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Source: Journal of Coastal Research, 2009(256) : 1264-1275

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/08-1146.1

Journal of Coastal Research	25	6	1264–1275	West Palm Beach, Florida	November 2009

The Role of Remote Sensing in Predicting and Determining Coastal Storm Impacts

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ABSTRACT

KLEMAS, V.V., 2009. The role of remote sensing in predicting and assessing coastal storm impacts. *Journal of Coastal Research,* 25(6), 1264–1275. West Palm Beach (Florida), ISSN 0749-0208.

Storm-induced flooding and other damage present a major problem as the coastal population continues to increase rapidly and sea level keeps rising. To predict the path and landfall of a hurricane or other coastal storm and assess the damage, emergency managers and scientists need continuous information on the storm's path, strength, predicted landfall, and expected damage over large areas. Satellite and airborne remote sensors can provide the required information in a timely and reliable way, as demonstrated by a case study of hurricane Katrina's impact on New Orleans and surrounding areas. Satellite images and hurricane hunter planes were used to track hurricane Katrina, with modelers predicting accurately its path, strength, surge level, and landfall location. Shore-based radars were used to confirm the data as the hurricane approached land. Medium- and high-resolution satellite sensors, helicopters, and aircraft were employed to assess damage to the city, including transportation, power, and communication infrastructures, and to adjacent wetlands and other coastal ecosystems. The lessons learned from hurricane Katrina are helping to optimize future approaches for tracking hurricanes and predicting their impact on coastal ecosystems and developed areas.

ADDITIONAL INDEX WORDS: *Hurricane tracking, hurricane impact, coastal flooding, New Orleans case study, coastal remote sensing.*

INTRODUCTION

More than half the total U.S. population lives in the coastal zone, which represents only 18% of total U.S. land area. These areas are becoming more developed every year. Over the next 15 years, the U.S. coastal population is projected to increase by about 25 million people, reaching 166 million people by the year 2015. These coastal communities will be highly vulnerable to coastal storms and flooding, which already account for more than 70% of annual U.S. disaster losses. As more people move to the coast, coastal flooding and erosion from storm surges and sea level rise will claim more private and public structures each year. With events such as the strong hurricanes of 2004 and 2005, losses can total billions of dollars per year (Gregg, 2007; Island Press, 2000).

In the U.S., tropical storms and hurricanes affect the coast from New England to Texas, with their season extending from June through November. Furthermore, each year, several mid-latitude cyclones evolve into powerful coastal storms along the U.S. Atlantic coast, called nor'easters, because of the strong winds that blow from the northeast. A particularly disastrous storm was the nor'easter of 1962, which ravaged the Mid-Atlantic Coast with a storm surge that tore down boardwalks and urban structures as it flooded communities up to 20 miles inland. Because commercial satellites were not available at that time, the resulting coastal damage could only be mapped from low-altitude aircraft with simple aerial film cameras (Mather *et al.,* 1964, 1967).

Direct hits by major hurricanes are usually more devastating than nor'easters because their wind speeds, storm surges, and waves are much higher. Environmental impacts from hurricanes include excessive nutrient loading, algal blooms, elevated oxygen demand resulting in hypoxia and anoxia, fish kills, large-scale releases of pollutants and debris, and spread of pathogens. Good overviews of the effects of hurricanes on coastal ecosystems are provided in recent journal articles (Greening *et al.,* 2006; Mallin and Corbett, 2006; Sallenger *et al.,* 2006). An important conclusion resulting from these articles is that many ecological components of estuaries and coastal systems were initially affected by the hurricanes, yet were quite resilient in sharp contrast to the long-term effects on coastal urban developments and infrastructure, such as roads and causeways.

The greatest danger to coastal communities is from a hurricane's storm surge. Storm surges develop when water is pushed toward the shore by the force of a hurricane's wind. Horizontally, the surge can fan out over several hundred miles of coastline. In general, the more intense the hurricane, and the closer a community is to the right-front quadrant, the larger the area that must be evacuated. Vertically, the surge can reach heights of more than 20 feet near the center of a Category 5 hurricane. Furthermore, the astronomical tide can add several feet to the storm surge. Such a surge of

DOI: 10.2112/08-1146.1 received 20 October 2008; accepted in revision 29 January 2009.

Table 1. *Saffir-Simpson index for storm classification.*

Hurricane classification			
Intensity	Pressure (mb)	Wind Speed (mph [km/h])	Storm Surge (ft [m])
Class 5	<920	>155 [>250]	>18 [>5.5]
Class 4	925–940	131–155 [211–250]	13–18 [4.0–5.5]
Class 3	945–965	111–130 [179–210]	9–12 [2.7–3.7]
Class 2	965–980	96–110 [154–178]	6–8 [1.8–2.4]
Class 1	>980	74–95 [119–153]	4–5 [1.2–1.5]

high water, combined with high tides and torrential rains and topped by battering waves, can be devastating to any coastal community. Hurricane storm surges with their associated wind speeds are shown on the Saffir-Simpson Index in Table 1 (Kantha, 2006). In addition to urban communities and beaches, nearly 100,000 km of coastal roadways are in the 100-year floodplain in the U.S., including many that are exposed to water surges and storm waves generated by hurricanes (Chen *et al.,* 2007).

Over the long term, coastal communities are also facing a rising sea level, caused mainly by global warming. A scientific consensus states that, as average temperatures increase worldwide, average sea levels will continue to rise globally. The sea level is rising because water expands as it is warmed and because water from melting glaciers and ice sheets is added to the oceans. Many scientists believe that because of melting glaciers and expanding ocean water, the sea level rise will accelerate in the future (IPCC, 2007). Since 1993, satellite observations have permitted more precise calculations of global sea level rise, now estimated to be 3.1 ± 0.7 mm/y over the period 1993–2003. The substantial sea level rise and more frequent storms predicted for the next 50 to 100 years will affect coastal cities and roads, coastal economic development, beach erosion control strategies, salinity of estuaries and aquifers, coastal drainage and sewage systems, and coastal wetlands (NOAA, 1999).

Because the coastal population continues to increase rapidly and road improvements have not kept up with this rapid population growth, more time is needed to accomplish an evacuation. Much of the population living in hurricane-prone areas has not recently experienced a direct hit by a hurricane or major storm, and they are reluctant to evacuate. As a result, emergency managers need advance information on the predicted path, intensity, and progress of a storm and associated waves and storm surge as early as possible before landfall. They also need real-time information during the peak of the storm to monitor flooding and to control rescue operations. Finally, by comparing the conditions in the affected areas before and after the storm, managers can assess the damage and plan urban recovery; the restoration of the power, transportation, and communication infrastructure; and improvements in levees and drainage canals.

