Modeling the Impact of a Patient Surge

Simulating the effects of flooding on health care facilities

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Los Alamos National Laboratory (LANL) has developed new GIS-based tools to qualify and quantify the risk and impact of flooding on the health care sector.

LANL's Energy and Infrastructure Analysis group is often called upon to respond to events that threaten critical infrastructure. The group is asked to return its analyses quickly. Depending on the event, *quickly* can range from days to hours.

For example, in 2008, the LANL Fast-Response Team provided more than 80 analysis products to evaluate the impacts of flooding in the Midwest and due to Hurricanes Gustav, Ike, and Holly. The water and dam infrastructure sectors are of special importance, because water is not only fundamental to human health but is required for electricity generation, waste conveyance, industrial applications, and irrigation. LANL energy and infrastructure researchers can model water distribution and waste collection, hurricane infrastructure impacts, dam failure and flooding, and other phenomena when evaluating water-related critical infrastructure.

The health care and public health sector can also be impacted by water availability, dam failures, and the effects of water-related weather events such as hurricanes and flooding. To further refine the interdependent relationships between these two sectors, the Energy and Infrastructure Analysis group has developed new tools to estimate risk and measure the impact of flooding on health care facilities.

GIS is an integral part of these tools. The LANL team has leveraged Esri's suite of GIS software, particularly the ModelBuilder application in ArcGIS Desktop, and ArcGIS Server, to simulate not only flooding caused by weather events or dam break conditions but also injuries and loss of life that can occur during and after such events. Results of flood simulations can be used to parameterize a geospatial health care model for evaluating the impact of a surge of injured persons on facilities in the region adjacent to the floodplain.

Flood Modeling

Flooding accounts for almost two-thirds of federally declared disasters, making it the largest disaster category in the United States. Flooding caused approximately $50 billion in property damage in the 1990s. Flooding in any given location fluctuates from year to

← Flooding accounts for almost two-thirds of federally declared disasters.
(Photograph courtesy of FEMA/Walter Jennings)

year, but an increase in flooding has been observed over the past century, attributed to both climate change and population growth in flood-prone areas.

To address this issue, the National Flood Insurance Program (NFIP) was formed to reduce the costs of flood damage and improve disaster assistance. NFIP is tasked with floodplain identification and mapping. However, these maps were created for insurance purposes, not for disaster mitigation or emergency response. Many NFIP maps are more than 10 years old, and coverage across the United States is not complete. Efficient and accurate hydrodynamic models must be used to fully understand the ramifications of flood disasters for any location. *[Computational numerical models are used to describe or represent the motion of water.]*

Two-Dimensional Modeling

Many hydraulic models have been developed that can simulate the inundation area of flood flow in one dimension using flood channel cross sections, but these models are not equipped to accurately represent more complex hydraulic flows in floodplains and urban environments. Two-dimensional modeling is more prevalent and gives more accurate results, but it is also more computationally demanding.

Meeting fast-response deadlines requires overcoming the computational limitations imposed by more sophisticated flood modeling. The Infrastructure Consequence Flood Inundation Tool 2D (ICFIT-2D), a custom GIS application, was written to quickly solve modified hydraulic equations that predict the timing, depths, and velocities of overland flow.

ICFIT-2D was later adapted as a stand-alone application written in Java that could be accessed from the web to provide accurate flood estimation for a wide range of flood events (e.g., dam/levee failures, surges, riverine flooding). It also takes advantage of multithreaded computing capability for fast-running simulations. The primary outputs of ICFIT-2D are time-stamped floodplain rasters that describe the depth, velocity, and peak flow attributes of the modeled event.

Injury and Loss-of-Life Methods

A key step in characterizing and evaluating the risks associated with flood or dam failure is to review the population within the floodplain extent to estimate the number of people injured, the extent of their injuries, and the number of lives lost. Historical data concerning flooding and dam failures that includes information related to the resultant deaths and injuries caused by proximity to a dam, any forewarning provided, and other factors have mainly been used to parameterize loss-of-life models. Few models have been developed that estimate injuries resulting from a flood, but these estimates are valuable for the development of emergency operations plans and resource allocation during and after an event.

In 2005, Edmund Penning-Rowsell, Peter Floyd, David Ramsbottom, and Suresh Surendran developed a method for estimating injury and loss of life during a flood using three factors: flood hazard, area vulnerability, and people vulnerability. The flood hazard rating is derived from depth, velocity, and debris characteristics of the flood—a spatial output from the ICFIT-2D model. The area vulnerability rating relates to the effective flood warning and preparation of the area, the speed of onset of the flood, and the characteristics of the land use or zoning of the area (e.g., residential homes, multi-story apartments, commercial/industrial properties, mobile homes). The people vulnerability factor is based on the degree to which people are exposed to the flood and the number of infirm/disabled or senior persons in that population.

