting of trees).

4.4.2 Neighborhood Damage Detection Using NOAA Aerial Imagery

An expert interpretation of the high-resolution aerial photography captured by NOAA in the days following Hurricane Katrina (Section 2.2) provided another more-detailed neighborhood-scale perspective on damage within the high-velocity flooding areas near the levee-breach sites in New Orleans. This approach was similar in concept to the visual inspection-based work completed using QuickBird satellite imagery (Section 4.4.1), and served to verify those findings.

The aerial-photo index shown in Figure 4-34 shows the locations of post-hurricane imagery of the New Orleans area acquired and posted online by NOAA. The sets of images used for the visual inspection of damage around the levee-breach locations are indicated by red boxes. Figure 4-35 demonstrates the characterization and interpretation of the levee-breach sites within New Orleans, using the NOAA images. The finer spatial resolution of the aerial images (37 cm) provides additional detail about the hazard effects of the high-velocity flows near the breaches. Although image processing was not required to use the NOAA aerial images for visual interpretation, georeferencing operations were necessary for use with other spatial data sets (e.g., GIS data within the VIEWS™ reconnaissance system).

Levee breach at the 17th Street Canal near the Hammond Highway bridge. The non-flooded area on the west side of the canal is Jefferson Parish, and the flooded area on the east side is Orleans Parish. This image shows the dramatic difference between flood and no-flood areas.

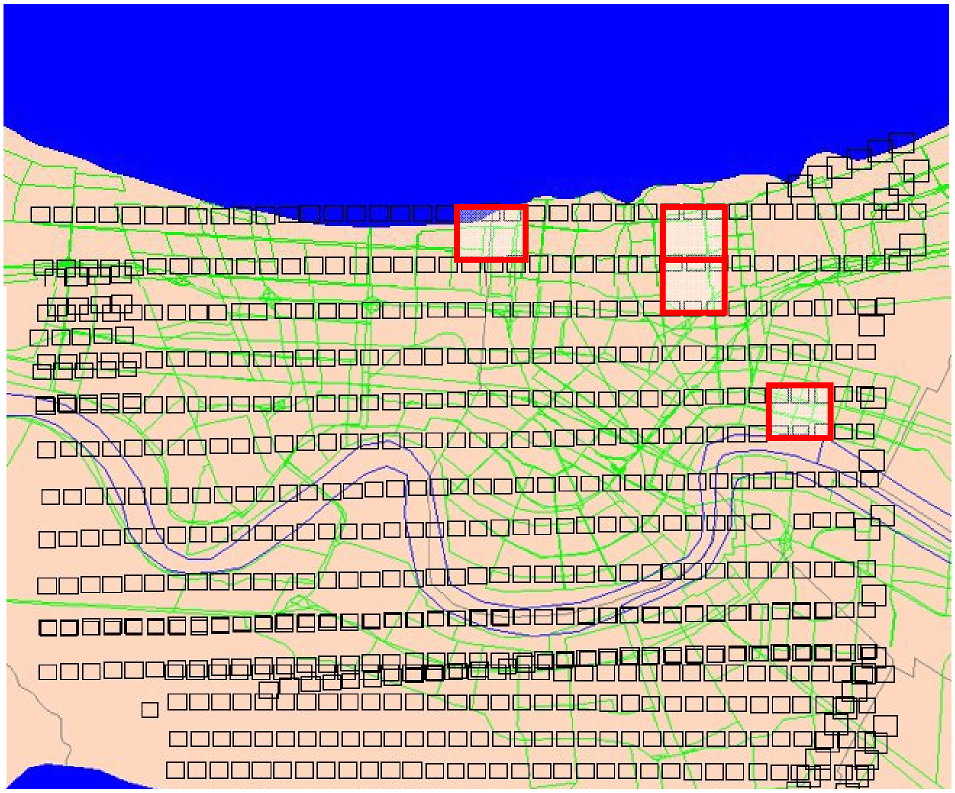
A failed section of the west bank of the London Avenue Canal levee south of the Robert E. Lee Boulevard Bridge.

A failed section of the east bank of the London Avenue Canal levee north of the Mira Beau Avenue Bridge.

Levee breach located on the east side of the Industrial Canal between Florida Avenue and North Claiborne Avenue, causing flooding in the Lower Ninth Ward. The destruction of buildings in this area of high-velocity flooding is evident from the scattering of the building roofs.

QuickBird images from DigitalGlobe, Inc., www.digitalglobe.com

Figure 4-33. 61-cm natural-color QuickBird images used to visualize the levee-breach locations.



Index map from NOAA

Figure 4-34. Location of NOAA aerial images for the New Orleans area acquired following Hurricane Katrina. Imagery for the major levee breach locations is indicated with the red boxes.

NOAA aerial image of levee breach at the 17th Street Canal near the Hammond Highway bridge.

NOAA images in the series capturing this location:
http://ngs.woc.noaa.gov/storms/katrina/24425584.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425580.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425575.jpg

NOAA aerial image of a failed section of the west bank of the London Avenue Canal levee south of the Robert E. Lee Boulevard Bridge.

NOAA images in the series capturing this location:
http://ngs.woc.noaa.gov/storms/katrina/24425546.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425542.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425537.jpg

NOAA aerial image of a failed section of the east bank of the London Avenue Canal levee north of the Mira Beau Avenue Bridge.

NOAA images in the series capturing this location:
http://ngs.woc.noaa.gov/storms/katrina/24425095.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425100.jpg
http://ngs.woc.noaa.gov/storms/katrina/24425091.jpg

NOAA aerial image of levee breach located on the east side of the Industrial canal between Florida Avenue and North Claiborne Avenue, causing flooding in the Lower Ninth Ward.

NOAA images in the series capturing this location:
http://ngs.woc.noaa.gov/storms/katrina/24428010.jpg
http://ngs.woc.noaa.gov/storms/katrina/24428006.jpg
http://ngs.woc.noaa.gov/storms/katrina/24428001.jpg

Figure 4-35. 37-cm natural color NOAA images used to view the levee-breach locations (Aerial images from NOAA).

4.5 Summary of Key Findings

- Hurricane Katrina presented a unique opportunity to apply prior damage assessment research findings in a multi-hazard context for: (1) storm surge; (2) wind pressure; (3) flood inundation; and (4) levee breach.

- From an operational standpoint, storm-surge and flooding information was utilized by Risk Management Solutions, Ltd. for verifying loss estimates. MCEER advanced technology reconnaissance teams utilized multi-hazard remote sensing-based damage data for deployment planning and support.

- From an operational perspective, it was necessary to draw on multiple imagery sources to meet different information needs within required timescales. ImageCat's PDV (Post-disaster Damage Verification) imagery provided rapid damage assessment within 48 hours of the event for point locations throughout New Orleans. NOAA imagery offered some of the first perspectives on damage along the Mississippi Coast. In the immediate aftermath of the event, cloud cover limited the acquisition of useable satellite imagery.

- Storm-surge extent was evaluated at a regional scale (Tier 1 of the Tiered Reconnaissance System (TRS) framework) through the NDVI-based analysis of a temporal before-and-after sequence of moderate-resolution Landsat-5 imagery acquired from USGS/NASA. Changes were identified along the entire coast, suggesting that extreme storm-surge scour has occurred.

- A neighborhood-scale perspective (Tier 2 of the TRS) on the landward limit of storm surge damage between Bay St. Louis and Biloxi was provided through the custom georeferencing and analysis of NOAA airborne imagery. On average, the most extreme damage where 90-100% of buildings were completely destroyed occurred within about ½ to 1 mile of the shore.

- A severity ranking system was developed to rapidly assess neighborhood wind damage effects using the library of 3,700 NOAA post-Hurricane Katrina aerial images. Hard-hit areas were identified using a ranking from Level 3 (high damage) to Level 1 (low damage). (A Level 0 ranking was also given to areas where wind damage was obscured by storm-storm damage.)

- Per-building wind damage to residential structures (Tier 3 of the TRS) was assessed for hard-hit neighborhoods by applying a 4-level remote sensing-based damage scale (developed by Womble 2005) to NOAA aerial images. Damage scales for commercial and industrial structures are under development.

- Evaluation of remote sensing coverage for waterfront properties demonstrated that storm surge proved far more damaging than wind pressures. In many cases, roofs experienced minimal wind damage, yet the portions of the buildings beneath were washed away.

- A rapid assessment of the New Orleans flooding situation was provided within 48-hours of the event by the ImageCat PDV program. HDV (High Definition Video) footage with a 5-15 cm spatial resolution showed the initial flooding status, capturing inundation within western districts which was absent from assessments conducted one week later.

- Flood inundation within the New Orleans area was evaluated at a regional scale using an NDVI-based analysis of a temporal "before" and "after" sequence of moderate-resolution Landsat-5 imagery acquired from USGS/NASA. Results indicate that Jefferson and St. Bernard Parishes were flooded as of September 7.

- A multi-temporal comparison of Landsat-7 images acquired throughout August and September 2005 show the rise and recession of flooding within New Orleans.

- A neighborhood-scale perspective on the extent of flooding in New Orleans on September 3 was obtained from multispectral QuickBird imagery. Lidar coverage was used by NOAA in combination with an estimate of flood extent to provide flood depths across the city.

- Levee breaches are clearly identified on 61-cm QuickBird satellite imagery of New Orleans and NOAA airborne coverage. Information including the extent of breach and location of high-velocity flooding can also be determined.

5.0 VIEWS™ Field Reconnaissance

As a part of MCEER reconnaissance activities in the wake of Hurricane Katrina, remote sensing technologies and the VIEWS™ system were used to rapidly collect high-resolution photograph and high-definition video surveys of damage throughout an extensive geographic area.

As shown in Figure 5-1, the deployments were conducted in two phases. The first deployment targeted the Mississippi Coast on September 7-9, 2005, while the second deployment was conducted on October 6-9, 2005 in the New Orleans area, covering most of Orleans Parish and parts of St. Bernard Parish. This two-phased deployment aimed to fulfill the objectives identified in Chapter 1 for the post-Hurricane Katrina field investigation:

(1) Performing rapid and widespread assessments of damage at a per-building scale, and
(2) Preserving the perishable damage characteristics of this unique multi-hazard event for future research activities.

Table 5-1 presents the deployment plan (see Section 3.2.2 and Table 3-2) summarizing the multi-hazard field survey activities conducted during the two-phased investigation. The following elements were considered as a part of the deployment plan:

- Specific objectives
- Level of Tiered Reconnaissance System (TRS) – See Section 3.1.
- Geographic extent
- General approach
- VIEWS™ base data
- Potential research products

As a part of the Phase 1 deployment, data collection activities focused on the coastal areas of Mississippi known to have experienced catastrophic damage to buildings and infrastructure. Following the multi-hazard site selection protocols outlined in Section 3.3.1, survey sites were selected based on several factors, including: remote sensing analysis; media reports of areas experiencing severe damage (especially urban areas with severe damage to residential and business properties); available windspeed estimates (NOAA 2005e); and the recommendations of experts on the survey team.

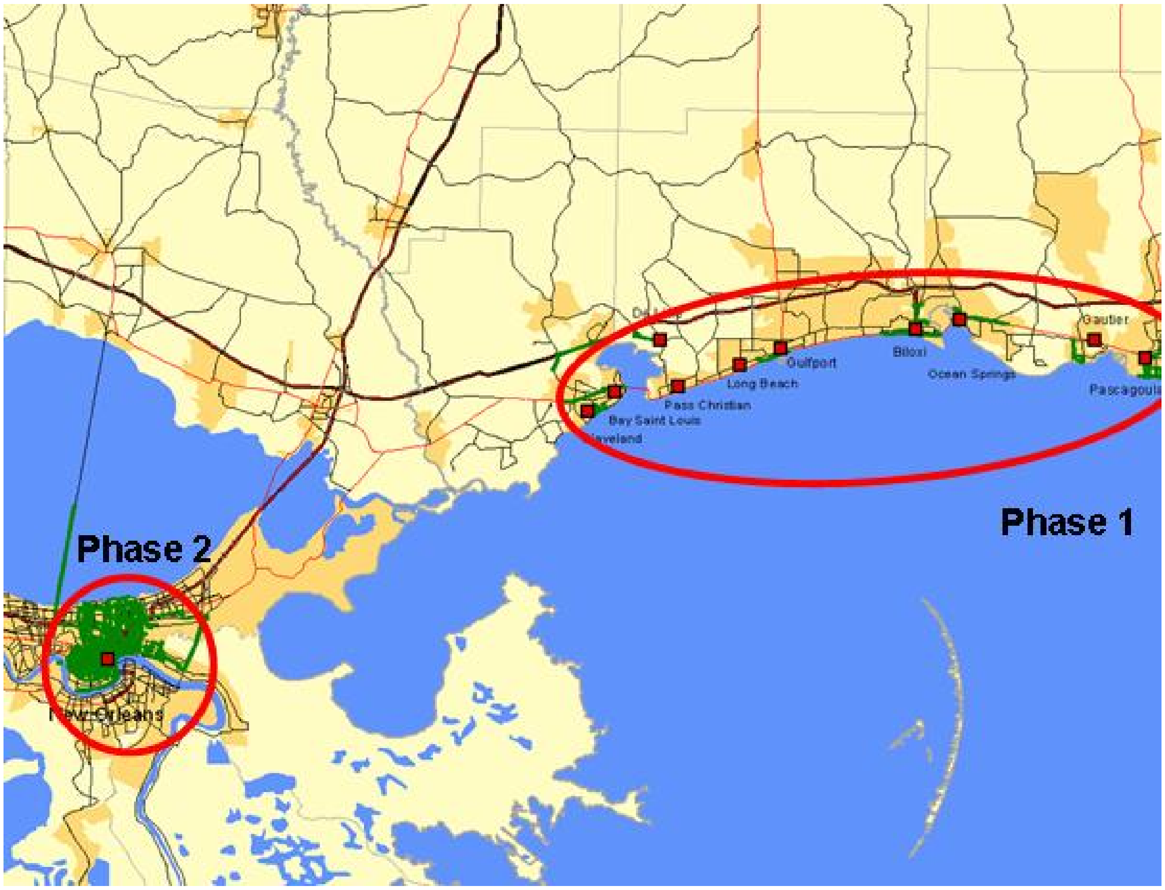


Figure 5-1. Geographic extent of the two-phased deployment showing the GPS route (green symbols) followed by the MCEER advanced technology field teams in coastal Mississippi (Phase 1) and New Orleans (Phase 2).

Considerable attention was placed on surveying a broad area along the Mississippi Coast to document a wide range of hurricane damage.

In line with findings from the Tier 1 and Tier 2 analyses of storm-surge extent (Section 4.1) and Tier 2 and Tier 3 evaluations of the spatial distribution of wind-pressure damage (Section 4.2), the MCEER advanced technology field team visited the areas hardest-hit by both wind pressures and storm surge (including Waveland, Bay St. Louis, Gulfport, and Biloxi) as well as the areas hit predominantly by storm surge (including Ocean Springs, Gautier, and Pascagoula). Access issues (ongoing recovery efforts) precluded field surveys within Pass Christian. For investigation of storm-surge damage, efforts were focused along the hard-hit coastal strip, approximately three-to-four blocks from the beach. For wind-pressure damage, efforts spanned neighborhoods throughout the affected region.