REMOTE SENSING REQUIREMENTS

Remote sensing systems have already proven their worth for observing storms and their effects on coastal communities (NOAA, 2006). However, to select the best set of remote sensing systems one must first define the requirements of key users, such as storm forecasters, emergency evacuation managers, coastal engineers, and various responsible officials at the city, county, state, and federal levels. With the wide variety of remote sensing systems available, choosing the proper data sources for tracking coastal storms and monitoring their impact on coastal urban communities can be challenging. Characteristics used to describe and compare analog and digital remote sensing systems are often grouped into four different types of resolution: spatial, spectral, radiometric, and temporal. Resolution is commonly attributed to an image and the sensor that provides the image data.

A coastal storm event can be divided into at least three phases: (1) before landfall, (2) during landfall, and (3) after landfall. As shown next, these three phases have quite different requirements for remotely sensed data.

Before Landfall

Storm surge flooding and high winds are the main hazards that render an area unsafe during a hurricane. A storm surge occurs when the hurricane's winds, forward motion, and low barometric pressure pile up water in front of the storm system as it moves toward the shore. Storm surge heights and waves depend on a combination of factors, including width and slope of the shelf, water depth, intensity of the storm, and the storm's forward speed and direction of movement. To assess the vulnerability of an area to storm surge, the maximum expected height of water must be compared with the elevation of the area to predict whether the area will be flooded during a range of storm scenarios.

Predicting Storm Surges and Inundation

One important model used by the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center to estimate storm surge heights and winds resulting from predicted or hypothetical hurricanes is the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model. It takes into account the pressure, size, forward speed, track, and winds of a hurricane. SLOSH is used to evaluate the threat from storm surges, and emergency managers use these data to determine which areas must be evacuated. SLOSH model results are combined with road network and traffic flow information, rainfall amounts, river flow, and wind-driven waves to identify at-risk areas (NOAA/CSC, 2008).

The dynamical SLOSH model computes water height over a geographical area or basin. The calculations are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads, and other physical features. Computations have been run for a number of basins covering most of the Atlantic and Gulf Coasts of the U.S. and offshore islands. The typical SLOSH grid contains more than 500 points located on lines extending radially from a common basin center. The distance between grid points ranges from 0.5 km near the center (where surge water heights are of more interest) to 7.7 km in the deep water at the edge of the grid. Bathymetric and topographic map data are used to determine a water depth or terrain height for each grid point. The model consists of a set of equations derived from the Newtonian equations of motion and the continuity equation applied to a rotating fluid with a free surface. The equations are integrated from the sea floor to the sea surface. The coastline is represented as a physical boundary within the model domain. Subgrid-scale water features (cuts, chokes, sills, and channels) and vertical obstructions (levees, roads, spoil banks, etc.) can be parameterized within the model. Astronomical tides, rainfall, river flow, and wind-driven waves have not been incorporated into the model. The primary use of the SLOSH model is to define flood-prone areas for evacuation planning. The flood areas are determined by compositing the model surge values from 200 to 300 hypothetical hurricanes. Separate composite flood maps are produced for each of the five Saffir-Simpson hurricane categories. The SLOSH model can also be run with forecast track and intensity data for an actual storm as it makes landfall (NOAA/CSC, 2008).

The U.S. Army Corps of Engineers merged the SLOSH model results with digital elevation models up to the 9-m contour of South Carolina's coast to create storm surge maps. These maps were developed by scanning U.S. Geological Survey (USGS) quadrangle sheets to create an electronic background map and by digitizing topographic information from these quad sheets along with supplemental elevation data provided by the U.S. Army Corps of Engineers. By processing the elevation from the base maps, a ground surface model was created and merged with SLOSH model results to create a storm surge map. In areas where the water surface elevation was greater than the terrain elevation, the area was shaded. The resulting maps represent the "maximum of the maximum" storm surge composite of hypothetical storms calculated at high tide, one depicting storms with slow forward speeds (8 and 24 km/h), and one depicting storms with fast forward speeds (40 and 56 km/h).

Remote Sensing Data

If the SLOSH model is used to estimate storm surge for an actual, predicted hurricane, forecast data must be put into the model every 6 hours over a 72-hour period and updated as new data become available (NOAA/NHC, 2008). This is achieved to a large extent with the use of remotely sensed data. The remote sensing systems used to provide near–real-time data for the models, include geostationary satellites (GOES), which sit above a fixed point on the equator at an altitude of 36,000 km and can provide estimates of the location, size, and intensity of a storm with their visible and thermal infrared imagers over large areas at a spatial resolution of 4 km (NOAA, 2006). In the visible region, clouds appear white because they scatter and reflect the sunlight. In thermal infrared images, clouds appear in varying shades of grey, depending on their temperature, which is determined by their height above Earth. Because geostationary satellites permanently view the same part of the globe, they can provide this information at very frequent intervals (*e.g.,* every 15 min). These images can be supplemented by daily passes of the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensor, providing a resolution of 1.1 km.

Table 2. *Spaceborne ocean sensing techniques.*

Color scanner	Ocean color (chlorophyll concentration, suspended sediment, attenuation coefficient)
Infrared radiometer	Sea surface temperature (surface temperature, current patterns)
Synthetic Aperture Radar	Short surface waves (swell, internal waves, oil slicks, *etc.*)
Altimeter	Topography and roughness of sea surface (sea level, currents, wave height)
Scatterometer	Amplitude of short surface waves (surface wind velocity, roughness)
Microwave radiometer	Microwave brightness temperature (salinity, surface temperature, water vapor, soil moisture)

Satellite radar systems can provide additional data on sea surface height, surface winds, and wave fields with radar altimeters, scatterometers, and Synthetic Aperture Radar (SAR), respectively (Table 2). Satellite microwave radiometers have also been used to estimate precipitation amounts and other hydrologic parameters for recent hurricanes like Katrina (Parkinson, 2003). As shown in Table 2, radar satellites can measure wave and sea surface height with altimeters, sea surface winds with scatterometers, and wave fields and other surface features, such as oil slicks, with SAR (Ikeda and Dobson, 1995; Martin, 2004). Along the coast, ground-based radars, such as the X-band marine navigation radars, can monitor waves, storm surges, and fronts over a 10-km range with 50-m resolution. Shore-based high-frequency radars can cover larger areas with a resolution of hundreds of meters. High-frequency radars can measure current speeds and wave height and direction. Because shore-based radars are stationary, they can sample frequently and continuously, thus complementing satellite radar data (Cracknell and Hayes, 2007; Robinson, 2004).

