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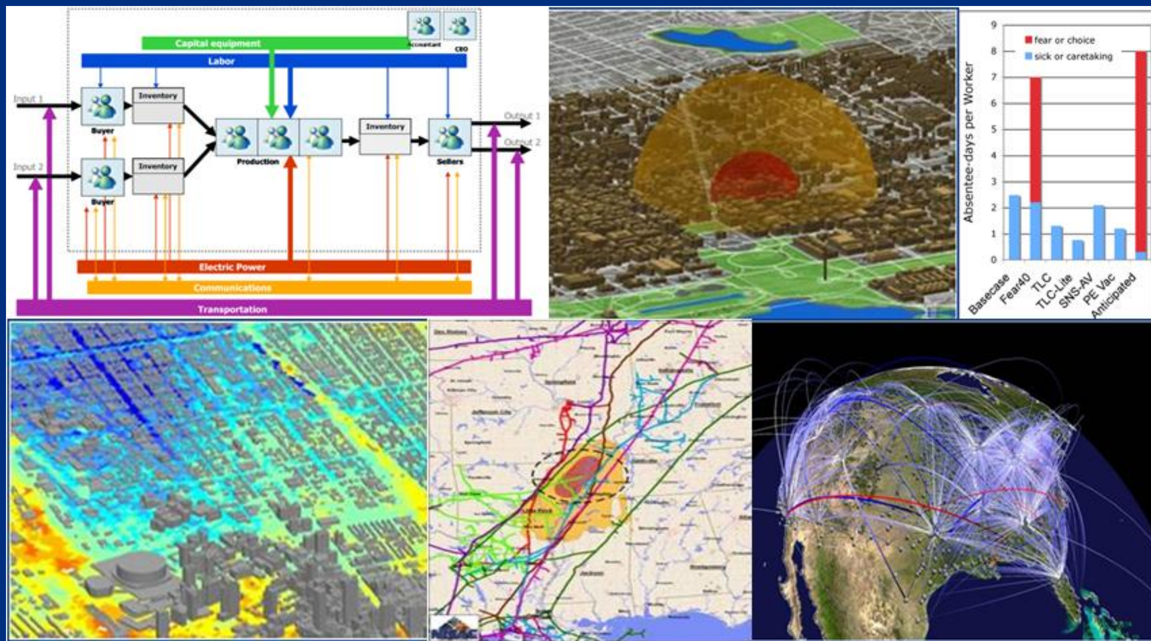

National Infrastructure Simulation and Analysis Center
Homeland Infrastructure Threat and Risk Analysis Center
Office of Infrastructure Protection
National Protection and Programs Directorate

Rainfall-driven Flooding Capability Development Report
March 2013

Homeland Security

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Executive Summary

Globally, floods are among the most frequent and costly natural disasters, both socially and economically. Many of these floods result from excess rainfall collecting in streams and rivers, then overtopping banks and flowing overland into urban environments, damaging critical infrastructure.

In Fiscal Year 2012, the National Infrastructure Simulation and Analysis Center's (NISAC) goal was to enhance its existing flood modeling and simulation capability to be able to estimate flooding from rainfall-runoff events. To accomplish this task, NISAC modified the existing flood modeling code-base using commodity high-performance computing hardware, making it more suitable for regional rainfall events. NISAC also implemented new modules within the existing flood code to account for hydrologic processes, such as spatially variable rainfall and infiltration. Analysts subjected the new hydrologic model to a verification and validation process, wherein analysts evaluated the model using a bench-scale experiment and watershed scale rainfall-runoff events. The bench-scale experiment indicated that the new hydrologic model is mass and momentum conserving and can adequately simulate runoff for depths of inches of water. The watershed scale simulations indicated that the hydrologic model is a good predictor of the discharge hydrograph when compared to observations if the input parameters, such as roughness and hydraulic conductivity, are adequately calibrated.

The intended use of the hydrologic model is to estimate flood potential during extreme rainfall events. The accuracy of the predictions is largely dependent on the availability of accurate spatial data for soil and roughness parameters. In addition, each simulation should be accompanied with a calibration exercise, which requires historical rainfall and river discharge observations.

Key Capability Improvements and Findings

- The NISAC flood modeling and simulation capability now includes the ability to evaluate rainfall/runoff events, which are useful in evaluating hazard conditions during hurricane events with heavy rainfall.
- To increase the computation efficiency such that it becomes feasible to simulate large watershed regions, the two-dimensional code was implemented on commodity high-performance computing hardware.
- The applicability of the flood modeling and simulation enhancements has been verified and validated against bench-scale and watershed-scale datasets. The results indicate that the hydrologic model can be a good predictor of rainfall-runoff hydrographs.
- The accuracy of the predicted hydrographs from the two-dimensional model depends on the validity of the soil and surface roughness datasets available. All modeling and simulation of watershed rainfall-runoff events should undergo a calibration process using historic observations before using them for predictive capability.

Table of Contents

Table of Figures

Table of Tables

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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.

NISAC developed the Infrastructure Consequence Flood Inundation Tools (ICFIT), a suite of flood modeling and simulation software and tools. The ICFIT suite includes a two-dimensional flood model that NISAC has used primarily for simulations in which overland flows are characterized by movement in two dimensions, such as flood waves expected from dam failures, storm surge, and tsunamis. Analysts use the two-dimensional capability for NISAC fast-response activities, including during hurricanes and spring flooding. NISAC also uses this capability to support preplanned studies such as the Regional Resilience Analysis Program (RRAP).

In Fiscal Year 2012, NISAC extended the existing capability of ICFIT and its two-dimensional flood modeling and simulation to include flooding from extreme rainfall events, i.e., 100-year return period events (and beyond). Capability enhancements include considerations for fast-response operational requirements (e.g., parallel computing enhancements for computational efficiency) and numerical enhancements to account for critical hydrologic processes. This report presents these enhancements, as well as the software implementation, data requirements, and the verification and validation of the new two-dimensional code.

1.1 Questions

Policy makers can use NISAC’s ICFIT for extreme rainfall events to address several questions, including:

- Which areas are at risk of flood damage during the rainfall event?
- Which critical infrastructure assets are at risk of damage from flooding during an extreme rainfall event?
- What impact can emergency measures, such as sand bagging, do to protect the population and infrastructure from flooding?

1.2 Decision Support

Globally, water-related natural disasters (e.g., floods and droughts) are among the most frequent and costly natural hazards, both socially and economically. Many of these floods result from excess rainfall collecting in streams and rivers that subsequently overtop banks and flow overland into urban environments. Floods can cause physical damage to critical infrastructure and present health risks through the spread of waterborne diseases. Rainfall-runoff models serve as valuable tools in urban planning and design for flood planning and mitigation and water resource management. These models have the ability to project the spatial-temporal extent of a flood hazard, which can subsequently be used to estimate the damage and cascading consequences within other sets of infrastructure and inform the development of flood mitigation strategies.