Table 5.1. Deployment plan, summarizing multi-hazard field survey activities conducted following Hurricane Katrina in Mississippi and New Orleans

GENERAL AIM	***Employ remote-sensing technology and the VIEWS™ system in the aftermath of Hurricane Katrina, to rapidly collect perishable field information about multi-hazard urban damage characteristics***				
SPECIFIC OBJECTIVE	1. To collect a visual geospatially-referenced record of storm-surge damage to buildings, utility lifelines & essential facilities	2. To collect a visual geospatially-referenced record of wind damage for buildings, utility lifelines & essential facilities	3. To collect a visual geospatially-referenced record of flood damage for buildings, utility lifelines & essential facilities.	4. To assess the efficacy of high-resolution imagery for delineating the boundary of urban flood inundation	5. To rapidly assess the severity of urban damage caused by flooding and high-velocity flooding (levee breach)
TRS LEVEL	Tier 3 (see Figure 3.2 and Table 3.1)	Tier 3	Tier 3	Tier 2	Tier 2 (see Section 4.4.1)
GEOGRAPHIC EXTENT	Extensive – multiple sites within Mississippi. Locations determined using Tier 1 and Tier 2 of the tiered reconnaissance system, the site selection protocol, plus media reports.	Extensive – multiple sites within Mississippi and Louisiana. Locations determined using Tier 1 and Tier 2 of the tiered reconnaissance system, the site selection protocol, plus media reports.	Extensive – numerous sites within New Orleans. Locations determined using Tier 1 and Tier 2 of the tiered reconnaissance system, the site selection protocol, plus media reports.	Extensive – numerous sites along the New Orleans flood boundary. Intensive – Subset of locations subject to intensive evaluation of transects perpendicular to the flood boundary.	Extensive – transects throughout New Orleans. Locations determined using Tier 1 of the tiered reconnaissance system, the site selection protocol, plus media reports.
GENERAL APPROACH	Within each study zone, deploy VIEWS™ from a moving vehicle and on foot to collect georeferenced digital video and photographs for buildings, lifelines and other critical facilities. Use available damage scales to interpret severity of damage.	Within each study zone, deploy VIEWS™ from a moving vehicle or on foot to collect georeferenced digital video and photographs for buildings, lifelines and other critical facilities. Interpret severity of damage using documented wind damage scales (e.g., Womble, 2005; FEMA, 2003a).	Within each study zone, deploy VIEWS™ from a moving vehicle or on foot to collect georeferenced digital video and photographs for buildings, lifelines and other critical facilities. Interpret severity of damage using documented flood damage scales (e.g., FEMA, 2003b).	Deploy VIEWS™ from a moving vehicle, following the flood boundary. Compare VIEWS™ GPS route with image-interpreted boundary. Deploy VIEWS™ on foot for a few selected locations to collect georeferenced footage along transects perpendicular to floodline.	Deploy VIEWS™ from a low-altitude aircraft on the day following the hurricane. Capture HDV stills of urban damage. Flight path spans the entire affected area, and includes neighborhoods sustaining multiple levels of damage.
VIEWS™ BASE DATA	● NOAA aerial photography ● Landsat false-color composite ● Landsat mosaic ● Streets, zip codes, counties vector layers ● Potential study sites/ critical areas vector	● High-resolution QuickBird imagery ● NOAA aerial photography ● Landsat false-color composite ● Landsat mosaic ● Streets, zip codes, counties vector layers ● Potential study sites/ critical areas GIS data	● High-resolution QuickBird imagery ● Landsat false-color composite ● Landsat mosaic ● Streets, zip codes, counties GIS data ● Potential study sites/ critical areas GIS data	● High-resolution QuickBird imagery ● Landsat mosaic ● New Orleans Digital Raster Graphic (DRG) mosaic ● Streets, zip codes, counties GIS data ● Extent of flooding GIS data	● Landsat mosaic ● Streets, zip codes, county GIS data ● Potential study sites/ critical areas GIS data
POTENTIAL RESEARCH PRODUCT	Geospatially referenced storm-surge damage observation catalogue for different building types and lifeline utilities for a major hurricane. Record of multi-hazard damage to individual structures	Geospatially referenced wind-damage observation catalogue for different building types and lifeline utilities for a major hurricane. Record of multi-hazard damage to individual structures	Geospatially referenced flood-damage observation catalogue for different building types and utility lifelines for a major hurricane. Record of multi-hazard damage to individual structures	Observations concerning the usefulness of high resolution imagery for mapping the extent of flooding. Possible refinement of flooding extent delineation. Accuracy assessment of edge-flooding line and comment on cause for deviation.	Geospatially referenced airborne catalogue of flood- and surge-related damage observations for different building types and utility lifelines. Multi-temporal record of multi-hazard damage to individual structures
POTENTIAL ISSUES	i) No established damage scale exists for storm surge. May have to modify scale from other hazard, e.g. flooding, tsunami.	i) Need to review available wind damage scale for buildings, lifelines, etc. ii) Efficiency may be improved by deploying multiple HDV cameras.	i) Access to affected areas may be limited. ii) Efficiency may be improved by deploying multiple HDV cameras.	i) Limited access to continuous stretches of the flood boundary. It may span inaccessible regions.	i) Potential airspace restrictions ii) Dataset comprises a linear sample collected along individual flight paths, rather than continuous coverage.

The Phase 2 deployment focused on the New Orleans area, with the objectives of examining damage caused by flood and levee breach and gathering valuable photo and video survey data throughout the city and within neighboring St. Bernard Parish. In areas near the levee-breach sites, unique damage characteristics were associated with high-velocity flooding, as water from Lake Pontchartrain began pouring into the city. The team recorded damage information within the various neighborhoods adjacent to the three levee-breach sites (see Figure 4-32).

5.1 VIEWS™ Field Reconnaissance System

The VIEWS™ (Visualizing Earthquakes with Satellites) system is a notebook-based field data collection and visualization system developed by ImageCat, Inc. through partial funding from MCEER. The VIEWS™ system integrates pre- and post-disaster remote sensing imagery with real-time GPS (Global Positioning System) readings and map layers, and operates in conjunction with a digital camera and digital video recorder.

VIEWS™ was initially developed for earthquake field reconnaissance following the December 2003 Bam (Iran) earthquake (Adams et al., 2004a), and has subsequently proved valuable for damage assessment in multiple types of disasters, including tsunamis (Ghosh et al., 2005) and hurricanes (Adams, 2004b, 2004c; Womble et al., 2005). Additional details of the VIEWS™ system are given by Adams et al. (2004a,b,c). Prior VIEWS™ deployments have employed a digital camcorder to acquire video data; however, the post-Hurricane Katrina deployments marked the first use of a High-Definition Video (HDV) recorder for VIEWS™ field data collection. The HDV camera supports a considerably higher image resolution (4 times) than a standard video-camcorder.

For Phases 1 and 2 of the post-Hurricane Katrina field reconnaissance effort, the VIEWS™ system was deployed from a moving vehicle and on foot. In the immediate aftermath of Hurricane Katrina, VIEWS™ was instead deployed from an aircraft as part of MCEER's PDV (Post-disaster Damage Verification) program. This PDV survey was conducted from August 30 to September 3, prior to the Mississippi and New Orleans deployments described in the following sections. (For additional details, see Section 4.3.1 and Figure 4.21.)

5.2 Mississippi Deployment (Phase 1)

The first phase of the post-hurricane field deployment was conducted along the impacted coastal area of Mississippi. The following sections document the post-hurricane damage reconnaissance planning process, the survey activities performed, and the methodologies employed for data collection and analysis.

5.2.1 Planning the Mississippi Deployment

Within days of Hurricane Katrina's landfall, MCEER assembled a field reconnaissance team, and the deployment planning process commenced. In terms of the study site selection, efforts were focused on field data collection throughout the impacted Mississippi coastal towns, ranging from Waveland/Bay St. Louis in the west to Pascagoula in the east. Following the conceptual protocol in Figure 3-3, team members used deterministic records of devastation to the Gulf Coast from remote sensing sources (see Sections 4.1 and 4.2), media reports, and damage assessments published by NOAA, FEMA, USACE, and USGS. The choice of study localities was also in part based on inference, taking into account NOAA windspeed estimates (NOAA 2005e), population centers, and the presence of key infrastructure elements (i.e., utility, transportation, and flood-control systems). Recommendations of local experts on the team were also considered in the selection of study areas.

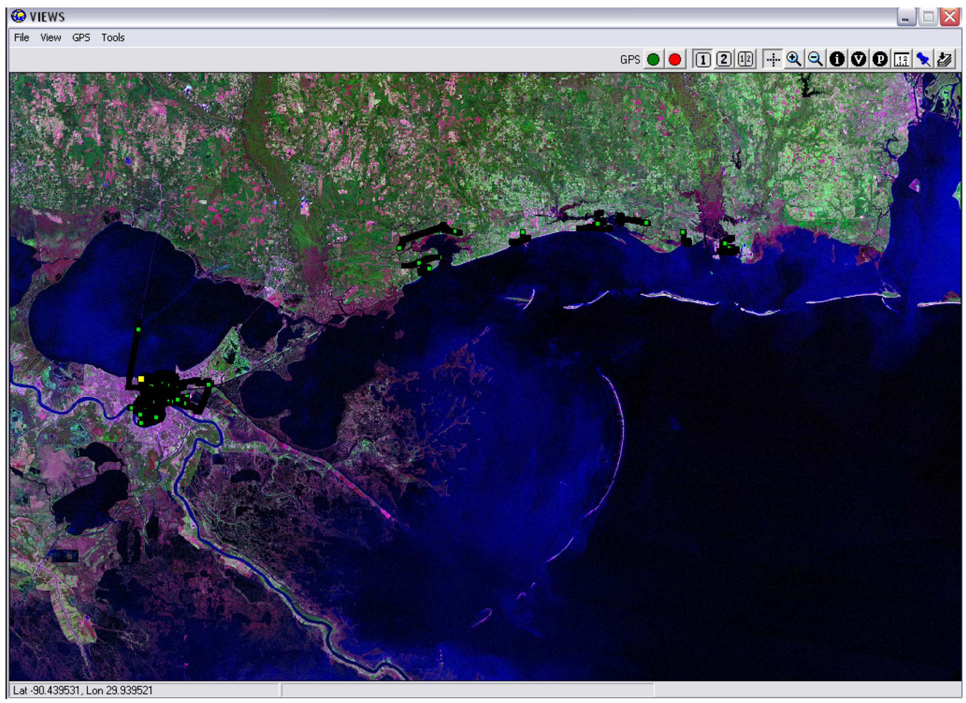
To capture a permanent record of perishable damage scenarios sustained at the sites along the Mississippi Coast, the field team employed remote sensing and GIS data sets within the VIEWS™ reconnaissance system. Base layers were obtained from a number of sources, including (1) USGS Landsat-5TM orthorectified false color composite mosaics (28.5 m resolution with average acquisition date of 1990 +/- 3 years) to locate urbanized areas and (2) high-resolution NOAA aerial images (Section 2.2.2) to assist field-survey team members in navigation and location of damaged areas. GIS data (shapefiles), including TIGER® streets, zip codes, and county boundaries, were also loaded into VIEWS™ for use in general navigation and reference.

5.2.2 Field Data Collection

Figure 5-2 is a screen shot of the VIEWS™ user interface, as it was deployed in *data collection* mode. In this image, USGS Landsat satellite imagery serves as the GIS mapping base layer and is overlaid with a vector-based street map. Through the GPS feed, routes taken throughout the damaged areas were logged and overlaid on the base map in real time. A georeferenced, HDV, GPS-linked photographic record of the damage areas was thereby collected, illustrating field damage observations and recovery efforts.

Using the data collection mode, the VIEWS™ damage survey of impacted areas was conducted by a four-member team from a moving vehicle driven at approximately 25-30 mph. Eleven hours of georeferenced HDV footage were recorded along the reconnaissance survey route. From the HDV footage, a library of approximately 18,900 georeferenced HDV photographs was extracted.

As planned during the site-selection phase, areas from the west end of the Mississippi Coast (closest to the storm center) to the east end of the Mississippi Coast were surveyed. Damage assessment focused on near-shore damage from storm surge, together with inland wind-pressure damage (occurring both in isolation and integrated with storm-surge damage). The following sections describe, in detail, the areas surveyed using the VIEWS™ reconnaissance system.

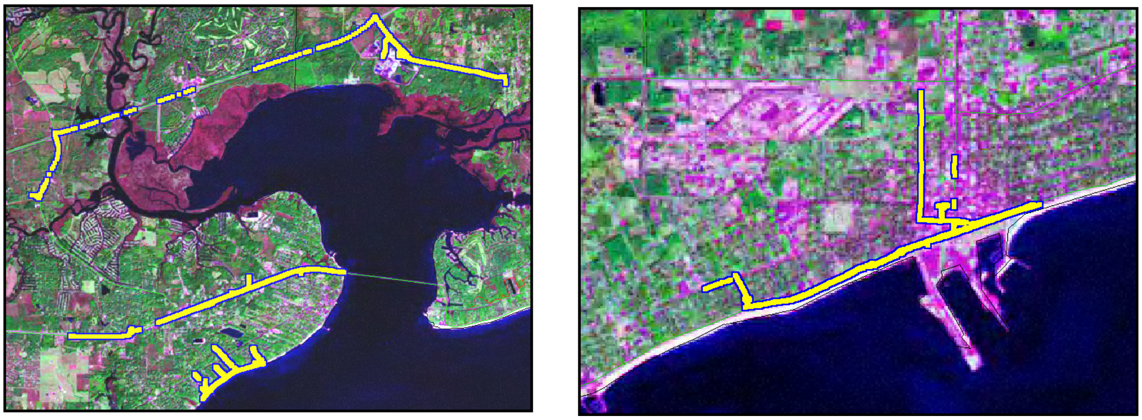


Landsat imagery from USGS

Figure 5-2. VIEWS™ user interface showing Landsat-5 TM imagery (Bands 7,4,2) and the GPS route (green symbols) followed by the field team in coastal Mississippi and New Orleans.

Waveland, Bay St. Louis, and Gulfport, Mississippi

Figures 5-3(a) and 5-3(b) show the routes surveyed by the MCEER field team using the VIEWS™ system in Waveland, Bay St. Louis, and Gulfport. The routes are denoted by a series of GPS points overlaid on the USGS Landsat mosaic. Homes in the coastal stretches of Bay St. Louis and Gulfport suffered extreme storm-surge damage, and in many cases were swept from their foundations. Both Bay St. Louis and Gulfport showed evidence of storm surge of up to approximately 20 ft. A major bridge of U.S. Highway 90 at Bay St. Louis lost all spans of the deck, leaving only piers. The Gulfport area lost many offshore casinos, which were carried hundreds of feet inland, with some deposited to the north of U.S. Highway 90. In addition to storm-surge damage, moderate wind-pressure damage was inflicted on many building roofs, including widespread loss of roof coverings and isolated structural damage.



(a) Waveland and Bay St. Louis (b) Gulfport

Landsat imagery from USGS

Figure 5-3. VIEWS™ deployment routes overlaid on Landsat satellite imagery.

Biloxi, Mississippi

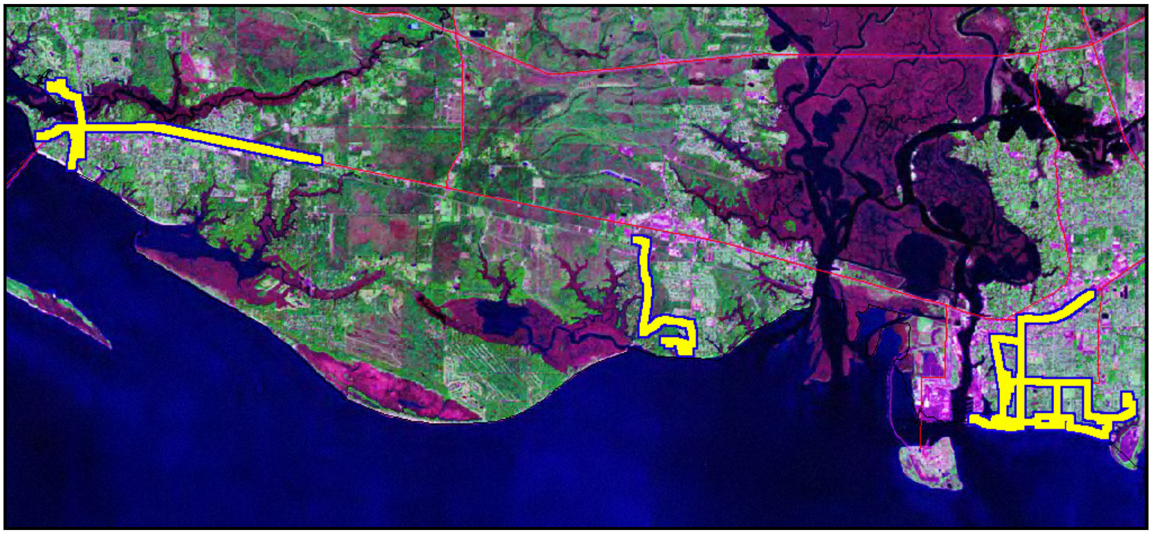
Figure 5-4 shows the VIEWS™ deployment route within the coastal city of Biloxi. Biloxi experienced heavy wind damage to the cladding of several high-rise buildings. A few casinos on barges were washed ashore, and numerous spans of the U.S. Highway 90 bridge were removed from their supporting piers. Wind-pressure damage consisted of the loss of roof coverings on numerous buildings, the loss of cladding on tall buildings, and isolated structural damage to the roofs of low-rise buildings.

Landsat imagery from USGS

Figure 5-4. VIEWS™ deployment route in Biloxi, Mississippi.

Ocean Springs, Gautier, and Pascagoula, Mississippi

Figure 5-5 shows the routes surveyed by the MCEER advanced technology field team in Ocean Springs, Gautier, and Pascagoula. In Pascagoula, many homes along the beach were swept off their foundations by the storm surge, while other homes remained in place but lost ground-floor walls and contents to the storm surge. Several waterfront homes near Ocean Springs and Gautier also were swept from their foundations or showed evidence of the storm surge washing through their ground floors. The storm-surge damage in Ocean Springs, Gautier, and Pascagoula was primarily confined to the first-floor level of the homes. Overall wind-pressure damage was minor compared to other areas of the Mississippi Coast, and consisted primarily of partial loss of roof coverings, with isolated buildings sustaining more severe damage due to wind pressures.