The NOAA National Hurricane Center uses NOAA and Air Force pilots to fly planes into the core of a hurricane to measure wind, pressure, temperature, and humidity and to provide the location of the center of the hurricane. When a hurricane gets close to land, it is monitored by land-based National Weather Service (NWS) Doppler weather radars. Thus local NWS stations are able to provide accurate short-term warnings of floods, high winds, and other weather hazards associated with such storms. NWS hurricane centers use numerical computer and statistical models to forecast the path, speed, and strength of coastal storms. Data from geostationary and polar orbit satellites, reconnaissance aircraft, and other sources are fed into these computer models. The models are then used to predict storm surge heights and the extent of the predicted flooding (NOAA, 2006).

The interface between the near-surface, high-wind environment of air and sea is critical in hurricane dynamics, yet too risky for manned aircraft to observe directly. One of the many new developments in hurricane tracking is unmanned hurricane hunter aircraft. An unmanned Aerosonde aircraft has already been used to track a hurricane's eye and boundary layer for 17 hours in wind gusts up to 105 km/h, from as low as 90 m from the ocean surface. The data transmitted from such unmanned aircraft will result in improved forecasting

Table 3. *High-resolution satellite parameters (Space Imaging, 2009; Digital Globe, 2008; Orbimage, 2009).*

Satellite Name	Sponsor	Launched	Spatial Resolution (m) Pan-chromatic	Multi-spectral	Spectral Range (nm) Panchromatic	Blue	Green	Red	Near Infrared	Swath Width (km)	Off Nadir Pointing	Revisit Time (days)	Orbital Altitude (km)
IKONOS	Space Imaging	Sept. 1999	1.0	4.0	525–928	450–520	510–600	630–690	760–850	11.3	±26°	2.3–3.4	681
QuickBird	Digital Globe	Oct. 2001	0.61	2.44	450–900	450–520	520–600	630–690	760–890	16.5	±30°	1–3.5	450
OrbView-3	Orbimage	June 2003	1.0	4.0	450–900	450–520	520–600	625–695	760–900	8	±45°	1.5–3	470

of winds and waves, protecting lives and minimizing economic impact.

During Landfall

All remote sensing systems, such as GOES and NOAA/AVHRR, used to track the hurricane over open water can also be used to observe the storm's landfall. However, during landfall, the emergency response teams need to know not only the predicted storm surge, wave height, and wind velocity, but also the actual flooding taking place. This requires high-resolution data obtained at frequent intervals with sensors that can penetrate the clouds and rain. Radar systems, such as SAR, qualify for this task because radar energy penetrates clouds and can detect flooding, even under tree canopies (Ramsey, 1995). Airborne and satellite radar systems can have resolutions from several to hundreds of meters depending on altitude. As soon as the hurricane clouds pass, high-resolution visible and near-infrared imagers on aircraft and satellites can be used to monitor flood conditions and other damage. Near-infrared spectral bands are particularly effective for discriminating inundated urban or natural areas from dry ones. Although urban areas require high-resolution data, such as the 0.6–4-m resolution provided by the satellites in Table 3, many of the surrounding natural inundated areas, such as wetlands, are more efficiently monitored with medium-resolution satellite systems, such as the Landsat Thematic Mapper (TM) or SPOT, at 10–30-m resolution.

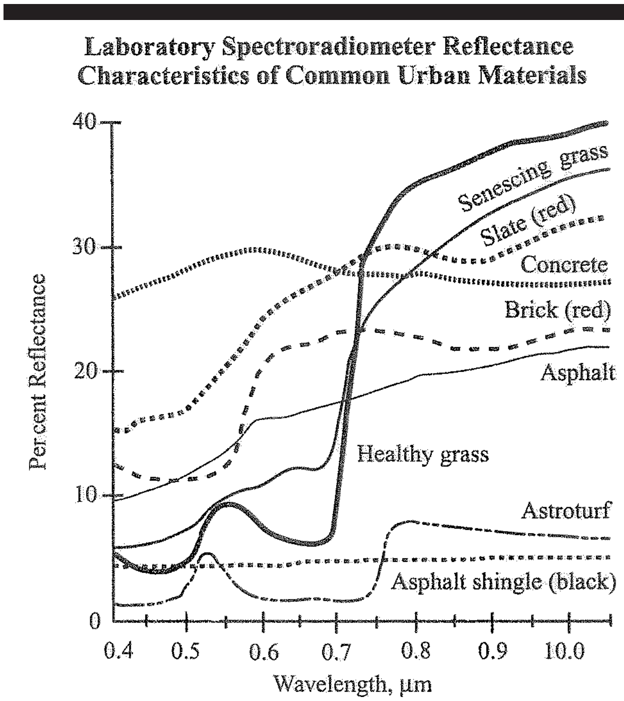

Figure 1. Laboratory spectroradiometer characteristics of common urban materials (Jensen, 2007).

After Landfall

After the storm has passed, there is a need to rescue remaining victims, survey the damage, and plan urban reconstruction projects and improvements in man-made and natural protective systems, such as levees and adjacent wetlands. This includes assessing the flood and wind damage to private, public, and commercial structures; removing debris; and replenishing sand on eroded beaches. Remote sensing data is being used to map urban and coastline changes caused by storm surges, flooding and winds. Usually, the new imagery is compared with historical aerial and satellite images and maps to pinpoint the destroyed urban structures, damaged roads and bridges, eroded beaches, wetland losses, and debris-covered areas (Jensen, 2007; Lunetta and Elvidge, 1998).

Remote Sensing of Storm Damage

When extracting urban/suburban information from remotely sensed data, it is usually more important to have high spatial resolution (1–5 m) than a large number of spectral bands. Like all cities, coastal urban areas require time series of high–spatial resolution imagery for mapping changes in individual structures or entire city blocks. Urban landscapes contain diverse assemblages of materials and shapes (*e.g.,* asphalt, concrete, metal, plastic, shingles, glass, water, grass, soil, *etc.*). Nonetheless, if the spatial resolution of the sensor is fine enough to obtain fairly pure pixels of each urban target, and thus minimize the number of mixed pixels, Figure 1 suggests that the spectra are different enough to allow spectral discrimination between most urban materials. Spatial resolutions of about 5–20 m would enable one to map urban features down to the Anderson USGS Land Cover Classification Level II (Anderson *et al.,* 1976; Jensen, 2007). Level III land cover is best obtained using high-resolution aircraft sensors or high-resolution (0.5–4 m) satellite imagers shown in Table 3 (Al-Tahir *et al.,* 2006; Campbell, 2007). Classification accuracy can be improved if photo-interpreters are

