Title: Topography-based Flood Planning and Optimization Capability Development Report

Author(s):
Judi, David R.
Tasseff, Byron A.
Bent, Russell W.
Pan, Feng

Intended for: Programmatic DHS deliverable report

Issued: 2014-02-26

National Protection and Programs Directorate
Office of Infrastructure Protection

Homeland Security

Topography-based Flood Planning and Optimization Capability Development Report

January 2014

The National Infrastructure Simulation and Analysis Center (NISAC) performed the modeling and simulation that supports this assessment.

Los Alamos National Laboratory
David R. Judi, PhD
Russell Bent, PhD
Byron Tasseff
Feng Pan, PhD

For further information, please contact:
Homeland Infrastructure Threat and Risk Analysis Center
U.S. Department of Homeland Security
risk@dhs.gov

Executive Summary

Globally, water-related disasters are among the most frequent and costly natural hazards. Flooding inflicts catastrophic damage on critical infrastructure and population, resulting in substantial economic and social costs. NISAC is developing LeveeSim, a suite of nonlinear and network optimization models, to predict optimal barrier placement to protect critical regions and infrastructure during flood events. LeveeSim currently includes a high-performance flood model to simulate overland flow, as well as a network optimization model to predict optimal barrier placement during a flood event.

The LeveeSim suite models the effects of flooding in predefined regions. By manipulating a domain's underlying topography, developers altered flood propagation to reduce detrimental effects in areas of interest. This numerical altering of a domain's topography is analogous to building levees, placing sandbags, etc. To induce optimal changes in topography, NISAC used a novel application of an optimization algorithm to minimize flooding effects in regions of interest.

To develop LeveeSim, NISAC constructed and coupled hydrodynamic and optimization algorithms. NISAC first implemented its existing flood modeling software to use massively parallel graphics processing units (GPUs), which allowed for the simulation of larger domains and longer timescales. NISAC then implemented a network optimization model to predict optimal barrier placement based on output from flood simulations. As proof of concept, NISAC developed five simple test scenarios, and optimized topographic solutions were compared with intuitive solutions. Finally, as an early validation example, barrier placement was optimized to protect an arbitrary region in a simulation of the historic Taum Sauk dam breach.

Key Capability Findings

- Linearized flow models are simple, but approximations made in such models render them incapable of capturing complex flows.
- Combining simplified, linear flow models with traditional linear optimization techniques proves difficult due to memory constraints.
- Monte Carlo sampling of barrier placement is mostly ineffectual due to the large number of possible topographies.
- Coupling nonlinear simulation results with a network optimization model allows for the generation of reasonable solutions in short periods of time, without substantial numerical limitations.

Table of Contents

Table of Figures

1 Introduction

Within the Department of Homeland Security (DHS) Office of Infrastructure Protection, and the Homeland Infrastructure Threat and Risk Analysis Center, the National Infrastructure Simulation and Analysis Center (NISAC) performs critical infrastructure analysis, modeling, and simulation in support of the DHS mission.

Globally, water-related disasters are among the most frequent and costly natural hazards. Each year, an average of 196 million people in over 90 countries are exposed to catastrophic flooding.[1] In the United States, flooding is the leading cause of disaster, accounting for nearly two-thirds of all Federal disasters.[2] Although flood losses tend to fluctuate yearly, there has been an increasing trend over the past century, attributed to climate change as well as population growth and development in flood-prone regions.[3,4]

Flooding can inflict catastrophic damage on critical infrastructure and population, resulting in substantial economic and social costs. As these concerns have risen, mitigating flood effects has become an increasingly complex problem. Nonetheless, responses to mitigate flooding effects are often ad hoc, often individual communities attempt to prevent flood damage through sandbagging and other operations as the flood reaches its peak. Such planning techniques are usually not quantified and are generally based on local experience. In addition, local flood defense planning techniques do not generally account for changes in flood behavior and how it may impact downstream communities.

NISAC is developing LeveeSim, a suite of nonlinear and network optimization models, to predict optimal barrier placement to protect critical regions and infrastructure during floods. LeveeSim currently includes a high-performance flood model to simulate overland flow, as well as a network optimization model to predict optimal barrier placement during a flood event.

When fully developed, analysts will be able to use the LeveeSim suite to determine effective resource distribution based on emergency planning goals and constraints. It may also be used with forecasted or worst-case flood scenarios to determine regions that may require special consideration. Flood hazard events include storm surges, periods of excess rainfall, dam breaches, and other incidents.