Landsat imagery from USGS

Figure 5-5. VIEWS™ deployment route in Ocean Springs, Gautier, and Pascagoula, Mississippi.

5.2.3 Classification of VIEWS™ Field Data

In the immediate aftermath of a disaster of Hurricane Katrina's magnitude and scale, rapidly and accurately establishing the extent and severity of damage, as well as related losses, is of high priority. Through the use of suitable damage scales, post-disaster damage information provided by remote sensing technology and the VIEWS™ reconnaissance system can support damage classification, and thereby loss estimation, across a broad geographic extent. This information can also serve to calibrate or validate probabilistic loss-estimation models (see, for example, Section 3.2.1) that predict damage (loss) as functions of hazard, exposure, and vulnerability. The classification of observed damage and associated quantification of losses requires a comprehensive building damage scale.

Interpreting damage on a per-building basis (see the deployment plan in Table 5-1) likewise requires a damage scale. Loss-estimation methodologies such as FEMA's HAZUS-Hurricane model provide a structural-based damage classification that categorizes occupancy type into five classes (termed "damage states"). The various building occupancies employed by the HAZUS-Hurricane model are:

- Residential
- Manufactured Homes
- Marginally or Non-Engineered Hotel/Motel & Multi-Family Residential

- Low-Rise Masonry Strip Malls
- Pre-Engineered Metal
- Engineered Residential and Commercial
- Industrial

The damage scale for residential buildings in the HAZUS-Hurricane model is reproduced in Table 5-2. Detailed description of the damage scales providing characteristics relating to the five damage states (0–4) for the remaining occupancies (e.g., industrial, manufactured homes, etc.) can be found in the *HAZUS-Hurricane Technical Manual* (FEMA 2003a). This classification scheme includes useful characteristics that may be interpreted from ground-based VIEWS™ HDV footage, but does not address the host of damage characteristics that are captured from airborne or satellite remote sensing platforms.

Table 5-2. HAZUS-Hurricane Damage States for Residential Construction

Damage State	Qualitative Damage Description	Roof Cover Failure	Window & Door Failures	Roof Deck Failure	Missile Impacts on Walls	Roof Structure Failure	Wall Structure Failure
0	**No Damage or Very Minor Damage** Little or no visible damage from the outside. No broken windows or failed roof deck. Minimal loss of roof over, with no or very limited water penetration.	≤2%	No	No	No	No	No
1	**Minor Damage** Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	<5 impacts	No	No
2	**Moderate Damage** Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 20% & 3	1 to 3 panels	Typically 5 to 10 impacts	No	No
3	**Severe Damage** Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	Typically 10 to 20 impacts	No	No
4	**Destruction** Complete roof failure and/or failure of wall frame. Loss of more than 50% of roof sheathing.	Typically > 50%	>50%	>25%	Typically >20 impacts	Yes	Yes

FEMA 2003a

In recognition of the need for damage descriptors for use in the remote sensing analysis of building damage, Womble (2005) proposed the Remote Sensing (RS) Damage Scale for residential buildings (Table 4-1), which describes wind-induced damage using four damage states. In this scale, building damage description is based primarily on visible damage to roof coverings and roof structures, as well as the presence of debris. The scale is applied to individual roof facets (slopes) rather than a building as a whole.

In the field investigation of Hurricane Katrina, an effort was made to collect video records of the complete range of damage states for the various building occupancies addressed by the HAZUS-Hurricane model and the Remote Sensing Damage Scale.

Examples of wind damage to residential buildings, classified according to the HAZUS-Hurricane model and Remote Sensing Damage Scale, are shown in Table 5-3. Examination of these images shows that the RS Damage Scale levels generally parallel the damage levels of the HAZUS-Hurricane model.

5.3 New Orleans Deployment (Phase 2)

The second field deployment using the VIEWS™ system yielded an extensive coverage of flood inundation and high-velocity flood (at the levee breach sites) damage information for New Orleans and the adjacent St. Bernard Parish. The following sections document the post-hurricane damage reconnaissance planning process, survey activities performed, and the methodologies employed for data collection and evaluation.

5.3.1 Planning the New Orleans Deployment

Immediately after Hurricane Katrina made landfall, it initially appeared that New Orleans had avoided major damage, since the eye had passed to the east of the city. In general, direct wind-pressure damage in New Orleans was minor to moderate. However, the resulting storm surge stressed the levee system, and levee breaches at multiple locations resulted in severe flooding throughout the city.

Hurricane Katrina was a somewhat unique event, given that in most previous major hurricanes (e.g., Hurricanes Andrew and Charley), direct wind-pressure damage has, in general, been responsible for the most widespread damage, with flooding and storm surge typically responsible for a smaller portion of overall damage. Accordingly, the primary objective of MCEER's

Table 5-3. Comparison of HAZUS-Hurricane and Remote Sensing Residential Building Damage Scales for a Full Range of Wind Damage States

HAZUS-Hurricane Damage States (from Table 5.2)	**Remote sensing Damage States** (from Table 4.1)	**Examples of Damage Observed in Field Studies**
0	**RS-A**	
1	**RS-B**	
2-3	**RS-C**	
4	**RS-D**	

FEMA (2003a) and Womble (2005)

post-hurricane field deployment was to collect as much evidence of damage as possible for this event. The rapid capture of ground-based observations of the damage characteristics of buildings and infrastructure was critical, as much evidence of wind and flood-related effects are “perishable” (i.e., subject to loss as water is drained and cleanup operations begin).

Although planning for the New Orleans deployment began immediately after Hurricane Katrina’s landfall, access to the field could not be achieved until early October 2005, when floodwaters had retreated sufficiently. Flood damage was therefore interpreted as a function of the high-water marks left on buildings, rather than attempting to drive through the deep flood waters.

To accomplish the objective of rapid data collection in New Orleans, the selection of neighborhoods for post-hurricane flood and levee breach damage assessment was based on deterministic factors (see Section 3.2.1), including the identification of hard-hit areas from remote sensing imagery (see Sections 4.3 and 4.4) as well as media reports. Inferential sources included the urban form of the city, proximity to levee-breach locations, and the timeframe for deployment. The recommendations of local expert team members were also considered in the selection of survey areas.

To streamline field survey activities, the city of New Orleans was divided into four zones (Figure 5-6), with zone boundaries defined based on significant urban features such as freeways, canals, and parish boundaries. Based on site-selection criteria, a list of potential study sites throughout New Orleans and adjacent St. Bernard Parish was created prior to the deployment (Figure 5-7) and served as a guide for the field investigation. Field data collection was undertaken within each zone, focusing on the most-heavily impacted neighborhoods. The field assessment spanned four days (October 6-9), and, in general, a survey of a single zone was completed in one day. Within each zone, effort was made to collect survey data on the major occupancy classes (e.g., residential, commercial, and industrial). Additionally, detailed observations were collected for government and institutional facilities.

Base map from Microsoft Streets & Trips

Figure 5-6. Four zones created to guide field investigation within New Orleans.

Table 5-4. Remote Sensing Imagery Utilized During the New Orleans Deployment

Imagery	Date	Timeframe	Coverage Area	Source
Landsat-5 TM Mosaic 28.5m satellite	1990s	Pre-Storm	Coastal LA, MS, AL	USGS
61-cm QuickBird satellite	9/03/2005	Post-Storm	New Orleans	DigitalGlobe
37-cm aerial	8/31/2005	Post-Storm	New Orleans	NOAA

The MCEER team obtained remote sensing imagery (satellite and aerial) from multiple sources. A summary of the remote sensing imagery utilized by the survey team during the field investigation is presented in Table 5-4. USGS Landsat orthorectified TM mosaic data (28.5 m resolution with average acquisition date 1990 +/- 3 years) served as a base layer within the VIEWS™ system. The team purchased high-resolution QuickBird post-storm imagery of the New Orleans area (Section 2.1.3) for use in guiding the field deployment and for later data analysis. NOAA high-resolution aerial images of New Orleans (Section 2.2.2) supplemented the satellite imagery and served as a helpful reference for the survey team. Additionally, GIS data, including TIGER® streets, zip codes, and county boundaries, were integrated with the VIEWS™ system for use in general navigation and reference.

5.3.2 Field Data Collection

The VIEWS™ damage survey of impacted areas in New Orleans was conducted by the four-member team from a moving vehicle driven at 25-30 mph. In general, access to the various residential neighborhoods did not prove to be a significant limitation. On occasion, admittance to heavily damaged institutional buildings and university campuses required special authorization. Accordingly, some of these sites proved inaccessible for damage documentation. Vehicular access to the levee breach sites was limited, so damage data collection in those areas was primarily conducted on foot. Sixteen hours of georeferenced HDV footage were recorded along the reconnaissance survey route. From the HDV footage, a library of approximately 27,000 georeferenced HD photographs was extracted.

The following sections describe the four zones surveyed by the MCEER advanced technology field team using the VIEWS™ reconnaissance system.

Zone 1: Orleans Parish (North of I-610)

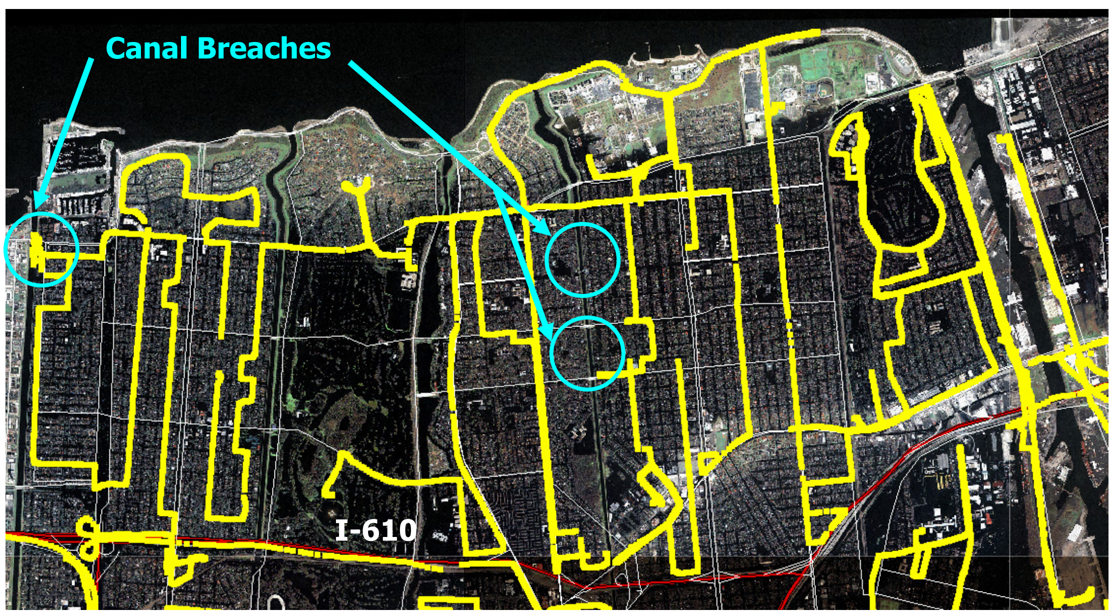
Zone 1 (Figure 5-8a) consists of the area between the 17th Street Canal and the Industrial Canal, north of I-610 in Orleans Parish. Buildings surveyed in this zone consisted primarily of residential buildings (approximately 95%), with some major educational institutions, government facilities, and parks. Two major levee breaches (along the 17th Street Canal and the London Avenue Canal) were located in this zone. The satellite image in Figure 5-8b shows the presence of floodwaters throughout this zone, as well as the GPS tracks delineating the survey route.

ZONE 1	ZONE 2	ZONE 3	ZONE 4
• **17th Street Canal Levee Breach**	• **Industrial Canal Levee Breach**	• **Fairgrounds race tracks**	• **Waterworks**
• **London Canal Levee Breach**	• Pump Station #1	• **Mid city-commercial areas**	• **Tulane University**
• **Southern University New Orleans Branch**	• Pump Station #2	• **Mid city – residential areas**	• **Loyola University**
• **University of New Orleans E Campus**	• **Sewage Treatment Plant**		• Southern Baptist Hospital Memorial Medical
• **University of New Orleans**	• **French Quarter**		• Audubon park
• Dillard university	• **Warehouse District**		• **Lower Garden Districts**
• JFK High School	• **Central Business District**		• **Uptown/ Garden Districts**
• **USDA Research**	• Charity Hospital		• **Commercial areas**
• **New Orleans Theological Seminary**	• **Tulane University Medical Center**		
• Spanish Fort	• **Superdome**		
• **Residential areas**	• **City Hall**		
• **Commercial areas**	• **Residential areas**		

Base map from Microsoft Streets & Trips

Figure 5-7. Listing and location of potential study sites in New Orleans. Bold font indicates that the sites were subsequently visited by the MCEER team.

(a) Zone 1 map with GPS points shown in green



(b) QuickBird imagery for Zone 1 with GPS points shown in yellow

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com

Figure 5-8. GPS points denoting the routes traversed in Zone 1 in New Orleans. The VIEWS™ system was used to record these routes with georeferenced HDV and digital photographs.

Inundation flooding, varying in depth from approximately 2 to 10 ft, was observed throughout this zone, while only minor damage from wind pressures was observed. Residential structures near the levee breaches were either severely damaged or completely destroyed by the velocity flooding. Some non-flooded residences were identified in the lakeshore areas and along Gentilly Boulevard but amounted to less than 10% of the residential structures surveyed in Zone 1.

Zone 2: Orleans Parish (Mid-City)

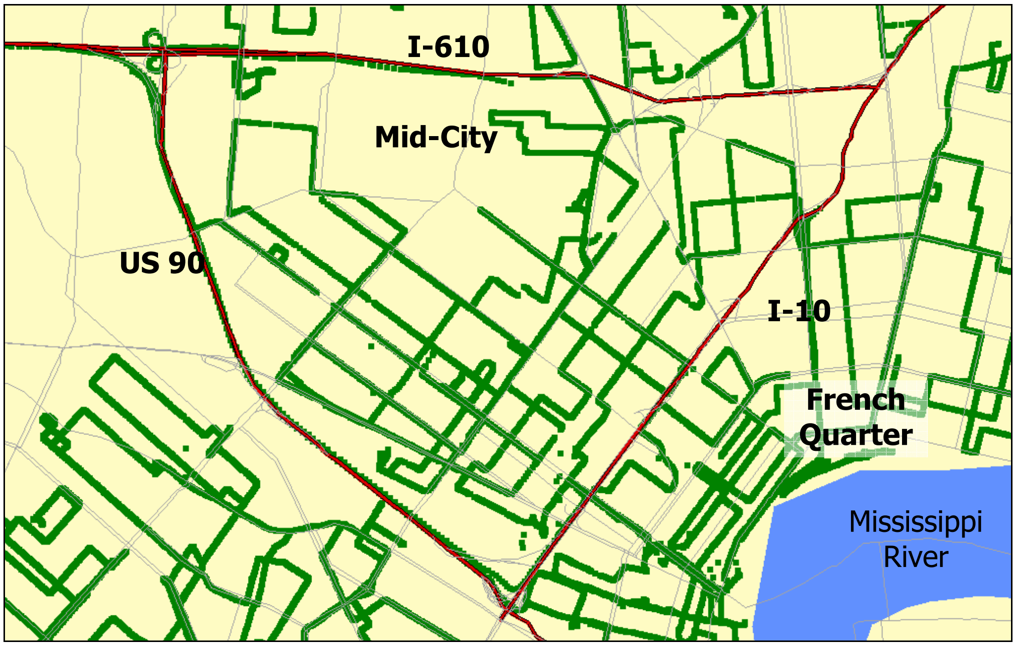
The Mid-City area of New Orleans was designated as Zone 2 for the field investigation (Figure 5-9a). The field investigation targeted the triangular area bounded by I-610 to the north, I-10 to the east, and U.S. Highway 90 to the west. There was a wide range of land use and occupancy categories within this area; in addition to residential neighborhoods, this zone comprised a substantial number of small-to-medium-sized businesses, schools, and hospitals.

Damage to residential structures was primarily due to flood inundation. Wind damage to buildings ranged from none to moderate.