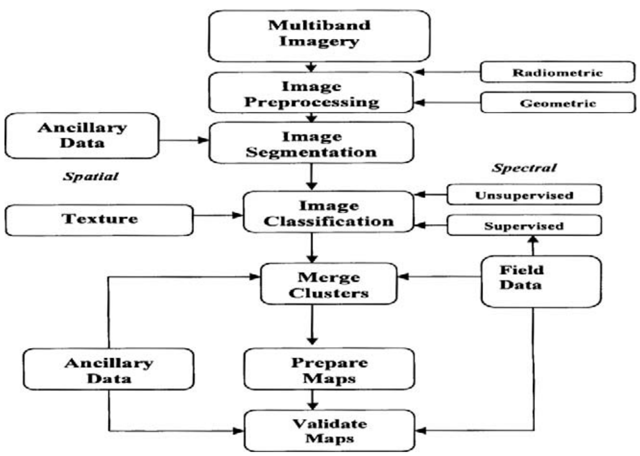

Figure 2. Typical image analysis approach.

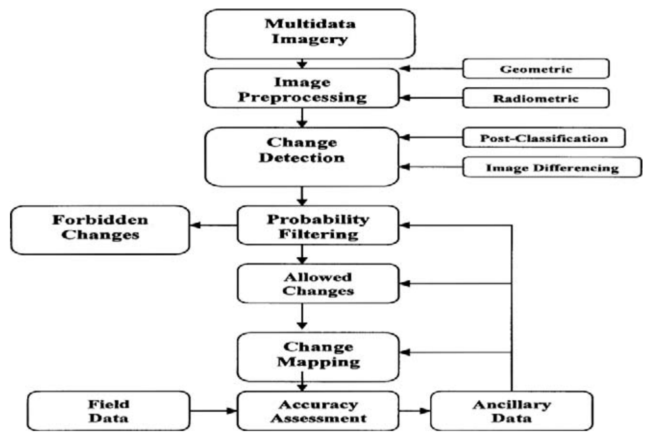

Figure 3. Change detection with the use of probabilities.

used to add spatial and contextual information to the image analysis process.

Tidal marshes respond quickly to the subtle effects of even small changes in sea level. Many coastal wetlands can cope with gradual sea level rise if they are not confined by man-made structures. However, hurricanes can devastate salt marshes and mangroves. Furthermore, inland systems are susceptible to saline incursions during storms. For instance, elevated soil salinity levels lingered for months after Hurricane Hugo hit South Carolina. This had adverse effects on upstream wetland and tree survival, as well as on nutrient cycling processes (Blood *et al.,* 1991). The status of wetlands adjoining coastal urban communities and other natural land cover can usually be mapped at medium resolutions of 10–30 m, as provided by Landsat TM or SPOT (Klemas, 2005; Lyon and McCarthy, 1995). Salinity can be obtained with airborne microwave radiometers.

The postlandfall images can be interpreted visually, similarly to aerial photograph interpretation. The main advantage of this approach is that the interpreter can use his knowledge of the coastal area to decipher complexities in the urban landscape that would be impossible for a computer to interpret. The human brain is able to combine and simultaneously interpret various image characteristics, including tone, texture, shape, size, shadow height, and spatial relationships. With the use of stereoscopes, the interpreter can also observe vertical as well as horizontal spatial relationships of the features in the image.

Nowadays, computer-aided analysis is used primarily for image classification. A typical digital image analysis approach for classifying coastal wetlands or land cover is shown in Figure 2. Before analysis, the multispectral imagery must be radiometrically and geometrically corrected. The radiometric correction reduces the influence of haze and other atmospheric scattering particles and any sensor anomalies. The geometric correction compensates for the Earth's rotation and for variations in the position and attitude of the satellite. Image segmentation simplifies the analysis by first dividing the image into ecologically or functionally distinct areas. Then training sites are identified for supervised classification and interpreted via field visits or other reference data, such as aerial photographs. Next, an unsupervised classification is performed to identify variations in the image not contained in the training sites. Training site spectral clusters and unsupervised spectral classes are then analyzed by cluster analysis to develop an optimum set of spectral signatures. Final image classification is then performed to match the classified themes with the project requirements (Jensen, 1996; Klemas, 2005; Lachowski *et al.,* 1995; Lillesand and Kiefer, 1994).

Land Cover Change Detection

Digital change detection of land cover by the use of satellite imagery can be performed by employing one of several techniques, including postclassification comparison and temporal image differencing between two images in a time series (Jensen, 1996; Lunetta and Elvidge, 1998). Postclassification comparison change detection requires rectification and classification of the remotely sensed images from both dates. These two maps are then compared on a pixel-by-pixel basis. One disadvantage is that every error in the individual date classification map will also be present in the final change detection map.

Temporal image differencing minimizes this problem by performing the traditional classification of only one of the two time-separated images. One band from both dates of imagery is then analyzed to find differences. Pixel difference values exceeding a selected threshold are considered as changed. A change/no change binary mask is overlaid onto the second date image and only the pixels classified as having changed are classified in the second date imagery. This method usually reduces change detection errors and provides detailed from–to change class information (Jensen, 1996). As shown in Figure 3, change analysis results can be further improved by including probability filtering, allowing only certain changes and forbidding others (*e.g.,* urban to forest). In digital change detection, it is very important that the images in the time series be corrected for variations in atmospheric, tidal,

