Temporal Analysis of Floodwater Volumes in New Orleans After Hurricane Katrina

By Jodie Smith and James Rowland

Satellite images from multiple sensors and dates were analyzed to measure the extent of flooding caused by Hurricane Katrina in the New Orleans, La., area. The flood polygons were combined with a high-resolution digital elevation model to estimate water depths and volumes in designated areas. The multiple satellite acquisitions enabled monitoring of the floodwater volume and extent through time.

Introduction

Remotely sensed satellite imagery was used to measure the extent of flooding in New Orleans caused by Katrina and to estimate the volume of flood water in the days following the hurricane. In addition, the images provided valuable information to help address questions being asked by the affected public and emergency response personnel. It is difficult to assess the magnitude of such an event from the ground, and it is time consuming to piece together the big picture from many differing personal accounts. The big picture views of Earth provided by satellites are invaluable in their ability to provide quick and comprehensive overviews of a situation. The immediate concerns of the response personnel following the hurricane were the extent of flooding and the location of the affected populations Residents forced to leave their homes wanted to know how long it would be before they would be able to return. Initial estimates of the volume of water inundating the city varied widely (Fanselau, 2005b; Gesch, 2005) and indicated the need for estimates based on additional available information.

Analysis

Satellite images acquired after Katrina's landfall provided an overview of the extent of flooding and were used to delineate polygons of inundated areas in a geographic information system (GIS). These flood polygons were then combined with a high-resolution digital elevation model

(DEM) to estimate water depths and volumes in the affected areas. A critical step in estimating volume is the determination of the maximum elevation of the water, which can vary significantly in complex urban environments with artificial barriers, such as levees, that trap flood waters or otherwise hinder their flow. This analysis is based on the delineation of polygonal areas protected by levees, defined by the U.S. Army Corps of Engineers (USACE) as pumping cells (fig. 1). An individual volume analysis was carried out for each of the USACE cells because it was not immediately clear how each of the many levees in and around New Orleans had been breached or topped. In addition, different areas of the city had a different number of operational pumps, which would result in different rates of drainage.

Digital satellite imagery from multiple sensors (Landsat 5, Landsat 7, and SPOT (Satellite pour l'Observation de la Terre)) was processed and analyzed to delineate flood polygons. Flood polygons for August 30, 2005 (fig. 2*A*), and September 2, 2005 (fig. 2*B*), were provided by the Dartmouth Flood Observatory (Anderson, 2005). Flood polygons for September 7, 2005 (fig. 2*C*) and September 15, 2005 (fig. 2*D*) were created at the U.S. Geological Survey (USGS) Center

for Earth Resources Observation and Science (EROS) with image-processing algorithms that identified water pixels from the satellite images. To improve the accuracy of the flood-volume estimates, the flood polygons were adjusted to include structures that were within the larger flood polygons but had rooftops above the waterline. These pixels were reclassified as flooded by using GIS techniques.