2 Inland Rainfall Flood Modeling and Simulation

Various types of models for rainfall-runoff flood simulation have been developed and used since the middle of the 20th century. These types of models are commonly referred to as hydrologic models. While some hydrologic approaches are stochastic, based on historic data to predict future hydrologic response, most hydrologic models are parametric and, to some extent, physically based.[1] Within the family of parametric models, there are two approaches for model development and simulation: lumped parameter and distributed parameter. Lumped parameter models rely on the concept of parameter homogeneity, specifically for soils, land use/cover, and rainfall. These models assign a single value for a parameter (e.g., soil type, which is used in infiltration estimations) and consider it representative of a larger area. Historically, lumped parameter models have been the most common approach to hydrologic modeling. The drawbacks of this approach are that the model is not completely physically based, thus, analysts rely on empirical relationships to define overland flow characteristics, and model development can be time-intensive when considering hydrologic modeling and simulation over large areas. In addition, these models are generally used to determine the runoff discharge hydrograph at a single point located at the outlet of a homogeneous watershed, therefore, spatial variability of river stage and flow is unknown. In addition, these approaches do not typically include methods in which the hydrograph can be routed downstream to evaluate the potential for flood hazards. While simpler rainfall-runoff models have been designed and used primarily for operational applications (e.g., dam operation guidance), comprehensive physics-based models can be used to generate hypothetical realities for both concept development and model testing.[2]

Distributed hydrologic models were developed to overcome some of the drawbacks of lumped parameter models. Distributed models utilize spatially variable datasets, such as soil and land use/cover, by dividing the modeling domain into discrete elements and assigning a parameter to each element. These models are physically based, employing the fundamental equations of mass, momentum, and energy to determine runoff and routing.[3] Historically, the use of these models has been limited because they require significant computational resources when modeling large watershed areas at fine resolution. However, distributed hydrologic models have become more popular as computing resources have become more efficient and available.[4] Studies have shown that distributed hydrologic models fare well when compared to lumped models, because of the improved ability to represent the spatial nature of watershed characteristics.[5]

The goal of this research is to develop a physics-based, distributed hydrologic model capable of modeling inland rainfall/runoff events. This hydrologic model uses the

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[1] Singh, V.P, Woolhiser, D.A., (2002). "Mathematical Modeling of Watershed Hydrology," *Journal of Hydrologic Engineering,* 7(4)(2002): 270–292.

[2] Mirus, B., Ebel, B., Heppner, C., Loague, K.. "Assessing the detail needed to capture rainfall-runoff dynamics with physics-based hydrologic response simulation," *Water Resources Research,* 47(2011): 1–18.

[3] Vieux, B. *Distributed Hydrologic Modeling using GIS,* Kluwer Academic Publishers, Netherlands. 2001

[4] Qu, Y., Duffy, C. "A semidescrete finite volume formulation for multiprocess watershed simulation," *Water Resources Research,* 43(8)(2007): W08419.

[5] Mirus, B., Ebel, B., Heppner, C., Loague, K.. "Assessing the detail needed to capture rainfall-runoff dynamics with physics-based hydrologic response simulation," *Water Resources Research,* 47(2011): 1–18

complete shallow water equations in two dimensions to properly represent inertial, gravity, and frictional forces. This physics-based approach will provide a higher spatial and temporal resolution of flood depth and velocity, which are critical flood characteristics for analyzing potential flood impacts to infrastructure and population.

2.1 Methodology

The hydrologic flood modeling and simulation capability is based on previous water modeling capability developments within NISAC. Specifically, the new capability is based on the two-dimensional shallow water equations used for overland flow modeling and simulation. NISAC modified these equations to account for hydrologic processes such as rainfall and infiltration. In addition, analysts implemented the code within a new computational architecture to take advantage of commodity high-performance computing hardware. The following sections discuss these enhancements in more detail.

2.1.1 Shallow Water Equations

NISAC uses two-dimensional shallow water equations to characterize the movement of water overland. The implementation of the equations is briefly described here. Details regarding the numerical implementation have been previously described.[6] Equations 1, 2, and 3 show the non-conservative form of the equations, which consist of a continuity and momentum equation in the *x*- and *y*-direction, respectively:

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

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

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

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 are estimated based on the Manning formula.

The numerical implementation uses an explicit finite difference scheme to solve the partial differential equations. An upwind differencing method is used for numerical stability, which has been shown to accurately represent both depths and timing of the flood wave. Previously, analysts implemented these equations in ICFIT using Java

[6] Judi, D. "Fast Response Flood Estimation Model Documentation Report," Los Alamos National Laboratory Technical Report, LA-UR-08-07950, 2008.

multithreading to provide desktop parallel computing on multicore computers, coupled with an effective domain-tracking algorithm.[7]

2.1.2 Computational Architecture

Because of the spatial nature of the hydrologic model, it is important to use efficient algorithms and parallel computing techniques to effectively reduce the computational time required for simulation. While previous computational enhancements to ICFIT have effectively simulated dam failures and tsunami events, there are limitations to its efficiency when considering hydrologic modeling. For example, domain tracking, which is used to eliminate computations on cells that do not have water during the simulation, is ineffective in a rainfall event in which all cells in the domain become wet. In addition, the computational cores on shared memory computers are limited, in most cases, to less than 24 cores. The utilization of graphics hardware for massively parallel computational problems, such as flood modeling and simulation, is an emerging computational architecture in science. The graphics processing unit (GPU) is an attractive parallel technique because graphics card hardware is inexpensive relative to other parallel computation techniques.

To implement the two-dimensional shallow water equations using GPU hardware, analysts first ported the code into the C/C++ language and the NVIDIA Compute Unified Device Architecture (CUDA) application programming interface (API) is used to access the parallel computational cores on the graphics card. The implementation follows as described in Kalyanapu et al.[8] Figure 2-1 illustrates the basic implementation of the GPU approach. The analyst provides inputs, such as topography and surface roughness, for the central processing unit (CPU). The CPU formats these data to be readable by the GPU using the CUDA API. The data are transferred to the GPU, where the computations of mass and momentum conservation are simultaneously completed using the available processors on the graphics card. Computed data are transferred back to the CPU when requested, for example, when the analyst requires data to be saved.

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[7] Judi, D., Burian, S., McPherson, T. . "Two-Dimensional Fast-Response Flood Modeling: Desktop Parallel Computing and Domain Tracking," *Journal of Computing in Civil Engineering*, 25(3)(2011): 184-191.
[8] Kalayanpu, K, Shankar, S., Pardyjak, E., Judi, D., Burian, S., "Assessment of GPU computational enhancement to a 2D flood model," *Environmental Modelling and Software*, 26(8), 1009–1016.

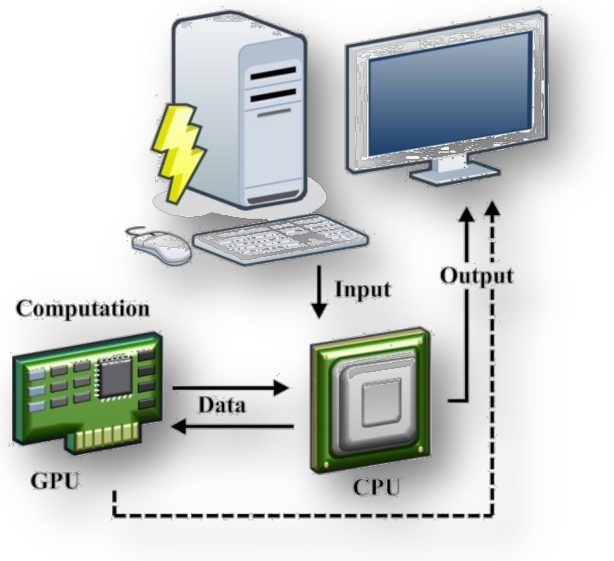

Figure 2-1. Schematic showing the GPU inland rainfall flooding implementation

This implementation has been shown to be effective in reducing computational time when compared to simulations completed on the CPU, up to 88 times faster.[9]

2.1.3 Hydrologic Modules

To predict rainfall-runoff adequately during precipitation events, the existing two-dimensional model must include additional source terms to account for the spatial and temporal nature of rainfall and infiltration, as shown in Equation 4:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = R(t) - I(t) \qquad (4)$$

where $R(t)$ is the rainfall rate at time t and $I(t)$ is the infiltration rate at time t. The rainfall rate is a source term obtained from a required input dataset, typically represented as a depth of water over a defined time interval. In addition to temporal variation, the rainfall rate and patterns vary spatially.