---

[1] United Nations Development Programme, “A global report: Reducing disaster risk – A challenge for development, 2004,” accessed February 3, 2014, www.undp.org/content/dam/undp/library/crisis prevention/disaster/asia_pacific/Reducing Disaster risk a Challenge for development.pdf.

[2] Mary W. Downton,; J. Zoe Barnard Miller, and Roger A. Pielke Jr., “Reanalysis of U.S. National Weather Service Flood Loss Database,” *Nat. Hazards Rev.* 6(1): (2005) 13–22. accessed February 3, 2014, http://ascelibrary.org/doi/abs/10.1061/%28ASCE%291527-6988%282005%296%3A1%2813%29.

[3] Roger A. Pielke, Jr., and Mary W. Downton “Precipitation and damaging floods: Trends in the United States, 1932-1997,” *Journal of Climate*, 13(20): (2000), 3625-3637, accessed February 3, 2014, http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282000%29013%3C3625:PADFTI%3E2.0.CO%3B2.

[4] Roger A. Pielke, Jr., Mary W. Downton, and J. Zoe Barnard Miller, “Flood damage in the United States, 1926-2000: A Reanalysis of National Weather Service Estimates,” Boulder, CO: University Corporation for Atmospheric Research, accessed February 3, 2014, http://sciencepolicy.colorado.edu/admin/publication_files/resource-487-2005.16.pdf.

1.1 Questions

Newly developed capabilities enable NISAC to quickly analyze scenarios to answer the following questions:

- Which areas are at risk of flood damage during a flood event?
- Which critical infrastructure assets are at risk of damage from flooding?
- How can emergency measures (e.g., sandbagging, building levees) protect population and infrastructure from flooding?
- Given a set of flood mitigation goals and constraints, what are the optimal alterations (e.g., minimize cost while maximizing flood protection) that should be made to a domain’s topography?

1.2 Decision Support

When fully developed, emergency response planners can use LeveeSim results to assess the impacts of and plan for flood-related disasters. Preplanning can include prepositioning resources to protect regions and assets of interest. Using LeveeSim results can inform economic analysis that infrastructure and emergency planners could use to identify priorities. As an example, planners could use LeveeSim results with economic analysis to understand how altering a flood protection budget may affect the flooding and impact of flood-prone regions.

2 LeveeSim Models

The LeveeSim suite is a novel integration of flood models and optimization algorithms. Prior to developing LeveeSim, NISAC conducted a literature search, which did not reveal similar types of integration. The flood model is used to define flooded regions based on a current state of underlying topography. The optimization model is used to develop recommendations (e.g., sandbag or barrier placement) for topographic alterations, based on cost and impact to the flood.

A LeveeSim analysis begins with the input of a flood scenario to a flood model. In the most basic form, analysts define a flood scenario using a gridded topography of the domain and a source from which water enters the domain. Areas where flooding is a concern (e.g., locations with critical infrastructure) are deemed areas of interest within the simulation domain. A simulation of the scenario is then run for a predefined duration, and the resulting data (e.g., water depths and velocities) are saved. The optimization model uses simulated input and output data from the flood model, in addition to the predefined areas of interest. The optimization model develops suggested flood defense locations that have the potential to protect the areas of interest. Using these suggestions, a new topography is generated by raising elevations at suggested locations, after which the simulation is repeated to evaluate the effect of the topographic alteration.

Currently, the optimization model is only used once to generate a new topography. In the future, simulation and optimization routines will be repeated until a globally optimal topography that diverts flow from the areas of interest is discovered. Figure 2-1 represents the LeveeSim workflow.