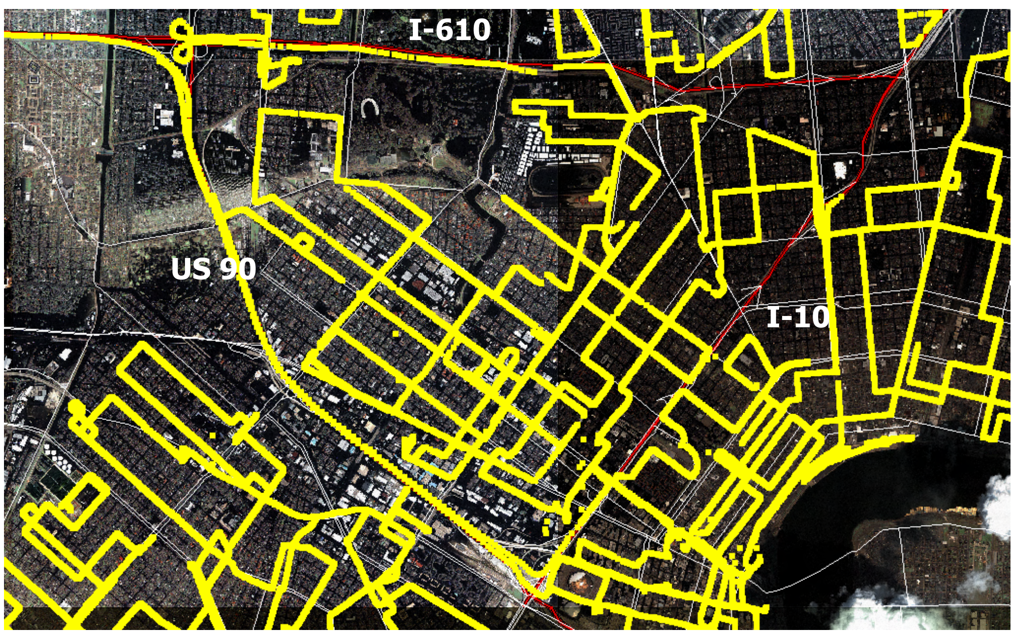
Zone 3: Orleans and St. Bernard Parishes

The region delineated as Zone 3 included the Central Business District (CBD), Warehouse District, and the French Quarter, situated northeast of U.S. 90 and east of I-10 (Figure 5-10a). These areas near and along the Mississippi River have a higher elevation and were less affected by the flood waters. The Industrial Canal levee breach location along the Lower Ninth Ward area of the St. Bernard Parish on the city's east side was also part of Zone 3. Flood damage in this area was among the most severe in New Orleans. The presence of floodwaters is evident in the satellite imagery shown in Figure 5-10b.

Complete destruction of buildings was observed over an area extending approximately five blocks from the breach in the Industrial Canal levee. The multistory structures of the CBD were mostly outside of the flood inundation zones, although some flooding (approximately 3-ft deep) on the northern edge of the CBD causing significant damage to the ground floors of buildings. Elsewhere, flood damage within the Warehouse District and the French Quarter ranged from none to minor. There was also minor wind damage (window breakage) to some of the multi-story structures of the CBD.



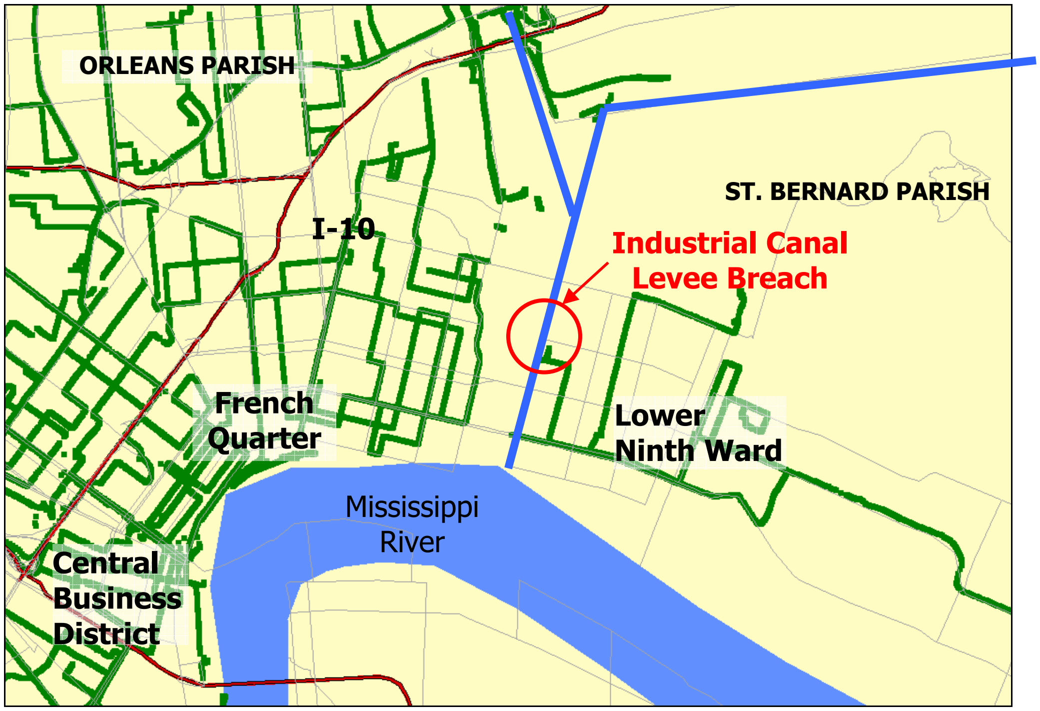
(a) Zone 2 map with GPS points shown in green



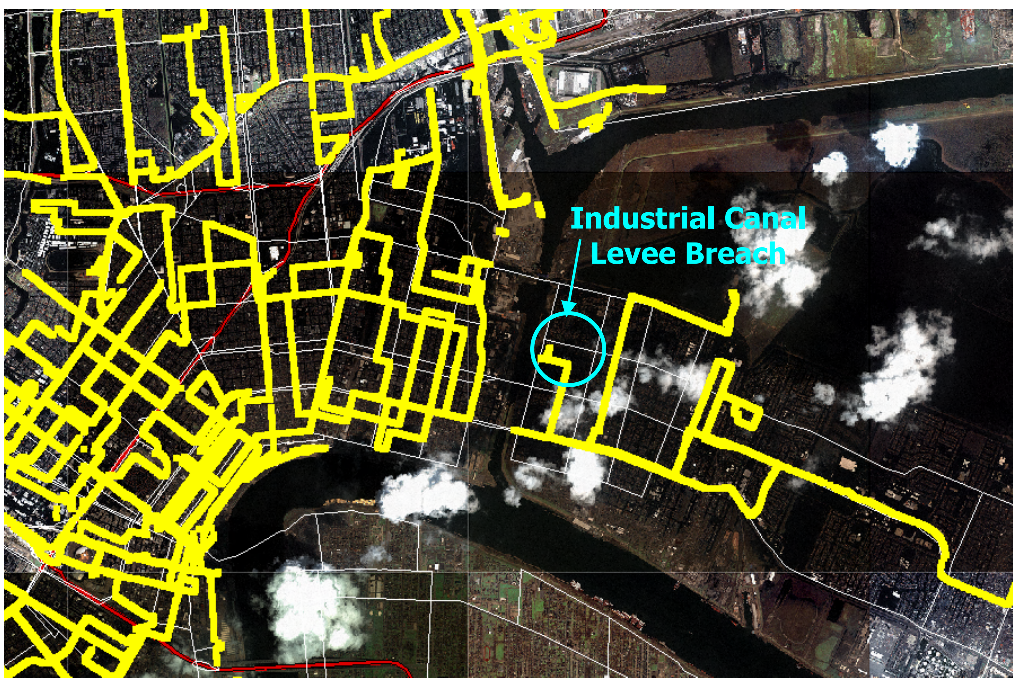
(b) QuickBird imagery for Zone 2 with GPS points shown in yellow

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com

Figure 5-9. GPS points denoting the routes traversed in Zone 2 in mid-city New Orleans. The VIEWS™ system was used to record these routes with georeferenced HDV and digital photographs.



(a) Zone 3 map with GPS points shown in green



(b) QuickBird imagery for Zone 3 with GPS points shown in yellow

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com

Figure 5-10. GPS points denoting the routes traversed in Zone 3 in New Orleans. The VIEWS™ system was used to record these routes with georeferenced HDV and digital photographs.

Zone 4: Orleans Parish (West of I-10)

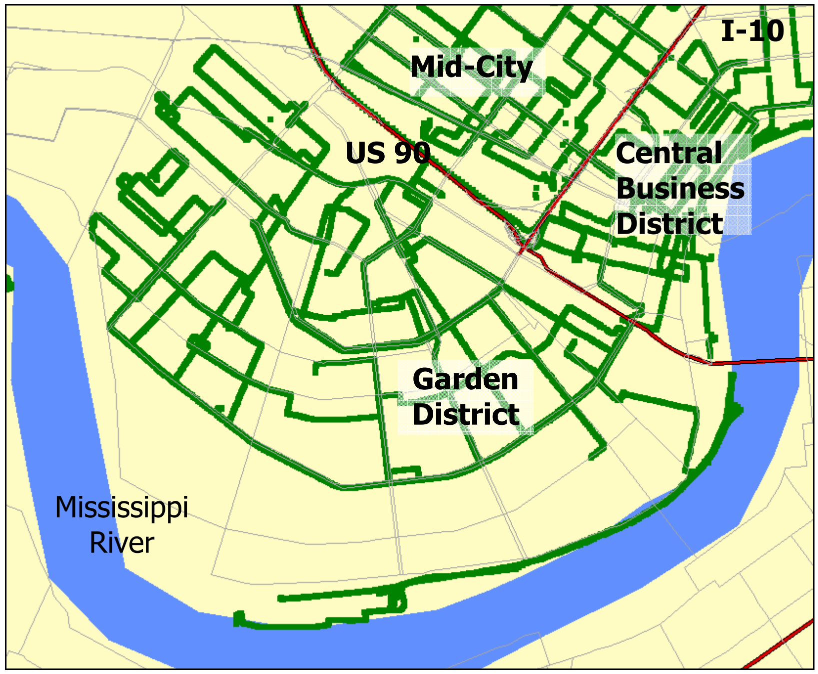
Zone 4 included the primarily residential neighborhoods of Uptown, Garden District, Carrollton, and Broadmoor in the area west of I-10 and north of St. Charles Avenue (Figure 5-11a). This area adjacent to the Mississippi River bank occupies a higher topographic elevation than surrounding areas and thus exhibited minimal damage due to flooding.

Residences in the Garden District primarily experienced minor-to-moderate damage from wind pressure (window breakage, roof-covering failure, and tree-fall impact). Outside the Garden District, damage to residential structures was due to flood inundation, with most homes experiencing severe damage from flooding. The majority of buildings also exhibited minor–to-moderate roof covering damage and window breakage.

In summary, the majority of damage to residential structures in the four New Orleans survey zones was due to flooding caused by breaches in the city's flood protection system. However, multi-story engineered structures within the Central Business District were mostly outside of the inundation zones. The most severe wind damage in New Orleans was primarily observed in mid- to high-rise buildings located in the downtown area.

5.3.3 Classification of Combined Wind and Flood Damage

Hurricane Katrina was unique in terms of the number of convergent hazards, and its devastating impact on New Orleans highlights key issues concerning damage assessment from a multi-hazard standpoint. After the initial (relatively minor) impact from wind pressures, New Orleans suffered extreme losses due to flood inundation and high-velocity flooding resulting from levee breaches. In the planning phase for the New Orleans deployment, it quickly became apparent that using a single-hazard damage scale to classify damage and quantify losses was inadequate given the combination of damage mechanisms. MCEER researchers thus developed a customized damage scale combining both wind-pressure and flood effects for consideration of the multi-hazard damage observed in New Orleans on a *loss-consistent* basis.



(a) Zone 4 map with GPS points shown in green

(b) QuickBird imagery for Zone 4 with GPS points shown in yellow

QuickBird imagery from DigitalGlobe, Inc. www.digitalglobe.com

Figure 5-11. GPS points denoting the routes traversed in Zone 4 in New Orleans. The VIEWS™ system was used to record these routes with georeferenced HDV and digital photographs.

As previously described in Section 5.2.3, FEMA's HAZUS-Hurricane model provides a structurally-based damage classification scale. Similarly, the HAZUS-Flood model (FEMA 2003b) provides credibility-weighted building water depth-damage curves to calculate physical damage to structures based on flood depth, flood elevation, and flow velocity. A new damage scale, combining the HAZUS-based damage scales for wind and flood was developed, to more accurately detail the *total damage* to buildings. In the absence of a one-to-one correspondence between the HAZUS-Hurricane model and the depth-damage definition of the HAZUS-Flood model, the individual damage scales were combined by categorizing the flood-depth damage curves into representative groups, corresponding with the damage/loss levels used by HAZUS-Hurricane (Table 5-2). To correspond with common construction practices within the New Orleans area, depth-damage curves for one- and two-story buildings were considered.

The resulting combined Wind-Flood (WF) Damage Scale is provided in Table 5-5 and was used to classify VIEWS™ damage observations throughout New Orleans. The scale considers both wind and flood-depth damage conditions. Damage conditions associated with direct wind-pressure damage include: *Roof Cover Failure; Window/Door Failure;, Roof Deck Failure;* and *Roof Structure Failure*. Notably, the *Wall Structure Failure* damage condition can be attributed to direct wind pressures and/or high-velocity floodwaters accompanying the levee breaches.

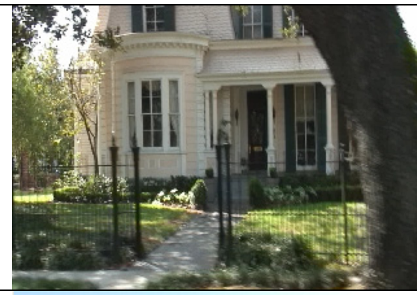
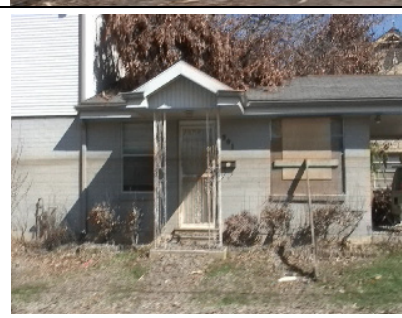
In terms of applying the table (and following the HAZUS methodology), the occurrence of the most severe damage condition denoted by a shaded cell in the table demands that the corresponding damage state be assigned. The "Stillwater Flood Depth" relates to gradually rising floodwaters, typically not adjacent to the levee breaches. Although some floodwaters had receded prior to the New Orleans deployment, the maximum flood-depth marks apparent on most buildings were within the WF Damage Scale.

The following sections provide examples of buildings in New Orleans that fall into each of the damage states described by the combined WF Damage Scale. Figure 5-12 provides examples of each damage state as depicted on high-resolution remote sensing imagery and VIEWS™ HDV ground observation data collected during the survey.