Infiltration accounts for a large part of the runoff losses within a watershed that reflect its ability to retain water. In general, during the initial period of rainfall, soils are able to retain more water, which is described with a higher infiltration rate. As the soil becomes saturated, the soil retails less water and water becomes runoff. To describe this process, NISAC uses the Green-Ampt conceptual model derived from Darcy's Law, to describe the fundamental relationship of the flow of a liquid through a porous media. Equation 5 is the Green-Ampt equation.

$$f_p = \frac{dF}{dt} = K\left(\frac{\psi_{wf}\Delta\theta}{F} + 1\right) \qquad (5)$$

[9] Ibid.

where f_p is the infiltration rate (millimeters (mm)/hour), F is the cumulative infiltration (mm), ψ_{wf} is the wetting front capillary pressure head (mm), $\Delta\theta$ is the difference between the soil porosity and initial soil water content (unitless), and K is the saturated hydraulic conductivity (mm/hour). These physically based infiltration parameters are generally derived from soil characteristics found in local and national datasets.

The ordinary differential equation shown in Equation 5 has been implemented using an implicit Newton iteration technique, in addition to an explicit solution.[10]

2.2 Data Sources

With the increased complexity of physics-based rainfall-runoff simulations, there is a corresponding increase in the data requirement for parameterization of the model variables (e.g., infiltration and roughness) compared to simulations for dam failures or tsunami events.[11] Table 2-1 is a summary of the data required and the data sources. Some of the datasets are spatial, indicating that there is variability in the dataset spatially, and some datasets are temporal, indicating that there is variability in the dataset temporally.

Table 2-1. Datasets required for rainfall-runoff modeling and simulation

Dataset	Data Sources	Variability
Rainfall	National Oceanic and Atmospheric Administration, Local*	Spatial/Temporal
Topography	U.S. Geological Survey (USGS), Local*	Spatial
Land Use/Cover	USGS	Spatial
Soils	USGS, Natural Resources Conservation Service, Local*	Spatial
Stream Gage	USGS, Local*	Temporal

*Local data might include local governments, municipalities, or organizations with a local interest in these environmental datasets (e.g., county governments often maintain a local network of rain gages).

There is an inherent uncertainty when using these spatial datasets for hydrologic parameter estimation. Several factors affect the level of uncertainty within any given dataset. For example, parameters may be affected by sampling resolution (e.g., soil type, land use/cover) or sampling accuracy (e.g., saturated hydraulic conductivity).[12] Therefore, distributed hydrologic models should be calibrated and validated before analysts use them to project outcomes. This typically involves searching for a

[10] Endreny, T., "Simulation of soil water infiltration with integration, differentiation, numerical methods, and programming exercises," *International Journal of Engineering Education*, 0(0)(2006): 1–10.
[11] Mirus, B., Ebel, B., Heppner, C., Loague, K.. "Assessing the detail needed to capture rainfall-runoff dynamics with physics-based hydrologic response simulation," *Water Resources Research*, 47(2011): 1–18.
[12] Vieux, B. *Distributed Hydrologic Modeling using GIS,* Kluwer Academic Publishers, Netherlands. 2001.

combination of saturated hydraulic conductivity and surface roughness that develops runoff hydrographs similar to observed runoff hydrographs.

2.3 Verification and Validation

Because the model has been ported to a new computational language and new hydrologic modules, analysts completed a few verification and validation exercises to ensure that the conceptual model was implemented correctly and adequately represents the complex physical nature of overland flows.

In many of the exercises described in the following sections, simulation results are a discharge hydrograph, defined as a flow rate over time at a given location. To compare the simulated hydrograph with a measured or observed hydrograph, NISAC used the Nash-Sutcliffe (NS) metric.[13] The NS metric has been widely used to assess predictive capability of hydrologic models, comparing simulated discharge rates with observations. Equation 6 shows the NS metric:

$$NS = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \qquad (6)$$

where *NS* is the Nash-Sutcliffe efficiency, from -∞ to 1, *T* is the event duration, *t* is the time, $Q_o{}^t$ is the observed flow rate at time *t*, $Q_m{}^t$ is the modeled flow rate at time *t*, and $\overline{Q_o}$ is the mean of the observations. An NS efficiency of 1 indicates a perfect prediction of discharge, whereas an NS efficiency of 0 indicates that the predictions are as accurate as the mean of the observations. An efficiency of less than zero indicates that the observed mean is likely a better predictor than the model. Generally, an NS efficiency above zero indicates that the model is a good predictor of runoff discharge.

2.3.1 Bench-Scale Runoff Validation

Rainfall-runoff simulations consist of much different flow characteristics when compared to simulations of dam failures and tsunami waves. For instance, the depths and velocities of rainfall events are much smaller. Therefore, it is important to ensure that mass and momentum are properly conserved by the numerical implementation. To accomplish this task, analysts obtained an experimental rainfall-runoff dataset from the literature.

Experimental datasets using laboratory data have been non-existent for rainfall-runoff modeling and simulation until recently. Cea et al. developed a bench-scale rainfall-runoff experiment, using an artificial topography and building configurations.[14] The artificial topography was created using sheet metal featuring a single discharge point. Buildings were placed on this base topography in various configurations to simulate different runoff conditions. In this experiment, Cea et al. created nine rainfall patterns, shown in Table 2-2, and eight geometric configurations in which the quantity and orientation of buildings were changed. NISAC used only six of the geometric configurations for its verification and validation simulations, ignoring building orientations not orthogonal to the

[13] Nash, J., Sutcliffe, J., "River flow forecasting through conceptual models part I- A discussion of principles," *Journal of Hydrology*, 10(3)(1970): 282-290.
[14] Cea, L., Garrido, M., Puertas, J. . "Experimental validation of two-dimensional depth-averaged models for forecasting rainfall/runoff from precipitation data in urban areas." *Journal of Hydrology*, 382, (2010) 88-102.

simulation domain. Figure 2-2 shows an example configuration. Details of the experimental setup can be found in Cea et al.'s paper.[15]

Table 2-2. Rainfall hyetographs for bench-scale simulations

Hyetograph*	Rainfall Rate (millimeters/hour)	Rainfall Duration (seconds)
Q7T20	84	20
Q7T40	84	40
Q7T60	84	60
Q15T20	180	20
Q15T40	180	40
Q15T60	180	60
Q25T20	300	20
Q25T40	300	40
Q25T60	300	60

*The hyetograph naming convention followed Cea et al., which is Q (rainfall rate) followed by the rainfall rate (liter per minute), T (time), followed by the duration (seconds) of the rainfall event.

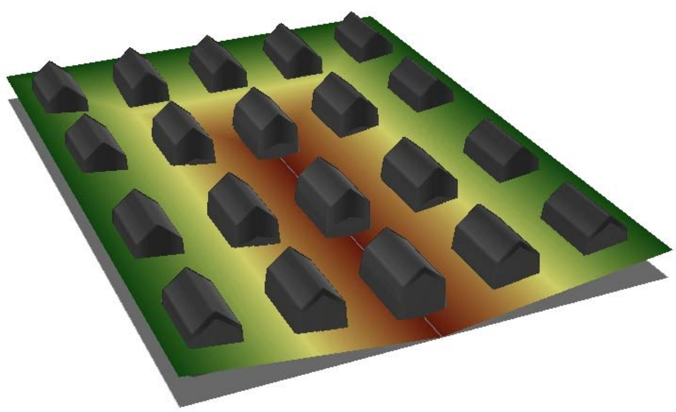

Figure 2-2. Geometry showing the Y20 configuration; Y indicates the building orientation and 20 indicates the number of buildings

[15] Ibid.

For each combination of geometry and rainfall pattern, Cea et al. collected the discharge at the outlet point of the domain. The authors provided NISAC with the base topography and the measured discharge hydrographs for each of their 72 combinations.

Using the topography provided by Cea et al., NISAC built six geometric configurations for the hydrologic model; the buildings were oriented in the *x* and *y* direction (including a staggered orientation, *s*), and consisted of 10 and 20 buildings. Using these geometries, analysts simulated each of the rainfall events and compared the results to the bench-scale observations. Figure 2-3 shows a sampling of the 54 simulations.