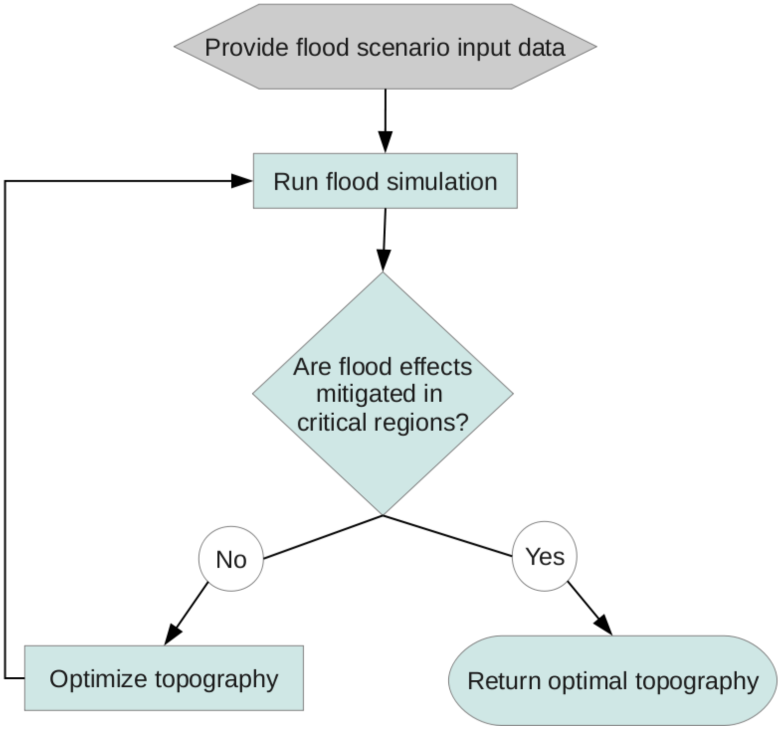

Figure 2-1. Generalized flowchart of the LeveeSim models

2.1 Flood Models

Due to its complex nature, water motion is notoriously difficult to characterize using numerical methods. Nonlinear models are often employed to accurately simulate flood events. However, optimization problems (e.g., the problem of finding the *best* solution from all feasible solutions) are often solved using linear techniques. To render the problem amenable to optimization techniques, NISAC developers initially considered a number of linear approaches to modeling floods in two dimensions. Although these models were later discarded in favor of a nonlinear model, developers learned important lessons during this initial stage.

2.1.1 Linearized Flood Models

NISAC developers first considered a flood model similar to that implemented by Noe.[5] However, after using this model to experiment with complex topographies, developers found the solutions were highly inaccurate when compared to solutions obtained using nonlinear models.

NISAC developers also considered a second linearized scheme, described by Mei, Decaudin, and Hu.[6] In this model, the domain is divided into a grid of connected columns. Flow between these columns occurs through a set of virtual “pipes” that connect adjacent columns. The equations that determine flow in these pipes are derived from the physical laws of hydrostatic pressure. This model’s behavior was surprisingly similar to nonlinear methods when damping parameters were adequately calibrated. However, calibrating these parameters was very difficult, so developers determined that this approach was infeasible for emergency applications. Although this model is not perfectly linear, it contains only one higher-order term, making it amenable to other linear programming techniques.

In the midst of researching linearized models, NISAC developers acknowledged a purely linear programming solution may be infeasible. While linearized models reduce numerical complexity, this type of framework would be incredibly memory-intensive when considering the domain size (e.g., number of grid cells and variables) for real flood events. As an example, a simulation containing only 10,000 time steps and 100,000 cells would require tens of gigabytes of memory to function.

2.1.2 Nonlinear Flood Model

Flood simulations generally employ nonlinear flood models. After experimenting with linear models, NISAC is using a nonlinear flood model, based on the shallow water equations, to simulate floods resulting from dam failure, storm surge, tsunami, and rainfall-driven flooding. The two-dimensional shallow water equations characterize the movement of water over land. The non-conservative form of the equations is shown in Equations 1, 2, and 3, which consist of continuity and momentum equations in the x- and y-directions:

---

[5] Karsten Noe, and Peter Trier, “Implementing rapid, stable fluid dynamics on the GPU,” accessed February 3, 2014, http://users-cs.au.dk/noe/projects/GPU_water_simulation/gpu-water.pdf.

[6] Xing Mei, Phillippe Decaudin, and Bao-Gang Hu, . “Fast hydraulic erosion simulation and visualization on GPU,” Published in *PG '07 Proceedings of the 15th Pacific Conference on Computer Graphics and Applications*, Washington, DC: IEEE Computer Society (2007).

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial H}{\partial x}+gS_{fx}=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial H}{\partial y}+gS_{fy}=0 \tag{3}$$

where h is the water depth, H is the water surface elevation, u is the velocity in the x-direction, v is the velocity in the y-direction, t is time, g is the gravitational constant, S_{fx} is the friction slope in the x-direction, and S_{fy} is the friction slope in the y-direction. The friction slope terms were estimated using the Manning formulation of surface roughness.

