The Hurricane–Flood–Landslide Continuum

BY ANDREW J. NEGRI, NINA BURKARDT, JOSEPH H. GOLDEN, JEFFREY B. HALVERSON, GEORGE J. HUFFMAN, MATTHEW C. LARSEN, JOHN A. MCGINLEY, RANDALL G. UPDIKE, JAMES P. VERDIN, AND GERALD F. WIECZOREK

The global losses of life and property from the floods, landslides, and debris flows caused by tropical storms are staggering. One key to reducing these losses, both in the United States and internationally, is to improve forecasts of pending events in a time frame of several hours to days before the event.

In some instances, the loss of life and property is the direct result of high winds and heavy rains. However, 82% of tropical cyclone deaths are due to flooding (Fig. 1), most of which occur well inland. For example, in 1998, Hurricane Mitch deluged parts of Guatemala, Honduras, El Salvador, and Nicaragua with rain, triggering intense floods and thousands of landslides that killed 11,000 people. In northwestern Nicaragua, at least 2000 people from a single village were buried alive by a massive lahar (debris flow). Although the National Oceanic and Atmospheric Administration (NOAA) released warnings for dangerously heavy rainfall during Mitch, much of this information either never reached local municipal officials in Central America, was misunderstood, or was not acted upon. In addition, the countries impacted most by the storm have only modest national weather services. We believe that if people had been better informed and prepared, substantially fewer would have died.

In August 2004, representatives from a number of organizations—NOAA, the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey (USGS)—along with other government agencies and academic institutions[1] convened in San Juan, Puerto Rico, at a workshop to discuss a proposed research project called the Hurricane–Flood–Landslide Continuum (HFLC). The purpose of the HFLC is to develop and integrate the multidisciplinary tools needed to issue regional guidance products for floods and landslides associated with major tropical rain systems with sufficient lead time that local emergency managers can notify vulnerable populations and protect infrastructure. All three lead agencies are independently developing precipitation–flood–debris flow forecasting technologies, and all have a history of work on natural haz-

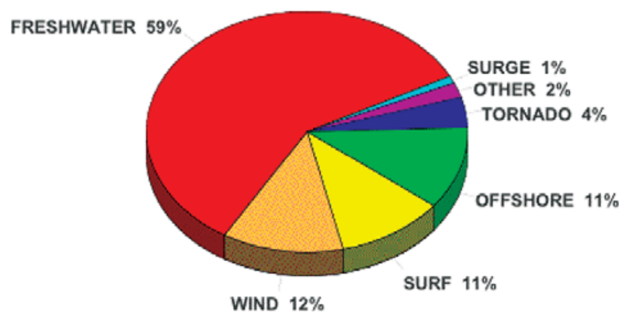

FIG. 1. Causes of U.S. tropical cyclone deaths, 1970–99, from Rappaport, NOAA/NWS Tropical Prediction Center.

AFFILIATIONS: NEGRI—Laboratory for Atmospheres, NASA/GSFC, Greenbelt, Maryland; BURKARDT—Policy Analysis and Science Assistance Program, U.S. Geological Survey, Fort Collins, Colorado; GOLDEN AND MCGINLEY—Forecast Systems Laboratory, NOAA, Boulder, Colorado; HALVERSON—Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Catonsville, Maryland, and NASA/GSFC, Greenbelt, Maryland; HUFFMAN—Science Systems and Applications, Inc. and NASA/GSFC, Greenbelt, Maryland; LARSEN—Office of the Chief Scientist for Hydrology, U.S. Geological Survey, Reston, Virginia; UPDIKE—U.S. Geological Survey, Denver, Colorado; VERDIN—EROS Data Center, U.S. Geological Survey, Sioux Falls, South Dakota; WIECZOREK—U.S. Geological Survey, Menlo Park, California
CORRESPONDING AUTHOR: Andrew J. Negri, Laboratory for Atmospheres, NASA/GSFC, Bldg. 33, Room C408, Code 613.1, Greenbelt, MD 20771
E-mail: andrew.j.negri@nasa.gov
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[1] These agencies and institutions were the U.S. Army Corps of Engineers, U.S. Agency for International Development/Office of Foreign Disaster Assistance, Organization of American States, and University of Puerto Rico.

ards both domestically and overseas. The workshop sought to initiate discussion among the three agencies about their highly complementary capabilities, and to establish a framework to leverage the strengths of each agency. Once a prototype system is developed, it could be adapted for use in regions—such as Central America or the Caribbean—that have a high frequency of tropical disturbances.