Table 5-5. Combined Wind and Flood (WF) Damage Scale for classification of VIEWS™ data in New Orleans

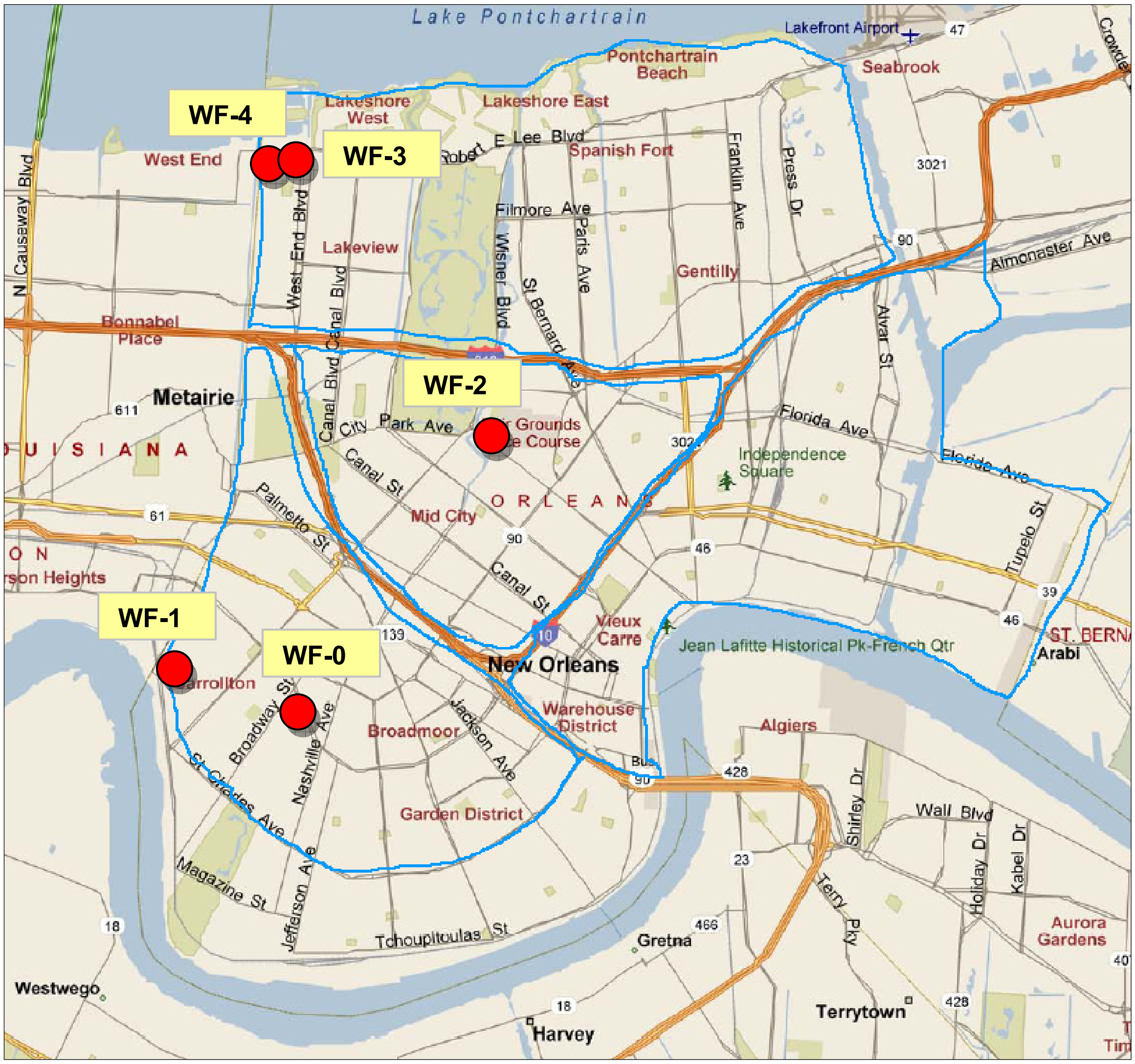
Damage State	Qualitative Damage Description	Roof Cover Failure[1]	Window/ Door Failures[1]	Roof Deck Failure[1]	Roof Structure Failure[1]	Wall Structure Failure[1,2]	Stillwater Flood Depth[2]
WF-0	**No Damage or Very Minor Damage** Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	≤2%	No	No	No	No	None
WF-1	**Minor Damage** Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	No	No	None
WF-2	**Moderate Damage** Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 20% & 3	1 to 3 panels	No	No	0.01 ft - 2 ft
WF-3	**Severe Damage** Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	No	No	2 ft - 8 ft
WF-4	**Destruction** Complete roof failure and/or, failure of wall frame. Loss of more than 50% of roof sheathing.	Typically >50%	>50%	>25%	Yes	Yes	>8 ft

NOTES: [1]Damage condition associated with wind damage.
[2]Damage condition associated with flood damage.

Damage State	Remote Sensing Base Data	VIEWS^{TM} Footage
WF-0		
WF-1		
WF-2		
WF-3		
WF-4		

QuickBird images from DigitalGlobe, Inc. www.digitalglobe.com

Figure 5-12(a). Classification of VIEWS^{TM} data in New Orleans using the combined Wind and Flood (WF) Damage Scale of Table 5-5. Locations of these buildings are shown in Figure 5-12b.



Base map from Microsoft Streets & Trips

Figure 5-12 continued (b). Overview map showing location of building damage samples in New Orleans. The corresponding VIEWS™ ground-survey images are shown in Figure 5-12a.

WF-0 (No Damage or Very Minor Damage)

This damage classification is limited to non-flooded areas, as the presence of floodwaters automatically moves the damage classification to WF2 - Moderate Damage. Wind-pressure damage in this classification requires no window or door penetrations, and a maximum of 2% loss of roof cover. The WF-1 damage state was rare in New Orleans, with most buildings exhibiting at least minor wind-pressure damage. Examples of buildings in this damage state are given in Figure 5-13.

Figure 5-13. Examples of buildings in the Garden District area classified in the WF-0 ("No Damage or Very Minor Damage") category.

WF-1 (Minor Damage)

This damage classification is also limited to non-flooded areas. Wind-pressure damage in this class requires a maximum of one window/door penetration and roof-cover loss between 2% and 15%. WF-1 was the predominant damage state observed for buildings in the non-flooded areas of Orleans Parish. Examples of buildings in this damage state are shown in Figure 5-14.

Figure 5-14. Examples of buildings classified in the WF-1 ("Minor Damage") category in an area of no flooding.

WF-2 (Moderate Damage)

Moderate damage was observed for most of the homes where flood depth above the finished floor ranged from a few inches to about 2 ft. Notably, most buildings within this category exhibited wind-pressure damage conditions consistent with the lesser WF-1 "Minor Damage" category; the presence of floodwaters alone was responsible for the higher damage classification. Examples of buildings in this damage state are presented in Figure 5-15.

Figure 5-15. Example of buildings in the WF-2 ("Moderate Damage") category in a newly developed neighborhood.

WF-3 (Severe Damage)

Severe damage was observed for homes where flood depth above the finished floor ranged from 2 to 8 ft. Some homes in the high-velocity area (near levee breaches) fell into this category. Apart from the floodwater depth, the wind damage to most houses assigned this category would otherwise result in damage states of only "Minor Damage" or "Moderate Damage." Figure 5-16 presents examples of buildings in the WF-3 damage state.

Figure 5-16. Examples of buildings in the WF-3 ("Severe Damage") category, in an older section of eastern New Orleans.

WF-4 (Destruction)

Destruction was observed for homes where flood depth above the finished floor exceeded 8 feet. Many homes in the high-velocity flood area (at levee breeches) also fell into this category because of the structural failure caused by the moving water. For most houses in this category, damage attributed directly to wind pressures would be classified as either "Minor Damage" or "Moderate Damage," consistent with observations that wind-pressure damage was secondary to flooding damage for a majority of buildings in New Orleans. Examples of buildings in the WF-4 damage state are given in Figures 5-17 and 5-18.

Figure 5-17. Standing buildings within the high-velocity flooding zone adjacent to the 17th Street Canal levee breach. These buildings exemplify the WF-4 ("Destruction") damage state.

Figure 5-18. Building washed away from its foundation in a high-velocity flooding zone adjacent to the London Avenue Canal levee breach. This building is representative of the WF-4 ("Destruction") damage state.

Upon return from the field deployment, the WF damage scale was applied to a sample of areas within New Orleans (Figure 5-19). The classification is based on expert visual interpretation of NOAA remote sensing images captured immediately after the event, in conjunction with the VIEWS™ data collected in the field. Figures 5-20 to 5-23 demonstrate the classification of building damage according to the WF Scale for various zones within New Orleans, presented using NOAA digital aerial images captured immediately after the event. This classification is based on expert visual interpretation of the NOAA images in conjunction with the VIEWS™ data collected in the field. Colored symbols superimposed on the NOAA aerial images indicate the assessed damage states (WF-0 to WF-4) of individual buildings according to the combined Wind-Flood (WF) Damage scale of Table 5-5. (Figure 5-12 provides examples of damage classification of VIEWS™ ground observation data collected during the survey.)

These classified areas are distributed throughout the city to capture examples of each damage class. Notably, within a given neighborhood, a large degree of consistency in damage state was observed. Transitional zones (Figure 5-24) occur approximately five blocks from the levee-breach site, and at the limit of levee-breach inundation.

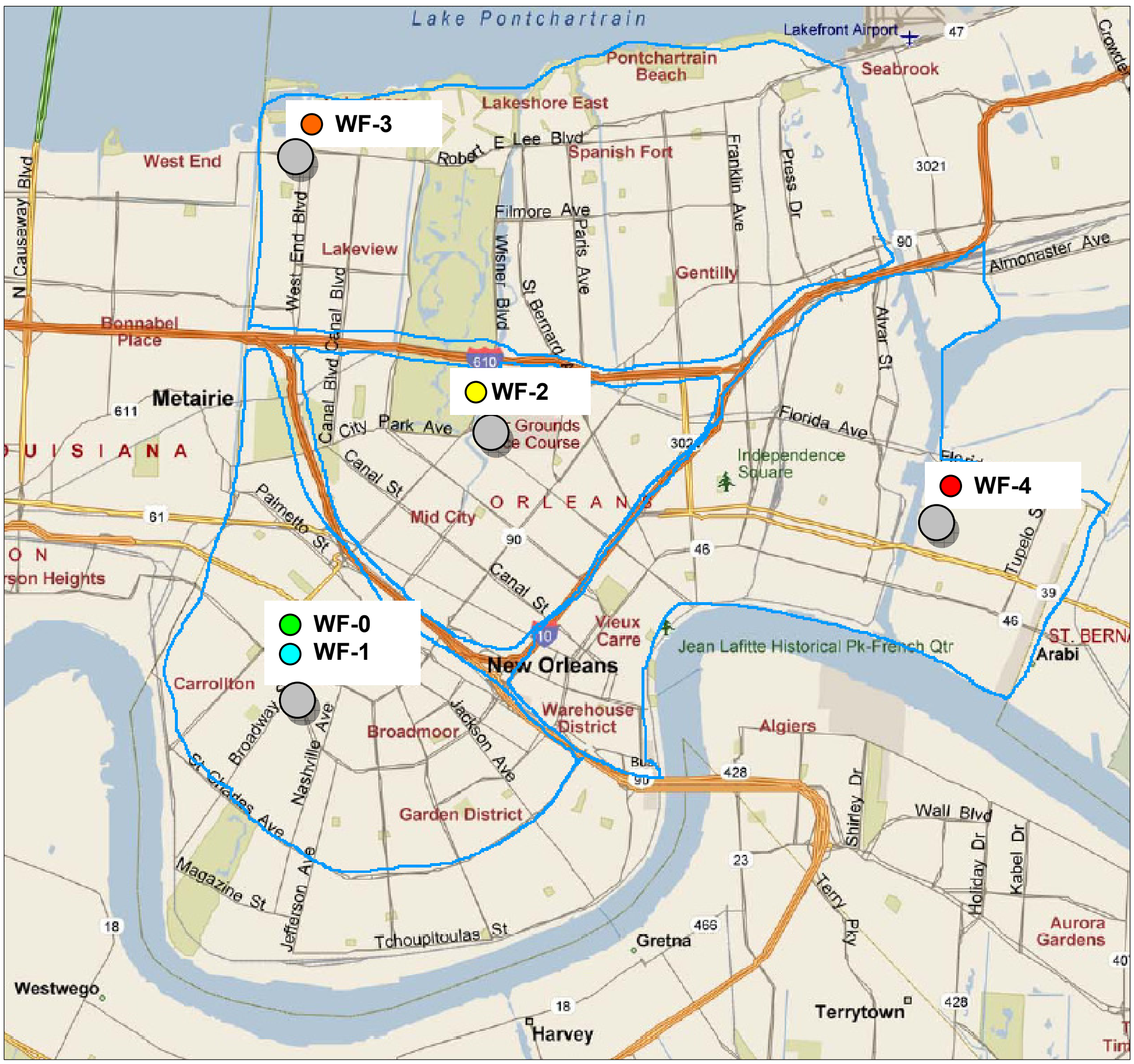
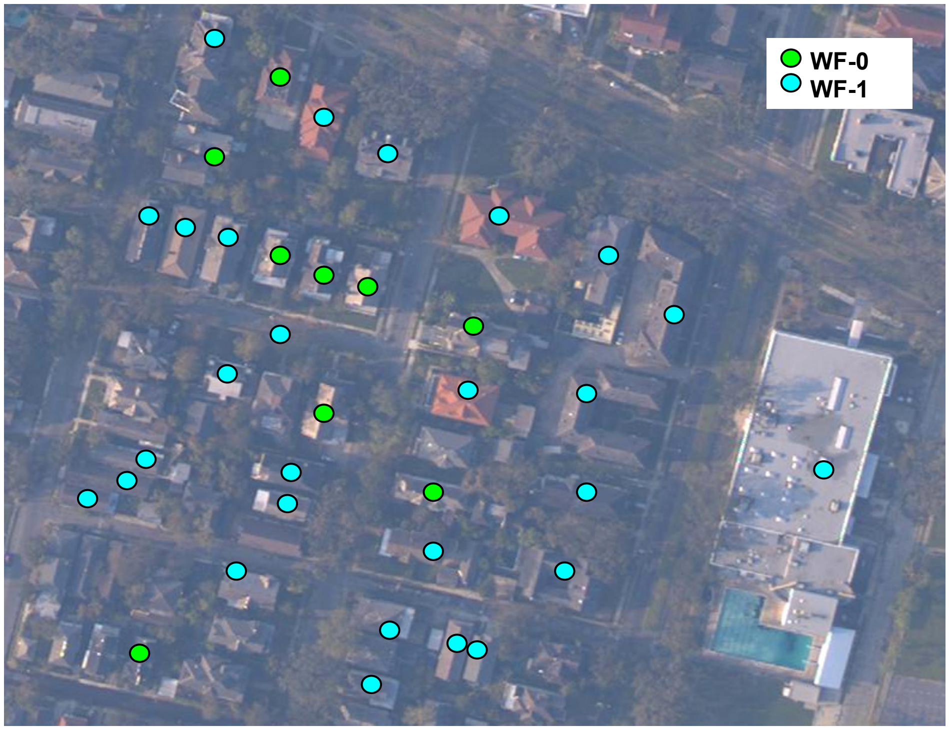


Figure 5-19. Locations of samples classified according to WF Scale in New Orleans. The detailed samples are shown in Figures 5-20 to 5-23.

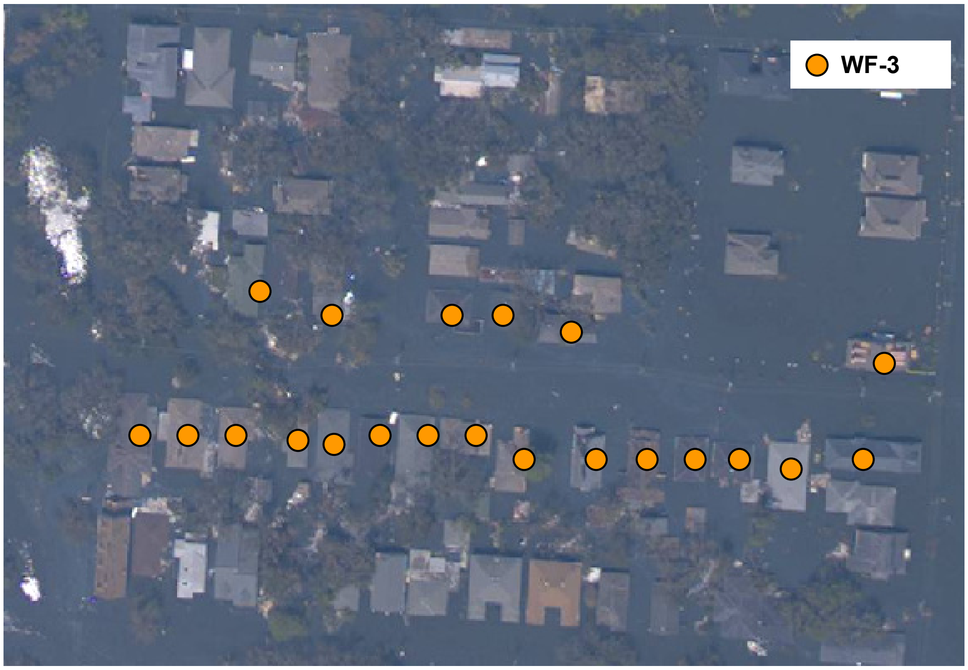


Base image from NOAA

Figure 5-20. Example of per-building visual assessment of combined wind and flood damage showing buildings with Damage States WF-0 and WF-1.

Base image from NOAA

Figure 5-21. Example of per-building visual assessment of combined wind and flood damage showing buildings with Damage State WF-2.