The numerical implementation of the equations used an explicit finite difference scheme to solve the partial differential equations, as outlined by Kurganov and Petrova.[7] To improve computational efficiency, NISAC developed a graphics processing unit (GPU) implementation of this model, similar to that described by Brodtkorb et al.[8]

This implementation of the nonlinear shallow water equations is state of the art. The underlying models do a good job of predicting flooded areas using a flood scenario, topographic data, and surface roughness. The challenge in using a nonlinear flood model to optimize flood modeling is the computational efficiency in simulating the event. The GPU implementation significantly reduces computation time, but the simulations remain generally more complex than models typically used in optimization problems. However, NISAC developers concluded that using a model that can accurately predict flood behavior is important.

2.2 Optimization Models

After simulating a flood event using the nonlinear model, the resulting data must be transferred to a separate routine that optimally adjusts the domain's topography. Developers considered two optimization models: a Monte Carlo approach (simulated annealing) and a network approach (maximum-flow, minimum-cut).

2.2.1 Simulated Annealing

NISAC developers initially coupled the nonlinear flood simulation with a simulated annealing optimization model, a Monte Carlo approach. Again, the analysis begins with the input of a flood scenario to the two-dimensional flood model. This scenario is then simulated using the original topography. At random, one grid cell's topographic height is adjusted, and the simulation is rerun. This process is repeated, and changes to the topography are continually accepted or rejected based on random probabilities. The simulated annealing process accepts topographic alterations that reduce flood impacts in areas of interest and rejects topographic alterations that do not improve flooding in areas of interest. As the simulated annealing process converges toward an optimized

---

[7] Alexander Kurganov and Guergana Petrova, "A second-order well-balanced positivity preserving central-upwind scheme for the Saint-Venant system," *Communications in Mathematical Sciences*, Volume 5, Issue 1: (2007), 133-160.

[8] Andre Brodtkorb, Martin Saetra, and Mustafa Altinakar,. "Efficient shallow water simulations on GPUs: Implementation, visualization, verification, and validation," *Computers & Fluids*, 55: (2012) 1-12.

topography (e.g., flooding at the areas of interest is reduced or eliminated), favorable changes are accepted, and unfavorable changes are more frequently rejected. Finally, the process ends with a set of user-defined parameters that are based on acceptable levels of flooding at areas of interest, and the user is left with a grid of altered topography. During the simulated annealing process, it is possible that the random selection of cells and topography changes may be misguided. Even for a relatively small domain (e.g., 256 × 256 cells), the approach produces an extremely large number of possible topographies. Even using a numerically efficient simulation framework, globally optimal topographies are difficult to find with this approach because there are many potential (and nonoptimal) solutions.

2.2.2 Maximum-flow and Minimum-cut Models

NISAC also applied maximum-flow (max-flow) and minimum-cut (min-cut) models to generate optimal topographies. Because min-cut is a static and linear optimization model, it can provide only a conservative approximation for placing barriers. Nonetheless, as long as the network and its capacities are reasonable defined, the model can generate adequate solutions. It is also computationally efficient and can be easily merged with the existing flood model as an iterative subroutine.

The general max-flow and min-cut models can be described as follows: Consider a directed capacitated graph $G(V, A)$, where V is the set of nodes and A is the set of directed edges. Edge e has a capacity c_e for all edges in A. There are also two additional nodes: s, the source node, and t, the sink node. An $s-t$ cut, separating s and t, provides a set of edges which, if removed, partitions V into two vertex sets: S containing s and T containing t. The min-cut minimizes the sum of all edge capacities and identifies a set of choke points in the network. Maximum-flow, as a dual problem to the min-cut model, is an important quantity used to analyze capacitated networks. The maximum-flow is the maximum amount of flow that can be sent from s to t. Because an $s-t$ cut separates s and t, each path from s to t intersects the $s-t$ cut at least once. The max-flow and min-cut theorem states the maximum amount of flow sent from s to t is the same as the value of the min-cut. Max-flow and min-cut models are some of the most celebrated results in theoretical graph theory, and they have been widely applied to analyze connectivity and capacities in many networks, including physical infrastructure networks. The min-cut model provides a method to find an effective way to separate s and t by removing the set of edges with minimum capacity. Min-cut and max-flow models are scalable for large networks. The results of these models often serve as the first-order analysis and provide a ground for validating more sophisticated and domain-specific models.

To apply min-cut and max-flow models to generate flood protection plans, analysts construct a network of the region of interest by dividing the region into a grid. Each grid cell is represented as a node in the network. Directed edges between two adjacent nodes model the flood in opposite directions. Using data from nonlinear simulations, edge capacities may be defined by a variety of physical data, including difference of water depths between adjacent cells, fluxes across cells, and velocities. It is clear that a meaningful definition of the network is required a priori.