In the method developed by Penning-Rowsell et al., the population within the floodplain is multiplied by the hazard rating—in this case, the spatial grid output from ICFIT-2D, with each cell containing its own hazard rating and the area vulnerability score, giving the exposed population. This number is multiplied by the people vulnerability score to predict the number of people in the exposed population who will be injured. Multiplying the injured population by an increased hazard rating provides an estimate of the number of deaths among the exposed population. This proposed injury and loss-of-life estimation method was implemented using ArcGIS and the ModelBuilder application and deployed via ArcGIS Server.

↓ Water infrastructure is uniquely important.
(Photograph courtesy of the Bureau of Reclamation/Alexander Stephens)

Injury and Loss-of-Life Tools

ModelBuilder greatly facilitated the automation of the Penning-Rowsell method by breaking each calculation into a visual, easy-to-follow task sequence. The model's structure can be grouped into three stages: preprocessing, calculations involving the hazard rating raster and the area/people vulnerability rasters, and the final spatial output and summarized results.

Preprocessing Population Data

Before flood risk can be addressed, the population in the flood zone needs to be determined. Gridded population datasets, such as Oak Ridge National Laboratory's LandScan dataset, can be ingested to characterize the population within the hazard area. To alleviate problems associated with grid resolution differences between population and simulated flood hazard grids, the population grid can be resampled and/or reprojected to the extent and cell size of the hazard rating raster.

Resampling only addresses cell size and doesn't change the value within the cells (i.e., population distribution among the resampled cells), so the output from the reprojection and resample tasks needs to be divided by an appropriate value so that the original geospatial population is preserved. As a final preprocessing step, the population at risk (i.e., population within the flood hazard) is identified and extracted.

Calculating Hazard Rating and Area/People Vulnerability

Using the model dialog box, the user assigns vulnerability parameters based on knowledge of the floodplain area. Penning-Rowsell et al. determined values that would provide a reasonable estimate for injuries and deaths when applied to several historic flood study cases. The vulnerability parameter domains in the tool dialog box were limited to those shown in the table. When the model is run, the values given by the user are entered into the model as new rasters with an extent and cell size equivalent to the hazard rating raster. After summing the area vulnerability scores, they are multiplied by the hazard rating. The results are reclassified such that values are capped at 100 (i.e., more than 100 percent of the population affected cannot be counted as a casualty). The people vulnerability scores arealso added. Both vulnerability rasters are then multiplied by 0.01 to arrive at percentage values for vulnerability.