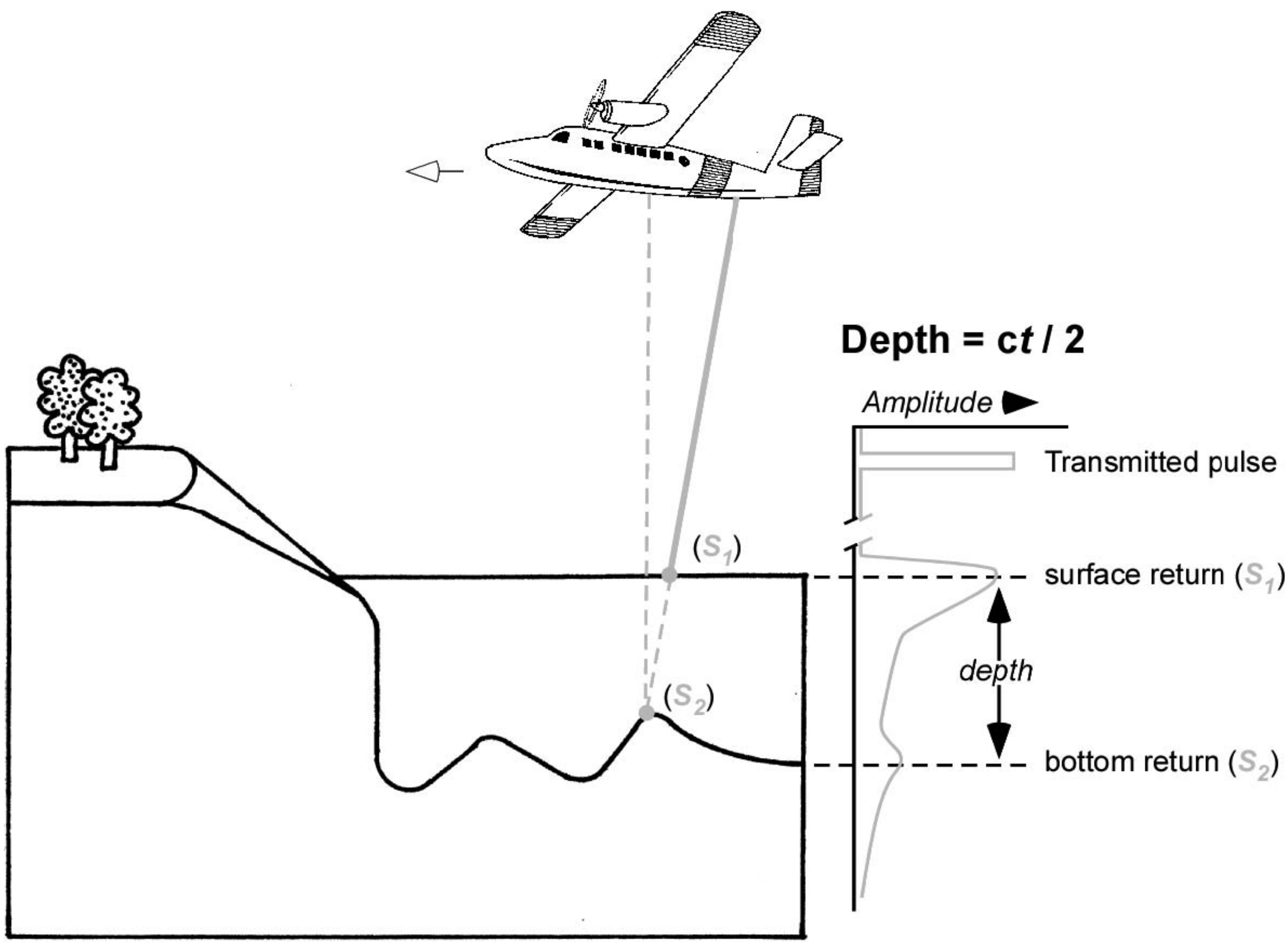

Figure 4. Principles of operation of a LIDAR bathymeter. The water depth can be calculated from the travel time difference (t) between the surface (S_1) and bottom (S_2) pulse returns.

seasonal, and other environmental conditions between the two image dates.

Synthetic aperture radar can also be useful because it can detect flooding even in areas with tall vegetation or buildings (Ramsey, 1995). Therefore, SAR and multispectral imagers, such as Landsat TM, are complementary in nature. Combining the SAR and Landsat TM imagery allows for the accurate depiction of flooding and urban destruction, including the identification of oil slicks and debris floating on water. Accurate maps showing the extent of flooding, oil slicks, and floating debris are vital for local and federal emergency managers to allocate resources to areas of greatest need and to aid urban and environmental planners in preparing for restoration (Rykhus, 2005).

Mapping Beach Erosion

To implement effective beach erosion control and coastal ecosystem protection strategies, coastal managers need information on long- and short-term changes taking place along the coast, including beach profiles, changes from erosion, wetlands changes from inundation, and so on. Topographic and bathymetric data can now be rapidly and accurately acquired at various spatial scales by airborne laser surveying, which is a type of remote sensing generally known as light detection and ranging (LIDAR). A laser transmitter/receiver mounted on an aircraft transmits a laser pulse that travels to the air-water interface, where a portion of this energy reflects back to the receiver (Figure 4). The remaining energy propagates through the water column and reflects off the sea bottom. The water depth is calculated from the time lapse between the surface return and the bottom return.

LIDAR surveys can produce 10-cm vertical accuracy at spatial densities greater than one laser pulse return per square meter (Ackermann, 1999; Krabill *et al.,* 2000). Examples of LIDAR applications include the regional mapping of changes along sandy coasts from storms or long-term sedimentary processes and the analysis of shallow benthic environments (Gutierrez *et al.,* 1998; Sallenger *et al.,* 1999). More recently, Global Positioning Systems (GPS), combined with new LIDAR techniques, make it possible to obtain accurate topographic and

Table 4. *Typical LIDAR flight parameters.*

Parameter	Value
Flying height	200–500 m
Spatial resolution	2–4 m
Vertical accuracy	±30 cm
Maximum map depth	50 m (clear water)
Typical *kd*	4
Coastal *k*	0.2–0.8 (d = 5–20 m)
Estuarine *k*	1.0–4.0 (d = 1–4 m)
Sounding density	3–15 m
Sun angle	18°–25° (minimize glare)
Scan geometry	Circular
Sea state	Low (0–1 Beaufort scale)
Water penetration	Green LIDAR (532 nm)
Aircraft height	Infrared LIDAR (1064 nm)
Positional accuracy	Differential GPS (0.5–2 m)

bathymetric maps, including shoreline positions (Brock and Sallenger, 2000; Irish and Lillycrop, 1999; Krabill *et al.,* 2000; Stockdon *et al.,* 2002). A particularly effective approach for studying sand dynamics along coastlines includes the combined use of airborne hyperspectral data and airborne LIDAR data (Brock *et al.,* 2001; Deronde *et al.,* 2006).

Typical flight parameters for airborne LIDAR are shown in Table 4. Optical water clarity is the most limiting factor for LIDAR depth detection. Therefore, it is important to conduct LIDAR overflights during tidal and current conditions that minimize water turbidity from sediment resuspension and river inflow. The LIDAR system must have a *kd* factor large enough to accommodate the water depth and water turbidity at the study site (k = attenuation coefficient; d = water depth). For instance, if a given LIDAR system has a $kd = 4$ and the turbid water has an attenuation coefficient of $k = 1$, the system will not be effective beyond depths of approximately 4 m. Beyond that depth, one may have to use acoustic echo-sounding techniques or side-scanning sonar systems.