In the current approach, the max-flow and min-cut models optimize barrier locations based on maximum fluxes recorded over the duration of a simulation. These flux values can be interpreted as a conservative estimate of the amount of water moved between adjacent cells per unit time. The max-flow model describes static flow patterns, and the min-cut model produces a list of grid cells with minimum total maximum fluxes to protect the assets by separating them from the flood sources. As an alternative, the maximum water depth at each edge obtained from the simulation can be used to derive the edge's capacity. Based on edge capacity, the min-cut model can produce an optimal solution that minimizes the number of barriers needed to separate assets from the sources of flooding. Developers are currently testing this alternative.

Iterations between the simulation model and the min-cut and max-flow models are as follows: Upon running a simulated event with an optimized topography, results are analyzed to determine if predefined critical assets were adequately protected. If not, new simulation data are provided to the max-flow, min-cut models, and the process is repeated.

The min-cut model can provide a solution for placing barriers to separate assets from a flooded region. Such separation is conservative, as the barrier completely partitions regions into two disjoint subregions: water cannot move between these subregions. However, it is possible that fewer resources may be used to protect assets from flooding. By placing barriers at the suggestion of the min-cut model, the solution may then be iteratively optimized in conjunction with the simulation model. Developers plan to perform this necessary extension of the current model in the near future.

2.3 Verification and Validation

As an early proof of concept, developers constructed five simple simulation scenarios; intuitive solutions (i.e., barrier locations) could be assumed by inspecting the scenario. Using the two-dimensional flood simulation, in coordination with the min-cut max-flow optimization routine, developers compared optimized topographies with original topographies. Developers then reran the simulations with optimized topographies to confirm differences in flood effects. In addition to the five simple scenarios, NISAC applied the proof of concept to a real-world application.

2.3.1 Bench-Scale Optimization

In all five scenarios, a block of water with a depth of 5 meters was initialized near the top of the domain. Near the center of each scenario, horizontal barriers of equal width and a height of 5 meters were constructed. In the center of each scenario barrier, a gap of varying width and zero height was maintained. Below each barrier, rectangular asset regions of varying sizes were arbitrarily defined. All scenarios included a domain consisting of 256 × 256 grid cells, with a grid cell resolution of 1 meter in the *x*- and *y*-directions.

Scenario 1 contains a one-cell-wide topographic gap, with one small asset located directly below the gap. Scenario 2 contains a wider gap, again with one small asset directly below. Scenario 3 contains the same wide gap, with a very large asset directly below. Scenario 4 contains a wide gap, with two large assets on the left and right.

Scenario 5 contains a wide gap and seven small assets located below the gap. Figure 2-2 displays these scenarios pictorially. Small, one-cell assets are circled.