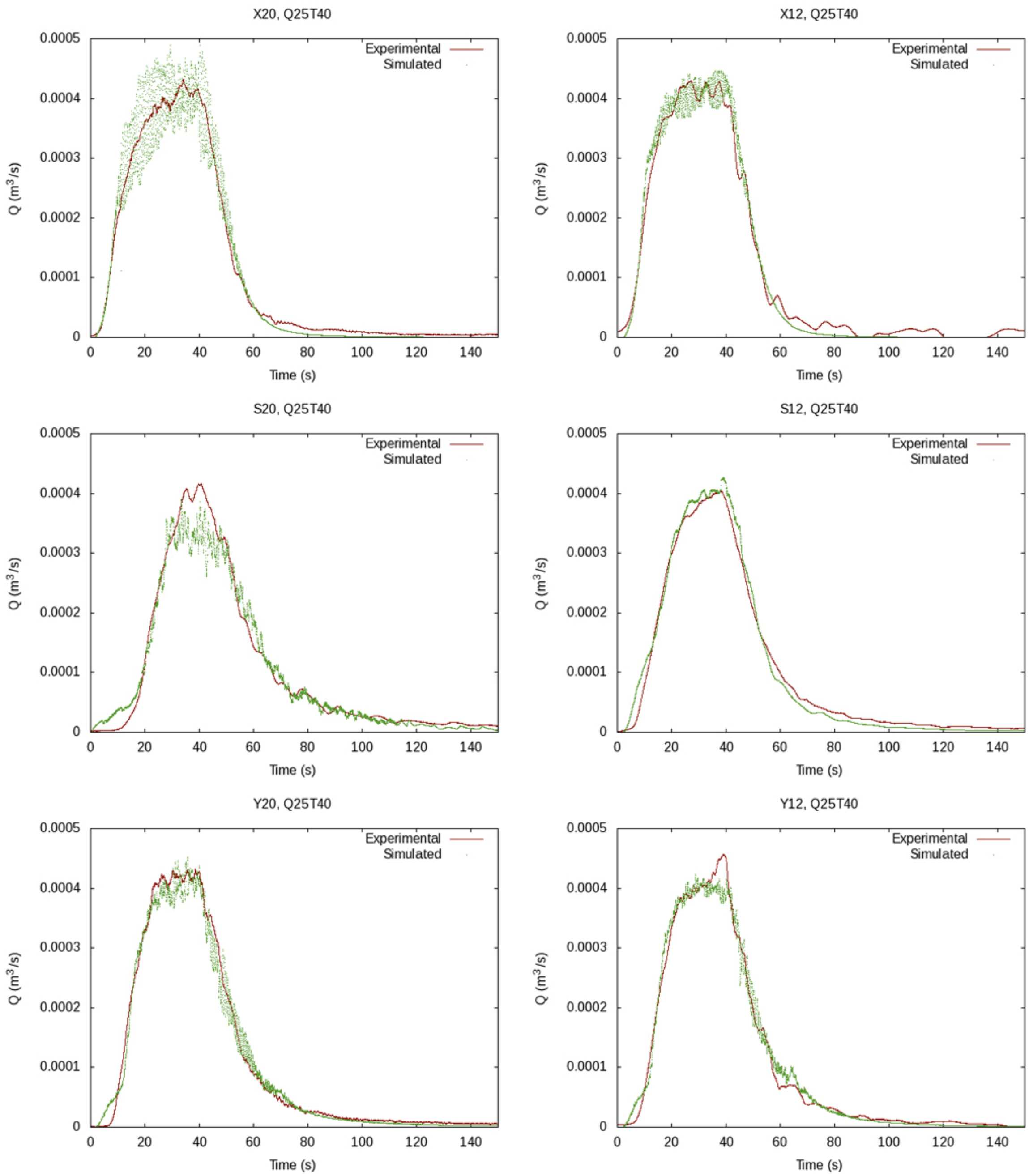

Figure 2-3. Select hydrographs for the bench-scale simulations

Analysts calculated NS efficiency for each of the 54 simulations, shown in Table 2-3. The average NS efficiency is 0.84 with a low efficiency of -1.34 and a high efficiency of 0.99. Overall, the performance of the model was excellent and the NS efficiency is an indication that the hydrologic model is a good predictor of overland flow runoff for this bench-scale experiment. It also indicates that the model is adequately conserving mass and momentum throughout the simulation.

Table 2-3. NS efficiencies for the 54 bench-scale simulations

		Model Geometry					
		Y20	Y12	X20	X12	S20	S12
Rainfall Hyetographs	Q7T20	0.84	0.38	-1.34	0.27	-0.18	0.23
	Q7T40	0.97	0.96	0.78	0.94	0.86	0.84
	Q7T60	0.98	0.89	0.82	0.95	0.84	0.94
	Q15T20	0.96	0.96	0.91	0.96	0.89	0.88
	Q15T40	0.99	0.98	0.95	0.97	0.97	0.97
	Q15T60	0.99	0.98	0.95	0.98	0.97	0.98
	Q25T20	0.98	0.97	0.95	0.88	0.95	0.89
	Q25T40	0.99	0.99	0.98	0.99	0.96	0.99
	Q25T60	0.99	0.98	0.97	0.99	0.96	0.99

2.4 Watershed-Scale Simulations

NISAC used the hydrologic model to simulate rainfall-runoff events in the Green's Bayou watershed in Texas and the Upper Los Alamos Canyon watershed in New Mexico. The results used parameters selected after a calibration process that included several simulations to determine appropriate ranges of parameters for the specific watershed. In all cases, the selected parameters remained within the range of expected values for the specific soil type of land use/cover.

2.4.1 Green's Bayou Watershed

The Green's Bayou watershed is located in Harris County, Texas, northeast of the Houston downtown area. The watershed is approximately 196 square miles and consists of a variety of land use/cover types and soil layers. The majority of the land use/cover is urban, consisting of residential, commercial, industrial, transportation, and open space. The elevation in the watershed varies from 425 feet above mean sea level (msl) to just 25 feet. Figure 2-4 shows the Green's Bayou watershed in the Houston metro area.

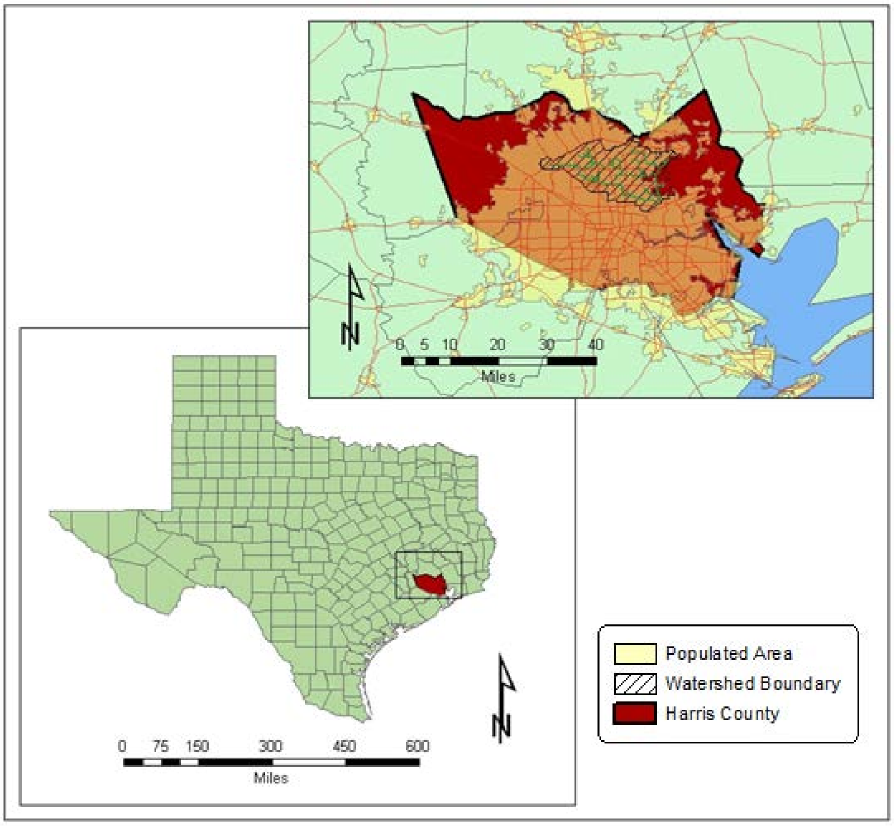

Figure 2-4. Green's Bayou watershed (hatched, upper right) located in Houston, Texas