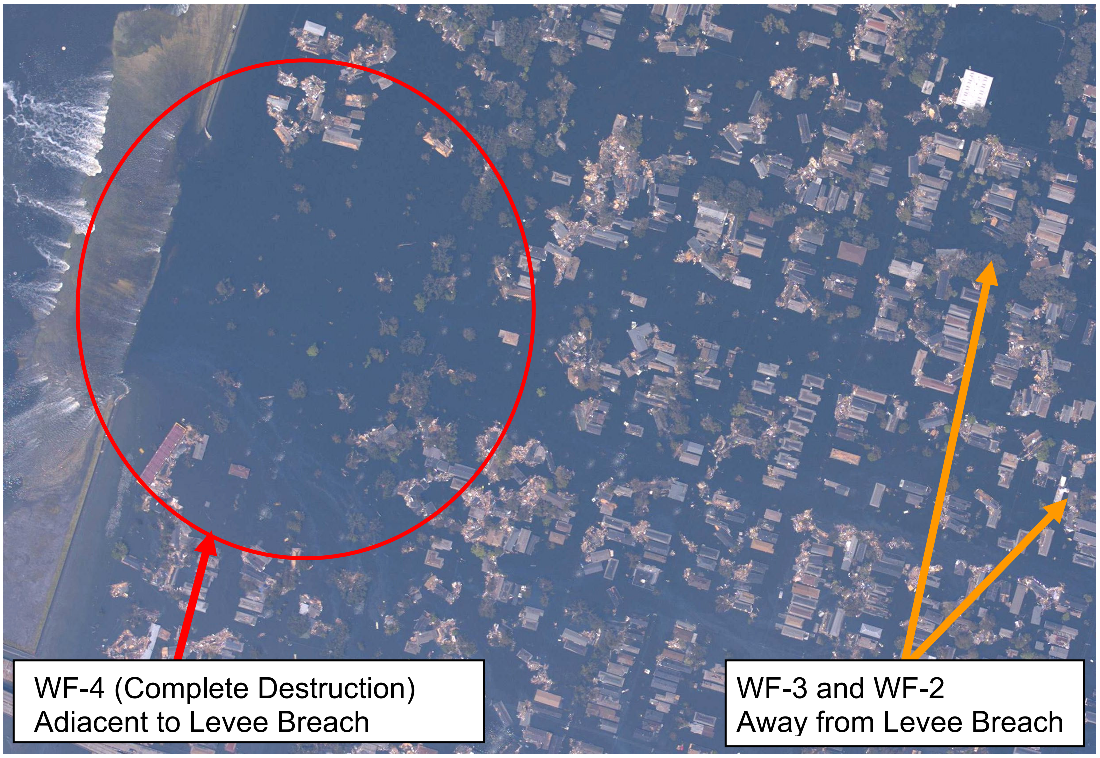


Base image from NOAA

Figure 5-22. Example of per-building visual assessment of combined wind and flood damage showing buildings with Damage State WF-3.

Base image from NOAA

Figure 5-23. Example of per-building visual assessment of combined wind and flood damage showing buildings with Damage State WF-4.



Base image from NOAA

Figure 5-24. Example of transitional damage zone near levee breach. Damage States WF-4 occur near the levee breach, while lesser damage states are found further away.

5.4 Summary of Key Findings

- The primary objective of MCEER's post-Hurricane Katrina advanced technology field deployment was to collect as much "perishable" evidence of multi-hazard (storm-surge, flooding, levee-breach and wind-pressure) damage as possible.

- In the aftermath of Hurricane Katrina, MCEER advanced technology field teams conducted damage assessments using VIEWS™ (Visualizing Earthquakes with Satellites) – a notebook-based field data collection and visualization system that integrates pre- and post-disaster remote sensing imagery with real-time GPS (Global Positioning System) readings and map layers, and operates in conjunction with a digital camera and digital video recorder.

- Through the use of suitable damage scales (e.g. the Womble (2005) Remote Sensing Damage Scale for residential buildings; also the FEMA

(2003a) HAZUS-Hurricane scale), post-disaster information provided by remote sensing technology and VIEWS™ can support damage classification and loss estimation and can serve to calibrate or validate probabilistic loss-estimation models.

- Post-Hurricane Katrina field reconnaissance involved deploying VIEWS™ from a moving vehicle, on foot, and from an aircraft as part of the rapid PDV (Post-disaster Damage Verification) program.

- VIEWS™ deployments to the Mississippi Coast from September 7-9, 2005, and New Orleans from October 6-9, 2005 successfully performed rapid and widespread assessments of damage at a per-building scale (Tier 3 of the Tiered Reconnaissance System framework).

- The VIEWS™ deployment in Mississippi captured 11 hours of video footage and a library of 18,900 high-definition video (HDV) stills of perishable multi-hazard damage characteristics for use in future research activities.

- In Mississippi, the MCEER advanced technology field team deployed VIEWS™ within areas that were hardest-hit by both wind pressures and storm surge (including Waveland, Bay St. Louis, Gulfport, and Biloxi) as well as the areas hit predominantly by storm surge (including Ocean Springs, Gautier, and Pascagoula). Storm-surge damage assessment focused on areas within about ½ mile from the beach. Wind-pressure damage assessment spanned neighborhoods throughout the affected region.

- The HDV footage indicates that along the Mississippi Coast, homes suffered extreme storm-surge damage, and in many cases were swept from their foundations. Bay St. Louis and Gulfport showed evidence of a storm surge up to ~20 ft. Deck spans from bridges on U.S. Highway 90 were lost at Bay St. Louis and Biloxi. In the Gulfport and Biloxi areas, some offshore casinos were carried inland.

- The MCEER advanced technology field team deployed VIEWS™ within New Orleans and St. Bernard Parish. Specifically, the team recorded damage information within the various neighborhoods adjacent to the three levee-breach sites.

- The VIEWS™ deployment in and around New Orleans captured 16 hours of video footage and a library of 27,000 high definition video (HDV) stills of perishable flood and surge-related damage characteristics for future research activities.

- To interpret post-Hurricane Katrina multi-hazard damage observed in New Orleans (flood, levee-breach, and wind) on a loss-consistent basis, MCEER researchers developed a customized five-level Wind-Flood (WF) Damage Scale. The scale combines HAZUS-based damage scales for wind and flood to characterize the total damage to buildings.

- Inspection of VIEWS™ HDV footage and high-resolution NOAA aerial imagery footage indicates that buildings within New Orleans sustained damage at all five levels of the WF scale. In general, neighborhoods experiencing high damage levels (WF-3 and WF-4) exhibited a marked consistency in damage for all properties. Variable damage levels were observed within transitional zones approximately five blocks from the location of a levee breach and at the flood inundation boundary.

- The majority of damage to residential structures in the four zones in New Orleans was due to flooding caused by breaches in the city's flood-protection system. One significant factor in the damage to residential construction was poor construction quality. Wind-pressure damage in New Orleans was primarily observed in the mid-rise and high-rise buildings located in the downtown area.

6.0 Application of Integrated VIEWS™ and Remote Sensing Data

The previous sections of this report have documented the availability, acquisition, and analysis of remote sensing imagery within a tiered reconnaissance framework, together with the collection of in-field damage information using the advanced technology-based VIEWS™ system. The following sections describe the integration and application of these remote sensing and VIEWS™ datasets for public outreach and dissemination in the immediate aftermath of Hurricane Katrina. The importance of the Hurricane Katrina data archive for "ground-truthing" is also discussed, as a requisite for developing new and improved remote sensing-based methodologies for post-disaster damage assessment. This chapter concludes with a vision for future research activities stemming from the Hurricane Katrina datasets that from a scientific standpoint will promote an improved understanding of remote sensing for post-disaster response, and from an operational standpoint will result in innovative new methodologies for rapid and accurate damage assessment.

6.1 Public Outreach and Dissemination

The goal of remote sensing-based windstorm damage assessment is to provide technological assistance for overall understanding of the disaster, disaster management, emergency management, and preservation of the damage scene for long-term studies and future mitigation efforts.

Public outreach and dissemination are of paramount importance to make available to those who need it – in a timely manner – the information generated through this technology. Among public users of this technology are individuals, government entities (local, state, and federal), emergency responders, long-term planners and policy makers, and insurance-industry (actuarial) researchers.

Distribution via the Internet has proven especially effective for the widespread and rapid dissemination of damage information on an international basis (see, for example, Respond 2006 and UNOSAT 2006). In the case of Hurricane Katrina, many evacuated residents of the Gulf Coast were able to determine the general status of their property and overall neighborhoods before returning by viewing NOAA aerial images posted online (Section 2.2.2).

VIEWS™ technology can also add important ground-based observations to the remote sensing data. Daily updates from MCEER advanced technology field teams deploying the VIEWS™ system in Mississippi (Section 5.1) and New Orleans (Section 5.2) were uploaded to the MCEER website, and thus were rapidly made available to the public, providing a first-hand look into the disaster areas (Figure 6-1).

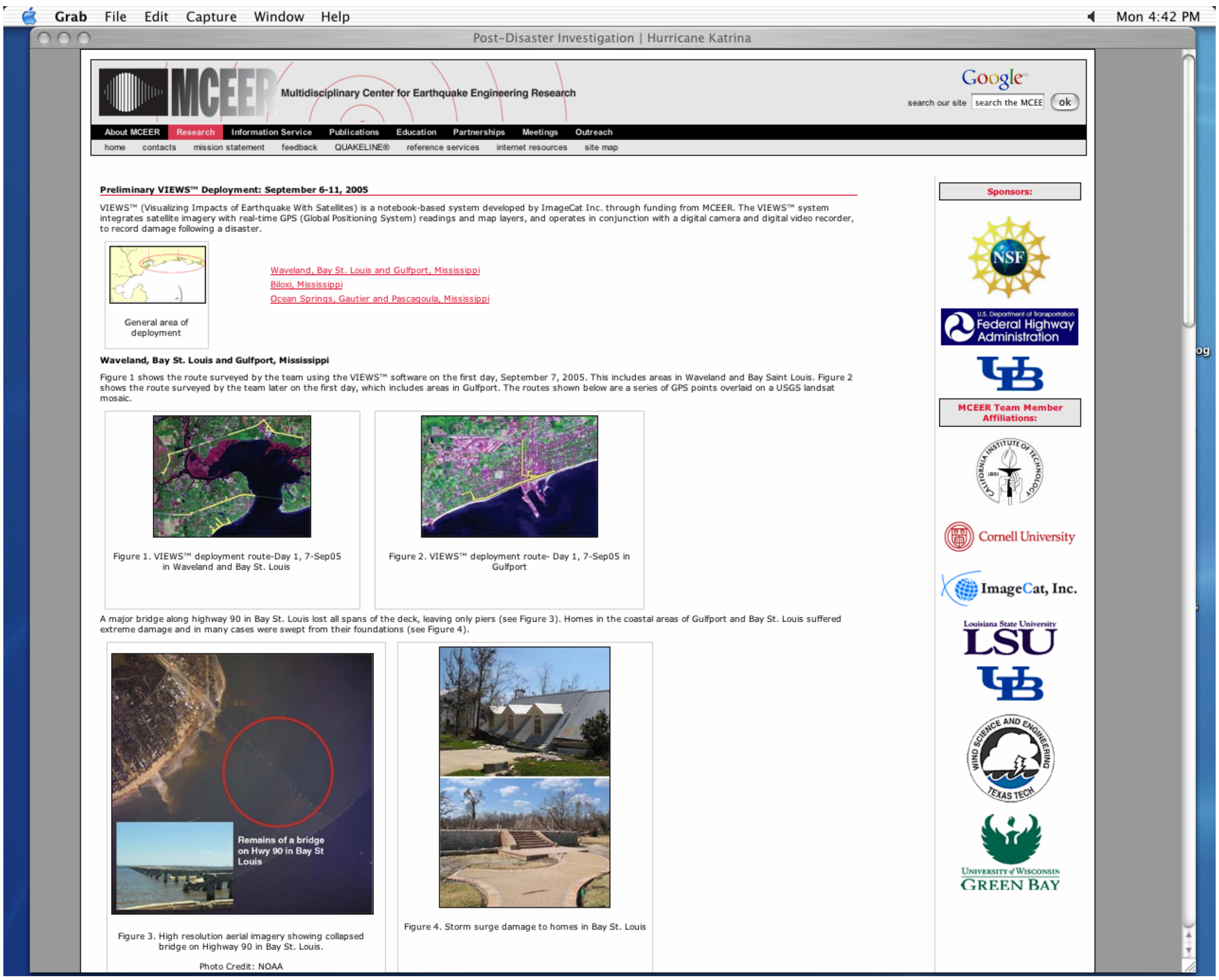


Figure 6-1. Daily reports submitted by the MCEER advanced technology field teams were made available on the MCEER website to provide first-hand observations of the storm damage (http://mceer.buffalo.edu/research/Reconnaissance/Katrina8-28-05 /Views.asp#3).

6.1.1 Google Earth

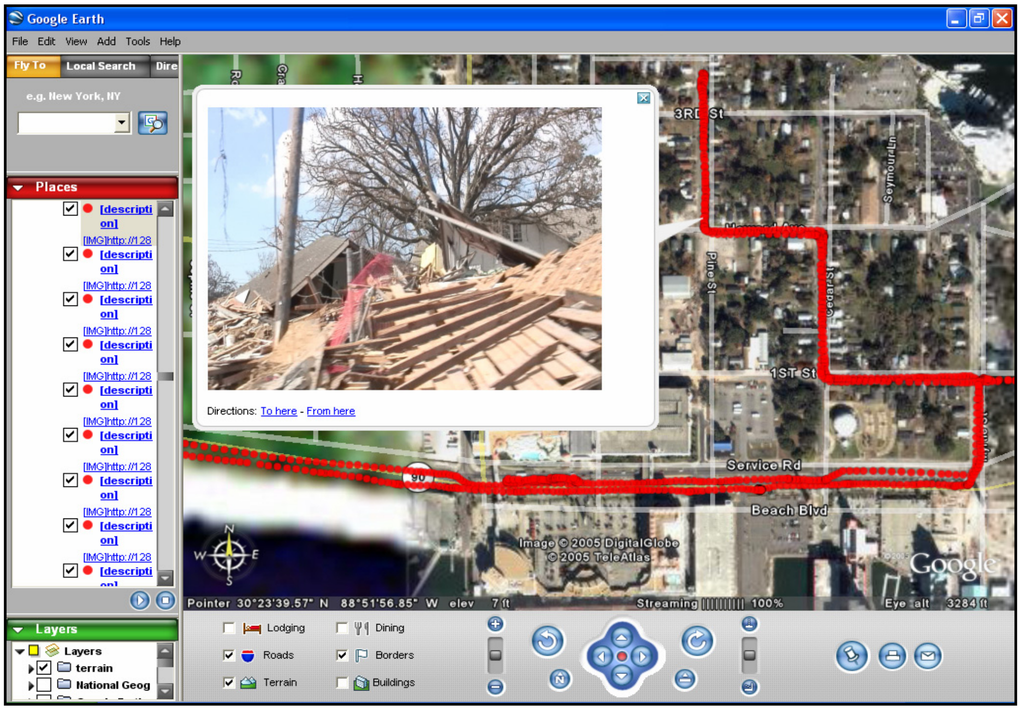
The Internet-based Google Earth application likewise provided a publicly-accessible means for distributing VIEWS™ ground reconnaissance information collected by the MCEER advanced technology field teams. Within the Google Earth framework, geographically referenced VIEWS™ field reconnaissance data are readily integrated with remote sensing imagery. Figure 6-2 shows samples of the VIEWS™ field-reconnaissance data within the Google Earth system; more than 18,000 images (12.2 GB) of damage along the Mississippi Coast, and more than 27,000 images (15.3 GB) from the New Orleans deployment, have been integrated with Google Earth.

Similarly, VIEWS™ data are appropriate for inclusion within other remote sensing and disaster-related data display systems, such as:

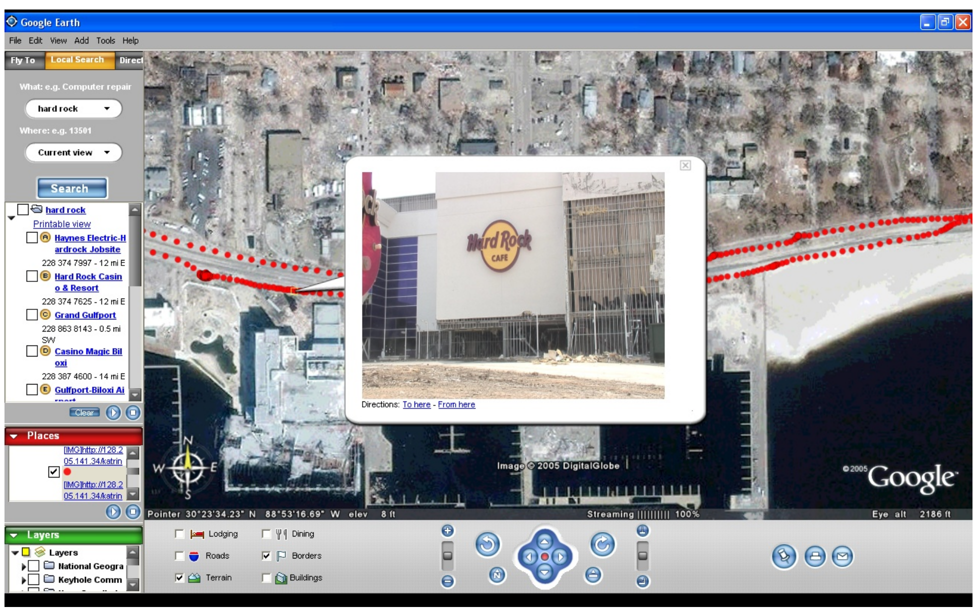
- DigitalGlobe Hurricane Media Gallery (*http://www.digitalglobe.com/katrina_gallery.html*)
- ESRI Damage Viewer (*http://arcweb.esri.com/sc/hurricane_viewer/index.html*)
- GeoEye/ SpaceImaging Gallery (*http://www.spaceimaging.com/gallery/hurricanes2005/katrina/ default.htm*).