AN END-TO-END PREDICTION SYSTEM FOR HEAVY RAINFALL, FLOODING, AND LANDSLIDES. We hope to integrate and apply a wide range of scientific disciplines to evaluate a continuum of hazards from the tropical disturbance at sea to the floods and landslides that ultimately result in loss of property and life; that is, to issue products that improve the forecasts of tropical cyclone effects at landfall as much as 48 h in advance. We envision an initial 3-yr project that will develop and implement a warning system for a prototype region in the Caribbean, specifically the islands of Puerto Rico and Hispaniola. The system will include satellite (and other real-time) observations, atmospheric and hydrological models, landslide models, and a coastal-surge model. The resulting products (see concept in Fig. 2) would be for use by nontechnical people. The HFLC would also require systems that evaluate threats to people, infrastructure, and economic systems, and an interactive hazard warning communication system, with fail-safe redundancy, that informs disaster managers at regional, national, and international levels.

NASA, NOAA, and USGS have already developed many of the relevant new tools and systems for this purpose, but these technologies need to be further integrated for practical use in emergency response and disaster mitigation. The HFLC initiative seeks to close the gap between the scientific state-of-the-art and the operational needs for reliable and timely information. A prototype study in Puerto Rico and Hispaniola, which have adequate data and a high hurricane frequency, makes it possible to demonstrate the relevance of such a system across a spectrum of technological and socioeconomic environments.

Assembling the end-to-end system will require interdisciplinary research and development to link data-assimilation systems and simulation models. For instance:

- Can state-of-the-art quantitative precipitation estimates and forecasting provide sufficient detail, accuracy, and timeliness to drive hydrological models of soil moisture and peak streamflows that are the basis of hazard early warnings?
- Can the new generation of mesoscale weather forecast models improve the lead time for hurricane warnings?
- What spatial and temporal scales of soil moisture and streamflow modeling are needed to support simulation and forecasting of ground failures and floods stemming from tropical storms?

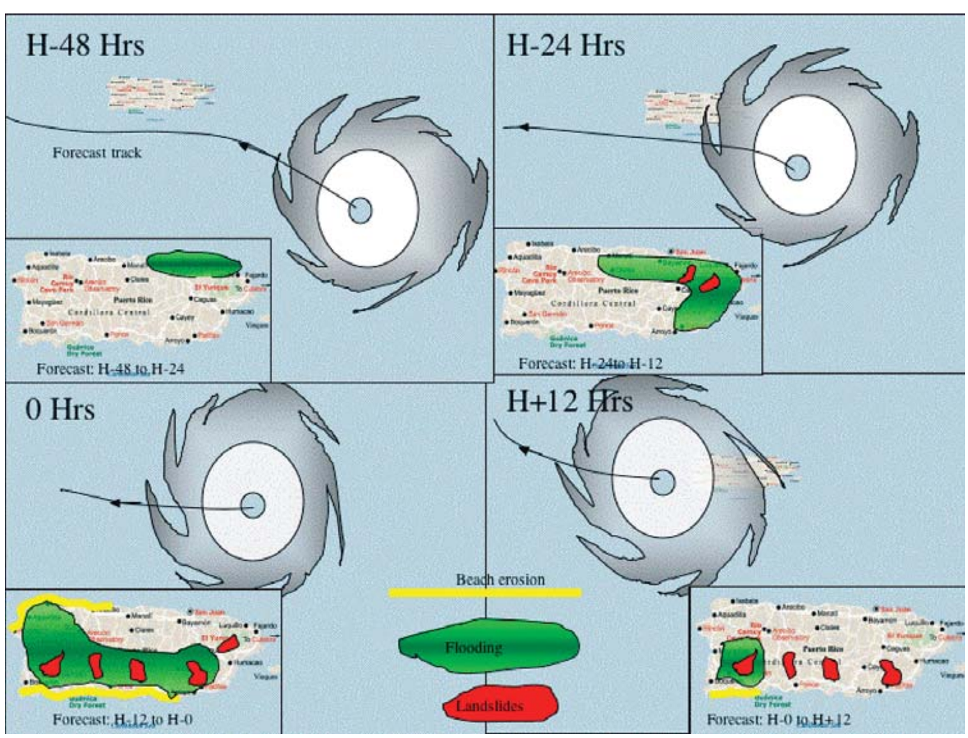

Fig. 2. A conceptual diagram of a potential forecast-guidance product for flooding, landslides, and beach erosion, from 48 h before to 12 h after the event.