NISAC divided the watershed into 27 sub-watersheds; all have an outlet located along the 29-mile long main channel. For this validation exercise, NISAC selected a sub-watershed located in the western-most region of the watershed for simulation because there is a rain gage located within the sub-watershed. The sub-watershed also has a U.S. Geological Survey (USGS) stream gage located at the outlet. The sub-watershed has a drainage area of 29 square kilometers. Soil data were obtained from the USGS STATSGO dataset. Based on these data, analysts determined that the soil types for the area consisted of fine sandy loam, sandy loam, and loam. The saturated hydraulic conductivity for the simulation ranged from 1.8 to 3.2 mm/hour, while the soil moisture deficit and the capillary suction head were 0.15 mm and 100 mm, respectively. Analysts derived the surface roughness from the National Land Cover Dataset (NLCD) 2006 land use/cover dataset and USGS 30-meter topographic data. NISAC used storm events and discharge hydrographs presented in Kalyanapu (2007).[16] NISAC selected the May 23, 1993, rainfall event to evaluate the predictive capability of the hydrologic model. The hyetograph in Figure 2-5 shows the observed rainfall for the event. Figure 2-6 shows both the observed and simulated discharges for the event.

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[16] Kalyanapu, A., "Geographic Information System Based Wide-Area Distributed Hydrologic Model," *Master's Thesis, Department of Civil and Environmental Engineering*, Salt Lake City, UT, 2007.

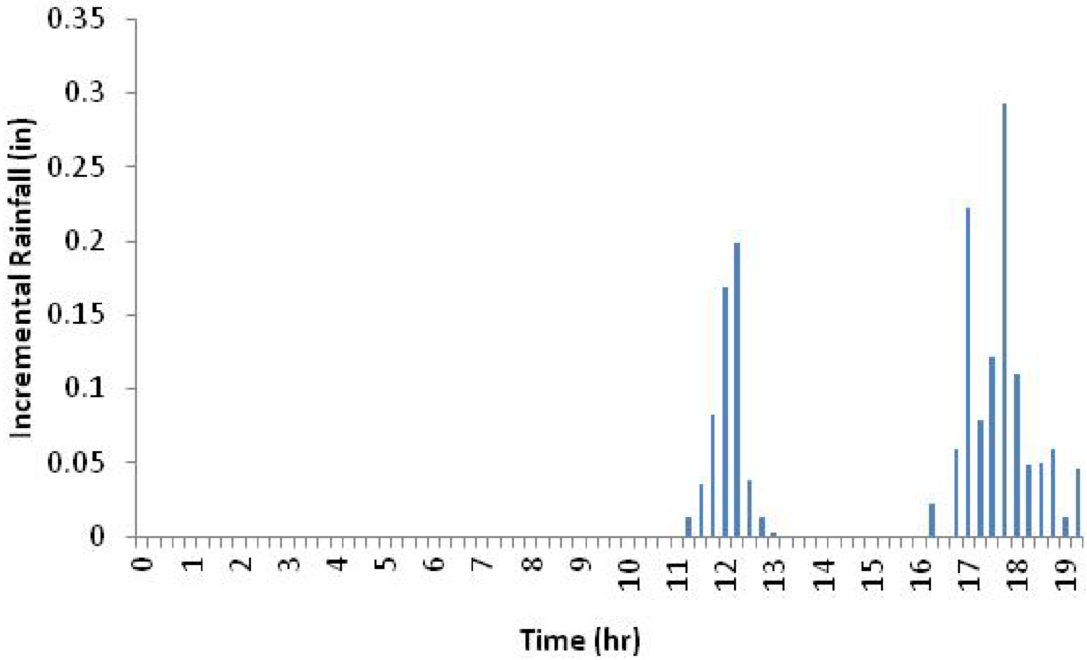

Figure 2-5. May 23, 1993, rainfall event in the Green's Bayou watershed

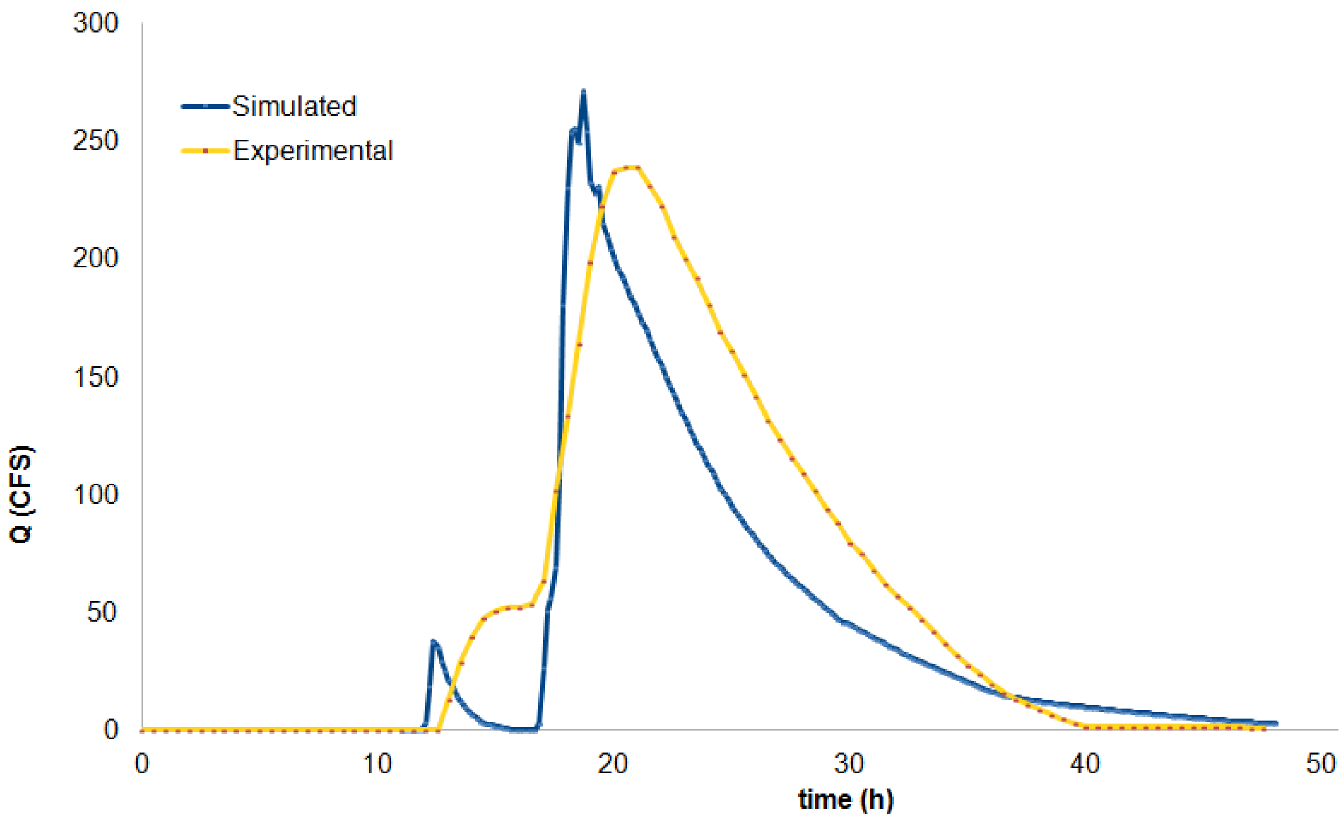

Figure 2-6. Rainfall-runoff event, May 23, 1993

In general, the shape of the simulated hydrograph is similar to the observed hydrograph. However, the simulated hydrograph appears to feature a sharper front on the hydrograph with a larger and earlier peak. The hydrologic model simulated a peak flow of 255 cubic feet per second (cfs) while the observed peak was 239 cfs, a 7-percent difference. The peak of the simulated hydrograph occurred at 18.3 hours, while the observed peak occurred at 20.5 hours. The simulated hydrograph compared to the observed hydrograph yielded an NS efficiency of 0.74, indicating that the hydrologic model using the selected parameters for the Green's Bayou is a good predictor of the discharge hydrograph.