Mapping hurricane damage sustained by submerged aquatic vegetation (SAV) and coral reefs requires high-resolution (1–4 m) imagery (Mumby and Edwards, 2002; Purkis, 2005). Coral reef ecosystems usually exist in clear water and can be classified to show different forms of coral reef, dead coral, coral rubble, algal cover, and sand lagoons and different densities of seagrasses, for example. SAV may grow in more turbid waters; thus, it is more difficult to map. High-resolution (*e.g.,* IKONOS) multispectral imagers have been used in the past to map eelgrass and coral reefs. Hyperspectral imagers should improve the results significantly by being able to identify more estuarine and intertidal habitat classes (Garono *et al.,* 2004; Maeder *et al.,* 2002; Mishra et al., 2006).

CASE STUDY: HURRICANE KATRINA'S EFFECT ON NEW ORLEANS

On the morning of August 29, 2005, Hurricane Katrina made landfall near the Louisiana/Mississippi border as a strong Category 3 hurricane. Because the storm had reached Category 5 at sea, it brought with it the storm surge of a much stronger hurricane. With wind speeds of about 205 km/h, a storm surge of 7.4 m, and heavy rains, Katrina devastated coastal areas in the region. It caused major flooding and destruction along the Central Gulf states of the United States, including such cities as New Orleans, Louisiana; Mobile, Alabama; and Gulfport, Mississippi. The storm surge, high winds, and resulting high water on Lake Pontchartrain breached the levees protecting New Orleans, a city located below sea level, and flooded about 80% of the city and neighboring parishes. Katrina also caused major damage to the region's oil and natural gas production and refining facilities. As a result, Katrina became the costliest hurricane to make landfall in the United States (Hayes, 2005; Rykhus, 2005).

Remote sensing played a major role in tracking the storm and the devastation it left behind in urban New Orleans and surrounding areas, including highways, beaches, and wetlands. Remotely sensed data were provided by many federal, state, and local agencies and commercial firms from satellites, aircraft, and helicopters. In this section, I review the effect of Hurricane Katrina on New Orleans in 2005 and show how remotely sensed data was used to track the hurricane, predict its future behavior, and survey the destruction it caused (Stone and Muller, 2005).

Tracking Katrina before Landfall

Katrina originated as a tropical depression near the Bahamas on August 23, 2005, strengthened to a hurricane, and proceeded to make landfall on the southern tip of Florida. Passing across Florida, Katrina weakened to a tropical storm. However, the warm waters of the Gulf of Mexico allowed it to rapidly intensify to a Category 5 hurricane, with maximum sustained winds of 280 km/h and gusts of 346 km/h, generating 16.7-m waves. Subsequently, Katrina made landfall as a Category 3 hurricane near Buras, Louisiana, and once more near the Mississippi/Louisiana border with sustained winds of about 205 km/h.

At landfall, hurricane-force winds extended 190 km from the center (NOAA, 2005). During its entire passage across the Atlantic and the Gulf of Mexico, Katrina was tracked by the GOES-12 geostationary satellite, NOAA polar orbiters with AVHRR sensors, other satellites, and many aircraft flights by NOAA and U.S. Air Force pilots. For instance, NOAA WP-3D Hurricane Hunter aircraft obtained airborne Doppler radar–derived wind speed cross sections as Katrina crossed the Gulf and made landfall on the Louisiana coast on August 29, 2005. Other data gathered included the location of the hurricane, its size, its speed and direction of movement, the size of the eye, the wind velocity, and the minimum central pressure.

The NWS National Hurricane Center was able to feed the satellite data into several different numerical computer and statistical models to attempt to forecast the path, speed, and strength of the hurricane. The Center also used computer storm surge models, such as the SLOSH model, to provide guidance on storm surge height and the extent of predicted flooding. Days before Katrina made landfall, NOAA's storm surge model predicted that Katrina's surge could reach 5.5 to 6.7 m above normal tide levels, and in some locations, as high as 8.5 m. The model predictions were sent in near–real time to various disaster management agencies at the local, state, and federal levels. Emergency managers used the data from

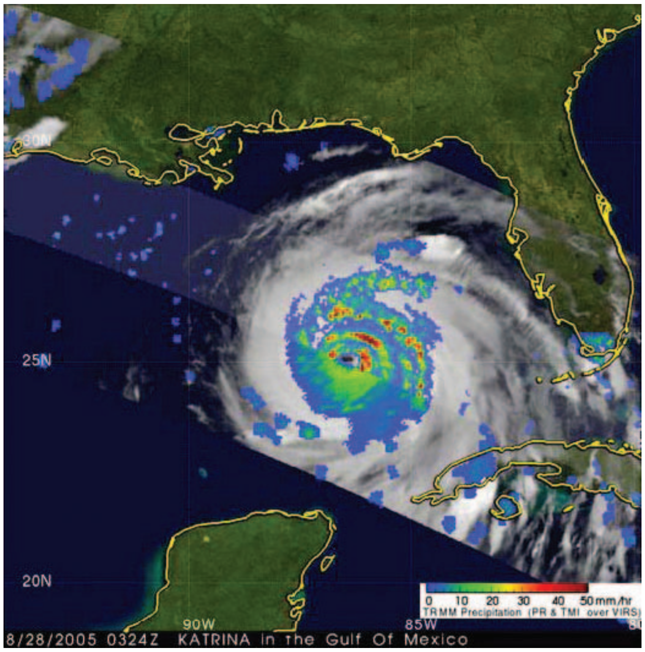

Figure 5. Hurricane Katrina in the Gulf of Mexico (TRMM precipitation over VIRS; NASA, 2005).

SLOSH to determine which areas must be evacuated (NOAA, 2005; NOAA/NHC, 2008).

Figure 5 shows a satellite image of Katrina as it passes over the Gulf of Mexico. The image was enhanced with the use of data from several sensors, including the Tropical Rainfall Measurement Mission (TRMM) satellite and its microwave imager (TMI). By measuring the microwave energy emitted by the Earth and its atmosphere, TMI is able to quantify the water vapor, cloud water, and rainfall intensity in the atmosphere. The image in Figure 5 was taken on August 28, 2005, when Katrina had sustained winds of 185 km/h and was about to become a Category 4 hurricane (Table 1) in the central Gulf of Mexico. The image reveals the horizontal distribution of rain intensity within the hurricane as obtained from TRMM sensors. Rain rates in the central portion of the swath are from the TRMM precipitation radar (PR). The PR is able to provide fine-resolution rainfall data and details on the storm's vertical structure. Rain rates in the outer swath are from the TMI. The rain rates were overlaid on infrared data from the TRMM visible infrared scanner (VIRS). TRMM reveals that Katrina had a closed eye surrounded by concentric rings of heavy rain (red areas) that were associated with outer rain bands. The intense rain near the core of the storm indicates where heat, known as latent heat, is being released into the storm (Pierce and Lang, 2005).