- Does the current state of debris-flow and landslide models enable decisive action by disaster managers at the local, regional, national, and international levels?
- What are the scale and resolution requirements of debris-flow and landslide models with respect to topography, geology, soil type, soil moisture, and land-cover data?
- How can geographic information system (GIS) technology integrate data and model output across the HFLC and provide the core of a decision and information system?
- What are the key database design issues that need to be resolved in devising a common geospatial-layered framework to support all elements of the continuum?

In the following sections, we address the required technology and the challenges each of these questions poses.

PRECIPITATION ESTIMATION. Ground-based radar, such as those from the National Weather Service (NWS) Doppler radar operated in Cayey, Puerto Rico, is the tool of choice to estimate precipitation. However, few developing countries have access to such radar data. Furthermore, the horizontal extent of the radar's coverage makes hurricane monitoring problematic.

In most locations, satellite-based estimates offer the best (and only) coverage. Fortunately, passive microwave instruments such as the U.S. Defense Department Special Sensor Microwave Imager (SSM/I) and the NASA Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) provide physically based, instantaneous rain estimates over both land and water. Deficiencies in temporal sampling can be overcome with geosynchronous infrared (IR) data. We envision using microwave-calibrated IR estimates at 15- to 30-min intervals and horizontal resolutions as fine as 4 km. A merged IR/microwave product from NASA is already available (with a 4- to 6-h delay) at 3-h intervals and 0.25° resolution. Satellite estimates also offer the potential for forecasting or nowcasting precipitation based on recent (3-h) estimates (e.g., Fig. 3).

In general order of decreasing accuracy, precipitation data can be derived from rain gauges, weather radar, passive microwave satellite, passive infrared satellite, and satellite sounder. However, availability of data is in almost exactly the reverse order. Gauges, in particular, are almost never available at the density required for accurate finescale estimates. The state of the field requires that the HFLC system be able to assimilate multiple observation-based estimates at different time/space resolutions, and to accept upgraded estimation schemes as the state-of-the-art advances. Observation-based estimation errors typically increase for complex terrain, which unfortunately is where flash floods and landslides are prevalent. As a result, it is a major goal of the HFLC to determine the best combination of scales and estimates for driving the flood and landslide models. We anticipate that the HFLC will employ different data sources as we move from routine broadscale monitoring for new events down to focused nowcasts in individual drainage basins.

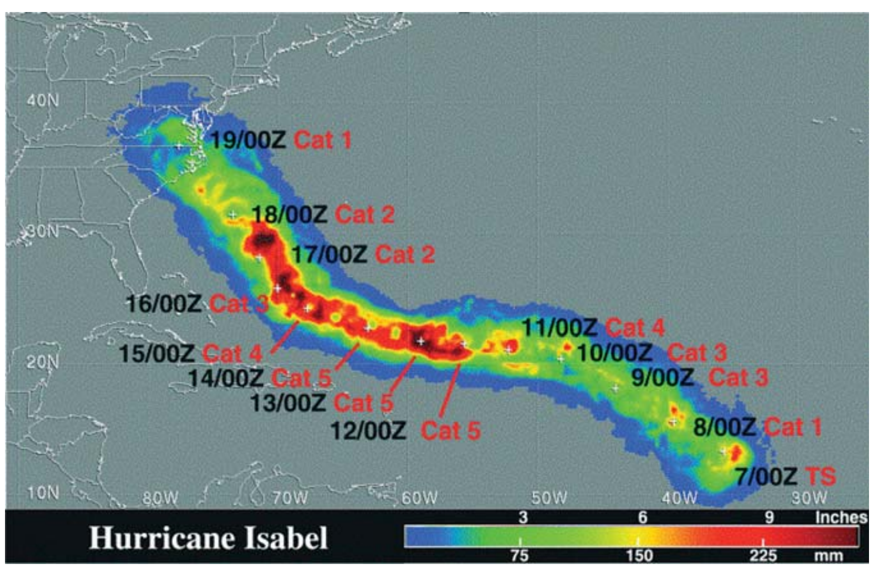

Fig. 3. Map showing real-time multisatellite precipitation analysis estimates of accumulated precipitation from Hurricane Isabel.