6.1.2 MSN Virtual Earth

The MSN Virtual Earth system provides another online platform for sharing the georeferenced VIEWS™ field-reconnaissance data integrated with remote sensing imagery. Figure 6-3 shows an example of the VIEWS™ field-reconnaissance data in the MSN Virtual Earth system.

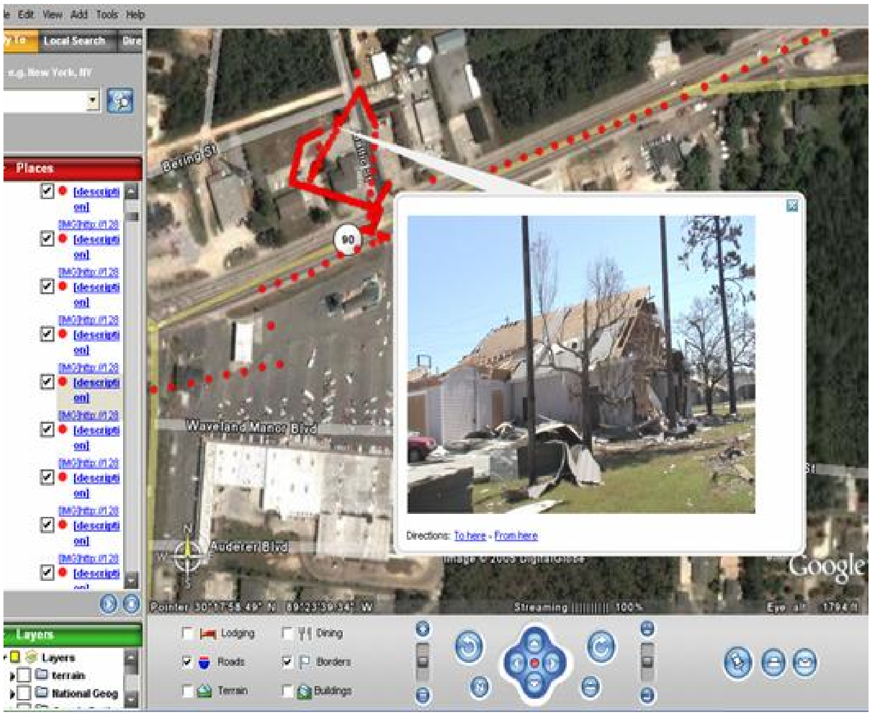


(a) This image set shows storm-surge damage in Biloxi, MS

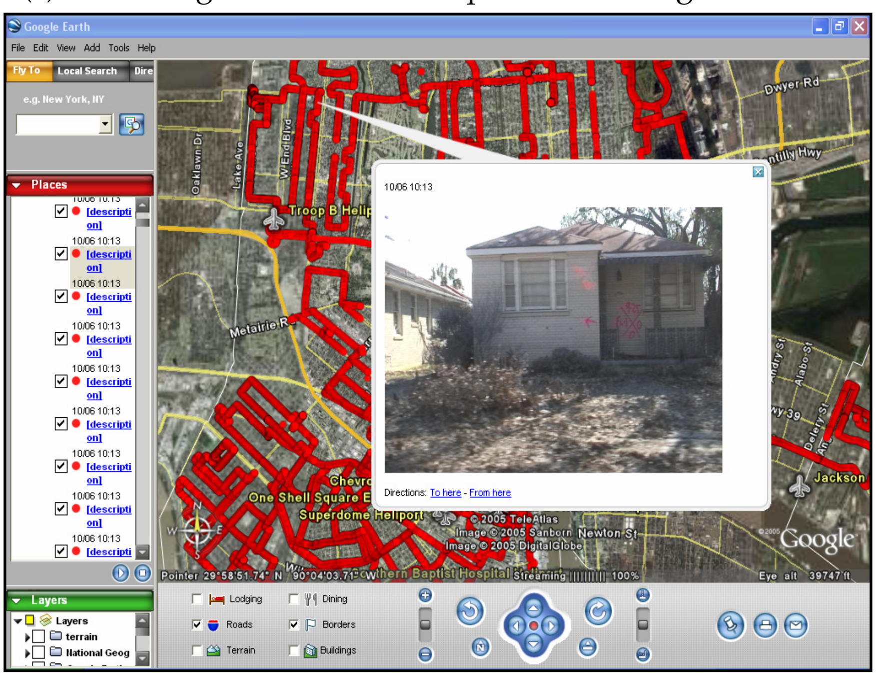


(b) This image set shows wind-pressure and storm-surge damage in Biloxi, MS

Figure 6-2. VIEWS™ field reconnaissance data accessible via the online Google Earth application. (http://mceer.buffalo.edu/research/reconnaissance/katrina8-28-05/views_dge.asp).



(c) This image set shows wind-pressure damage in Waveland, MS



(d) This image set shows flooding damage in New Orleans

Figure 6-2 (continued). VIEWS™ field reconnaissance data accessible via the online Google Earth application.

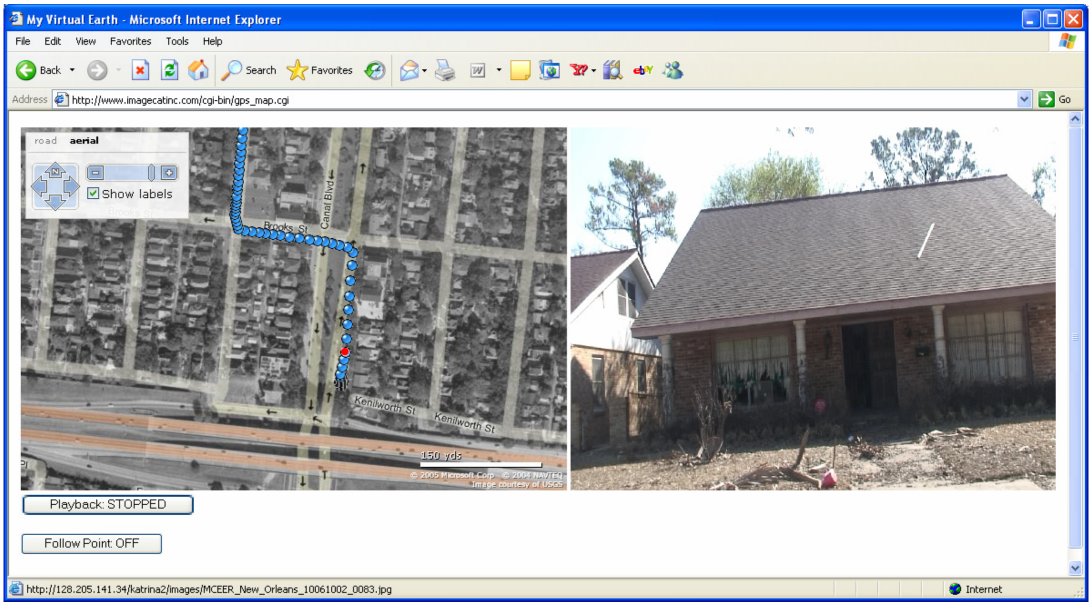


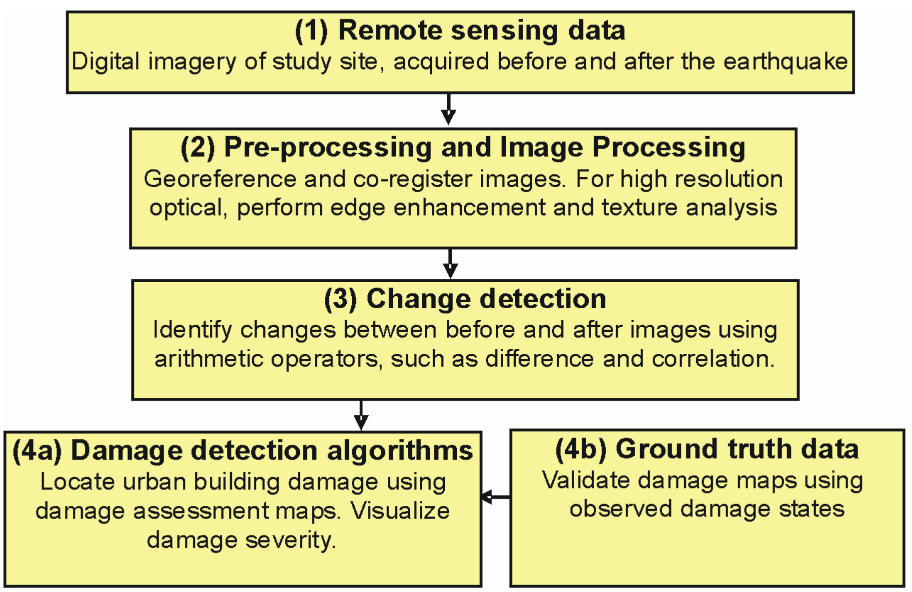
Figure 6-3. An example of the VIEWS™ field reconnaissance data in the MSN Virtual Earth system.

6.2 Ground Truthing

Ground truthing surveys play a critical role in the remote sensing assessment of damaged buildings by providing verification of damage signatures observed in satellite and airborne data (Eguchi et al., 2003). While remote sensing, in general, provides a synoptic overview of a region of interest, complementary ground observations provide additional details about damage mechanisms that cannot be discerned from remote sources alone. Nadir (or overhead) imagery is ideally suited for viewing horizontal surfaces (e.g., roofs). However, it is of more limited value for vertical surfaces (e.g., walls), where specialist oblique (or sideways-looking) imagery (e.g., as provided by Pictometry 2006) instead provides a realistic perspective. Comprehensive assessments of building damage cannot generally be made based on overhead imagery alone. For example, construction quality, which is a key to the windstorm performance of a structure, is best assessed through ground survey (Marshall 2001). Integration and correlation with ground-based surveys is therefore essential for accurate and complete interpretation of the remote sensing imagery.

In terms of application, Figure 6-4 presents a methodological framework for the assessment of damage to buildings. The quantitative analysis of before-and-after remote sensing data is integrated with field-derived ground-truth information to establish "signatures" of damage severity (Adams et al., 2004a). Although initially developed for earthquakes, this approach is applicable to multiple hazards. While damage assessment techniques are currently semi-automated or based on expert interpretation, ultimately, the *automated* integration of remote sensing characteristics with empirical relationships through statistical analyses (Crandell 1998, 2002; He et al., 2005) of ground-truthing data samples promises near-real-time inferences about the total population from a sample of structures.

As described in Chapter 5, the Data Collection module of the VIEWS™ system was used to acquire a library of post-Hurricane Katrina imagery, the potential applications of which include ground truthing. During field reconnaissance activities, MCEER advanced technology field teams collected more than 27 hours of georeferenced HD video in Mississippi and New Orleans, from which a library of approximately 46,000 still images were extracted. Figure 6-5 shows the VIEWS™ Data Collection module in action.



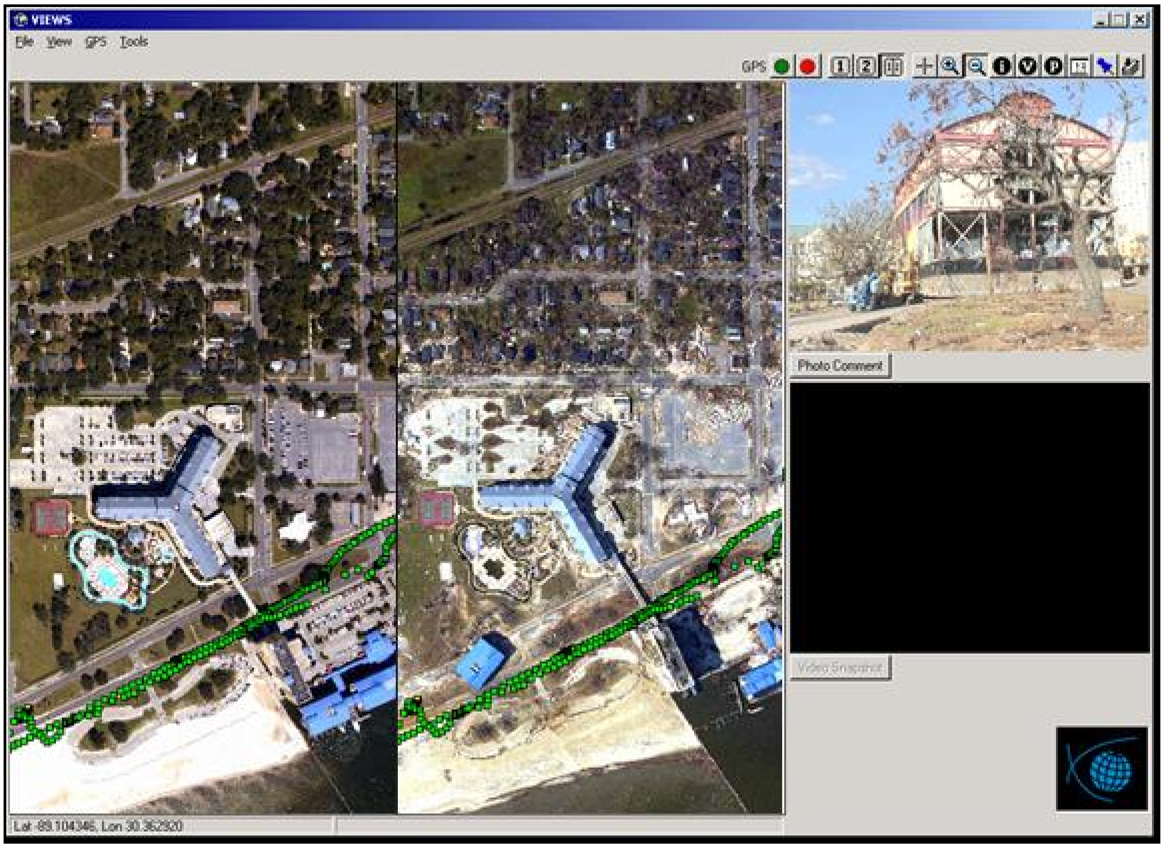
Adams (2004a)

Figure 6-4. Methodology for building earthquake damage detection, integrating satellite imagery with ground-truthing data. The methodology is applicable to multiple hazards.

Figure 6-5. Examples of the VIEWS™ reconnaissance system deployed in Mississippi and New Orleans following Hurricane Katrina.

Upon return from the field, the VIEWS™ Visualization mode facilitates the post-reconnaissance evaluation and analysis of the damage data. Figure 6-6 shows a typical user interface, focused on the storm-surge affected coast of Mississippi. Pre- and post-storm images are shown in the main screen, overlaid with the GPS route followed by the field team. A sample of the georeferenced still images is shown on the right side of the screen. Users can pan around the entire field deployment zone, accessing still images and video segments at will by clicking on the GPS point. Sample images can be output for features of interest.

VIEWS™ Visualization mode has proved to be particularly helpful for rapidly assessing post-hurricane damage (DigitalGlobe 2005; ImageCat 2005) and studying the remote sensing signatures of various types of damage to the built environment. Womble (2005) describes the use of digital change-detection procedures applied to before-and-after remote sensing images of buildings damaged by Hurricanes Charley and Ivan in 2004. This research constituted a major advance toward developing correlations between remote



Digital aerial images by NOAA

Figure 6-6. Examples of the VIEWS™ Visualization mode screen interface, showing GPS routes followed by the reconnaissance teams superimposed on before-and-after remote sensing imagery.

sensing signatures of wind-pressure damage and actual damage states observed in the field (see Tables 4-1 and 5-3). Ultimately this research offers the potential for rapid and automated assessments of damage driven by remote sensing technology.

Through the use of Hurricane Katrina VIEWS™ data, comparable correlations can be made for other hazards, such as flooding and storm surge, in addition to further validation of wind-pressure relationships. Although present research has concentrated on residential buildings, correlations may also be developed for alternate construction and/or occupancy classes (e.g., commercial and industrial properties) and for additional infrastructure elements, including roads, bridges, and utility lifelines. Figure 6-7 illustrates the way in which integrated remote sensing data and in-field observations provide the building blocks for new damage scales incorporating these

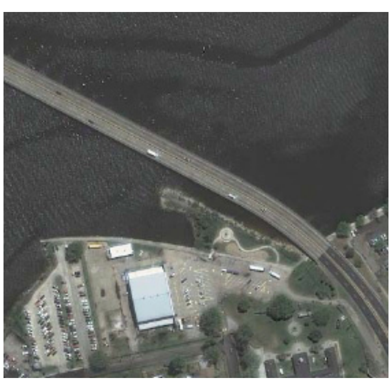
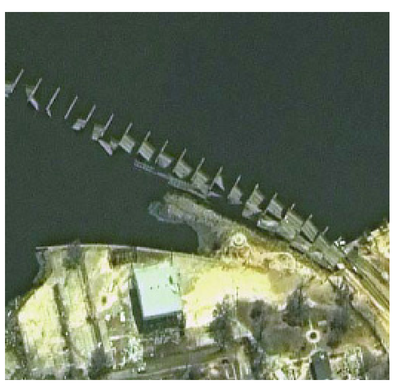
Remote sensing Images		Ground-Truthing Images
Pre-Storm	Post-Storm	
Wind Pressure - industrial  Photo Credit: NOAA	 Photo Credit: NOAA	
Storm Surge - residential  Photo Credit: NOAA	 Photo Credit: NOAA	
Storm Surge - infrastructure  Photo Credit: DigitalGlobe, Inc.	 Photo Credit: DigitalGlobe, Inc.	