2.4.2 Upper Los Alamos Canyon Watershed

The Upper Los Alamos Canyon watershed, shown in Figure 2-7, is located just southwest of Los Alamos, New Mexico. The watershed area is approximately 9 square miles and ranges in elevation from 6,370 to 10,450 feet above msl. The watershed receives between 13 and 20 inches of precipitation per year[17] and has an ephemeral stream that eventually discharges into the Rio Grande. The watershed has a stream gage at the outlet of the watershed, maintained by Los Alamos National Laboratory (LANL). LANL has a network of rain gages, however, there are no rain gages located within the watershed. NISAC selected the closest rain gage to the watershed, which was located approximately 0.5 miles southeast of the watershed outlet within LANL Technical Area 3.

Figure 2-7. Upper Los Alamos Canyon watershed near Los Alamos, New Mexico

[17] Wilson, C., Carey, W., Beeson, P., Gard, M., Land, L., "A GIS-based hillslope erosion and sediment delivery model and its application in the Cerro Grande burn area," *Hydrological Processes*, 15 (2001): 2995–3010.

NISAC obtained historical data for rain and stream gages from LANL's Environmental Services Division. Analysts selected the August 16, 2010 rain event, which resulted in more than 1 inch of rainfall over about 2.5 hours, as shown in Figure 2-8. The stream gage at the outlet of the watershed indicated that this storm event resulted in a runoff discharge of approximately 6 cfs.

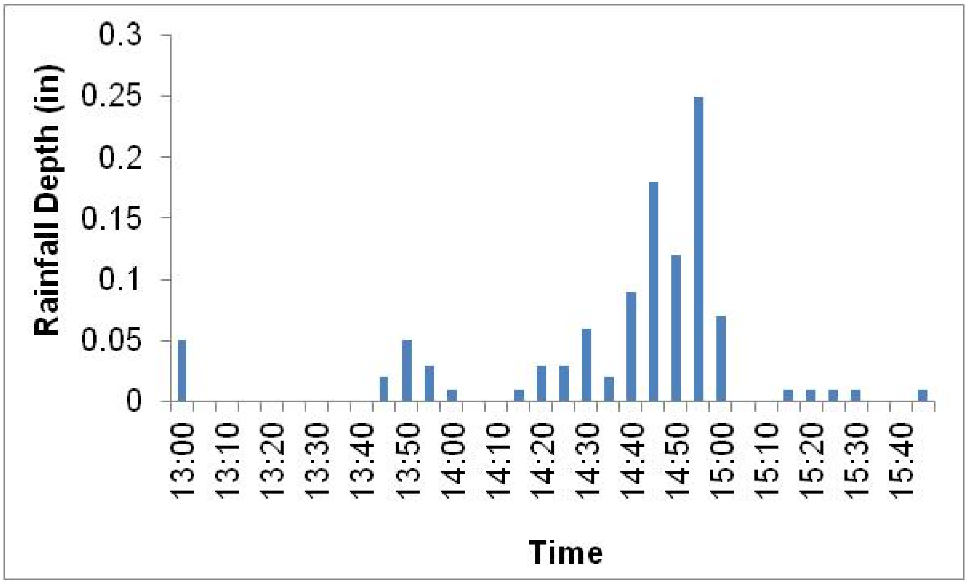

Figure 2-8. August 16, 2010, rainfall depths near LANL Technical Area 3

NISAC conducted a simple sensitivity analysis for this rainfall event by simulating the rainfall-runoff using a range of hydrologic parameters. These parameters included infiltration (conductivity, soil moisture deficit, and wetting front suction head) and surface roughness. NISAC did not select spatially variable parameters for the sensitivity analysis; each parameter was constant throughout the watershed. Table 2-4 shows the simulations and the corresponding parameter selections. Figure 2-9 shows the hydrographs for each of the simulations.

Table 2-4. Hydrologic parameters used for simulation of rainfall-runoff in the Upper Los Alamos Canyon watershed

Run	Saturated hydraulic conductivity *k* (mm/hr)	Difference soil porosity and initial soil water content $\Delta\theta$	Wetting front capillary pressure head ψ_{wf} (m)	*Surface Roughness*
1	10.80	0.4	0.1	0.1
2	11.88	0.32	0.1	0.1
3	11.88	0.32	0.1	0.13
4	13.32	0.32	0.1	0.05
5	13.32	0.32	0.1	0.055
6	13.32	0.4	0.1	0.055
7	13.32	0.32	0.1	0.08
8	18.90	0.3	0.1	0.34

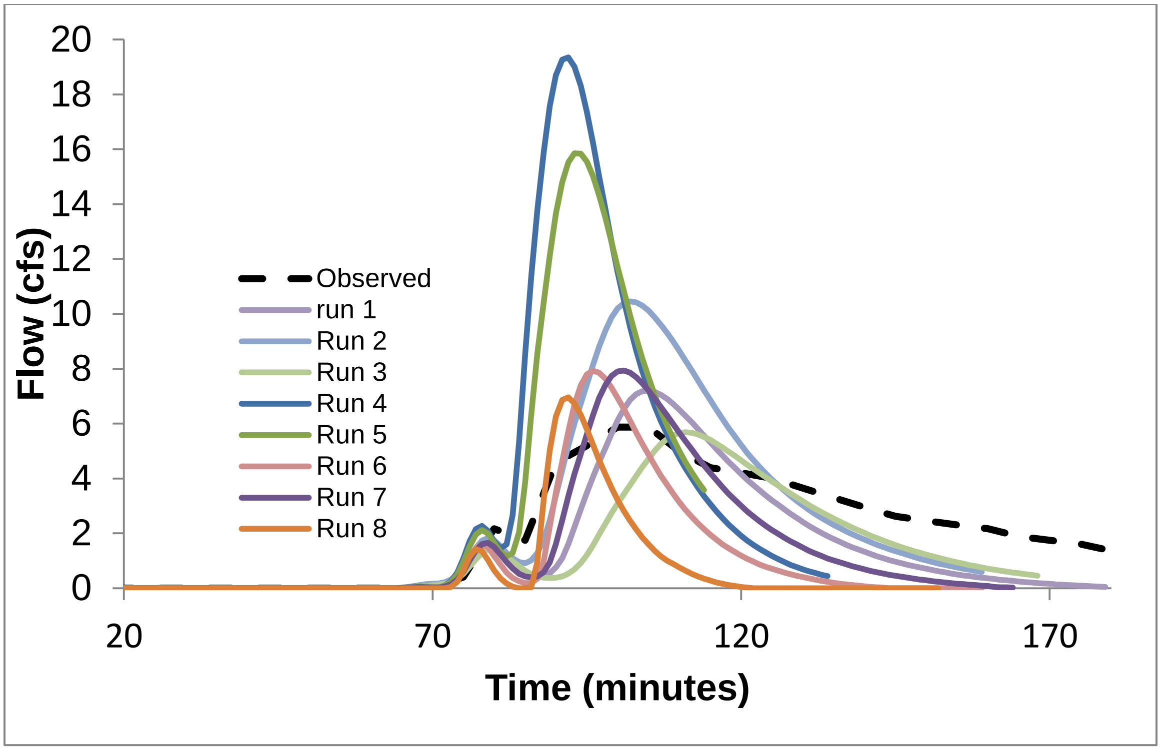

Figure 2-9. Hydrographs simulated using varying parameters in the Upper Los Alamos Canyon watershed

Clearly, the simulated hydrograph is sensitive to the hydrologic input parameters. Results indicate that the simulated hydrograph is especially sensitive to the surface roughness and the hydraulic conductivity. Intuitively, the surface roughness had the greatest effect on the timing of the hydrograph, but also had an effect on the magnitude of the peak discharge. In general, a higher roughness coefficient resulted in a later arriving peak discharge at a lower magnitude (called the hydrograph attenuation). The soil hydraulic conductivity had the greatest effect on the volume of discharge at the outlet, where the timing and the peak were largely controlled by the roughness parameter. These results highlight the need for parameter calibration when performing hydrologic simulations.