FORECAST MODELS. As tropical-cyclone track and intensity forecasts improve, we need to provide quality initial input parameters for the weather prediction models. The Local Analysis and Prediction System (LAPS) integrates data from virtually every meteorological observation system into a high-reso-

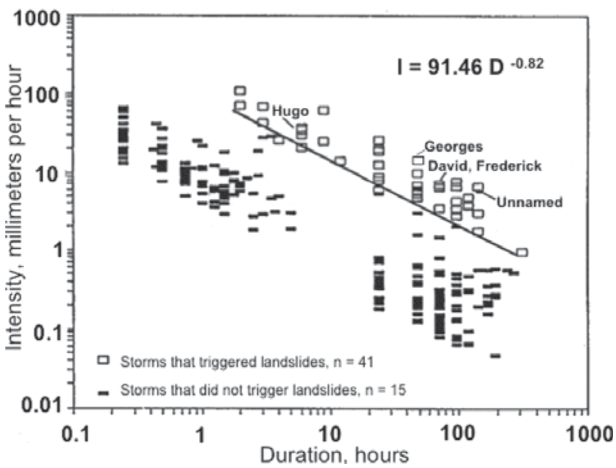

Fig. 4. Relation between average rainfall intensity (mm) and duration (h) for 256 storms in Puerto Rico from 1959 to 1991. The line represents the lower bound of an intensity–duration threshold for storm rainfall that triggered landslides, modified from Larsen and Simon (1993).

lution gridded framework. LAPS is a "go-anywhere" system that has been ported to many locations and hardware hosts and ensures spatial and temporal detail and consistency between current and previous observations. LAPS cloud and precipitation analysis currently utilizes radar, but will be upgraded to include satellite estimate techniques.

LAPS forecast skill is enhanced by initializing the modeling components with the diagnosed clouds and precipitation (see Jian et al. 2003). LAPS output includes precipitation at high temporal resolution that matches the input requirements of the hydrological and landslide models, including frequent data updates such as radar at 6-min intervals. In addition, we can leverage existing work in the area of transportation weather to explore the utility of mesoscale ensemble prediction in the system.

HYDROLOGIC MODELS. USGS and NOAA scientists use a variety of sophisticated operational hydrologic models for flood prediction, which could be adapted for use in data-poor settings, such as the island of Hispaniola. Hydrologic models will take the model- or satellite-estimated precipitation to create maps of flooding, a process now underway in the USGS Mekong River Project.

Estimating the areal distribution of precipitation is a long-standing problem in hydrology. Gauge observations are thought to accurately represent rainfall only at the gauge itself. The hydrometeorological network in the United States has one gauge per 700 km^2. However, the USGS rainfall stations on Puerto Rico have a much higher density of one station per 67 km^2 (see **http://pr.water.usgs.gov**), which greatly improves our ability to calibrate and test models.

Remote-sensing data will increasingly complement the spatial interpolation of precipitation station data. Station data, microwave imagery from polar-orbiting satellites, and geostationary IR data can be blended to produce estimates of 24-h precipitation accumulations as described in the previous section.

LANDSLIDE MODELS. When combined with physical data about hill slopes, prior landslide events can help indicate the susceptibility of similar areas to future landslides. One goal of the HFLC is to develop and implement a system for forecasting landslides on a regional scale with a resolution that is consistent with the hurricane- and flood-forecast components and the quality of topographic and geologic data. In addition to a model to identify where landslides are likely to occur, the HFLC needs a model to define the minimum rainfall required to trigger landslides in different places. Empirical models and rainfall thresholds for Puerto Rico and Central America may be suitable for these forecasting needs (e.g., that of Larsen and Simon in their 1993 *Geografiska Annaler* article).

The current generation of landslide and debris-flow models is probabilistic because the scale of the phenomenon is small compared to the resolution of the currently available rainfall estimates. Nonetheless, simple solutions, such as the intensity-versus-duration plots, offer discrimination of landslide versus non-landslide rainfall conditions for Puerto Rico (Fig. 4). We plan to test improved models by adding slope and elevations from Digital Elevation Model (DEM) data (Fig. 5), with the goal of improving the spatial scale of the estimates. We also expect to use NASA Shuttle Radar Topography Mission (SRTM) or other altimetry data. Combining this information with frequently updated rainfall amounts and forecasts, the HFLC system will compare conditions to (predetermined) landslide susceptibility and graphically display high, medium, or low landslide probability for a specified number of hours into the future. The system could also alert authorities to impending landslide hazards.

A methodology refined in Puerto Rico can be applied to places like Haiti and the Dominican Republic, which have a similar topography, climate, and geology, as well as to mountainous areas of the continental United States.

THE ROLE OF GIS AND DELIVERY SYSTEMS.