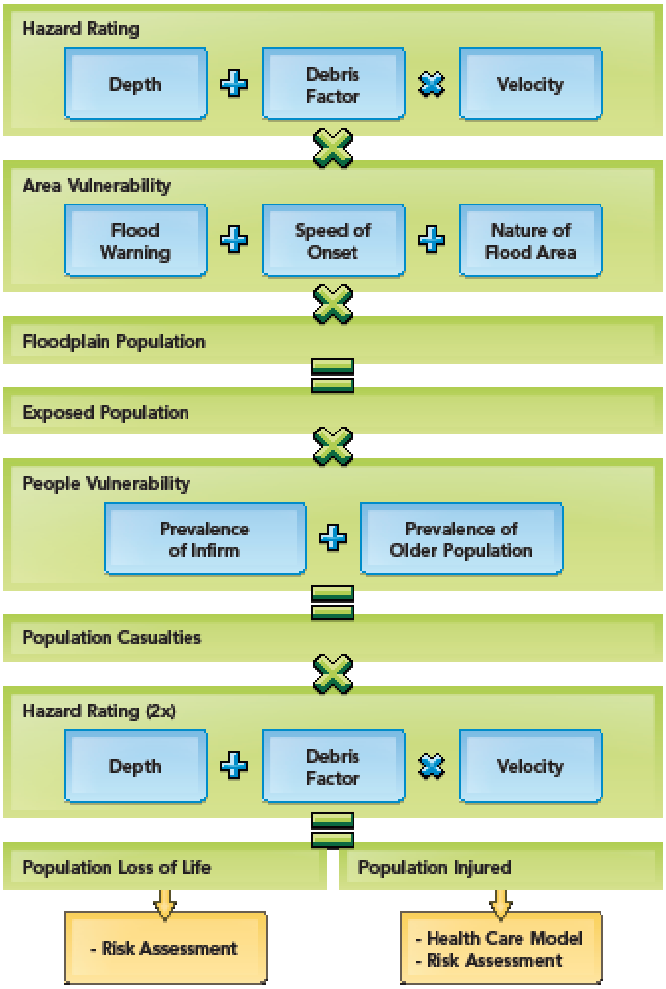
Area Vulnerability

Nature of Area	1	Low Risk Area	Multistory apartment buildings, taller commercial or industrial properties
	2	Medium Risk Area	Typical residential area (two-story homes), low-rise commercial/industrial properties
	3	High Risk Area	Bungalows, mobile homes, busy roads, parks, single-story schools, campsites
Speed of Onset	1	Low Risk Area	Very gradual onset of flooding; spans several hours
	2	Medium Risk Area	Gradual onset of flooding; spans approximately an hour
	3	High Risk Area	Rapid flooding; occurs in less than an hour
Flood Warning	1	Low Risk Area	Effective tried-and-tested flood warning and emergency planning, some flood warning
	2	Medium Risk Area	Flood warning system present but limited, very little flood warning received
	3	High Risk Area	No flood warning system and no flood warning received

People Vulnerability

Very old people (> 75 years) as percentage of general population	10	Low Risk Area	Well below the national average
	25	Medium Risk Area	Near or at the national average
	50	High Risk Area	Well above the national average
Infirm people as percentage of general population	10	Low Risk Area	Well below the national average
	25	Medium Risk Area	Near or at the national average
	50	High Risk Area	Well above the national average

↑ Table 1: Parameters for the Penning-Rowsell method



↑ Conceptual diagram of the Penning-Rowsell method for estimating injury and loss of life

ArcGIS Server as a Tool Hub

An important aspect of any fast-response analysis effort is staff availability. If only one person in the office knows where a critical tool is and how it functions but is unable to stay or return to the command center during a fast-response event, the entire analysis comes to a halt.

It is therefore paramount for emergency response groups to boost their resilience by cross-training staff so they understand how fast-response tools work and keep those tools and extensions in a central location on shared servers that are easily accessible. For all GIS-related tasks, ArcGIS Server has become a core component simply because it makes specialized tools available to anyone at the command center with a desktop installation of ArcGIS.

Depending on their requirements, some tools are also available without the desktop interface and can be used over the web. The injury and loss-of-life model described in this article is limited to a desktop interface because one of the primary inputs is the hazard rating raster file. However, a web implementation may be useful if the raster is first converted to an ASCII text file, which is an acceptable input for web-deployed geoprocessing.

Demands on Health Care Facilities

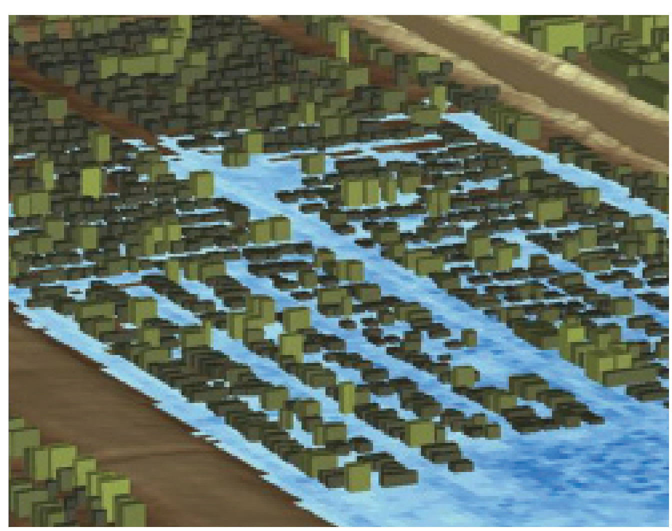
To estimate the impact of flooding on the health care sector, the LANL Energy and Infrastructure Analysis group uses a health care facility model that focuses on hospital networks and the attributes for each hospital such as bed capacities and expected occupancy. When the health care model is run, data from the American Hospital Association (AHA) Annual Survey Database Fiscal Year 2008 and the Dartmouth Atlas of Health Care (DAHC) is retrieved for hospitals in and around the floodplain region.

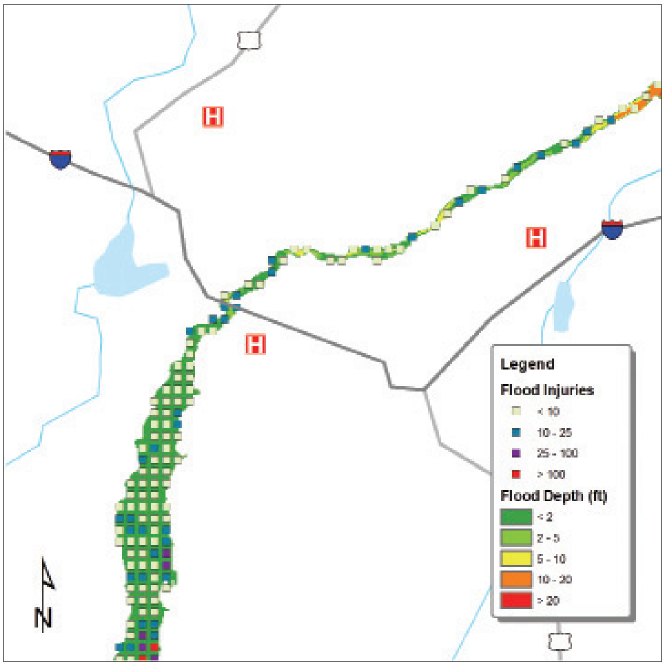
Generating Final Output and Summarized Results