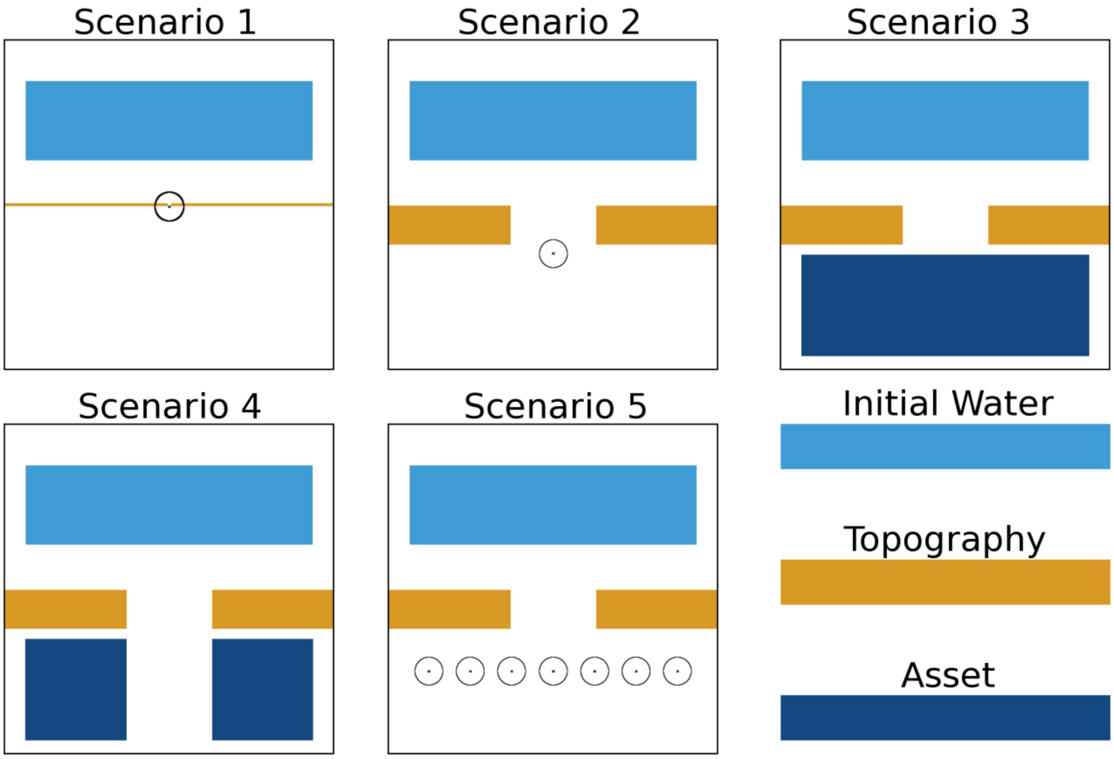

Figure 2-2. Setup of the five bench-scale scenarios

As each simulation begins, the initial floodwater spreads rapidly under the influence of gravity, reflecting upward near barriers and traveling downward through each gap. In Scenario 1, the gap is very small, and most water is reflected upward by the barrier. In all other scenarios, a significant volume of water is forced through the larger gap in the barrier. The assets have no topographic heights and, thus, do not influence flow patterns.

Upon running each scenario, maximal flux (e.g., unit flow information with units of length squared per second) data were stored and utilized by the max-flow, min-cut optimization model. Maximal flux is the largest transfer of water between cells at a time step over the duration of the simulation. Flux was selected as the variable of interest from the flood model because it is a function of both depth and velocity of water transferred. Using the maximal flux, the optimization algorithm determined optimal locations for barrier placement. The fluxes at these optimal locations were then normalized to a maximum of unity and multiplied by the maximum topographic height in the scenario (5 meters). These resulting values were then added as heights to the suggested topographic locations. Finally, the simulation was rerun using the optimized topography. Developers then compared maximum depth values, using each simulation’s original and optimized solutions, relative to the areas of interest. Figure 2-3 shows the results of these analyses.