As the hurricane picked up strength passing over warm Gulf water, by August 26 many of the computer models had shifted the potential path of the hurricane 240 km westward from the Florida Panhandle, putting New Orleans right in the center of the predicted track. On August 28, the National Weather Service field office in New Orleans issued a bulletin predicting catastrophic damage to New Orleans and the surrounding region. Anticipated effects included destruction of most of the houses in the city, severe damage to industrial buildings, all windows blowing out in high-rise office buildings, and creation of a huge debris field of trees, telephone poles, cars, and collapsed buildings. This also raised the possibility of New Orleans facing an unprecedented storm surge that could go over the top of the levees protecting the city, causing major flooding, which would make the city uninhabitable for weeks (NOAA, 2008).

When the hurricane got close to land, it was also monitored by land-based weather radars. The NWS Doppler weather radars can provide detailed information on hurricane wind fields, their changes, precipitation, and so on. Thus, local NWS stations were able to provide accurate short-term warnings for flooding, high winds, and other weather hazards associated with the storm.

Observing Flooding and Urban Damage

In addition to wind damage, which reached inland as far as 240 km, Hurricane Katrina produced a massive storm surge of 7.3–8.5 m along the western Mississippi coast across a path of 32 km, tapering off to a height of about 6 m along the eastern Mississippi coast. Even though it weakened before landfall, several factors contributed to the extreme storm surge: (1) the massive size of the storm, (2) the strength of the system (Category 5) just before landfall, and (3) the shallow slope off the coast. Furthermore, Katrina's winds were a strong Category 3 at landfall, but because it had reached Category 5 at sea, it brought with it the storm surge of a much stronger hurricane. The surge caused the level of Lake Pontchartrain to rise, straining the levee system protecting New Orleans. Significant failures occurred in the levee system on August 30 and water poured into the city. Eventually 80% of the city was under water at depths up to 20 feet (6 m). The city was pumped dry only by September 20. However, the storm surge from Hurricane Rita on September 23 caused a new breach in a levee and many parts of the city were flooded again (Hayes, 2005; NOAA, 2005).

To map the flooding in New Orleans and its vicinity, a multi–data base approach was used. The map was created by incorporating SAR and other images acquired during the flood with a preflood Landsat enhanced TM image mosaic. The ability of SAR to penetrate clouds and vegetation cover made it quite useful for flood mapping. Also, SAR provided information on urban damage that complemented the spectral information from optical multispectral imagers, such as Landsat TM and other satellites. The Landsat TM and other remotely sensed images gave emergency managers and coastal engineers a clear view of inundated areas and helped plan pumping and other recovery efforts.

Sections of levees designed to channel canals through New Orleans crumbled under the battering waves and storm surge of the hurricane. The breaks allowed water to flow from Lake Pontchartrain into New Orleans, inundating the city. The actual levee breaks with water rushing into the city could clearly be seen in high-resolution satellite imagery, such as IKO-

Figure 6. QuickBird satellite images of New Orleans levee breaks (Digital Globe, 2005).

NOS and QuickBird (Table 3). On August 31, 2005, the QuickBird satellite captured images of two levee breaks, as shown in Figure 6. The top image shows the 240-m-long breach in the levee along the Industrial Canal in East New Orleans. Water is pouring through a break in the canal in the lower half of the image. The streets on the opposite side of the Industrial Canal are also flooded, because of similar breaches in canals to the west.

The lower image in Figure 6 shows the 145-m-long breach in the 17th Street Canal in West Orleans. Water is flooding the areas on the east side of the canal, but the west side remains dry. The enlarged version of this image also shows widespread debris scattered across dry areas. Satellites, aircraft, and helicopters also provided valuable imagery showing damaged bridges, highways, port facilities, oil rigs, and other coastal infrastructure (Digital Globe, 2005; NASA, 2005). To assess the hurricane damage to the levee system, the Army Corps of Engineers used topographic data obtained with a helicopter-mounted LIDAR sensor over the hurricane protection levee system in Louisiana. This information was very valuable for planning specific repairs and general reconstruction efforts.

As part of its update on New Orleans' levee system, the Army Corps of Engineers has unveiled a Google Earth map overlay system for public distribution, demonstrating the continuing flood risks on a block-by-block basis. The overlays offer residents the opportunity to visualize predicted flood levels at their homes for 152 different storm situations, ranging in severity from a 50-year storm to a 5000-year storm. The maps are based on the risk analysis of an Interagency Performance Evaluation Taskforce (IPET), and incorporate three factors: hazards (probability of various natural disturbances), protection system (performance of levees, floodgates and floodwalls), and consequences (loss of life and property). The resulting maps and figures illustrate the predicted results of the Corps' rebuilding and redesigning efforts: Many at-risk neighborhoods in New Orleans would still flood in the case of a severe storm, but many of the vulnerable areas within those neighborhoods have decreased in size, and compared with 2005, other parts of the city are less vulnerable with the Corps' additional protections (USACE-IPET, 2008).

Within weeks after Katrina's landfall, government agencies such as the Federal Emergency Management Administration (FEMA), NOAA, and the Army Corps of Engineers provided timely up-to-date coastal flood hazard information to local, regional, state, and federal officials to guide reconstruction in the portion of the Gulf coast most severely affected by the hurricane (FEMA, 2005). Much of the information was based on data obtained from airborne and satellite remote sensors. For instance, NOAA and FEMA produced maps of surge inundation, flood depth, road and port closures, power grid outages, and so on. Also, Gulf coast families were able to determine whether their homes were still standing by viewing NOAA aerial photographs online.

Mapping Wetland Losses and Regional Landscape Changes

Coastal wetlands are a highly productive and critical habitat for a number of plants, fish, shellfish, and other wildlife. Wetlands also provide flood protection, protection from storm and wave damage, water quality improvement through filtering of agricultural and industrial waste, and recharge of aquifers. After years of degradation from dredge and fill operations, impoundments, urban development, subsidence/erosion, toxic pollutants, eutrophication, and sea-level rise, wetlands are finally receiving public attention and protection (Morris *et al.,* 2002; Odum, 1993).