GIS technologies are needed in the HFLC for database development, modeling, decision support, and products. GIS software, which is used to acquire, manipulate, store, and analyze data, is essential to the success of the HFLC project.

Most importantly, GIS provides a geospatial database that is essential for modeling, analysis, and display. For example, HFLC involves modeling based on the spatial distribution of near-real-time precipitation rates and winds, elevations and drainage, vegetation, and urbanization. Modeling precipitation, hydrology, and landslide susceptibility translates physical and geological processes into graphical outputs. GIS organizes the geospatial data for developing suitable models and for displaying the modeling results. As models are refined and as a decision-support system for forecasts becomes operational, GIS will continue to be an important support—if not operational—component.

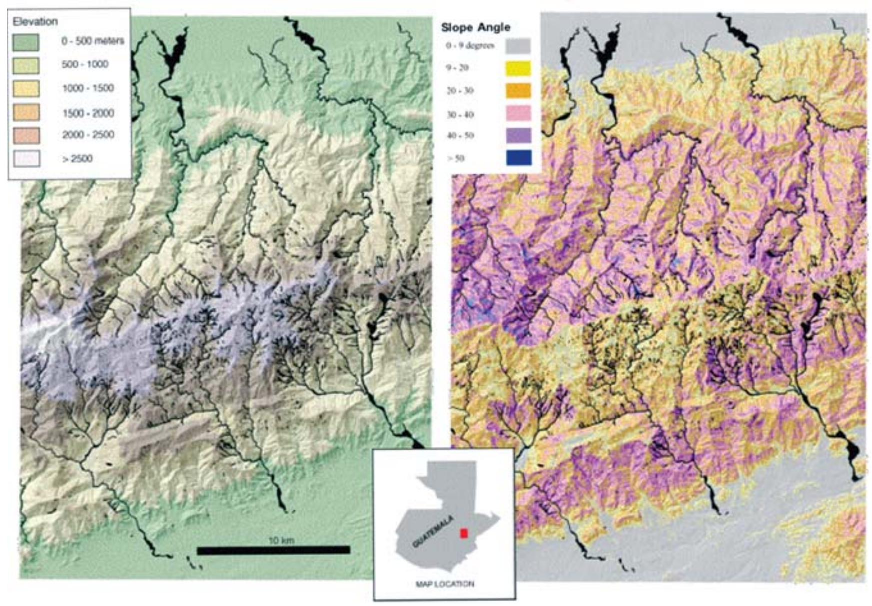

Fig. 5. DEM data of elevation and slope for potential use in a landslide model, from Coe et al. (2004).

OTHER ISSUES.

To ensure that products are targeted to the appropriate users, we need to assess how hazard communications move and decisions are made. In 2001, Comfort et al. stressed in the *Journal of Contingencies and Crisis Management* the importance of increasing local or regional capacity for communication and coordination. Researchers will interview representative disaster or hazard management entities in Puerto Rico, the Dominican Republic, and Haiti to analyze the disaster/hazard-management system, its formal and informal communications, and its constraints and information gaps. N. W. Chan has used a similar approach, as described in the journal *Disasters* in 1997.

The delivery of warnings will vary geographically because the willingness to accept technology and innovation varies. Our assessment will also query households, asking individuals about where they would seek information or assistance if confronted with a hazard and what kinds of assistance they would expect. Our research will then move up to higher levels of the community hierarchy, asking similar questions.

For HFLC, however, it is not the decisions that provide value, but the actions following those decisions. Ultimately, the output from our decision-support systems should be effective and easily interpreted by nontechnical people. An example might be the potential inundation map shown in Fig. 6.

SOCIAL VULNERABILITY.

Analyzing census data with GIS tools, we can identify specific areas where people are at risk for floods and landslides. Some factors further increase social vulnerability, such as limited access to political power and representation, lack of access to resources (including information and technology), lack of social capital (like social networks), and poor health. Beliefs and customs, and the age, type, and density of infrastructure, buildings, and lifelines are also factors that affect risk and potential losses. In the August 2003 *Natural Hazards Review,* Pielke et al. concluded (unfortunately) that the disaster from Mitch in Honduras and Nicaragua should have been expected to occur and may very well occur again soon. This is because of the extreme population increases in the region, coupled with many of the people living in areas vulnerable to disasters of flash flooding and mud slides.