The final steps of the Penning-Rowsell methodology involve multiplying the population within the floodplain by both vulnerability percentage rasters to arrive at a number of casualties within the floodplain. The term *casualty* here describes the number of people who are hurt or killed during a flood event. The initial hazard rating raster is multiplied by a fatality coefficient to identify hot spots where deaths are more likely to occur. This value is also converted to a percentage and multiplied by the casualty raster. The result is a spatial arrangement of where fatalities are likely to occur within the context of the calculated casualties.

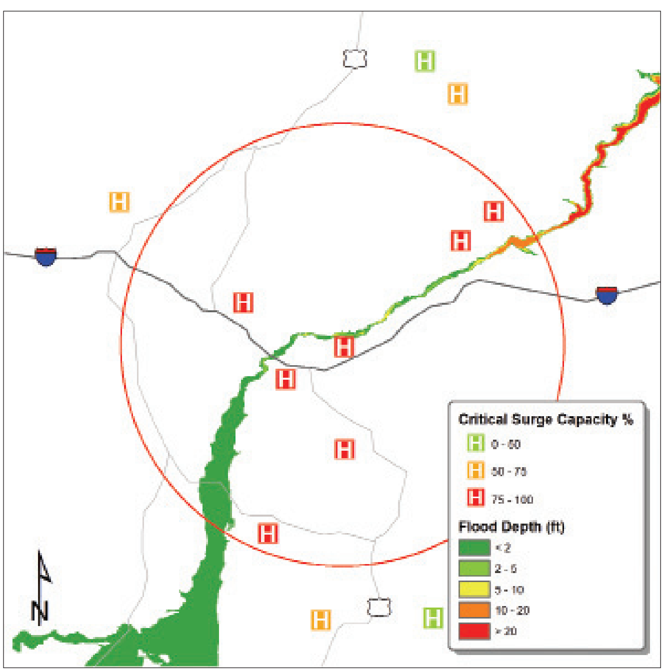
Simple subtraction of the fatality raster from the casualty raster yields the final injury raster—a spatial depiction of where injuries are likely to occur.

↓ ICFIT-2D models overland flood flows.





↑ Mapping the impact of a flood on hospitals and people in the floodplain



↑ Mapping surge in critical care need and its impact on facility capacity

The hospitals in the model are capable of responding to changes in patient condition as they progress from critical to noncritical care, or vice versa, to their eventual discharge or death. One important assumption of the model is that hospitals can only admit patients on demand if they have the available capacity. If they reach full capacity during the model run, surplus patients become a surge that must be relocated to the next nearest hospital with available capacity. Hospitals in or very close to the floodplain are considered to be in need of evacuation and become part of the surge.

Based on the available literature concerning injury severity and survivability, a portion of the injured are assigned a severity rating of either critical or noncritical. As the model runs, it allocates critical and noncritical patients to nearby hospitals until they reach capacity. The model takes into account how long these patients must stay in the hospital to either recover or die. Surplus patients are taken to the next nearest hospital until that hospital reaches capacity, and so on, until the entire injured population has been allocated.

The model also allocates regular care for noncritically injured patients, but at a slower rate, reflecting the lessened urgency of this allocation. During a typical simulation run, the noncritically injured are allocated to the surrounding facilities located in a much larger impact radius.

Conclusion

The ability to realistically simulate and predict the cascading impacts from an adverse event or disaster is key to characterizing its risk. It can also help with emergency planning, mitigation, and resource allocation before and after the event. The LANL Energy and Infrastructure Analysis group has worked tirelessly to develop the tools needed to accurately model such impacts. From hydraulic/hydrologic models to energy infrastructure to injury and health care simulations, GIS has become an invaluable tool for these analyses, especially when the turnaround times are short and lives are at stake. The LANL Energy and Infrastructure Analysis group is dedicated to the mission of making the nation safer and reducing the risks to infrastructure that support our way of life. For more information, contact

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References

Penning-Rowsell, Edmund, Peter Floyd, David Ramsbottom, and Suresh Surendran. "Estimating Injury and Loss of Life in Floods: A Deterministic Framework," *Natural Hazards,* Vol. 36, Numbers 1–2, pp. 43–64.