Using the same rain event, NISAC analysts used spatially varying hydrologic data to simulate the rainfall and runoff. The surface roughness was derived from the NLCD. Figure 2-10 shows the distribution of roughness parameters within the watershed. Figure 2011 shows the spatial variability.

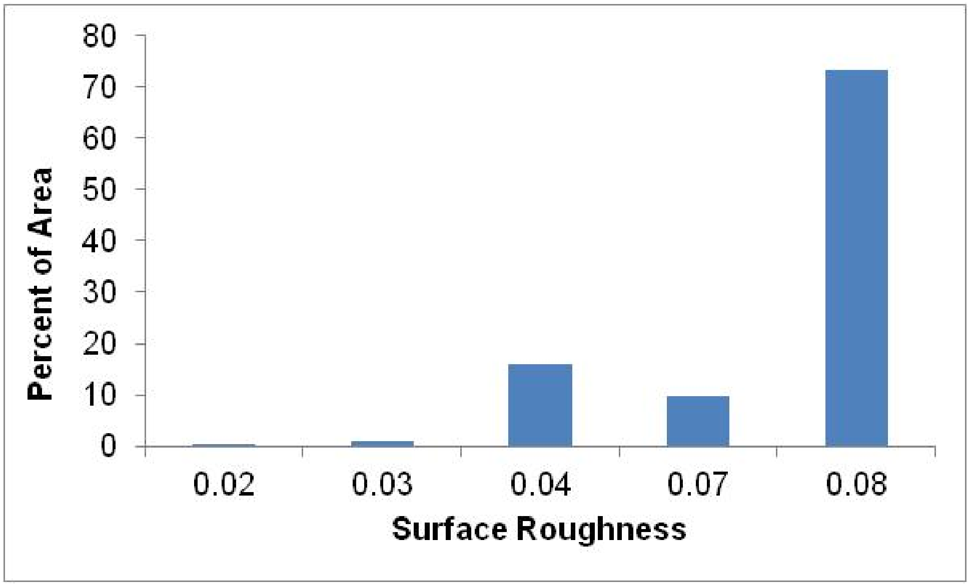

Figure 2-10. Distribution of surface roughness values for the Upper Los Alamos Canyon watershed

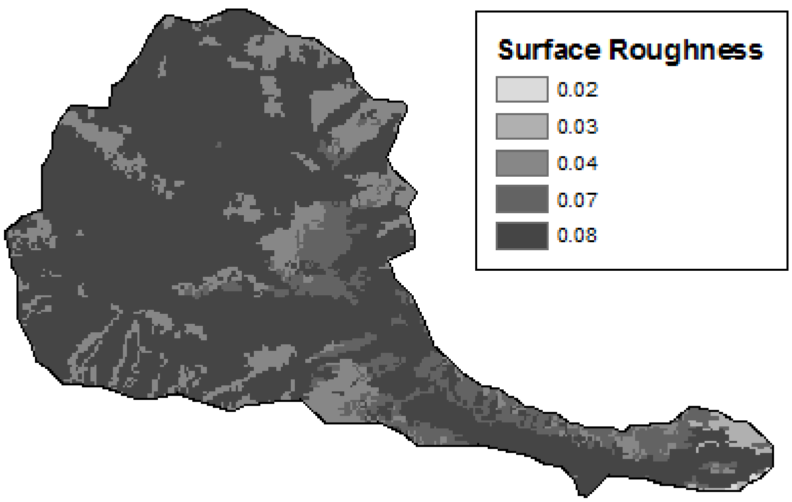

Figure 2-11. Spatial variability of surface roughness in the Upper Los Alamos Canyon watershed

Analysts derived the hydraulic conductivity using the USGS State Soil Geographic (STATSGO) dataset and surface roughness. Using the derived, spatially variable hydraulic conductivities from STATSGO initially resulted in a discharge hydrograph with significantly more simulated volume than observed volume. Therefore, NISAC analysts reduced the hydraulic conductivities by 25 percent. Figures 2-12 and 2-13 show these hydraulic conductivities. Figure 2-14 shows the discharge hydrograph resulting from these input parameters.

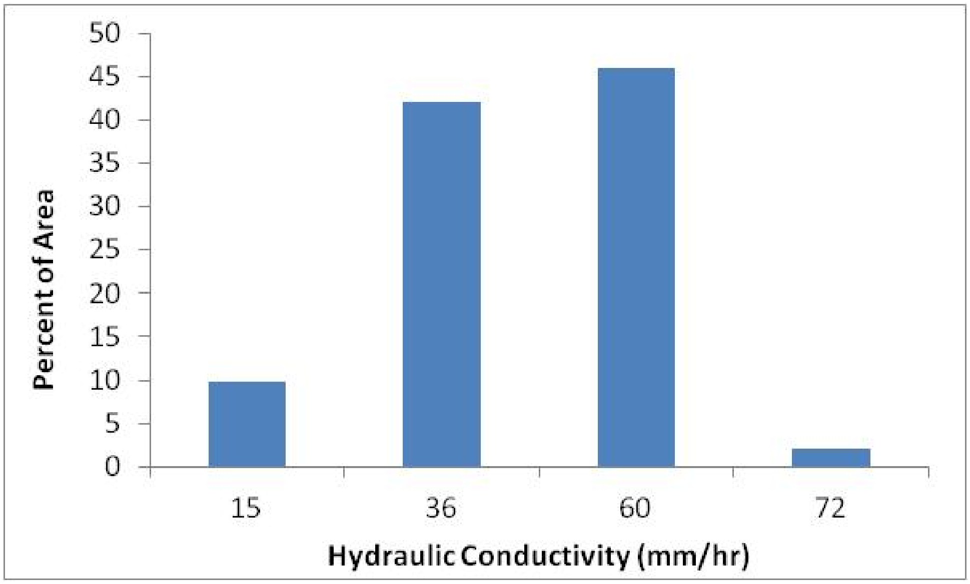

Figure 2-12. Distribution of hydraulic conductivity within the Upper Los Alamos Canyon watershed

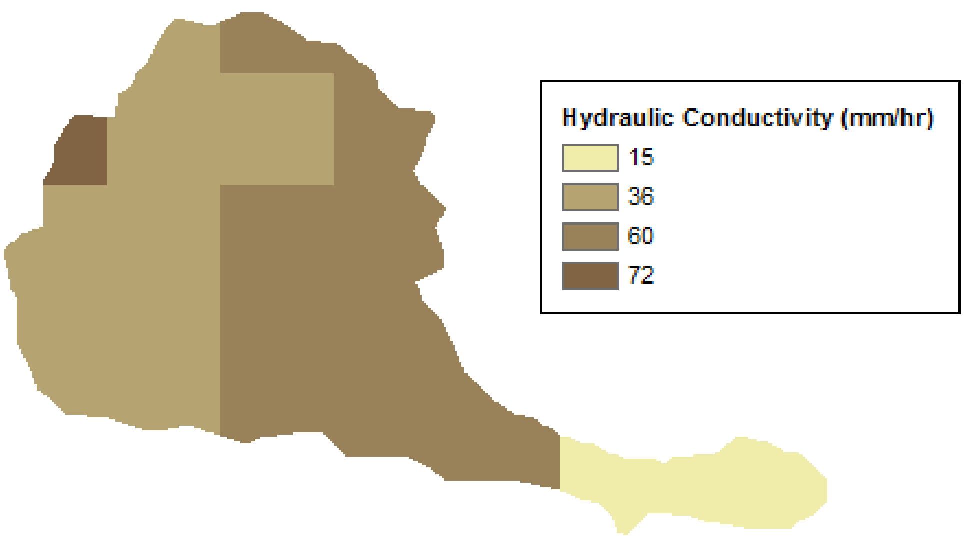

Figure 2-13. Spatial varying hydraulic conductivity derived from STATSGO data for the Upper Los Alamos Canyon watershed