A DEM with a spatial resolution of 32.8 ft (10 m) was derived from light detection and ranging (lidar) data that were collected in 2002. The lidar data have a vertical accuracy of 11.8–23.6 inches (30–60 cm) (Cunningham, 2004). To calculate flood-volume estimates, elevation values from the DEM were analyzed for the satellite-derived flood polygons. In addition, four polygonal cells were created to approximate the current water pumping cells defined by USACE (U.S. Army Corps of Engineers, 2005b), and water levels were evaluated for each of the pumping cells individually. The maximum water levels within the flood polygons were analyzed to identify a threshold for erroneous high-valued outlier pixels. High-resolution IKONOS (Space Imaging®, Thorton, Colo.) satellite imagery was available for each of the dates for which flood polygons were derived and was used
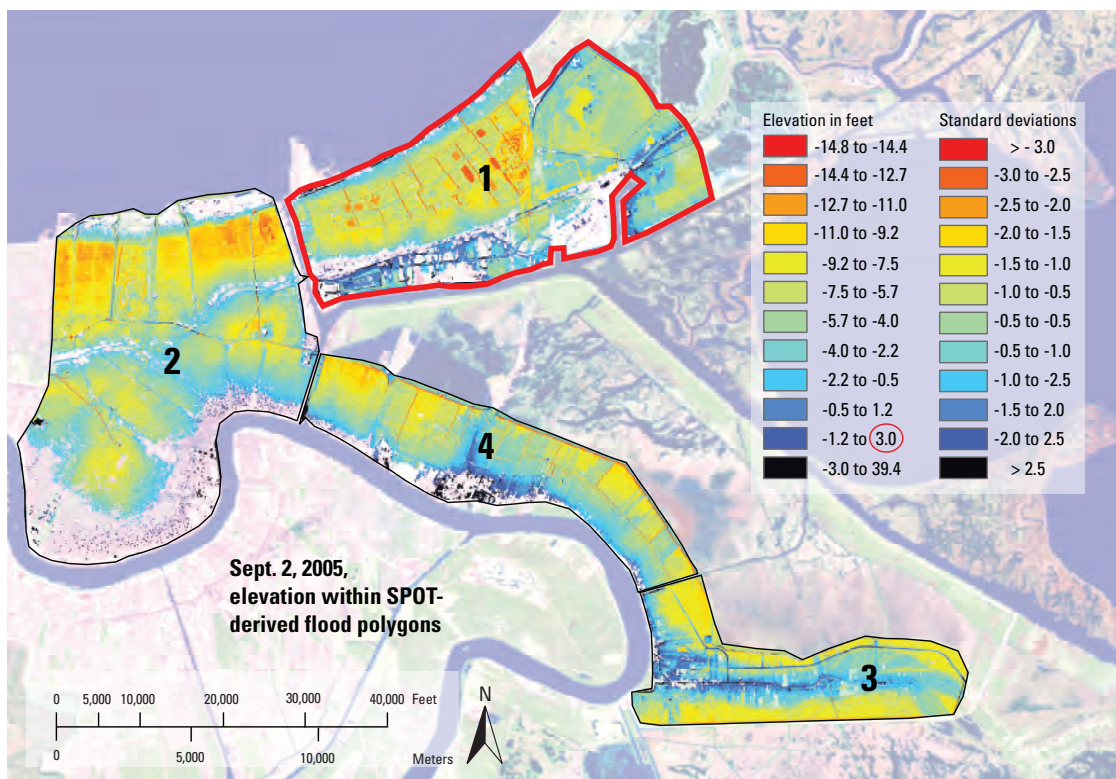
Figure 1.   Example of how the maximum water level was determined. The numbered polygons define approximate U.S. Army Corps of Engineers pumping cells. Each cell defines independent data sets of elevation values within the flooded areas, each classified by standard deviation. The equivalent classification values in feet are shown for cell 1 (with the red border). The red circle in the equivalent legend shows the position from which the maximum water elevation used for the volume calculation was selected: 3 feet for cell 1; other cells will have different values here.
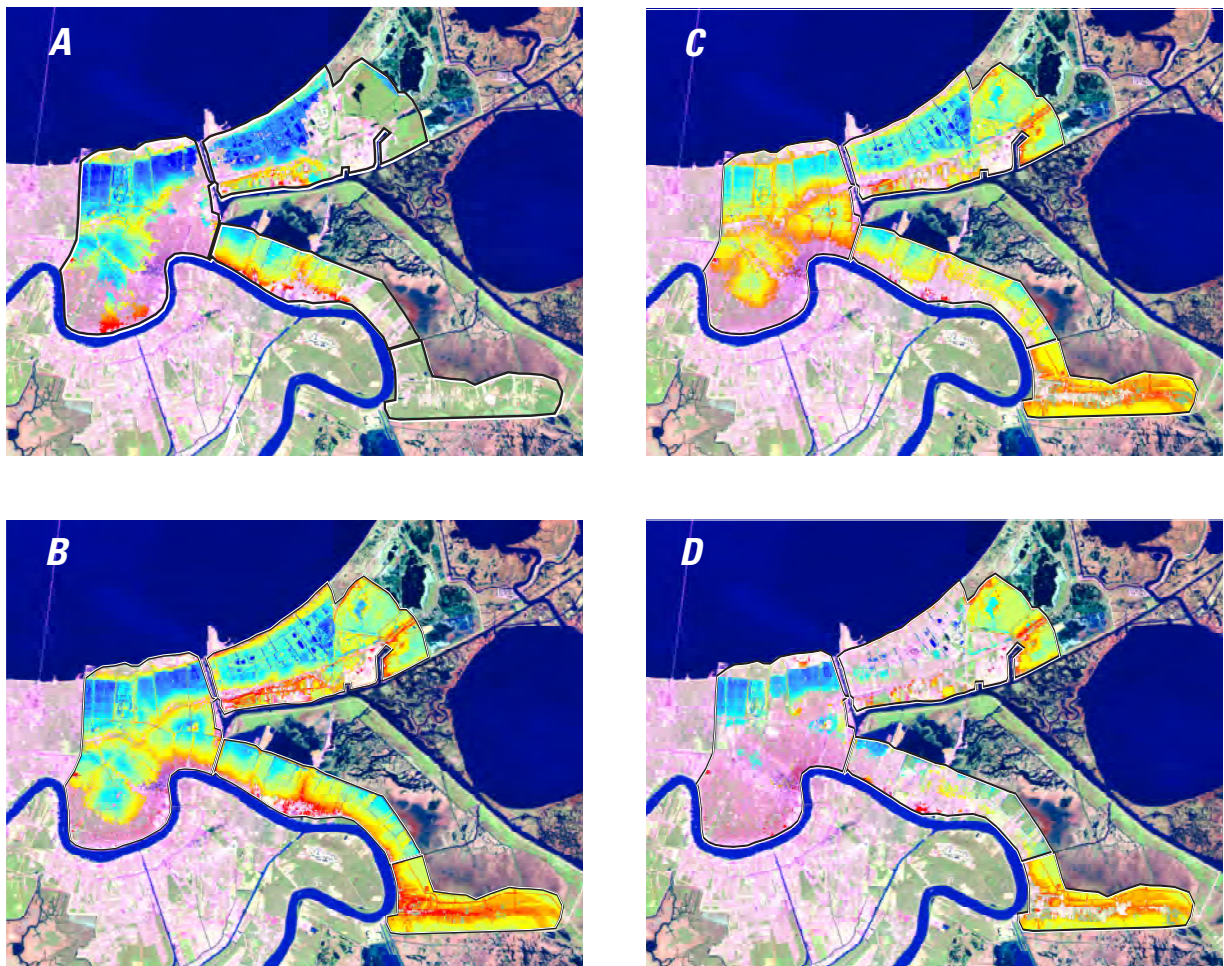
Estimated water depth based on flood polygons created from Landsat 7 image on Aug. 30, 2005 (background image: 2004 Landsat 7 mosaic)