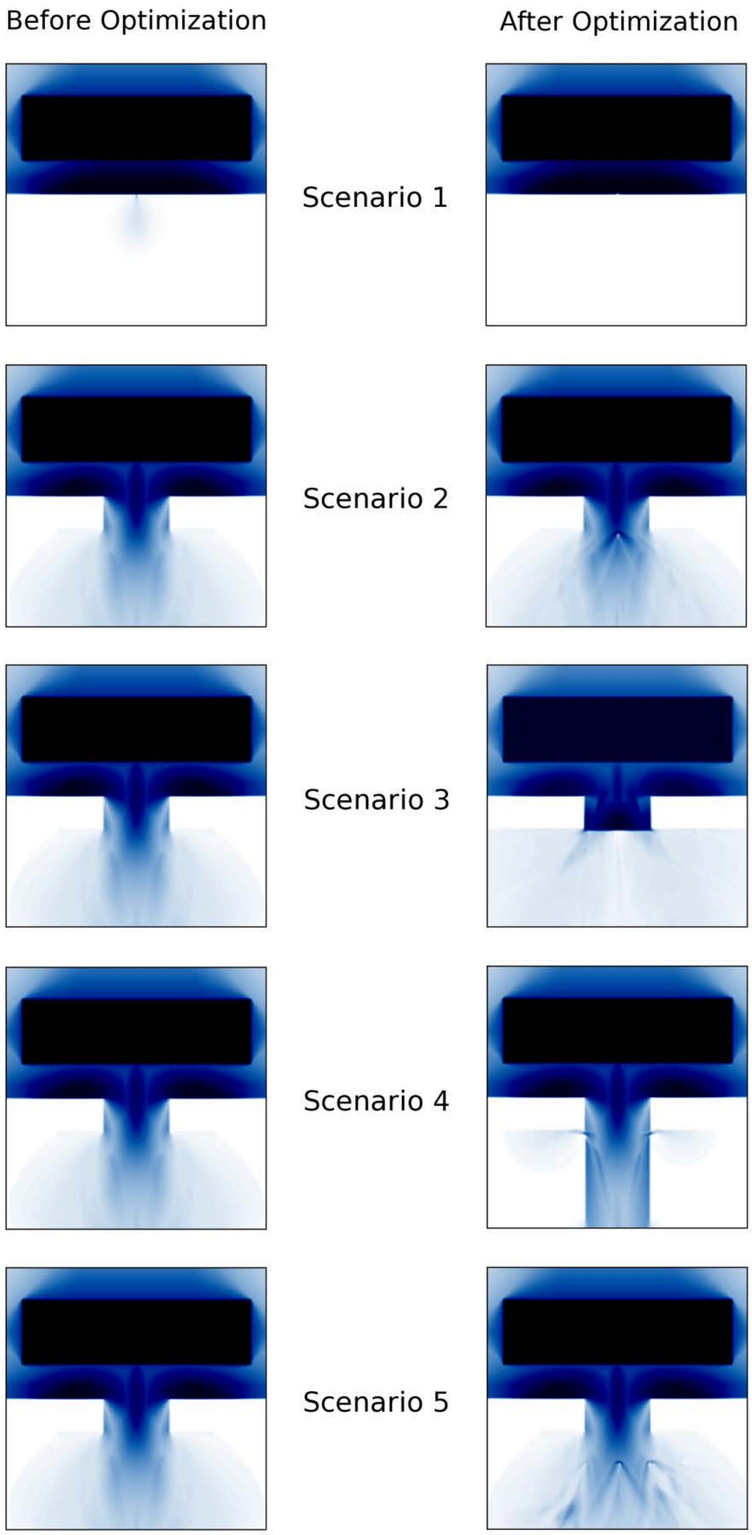

Figure 2-3. Comparison of original and optimized peak flood depths for the five bench-scale scenarios

In Scenario 1, the original topography resulted in flooding of the asset directly below the gap. The optimized topography closes this gap completely, preventing all water from entering the bottom of the domain, thus, protecting the asset. In Scenario 2, the asset is protected through the formation of barriers around the edges of the asset. This appears to be an optimal solution, as blocking the entire gap would require a larger number of barriers. Scenario 3 suggested a nearly optimized topography that almost closed the entire gap. The resulting flooding of the asset is noticeably smaller, although the areas of interest have some flood effects. Scenario 4 suggested a topography that constrained flow through the gap to a downward column, protecting the assets. However, it appears that there are many unnecessary barriers; it would clearly be more optimal to block the entire gap. Finally, Scenario 5 presented an optimized topography that again constructed individual barriers around the assets, a reasonable solution.

Aside from Scenario 4, the max-flow, min-cut model solutions are very similar to topographies optimized via intuition. However, it is also clear that some of these solutions are inadequate. In particular, Scenario 3 produced a solution near the anticipated optimized topography, although important corner edges were not blocked. Scenario 4 resulted in a somewhat counter-intuitive solution, although it constrained flooding effects to a reasonable extent. Currently, the optimization algorithm describes the “cost” of placing barriers as a function of flux. It may be more reasonable to assume each barrier also has a cost of placement, perhaps as a function of necessary barrier height. Nonetheless, the current max-flow, min-cut model provides very reasonable solutions using only very crude approximations of flow patterns.

2.3.2 Real-World Flood Optimization

To test the LeveeSim tool, NISAC developed a scenario based on the Taum Sauk dam failure. Taum Sauk is a pump-storage hydroelectric power plant located in Reynolds County, Missouri. It has a storage capacity near 5.7 million cubic meters. The reservoir, now rebuilt, sits approximately 232 meters above the floodplain of the east fork of the Black River. On December 14, 2005, a 207-meter-wide section of the reservoir failed suddenly as a result of overfilling of the storage facility. The resulting flood wave rushed down Proffit Mountain and into Johnson’s Shut-Ins State Park, and, subsequently, into the east fork of the Black River and, finally, into a lower storage reservoir. The reservoir emptied within 25 minutes.

For this study, NISAC used topography from a U.S. Geographical Survey (USGS) 30-meter digital elevation model covering the extent of the flood area. NISAC also used a hydrograph developed by the USGS for flood event reconstruction. This hydrograph was developed from a volume analysis of the embankment failure.[9] This study determined the peak discharge to be about 8,100 cubic meters per second, peaking approximately 6 minutes after the breach.

The severity of the event and the complex topography describing its domain made it a reasonable candidate for validation of the LeveeSim tool. To optimize the topography,

---

[9] Paul H. Rydlund, Jr., “Peak discharge, flood profile, flood inundation, and debris movement accompanying the failure of the upper reservoir at the Taum Sauk pump storage facility near Lesterville, Missouri.” USGS Report, 2006, accessed February 3, 2014, http://pubs.usgs.gov/sir/2006/5284/pdf/SIR06-5284_508.pdf.