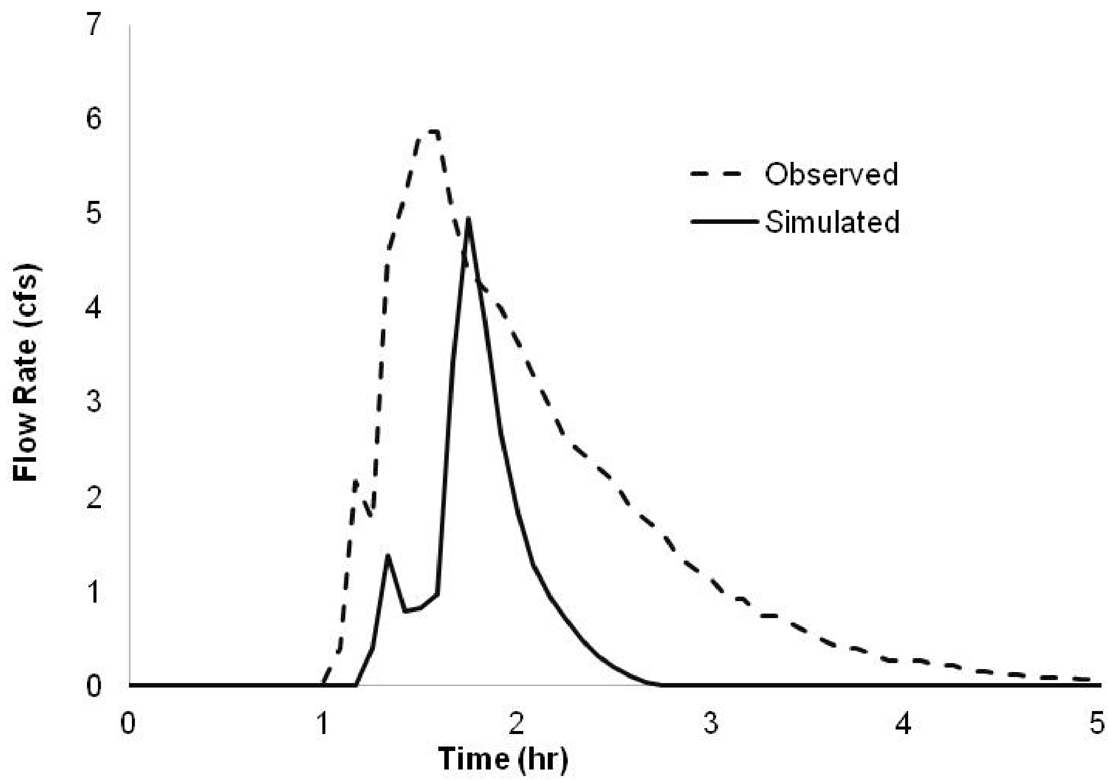

Figure 2-14. Semi-calibrated rainfall-runoff hydrograph for the August 16, 2010, event in Upper Los Alamos Canyon

NISAC evaluated the Nash-Sutcliffe efficiency for the results shown in Figure 2-14 and found an efficiency of 0.283. This indicates that this hydrologic model, including the selected hydrologic parameters, is a better predictor than the mean of the observed data. However, this efficiency is not as high as the efficiency obtained in the bench-scale simulations or in the Green's Bayou watershed simulations. It is possible that with a more robust calibration method, this efficiency could be increased, which would not only globally adjust the parameters systematically, but also vary the parameter in space.

3 Conclusion

This research has enhanced the flood modeling and simulation capability within NISAC. Analysts can now simulate and evaluate flood risks related to rainfall events. This research has enhanced the flood modeling and simulation capability within NISAC. Previously, NISAC was able to simulate flooding resulting from dam/levee failures, tsunamis, and storm surge. Because the existing capability could not represent hydrological processes, i.e., infiltration, analysts could not simulating rainfall-driven flooding, such as monsoonal storms or precipitation associated with hurricanes. Using this enhanced capability, NISAC analysts can now simulate the potential flood impacts driven by rainfall precipitation events.

NISAC has tested this capability on bench-scale and small watersheds with good performance. These hydrologic simulations depend on geospatial data for simulation, including topography, precipitation, and soil datasets. These data are generally available as national datasets from Federal agencies. However, the accuracy of the data varies and, when possible, national datasets should be supplemented with higher resolution local datasets. This research has shown that regardless of dataset, a calibration process to find the range of model parameters suitable to accurately simulate the hydrologic response during a rainfall event is necessary. This calibration process requires well-correlated rainfall and discharge measurements within the watershed of interest. These data can be difficult and laborious to find, making calibration challenging. In some cases, such as fast-response analyses and when data are not available, analysts may be forced to use the hydrologic modeling and simulation capability without proper calibration. In these cases, subject matter expertise would be used to evaluate appropriate model parameters and closely scrutinize model results. Results from an uncalibrated model can be used with caution.

Future research efforts relative to the ICFIT hydrologic modeling and simulation should investigate spatial data resolution impacts (e.g., topographic data) on simulation results. Coarse resolution data are often used to reduce computation time during fast-response activities. The impact that this coarsening has on overland flow characteristics is not clearly understood. In addition, an automated calibration process using Monte Carlo sampling techniques over the input parameter space should be implemented to enhance analysis capability.

Acronyms and Abbreviations

API	application programming interface
cfs	cubic feet per second
CUDA	Compute Unified Device Architecture
DHS	Department of Homeland Security
GIS	geographic information system
GPU	graphics processing unit
HSIP	Homeland Security Information Protection (dataset)
ICFIT	Infrastructure Consequence Flood Inundation Tools
LANL	Los Alamos National Laboratory
mm	millimeter
msl	mean sea level
NISAC	National Infrastructure Simulation and Analysis Center
NLCD	National Land Cover Dataset
NS	Nash-Sutcliffe (metric)
STATSGO	State Soil Geographic dataset
USGS	U.S. Geographical Survey

Glossary

hydrograph	A graphical representation of the stage or discharge as a function of time at a particular point on a watercourse; a time-discharge curve of the unsteady flow of water. A graph showing, for a given point on a stream, river, or conduit, the discharge, stage, velocity, available power, rate of runoff, or other property of water with respect to time. This can be measured or modeled.
hyetograph	A graphical representation of rainfall intensity with respect to time
National Land Cover Dataset	A mapping of the lower 48 United States, Hawaii, Alaska, and Puerto Rico into a comprehensive land cover product, the National Land Cover Database (NLCD) uses decadal Landsat satellite imagery and other supplementary datasets.
return period	A return period, also known as a recurrence interval, is an estimate of the likelihood of an event, such as an earthquake, flood, or a river discharge flow. It is a statistical measurement typically based on historic data denoting the average recurrence interval over an extended period.
soil hydraulic conductivity	Soil hydraulic conductivity is a property of soil that describes the ease with which a fluid (usually water) can move through pore spaces or fractures.
soil moisture deficit	The difference between the amount of water actually in the soil and the amount of water that the soil can hold.
surface roughness	A measure of the texture of a surface.
wetting front suction head	Also known as capillary suction, the wetting front suction head is a measure of the adhesive forces from the soil on the liquid at the wetting front.

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