☐ Approximate USACE pumping cells

Depth in feet

🟥	0 to 1.6	🟩	9.8 to 11.5
🟧	1.6 to 3.3	🟦	11.5 to 13.1
🟧	3.3 to 4.9	🟦	13.1 to 14.8
🟨	4.9 to 6.6	🟦	14.8 to 16.4
🟨	6.6 to 8.2	🟦	>16.4
🟩	8.2 to 9.8		

Figure 2. Water-depth maps used for calculating water volume per cell: (*A*) August 30, 2005; (*B*) September 2, 2005; (*C*) September 7, 2005; and (*D*) September 15, 2005. Polygons (cells) portrayed on the maps approximate U.S. Army Corps of Engineers water-pumping units.

to spot check the margins of the flood polygons to assess the error in the flood extent. Pixels within the flood polygons with elevation values greater than 2.5 standard deviations above the mean were judged to be erroneous values because these pixels did not appear to be flooded in the IKONOS imagery. Adopting this standard resulted in better agreement in water delineation between the flood polygons and the IKONOS imagery. Including the outlier pixels would have caused overestimation of both flood depth and flood volume. The elevation value just below the 2.5 standard deviation cutoff was used as the maximum water level within each USACE cell. This method was independently applied to each of the four cells on each of the four dates.

For each of the USACE cells defined on the flood maps, the inundation depth for each pixel within the flood polygons was calculated by determining the difference between the elevation value (from the DEM) and the maximum water level determined in the previous step (fig. 1). Water volume for each pixel was then calculated by multiplying the depth by the pixel area. Pixel volumes were summed up within each USACE cell to obtain the total water volume within each of the four cells. The resulting volume estimates for each of the cells on each of the four dates are summarized in table 1.

Results

The satellite images show that floodwater extent increased during the first few days after Katrina's landfall (fig. 2). According to the available imagery (August 30; September 2, 7, and 15) the date of maximum inundation in the city occurred around September 2, but satellite imagery was available only for selected dates, so the exact date of maximum flooding and, consequently, the maximum volume of water cannot be determined precisely. Nevertheless, this analysis provides an estimated volume of approximately 131 billion gal (495,888,946 m^3) of water for September 2, 2005. After this date, the volume of water in the city appeared to decrease (fig. 3), and as more pumps became operational,

the rate of decrease accelerated (Fanselau, 2005a; U.S. Army Corps of Engineers, 2005a).