Louisiana has been loosing its wetlands for many years. The USGS reports that Louisiana lost 4925 km^2 of land between 1932 and 2000, with an average 88 km^2 of land lost every year (Farris, 2005). Natural and anthropogenic causes for wetland loss are many; however, the primary long-term reason that wetlands are shrinking is water use. Canals and levees prevent the regular floods along the Mississippi River that would normally carry sediment to the wetlands. Because the sediment is not replaced by regular floods, the daily ebb and flow of the ocean gradually eats away at the wetlands. Therefore, the Louisiana coast can ill afford the devastation caused in its wetlands by Hurricane Katrina.

Hurricane Katrina's strong winds, storm surges and heavy rainfall damaged many ecosystems along the Gulf coast. In southeastern Louisiana, Katrina transformed nearly 100 mi^2 ($\sim$260 km^2) of marsh into open water. Most of the loss east of the Mississippi River was attributed to the effects of Katrina's storm surge. Vegetation was ripped out and sand washed in, scouring and damaging mangrove roots and harming the animals that live there. Large influxes of eroded sediment reduced habitat for coastal birds, mammals, and invertebrate species. Barrier islands were submerged and eroded. Entire seagrass beds, which are critical to fish, sea turtles, and marine mammals, were uprooted and destroyed during the storm. Coral reef beds were scoured, torn, and flattened, causing population reductions in animals such as sea urchins, snails, and fish. Katrina inundated marshes and swamps with saltwater and polluted runoff from urban areas and oil refineries, affecting amphibians and reptiles because of their sensitivity to toxins and other pollutants. Large areas of wetlands were lost, some of them permanently (Barras, 2006; Provencher, 2007). The resulting wetland losses caused by Katrina were mapped by NASA, NOAA, and USGS scientists over large areas using medium-resolution satellite imagery and GIS. Time series of Landsat TM, MODIS (moderate-resolution imaging spectroradiometer), and other imagery were used not only to observe the immediate damage to wetlands, but also to monitor their recovery.

The satellite images demonstrated how coastal wetlands function to protect inland regions and coastal communities from storm surges unleashed by powerful hurricanes. The wetlands act as a sponge, soaking up water and diminishing the storm surge. If the wetlands had not been there, the storm surge could have penetrated much farther inland. By contrast, no wetlands existed to buffer New Orleans from Lake Pontchartrain; therefore, the storm forced lake water to burst through the levees that separated it from the city (NASA, 2005).

SUMMARY AND CONCLUSIONS

Storms and their effects on coastal communities can be monitored and mapped with the use of a wide range of remote sensors on satellites and aircraft. Hurricanes can be tracked at frequent intervals by aircraft and satellites equipped with thermal infrared, visible, and microwave sensors. As the storm approaches land, satellite and land-based weather radars can measure hurricane winds, ocean currents, waves, precipitation, and other key parameters. Flooding from the storm surge can be monitored with high-resolution (1–4 m) multispectral imagers and radar on aircraft and satellites. The high-resolution images clearly show detailed damage, such as levee breaches in New Orleans caused by Hurricane Katrina. Wetland losses and changes in the surrounding landscape are best mapped with medium-resolution (10–30 m) systems, such as Landsat TM or SPOT. Airborne LIDAR systems can provide accurate data on coastline changes resulting from beach erosion, including bathymetry and topography. New satellites with advanced sensors are being launched that will provide high–spatial resolution and hyperspectral imaging capabilities. Also, new image classification algorithms and improved hydrologic models are being developed. These new remote sensors and models will further improve our ability to track and predict storms and their impact on coastal communities.

During Hurricane Katrina, many types of remotely sensed data were provided by NOAA, NASA, and other agencies before, during, and after landfall to hurricane modelers, who issued warnings to emergency managers at the local, state, and federal levels. The path, strength, and speed of the hurricane were predicted quite accurately by the NOAA/NWS National Hurricane Center with the use of data from geostationary (GOES) and polar orbit (NOAA/AVHRR) satellites and airborne trackers. Despite the timely environmental data and urgent warnings, neither the officials nor the public reacted fast enough in a coordinated manner to prevent major loss of lives. Numerous studies had warned of this catastrophic scenario, and as it developed, many scientists watched with frustration. For weeks after landfall, boats and helicopters were used to rescue people and survey the damage, using remotely sensed images of flooding to guide the rescue operations. Thousands of employees from NOAA, NASA, the U.S. Coast Guard, and various other agencies were involved with Hurricane Katrina, performing urgent tasks such as forecasting the storm, rescuing victims, surveying and clearing waterways and roads, responding to oil and chemical spills, and testing fisheries (NOAA, 2005, 2006, 2008).

Katrina damaged 272 km of the 564-km hurricane protection system that surrounds New Orleans and was blamed for more than 1570 deaths in Louisiana alone. The actual damage from the winds and storm surge and the resulting flooding was assessed from maps and observations provided by digital imagers and film cameras on aircraft, helicopters, and satellites. Several teams, including one from the University of Mississippi, used GIS with a beta version of Google Earth preloaded on laptops to survey and map the destruction and flooding. Also, because the storm destroyed many of the structures, landmarks, and signs along the Mississippi coast, the only reliable method of navigation was to use GPS (NOAA, 2008; USACE-IPET, 2008).

Google Earth delivered a vivid three-dimensional model of the city and its surroundings, providing a high-performance visualization interface that runs on standard PCs and commodity servers (Yarbrough and Easson, 2005). The technology's ability to provide spatial information made it indispensable during the emergency response and recovery from Hurricane Katrina. In 2005, the Army Corps of Engineers unveiled a Google Earth map overlay for public distribution, demonstrating continuing flood risks on a block-by-block basis, giving inhabitants the opportunity to visualize predicted flood levels at their homes for various storm conditions (USACE-IPET, 2008).

According to the External Review Panel of the American Society of Civil Engineers (ASCE), the repair work that has taken place since Katrina struck has improved and strengthened the hurricane protection system and has reduced the risk relative to pre-Katrina conditions. However, the risk to human life, property, and quality of life is still quite high. Flooding could still cause massive devastation to property, communities, the economy, and people. In the panel's opinion, a 1-in-10 chance every 50 years of catastrophic flooding of the city and loss of property, life, and lifestyle is unacceptable as a design basis for an engineering system (ASCE-

ERP, 2008). Nonetheless, the lessons learned from Hurricane Katrina's impact on New Orleans will further improve our ability to remotely track coastal storms and document their effects on coastal communities. The analysis of Katrina's impact will help refine storm surge and wave prediction models as an effective tool for engineering design of coastal infrastructure, such as levees, and facilitate hurricane emergency management. The data will also help improve vulnerability analyses for evaluating flood risk, potential response costs, and wetland losses for different sea level rise scenarios and storm conditions.

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