NISAC used the procedure described in Section 2.3. The complexity of the scenario warranted special attention. After running the simulation using the original topography, analysts used a variety of data to define capacities in the max-flow, min-cut algorithm. These data included maximum and instantaneous fluxes. Using these quantities, topographies were optimized by raising areas that encompassed the dam breach source or asset. However, these solutions were trivial and unlikely to be truly optimal in real-world conditions.

Analysts then defined capacities in the max-flow, min-cut routine using averaged maximum water depths. The breach source cell was also restricted from being topographically altered. Maximum depths at cells defined by the min-cut model were then normalized to unity, and these values were scaled by the maximum topographic height in the domain. The resulting optimized topography raised a small line of cells near the asset area. It is important to note that, because of the current scaling technique, the resulting topographic changes were unrealistically large. However, as developers are only concerned currently with finding adequate *locations* of barriers, the solution was deemed to be adequate.

After simulating the breach event using this optimized topography, developers found that flood effects in the asset region were successfully mitigated, although small water depths (on the order of 1 centimeter) still existed within portions of the asset area. Figure 2-4 shows a comparison of the Taum Sauk dam breach effects before and after topographic optimization.

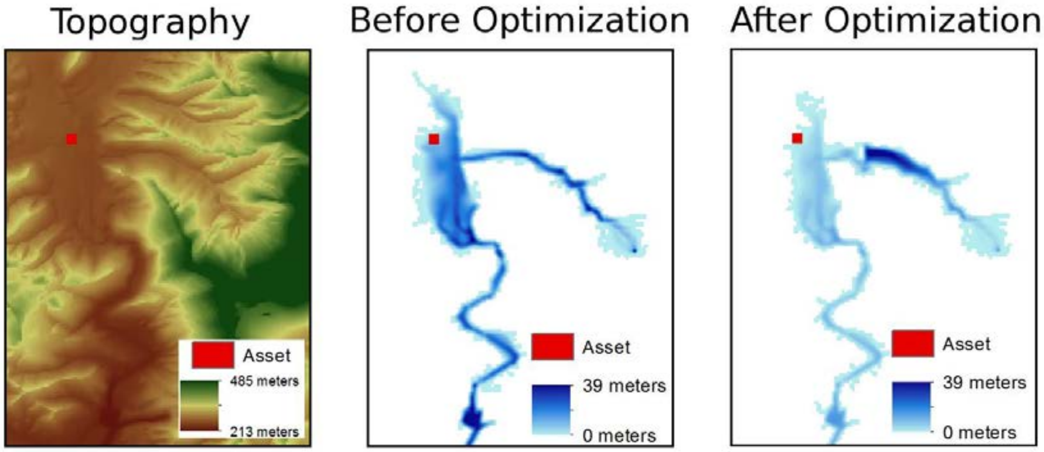

Figure 2-4. Comparison of Taum Sauk dam breach effects before and after topographic optimization

3 Conclusion

The LeveeSim capability development greatly enhances NISAC’s emergency flood response capabilities. Developers have a prototype flood-optimization method that has the potential to quickly simulate and evaluate flood risks related to a variety of scenarios and domains. Using resulting simulation data, analysts can pinpoint regions that should be protected during or before a flood event. Using the LeveeSim suite, analysts will be able to suggest optimized flood mitigation strategies. To date, NISAC has tested this capability using five bench-scale scenarios, as well as a data-based scenario of the historic Taum Sauk dam breach. In all cases, the proof-of-concept model provided reasonable solutions in faster than real-time. The most significant challenge in converging toward an optimal solution more efficiently is the computational intensity of the nonlinear flood simulation. These preliminary successes make the tool particularly attractive for future development and use.

Future development efforts should use a variety of scenarios; developers should examine LeveeSim solutions to these scenarios closely. LeveeSim could be applied to more advanced and less-intuitive, bench-scale and watershed-scale scenarios. Nonoptimal solutions and their causes should also be researched more thoroughly. In particular, the max-flow, min-cut model should incorporate methods to minimize costs (e.g., the total number of sandbags). A budget-analysis tool should also be coupled with the tool; this would allow emergency planners to observe the effects budget has on the mitigation of flood damage.

Acronyms and Abbreviations

DHS	Department of Homeland Security
GPU	graphics processing unit
LANL	Los Alamos National Laboratory
NISAC	National Infrastructure Simulation and Analysis Center
USGS	U.S. Geographical Survey