This application demonstrates the utility of mid-resolution satellite data, in conjunction with high-resolution DEMs, for the measurement of flood area and volume for emergency response activities. A topographic analysis based on an early assumption that the flood waters had equalized with the level of Lake Pontchartrain (Gesch, 2005) produced a volume estimate of approximately 80 billion gal (302,832,944 m^3) for the date of September 2. The USACE estimate for total volume of water pumped from New Orleans is 224 billion gal (847,932,243 m^3) (U.S. Army Corps of Engineers, 2005b). This time series analysis of satellite-derived flood polygons produced an estimate of approximately 131 billion gal (495,888,946 m^3) for September 2. Estimates varied greatly depending on the methods and assumptions used; however, satellite data provide a basis for verifiable and repeatable analyses and demonstrate the need to obtain such data in a timely manner.

Conclusion

Urban environments have artificial and natural barriers to the flow of water that complicate the calculation of volume estimates. It should be emphasized that this analysis assumed that the USACE pumping cells represented homogeneous areas with respect to water levels and drainage rates. Close examination of the depth maps (fig. 2) reveals that there may have been other barriers which were not taken into account by this analysis. Development of barrier-detection methods may be an area of future research to improve this type of emergency response.

These results have not been verified or validated with ground-based information and are subject to revision. It is important to note that this analysis was completed on four snapshots in time and it is likely that it may not have captured the maximum inundation volume caused by Katrina. As stated above, the maximum volume derived from this analysis is significantly less than the volume published by the USACE (U.S. Army Corps of Engineers, 2005b). Determination of why there is such a large difference between the two estimates would require an analysis of the methods and assumptions used by USACE to derive their estimate, and that information was not available at the time of this analysis. Nevertheless, the temporal history of Katrina flooding constructed by this study could be useful for reconstruction efforts, as well as for assessing the accuracy and effectiveness of emergency preparedness scenarios and response plans.

Table 1. Summary of approximated volumes for each U.S. Army Corps of Engineers pumping unit for each day of analysis (in gallons) during 2005.

[PC, pumping cell]

	Aug. 30	Sept. 2	Sept. 7	Sept. 15
PC 1	26,733,419,000	43,318,140,000	41,127,626,000	16,630,714,000
PC 2	44,932,760,000	52,012,307,000	32,184,081,000	20,646,631,000
PC 3	0	13,361,664,000	10,266,968,000	11,584,261,000
PC 4	13,364,200,000	22,073,107,000	15,351,355,000	7,325,834,000
Total	85,030,379,000	130,765,218,000	98,930,030,000	56,187,440,000
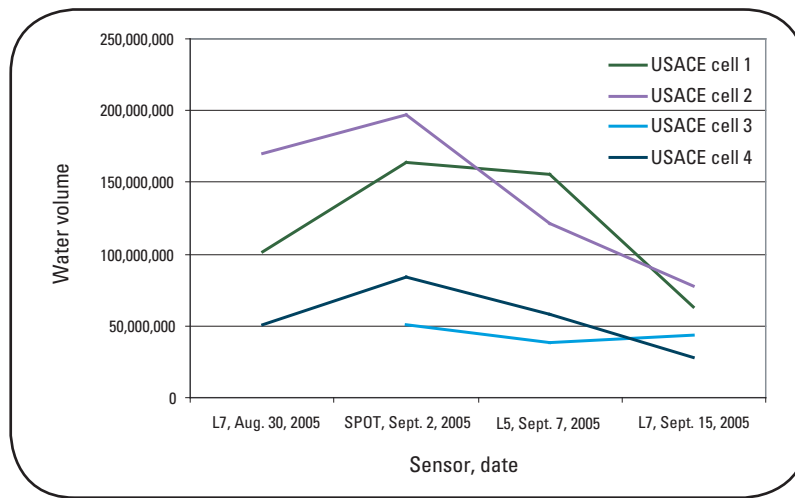
Figure 3. Water volumes by cell for individual dates (in billion gallons). The U.S. Army Corps of Engineers (USACE) cells referenced in the chart are identified in figure 1.

Acknowledgments

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