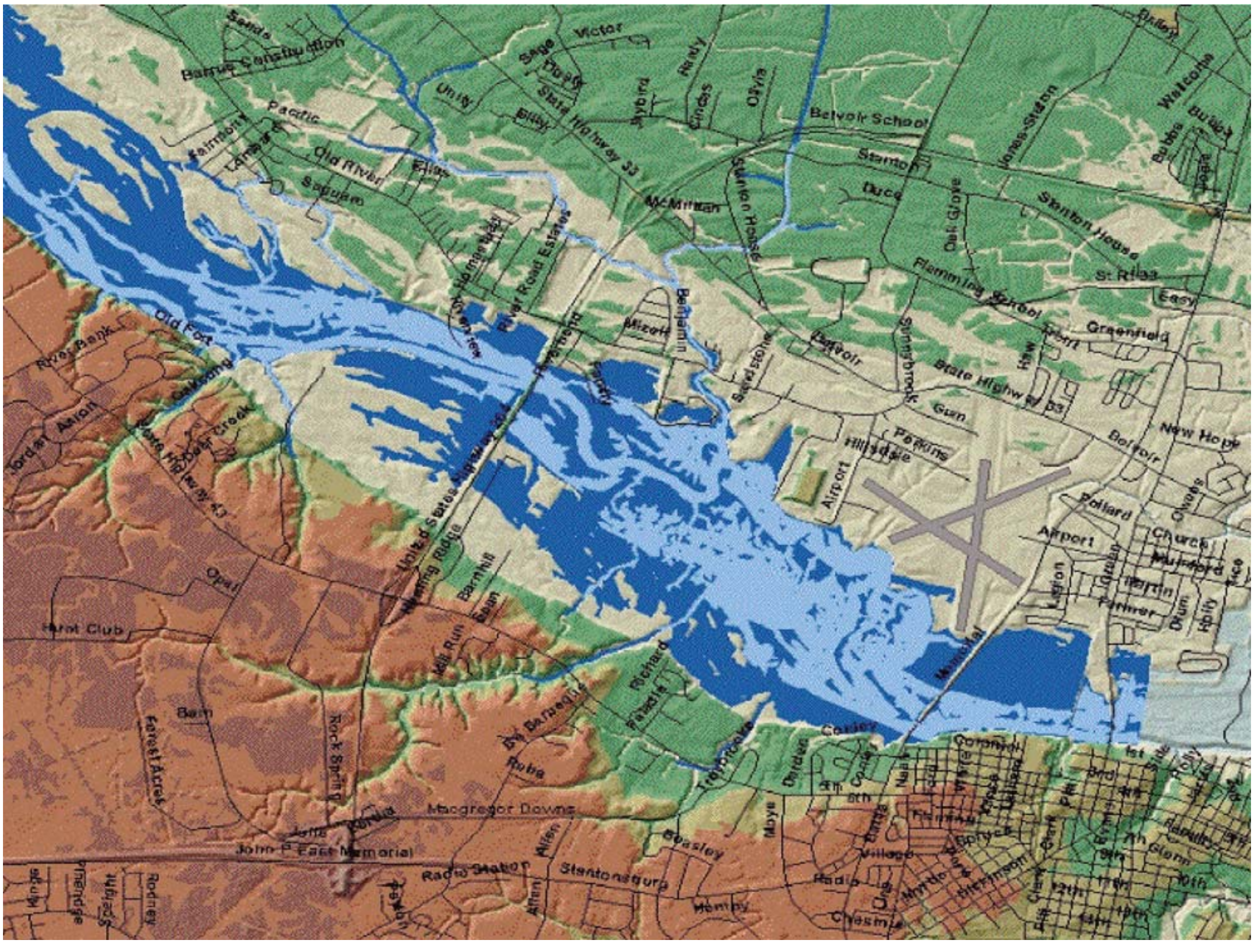

Fig. 6. Output from a flood model, superimposed on a street-level map (courtesy of NOAA/NWS Southeast River Forecast Center and NOAA Coastal Services Center).

SUMMARY. The global losses of life and property from the floods, landslides, and debris flows caused by tropical storms are substantial. One key to reducing these losses, both in the United States and internationally, is better forecast capability, particularly in developing nations. Warnings of even a few hours or days can mitigate or greatly reduce catastrophic losses of life.

We describe an initial 3-yr project to develop and transfer a warning system to a prototype region in the central Caribbean. This would capitalize on improvements over the past decade in surface and satellite data coverage over these islands as well as on TRMM satellite coverage, better knowledge of island geomorphology, and new models that couple rain intensity and duration with landslide occurrence in the region. The current revolution in dissemination systems and communications will permit us to develop and deliver tailored graphical products in a timely fashion to local weather offices and emergency management officials in the affected islands.

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