Figure 6-7. Examples of pre-storm and post-storm remote sensing imagery with corresponding ground-truthing images.

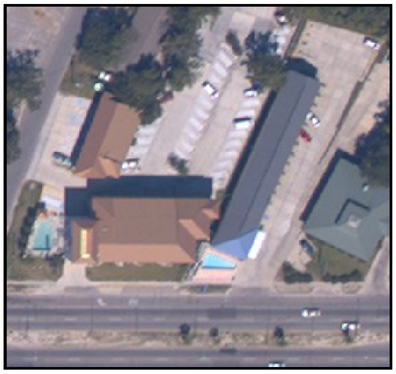
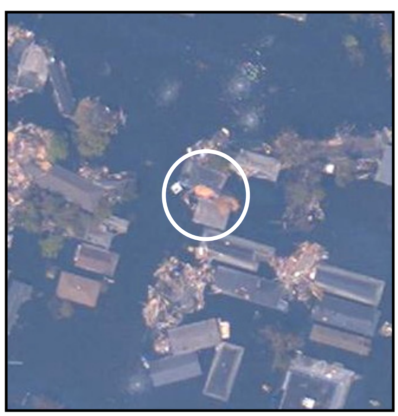
Storm Surge – hotel  Photo Credit: NOAA	 Photo Credit: NOAA	
Storm Surge - residential  Photo Credit: NOAA	 Photo Credit: NOAA	
Flooding- residential  Photo Credit: DigitalGlobe and Google Earth	 Photo Credit: NOAA	

Figure 6-7 (continued). Examples of pre-storm and post-storm remote sensing imagery with corresponding ground-truthing images.

Wind Pressure + Storm Surge - church  Photo Credit: NOAA	 Photo Credit: NOAA	

Figure 6-7 (continued). Examples of pre-storm and post-storm remote sensing imagery with corresponding ground-truthing images.

different types of structures and infrastructures. In this figure, examples are presented for a range of different damage sources, and for different classes of urban structure and infrastructure. As noted in the following section, additional research activities are recommended to develop these multi-hazard/multi-structure relationships.

6.3 Future Work

As urban development continues to expand along the U.S. hurricane coast, more people and infrastructure are subjected to potential risks of hurricane damage. There is a pressing need to formalize the implementation of advanced technology-based procedures for post-hurricane reconnaissance as part of response activities.

In addition to providing a synoptic view of damage and preserving post-disaster conditions for future reference, remote sensing technologies offer tremendous potential for rapid damage assessment in (ultimately) an automated manner. The application of advanced technology for post-disaster damage assessment is an emerging application, which, although widely used following Hurricane Katrina (Chapter 4), promises further improvements in efficiency and accuracy as new imaging systems, satellite constellations, and damage detection algorithms come online.

The remote sensing-based analyses of natural disasters such as the Boumerdes (Algeria) and Bam (Iran) earthquakes (Adams et al., 2004a,b), Hurricanes Charley and Ivan (Adams et al., 2004d; Womble et al., 2005), the

Southeast Asian Tsunami (Adams et al., 2005a,b; Ghosh et al., 2005; Chang et al., in press), and Hurricane Katrina (a combination of multiple hazards) have all contributed to this base of knowledge, together with the maturing and progressive application of protocols for damage assessment. However, it is important to recognize that although significant progress has been made to date, with each new disaster, additional damage data are needed to populate the remote sensing and ground-truthing databases for use in calibrating and standardizing damage assessment algorithms.

In particular, it is recommended that future research activities be pursued which focus on:

- Unraveling juxtaposed damage signatures (e.g., wind, flood, and storm surge)
- Developing and calibrating damage scales for individual hazards
- Developing and calibrating damage scales for combined hazards
- Developing automated damage assessment algorithms

In is envisioned that this research agenda will culminate in a methodology for remote sensing-based, automated, multi-hazard, per-building damage assessment.

6.4 Summary of Key Findings

- In the aftermath of Hurricane Katrina, remote sensing and VIEWS™ datasets were disseminated for operational decision support and public outreach.

- Evacuated residents from the Gulf Coast and New Orleans were able to determine the damage status of their property and neighborhood before returning, by viewing NOAA aerial images posted online.

- Daily situation updates from the VIEWS™ field-reconnaissance teams in Mississippi and New Orleans were rapidly disseminated to the public through the MCEER website (*http://mceer.buffalo.edu/research/Reconnaissance/ Katrina8-28-05/*), providing a first-hand look at the disaster areas.

- The Internet-based Google Earth and Microsoft Virtual Earth applications enabled the quick and widespread distribution of VIEWS™ field reconnaissance information. More than 18,000 images (12.2 GB) of VIEWS™ HDV damage data for the Mississippi Coast, and more than

27,000 images (15.3 GB) for New Orleans have been integrated within the Google Earth system.

- VIEWS™ data is a valuable source of ground-truth information, which can be studied on return from the field using the VIEWS™ visualization mode. Ground truthing plays a critical role in the remote sensing assessment of damaged buildings by providing verification of the damage signatures through additional information about damage mechanisms that cannot be discerned from satellite and airborne imagery alone.

- While a remote sensing-based wind damage scale has been developed for residential structures, research is ongoing to develop damage scales for alternate hazards, such as storm surge, and structural types, such as commercial properties.

- Future work integrating remote sensing and VIEWS™ data will focus on improving the efficiency and accuracy of damage detection techniques, and developing standardized algorithms. Specifically, research is needed to unravel juxtaposed damage signatures (e.g., wind, flood, and storm surge), and to develop new damage scales for individual and combined hazards.

7.0 Key Findings and Future Work

As a natural disaster, Hurricane Katrina was record-breaking because of the unique convergence of multiple hazards within a single event (namely windstorm, storm surge, flooding, and levee breach), and also due to its status as the costliest U.S. hurricane on record. From a technology standpoint, Hurricane Katrina is also important, as it marks the first event where the "eye in the sky" was used operationally to assess the unfolding situation and to record damage from multiple hazards.

This final chapter of the report provides an overview of the key ways in which remote sensing helped, and moving forwards will continue to help, in the aftermath of Hurricane Katrina. A vision of key advanced technology research thrusts that are necessary to help mitigate against and optimize the response to future windstorms and multi-hazard disasters is also provided.

7.1 Uses and Availability of Remote Sensing Data Following Hurricane Katrina

- The 2005 hurricane season has seen the implementation of post-disaster information derived from remote sensing data by risk modeling companies. In the aftermath of Hurricane Katrina, remote sensing imagery supported deployment planning, field reconnaissance, and damage assessment activities, and when distributed online, was also used extensively by evacuated homeowners to gauge damage to their property.
- Following Hurricane Katrina, the "eye in the sky" rapidly captured detailed images of the unfolding post-disaster situation. The images are "high-resolution," showing damage on a scale of 15-61 cm. With ground access to affected areas limited in the days after Hurricane Katrina, this imagery captured accurate and objective information about wind and surge damage to individual buildings, together with the unfolding levee breach and flood situation.
- For New Orleans, the first cloud-free high-resolution coverage of flood and wind damage was provided on August 30 by the VIEWS™ system, deployed through ImageCat's PDV (Post-disaster Damage Verification) program. For the Mississippi Coast, the first cloud-free coverage of storm-surge and wind-pressure was provided on August 30 by NOAA.
- High-resolution satellites collected coverage of the disaster zones just one day after the event. However, the imagery was affected by residual cloud cover from the storm. The first cloud-free, high-resolution satellite imagery of New Orleans was acquired by OrbView on August 30 and QuickBird on August 31. Partially cloud-free coverage of Mississippi was

acquired by QuickBird on August 31, followed by OrbView and IKONOS on September 2.

- NOAA imagery was initially made available online in a non-geographically referenced format, which severely limits its use for mapping and analysis. MCEER researchers at ImageCat quickly developed a custom algorithm to coarsely process the data for immediate use in damage assessment. Several days later, the images were also distributed online through Google Earth.

7.2 Remote Sensing For Reconnaissance Planning and Support

- Within a Tiered Reconnaissance System (TRS) framework, remote sensing images acquired by satellites and aircraft can be used to guide and inform reconnaissance activities. Following Hurricane Katrina, activities conducted by MCEER researchers at ImageCat and MCEER advanced technology field teams spanned: (1) Tier 1 – the "regional" evaluation of damage extent; (2) Tier 2 – recording the severity of damage at a "neighborhood" scale; and (3) Tier 3 – detailed "per-building" assessment damage. At Tier 3, detailed reconnaissance was completed using a combination of the VIEWS™ in-field system and remote sensing data from satellites, NOAA, and the PDV program.
- Before deploying, MCEER advanced technology field teams employed a multi-hazard site selection protocol which integrated deterministic, probabilistic, and inferential information sources. Teams also developed a deployment plan that is a proven tool for streamlining and prioritizing in-field operations and for ensuring that all objectives are achieved.

7.3 Damage Detection Using Remote Sensing

- Hurricane Katrina presented a unique opportunity to operationally deploy damage assessment research outputs from MCEER Thrust Area 3 (Emergency Response and Recovery) for analyzing: (1) storm surge, (2) wind pressure, (3) flood inundation, and (4) levee breach.
- Storm surge extent throughout the Mississippi Coast was evaluated using: (1) an analysis of before-and-after Landsat-5 satellite imagery from USGS/NASA, which suggested that the entire coast was affected; and (2) an evaluation of NOAA airborne imagery, which showed that 90-100% of buildings were completely destroyed within about ½ to 1 mile of the shore. Remote sensing images quickly showed that in this area, storm surge proved far more damaging than wind pressure.
- Per-building wind damage to residential structures was assessed using a remote sensing-based damage scale. To rapidly assess wind damage

across the region, a new severity ranking system was developed for the library of 3,700 NOAA images.

- The New Orleans flooding situation was assessed: (1) within 48 hours of the event using the ImageCat PDV program, capturing inundation within western districts that was absent from assessments conducted one week later; (2) for the entire city using a before-and-after sequence of Landsat-5 imagery; and (3) at a neighborhood-scale using multispectral QuickBird satellite imagery.
- Levee breaches are clearly identified on 61-cm QuickBird satellite imagery of New Orleans and NOAA airborne coverage. Information such as the extent of breach and location of high-velocity flooding can be determined.

7.4 Field Reconnaissance and Damage Detection Using VIEWS™

- MCEER's advanced technology field teams conducted damage assessments in the aftermath of Hurricane Katrina using VIEWS™ (Visualizing Earthquakes with Satellites) – a notebook-based field data collection and visualization system deployed from a moving vehicle, on foot, or from an aircraft. It integrates pre- and post-disaster remote sensing imagery with real-time GPS (Global Positioning System) readings and map layers, and operates in conjunction with a digital camera and digital video recorder.
- VIEWS™ deployments to the Mississippi Coast from September 7-9, 2005, and New Orleans from October 6-9, 2005 successfully performed rapid and widespread assessments of wind, storm-surge, and flood damage at a per-building scale. For the Mississippi Coast from Waveland/Bay St. Louis to Pascagoula, 11 hours of video footage and a library of 18,900 high-definition video (HDV) stills were collected. For New Orleans and St. Bernard parishes in New Orleans, the library comprises 16 hours of video and 27,000 HDV stills.
- To interpret post-Hurricane Katrina multi-hazard damage on a loss-consistent basis, MCEER researchers employed a remote sensing-based damage scale for residential buildings (Womble 2005) that links to the FEMA (2003a) HAZUS-Hurricane scale. They also developed a new five-level Wind-Flood (WF) damage scale that combines HAZUS-based damage scales for wind and flood to characterize the total damage to buildings.
- VIEWS™ footage indicates that homes suffered extreme storm-surge damage along the Mississippi Coast, with many swept from their foundations, and evidence of surge up to about 20 ft. Deck spans from U.S. 90 bridges were lost, and offshore casinos were carried inland.

Buildings within New Orleans sustained damage at all levels of the WF scale.

7.5 Public Distribution of VIEWS™ and Remote Sensing Data

- In the aftermath of Hurricane Katrina, daily situation updates from the VIEWS™ field reconnaissance teams in Mississippi and New Orleans were publicly distributed through the MCEER website, providing a first-hand look at the disaster areas.
- The Internet-based Google Earth and Microsoft Virtual Earth applications enabled the quick and widespread distribution of VIEWS™ field-reconnaissance information. More than 18,000 images (12.2 GB) of VIEWS™ HDV damage data for the Mississippi Coast, and more than 27,000 images (15.3 GB) for New Orleans have been integrated within the Google Earth system.
- Evacuated residents from the Gulf Coast and New Orleans were able to remotely determine the damage status of their property and neighborhood, by viewing NOAA aerial images posted online.

7.6 Future Work

- While a remote sensing-based wind damage scale has been developed for residential structures, research is ongoing to develop damage scales for alternate hazards, such as storm surge, and structural types (e.g., commercial/industrial). This will utilize VIEWS™ data as a source of ground-truth information to verify remote sensing observations.
- Future work integrating remote sensing and VIEWS™ data will focus on improving the efficiency and accuracy of damage detection techniques, and developing standardized algorithms. Specifically, research is needed to unravel juxtaposed damage signatures (e.g., wind, flood, and storm surge), and to develop new damage scales for individual and combined hazards.
- Operationally, a formal post-disaster field reconnaissance planning and site selection system may be envisioned, integrating available information layers to identify the nature of impacts (flooding, storm surge, etc.) and rank their severity.

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APPENDIX A: Links to Associated Internet Information

Canadian Space Agency (Radarsat)
http://www.space.gc.ca/asc/eng/satellites/radarsat1/featured_north_america.asp

ESRI Disaster Viewer
http://arcweb.esri.com/sc/hurricane_viewer/index.html

DigitalGlobe Hurricane Media Gallery
http://www.digitalglobe.com/katrina_gallery.html

GeoEye / SpaceImaging Gallery
http://www.spaceimaging.com/gallery/hurricanes2005/katrina/default.htm

Google Earth
http://earth.google.com

Google Earth – Linked VIEWS™ Data
http://mceer.buffalo.edu/research/Reconnaissance/Katrina8-28-05/views_dge.asp

International Charter – Space and Major Disasters
http://www.disasterscharter.org/disasters/

International Charter – Hurricane Katrina
http://sertit.u-strasbg.fr/documents/louisiane_2005/louisiane05_en.html

LaCoast Aerial Photography – Hurricane Katrina
http://www.lacoast.gov/maps/2005katrina/

NASA Earth Observatory – Hurricane Katrina News
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13089
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13089
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13090
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13094
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13095
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13096
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13100
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13101
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13104
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13112
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13113
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13120
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13133

http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13134
http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13147

NASA Hurricane Resource Page
http://www.nasa.gov/vision/earth/lookingatearth/hurricane_2005.html

NASA EO-1 – Hurricane Katrina Images
http://landsat.gsfc.nasa.gov/main/katrina_eo1.html

NASA Landsat 7 – Hurricane Katrina Images
http://landsat.gsfc.nasa.gov/main/katrina2.html

NASA – Looking at Earth
http://www.nasa.gov/vision/earth/lookingatearth/h2005_katrina.html

NASA MODIS Image Gallery
http://rapidfire.sci.gsfc.nasa.gov/gallery/?search=katrina
http://rapidfire.sci.gsfc.nasa.gov/katrina/

NASA – Terra Satellite Overview
http://cires.colorado.edu/~maurerj/terra.htm

NOAA Hurricane Research Division – Hurricane Katrina
http://www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/index.html

New York Times – Hurricane Katrina Feature
http://www.nytimes.com/packages/html/national/2005_HURRICANEKATRINA_GRAPHIC/

Radarsat – Hurricane Katrina News Feature
http://gs.mdacorporation.com/news/feature/current_event_katrina_sep05.asp

USGS Hurricane Katrina Disaster Response
http://eros.usgs.gov/katrina/

USGS Hurricane Katrina Geospatial Data
http://eros.usgs.gov/katrina/datasets.html

USGS Hurricane Katrina Impact Studies
http://coastal.er.usgs.gov/hurricanes/katrina/

USGS Public Data (Disasters)
ftp://edcftp.cr.usgs.gov/pub/data/disaster/katrina/

USGS Science Discussions
http://eros.usgs.gov/katrina/science.html/

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