01 Mar 2017

Real-time Flood Forecasting And Information System For The State Of Iowa

Witoldld F. Krajewski

Daniel Ceynar

Ibrahim Demir

Radoslaw Goska

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/civarc_enveng_facwork/2647

Recommended Citation

W. F. Krajewski and D. Ceynar and I. Demir and R. Goska and A. Kruger and C. Langel and R. Mantillla and J. Niemeier and F. Quintero and B. C. Seo and S. J. Smallll and L. J. Weber and N. C. Young, "Real-time Flood Forecasting And Information System For The State Of Iowa," *Bulletin of the American Meteorological Society*, vol. 98, no. 3, pp. 539 - 554, American Meteorological Society, Mar 2017.
The definitive version is available at https://doi.org/10.1175/BAMS-D-15-00243.1

REAL-TIME FLOOD FORECASTING AND INFORMATION SYSTEM FOR THE STATE OF IOWA

Witold F. Krajewski, Daniel Ceynar, Ibrahim Demir, Radoslaw Goska, Anton Kruger, Carmen Langel, Ricardo Mantilla, James Niemeier, Felipe Quintero, Bong-Chul Seo, Scott J. Small, Larry J. Weber, and Nathan C. Young

Iowa Flood Center's automated real-time flood forecasting and information system serves as a complement to the National Water Center's proposed national system.

After the devastating floods of 2008 (Budikova et al. 2010; Smith et al. 2013; Gupta et al. 2010), Iowa legislators established the Iowa Flood Center (IFC) at the University of Iowa in 2009 (see Fig. 1). The IFC is an academic research unit under the College of Engineering, hosted at IIHR–Hydroscience and Engineering (IIHR). It was established at IIHR in recognition of IIHR's 90 years of research in the fields of fluid mechanics, river processes, and water resources engineering, as well as its prominent international reputation (Mutel 1998).

The legislature's charge to the IFC reflects the widely recognized situation in June 2008, that is, a critical lack of flood information (Mutel 2010). Devastating floods that inundated Cedar Rapids came as a surprise, leaving residents and businesses little time to evacuate; residents of Iowa City and the University of Iowa campus watched helplessly as floods compromised more and more buildings after the Coralville Dam lost its controlled-release functionality. Overall, the 2008 flood upended countless lives and livelihoods and caused between $8 billion and $10 billion in damages—at the time, the fifth-largest disaster in the history of the United States.

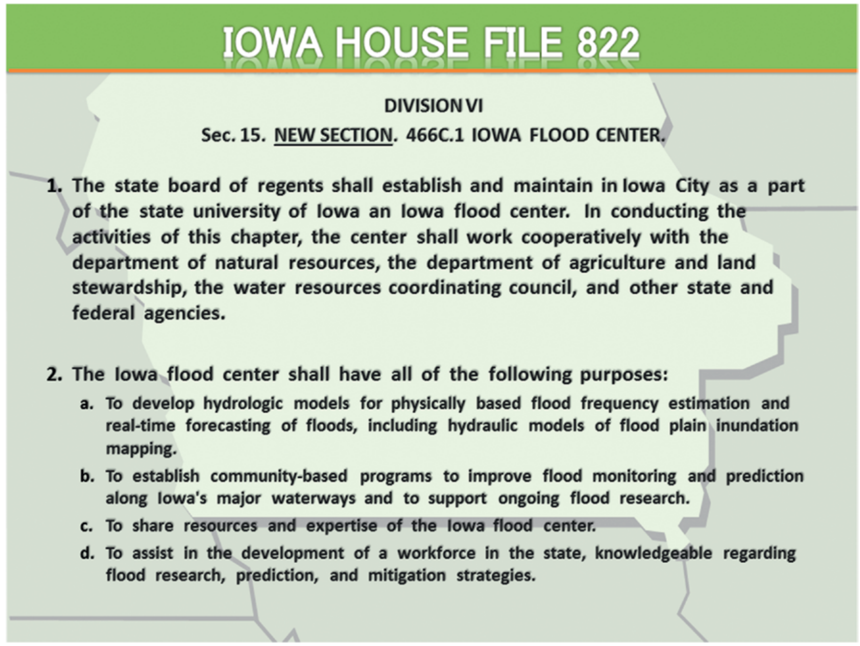
These events set the stage for IFC priorities. To improve the availability of flood-relevant information to Iowans, the IFC has been working on several fronts that are becoming increasingly integrated. Specifically, researchers developed a low-cost sensor (Kruger et al. 2016) to measure water surface elevation in streams and rivers; calculated the extent of water inundation for a range of flows in rivers around

AFFILIATIONS: Krajewski, Ceynar, Demir, Goska, Kruger, Langel, Mantilla, Niemeier, Quintero, Seo, Small, Weber, and Young—IIHR–Hydroscience and Engineering, University of Iowa, Iowa City, Iowa
CORRESPONDING AUTHOR E-MAIL: Witold F. Krajewski, witold-krajewski@uiowa.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-15-00243.1

In final form 14 June 2016

the largest communities in Iowa; and developed a statewide, high-resolution, real-time streamflow (flood) forecasting system that makes predictions every 15 min for over 2,000 locations. All these tools are publicly accessible through an interactive online portal known as the Iowa Flood Information System (IFIS; Demir and Krajewski 2013; Demir et al. 2015). The general public, as well as state and local authorities, including those with the responsibility for public safety, used information provided by IFIS during floods in 2013, 2014, and 2015.


IOWA HOUSE FILE 822

DIVISION VI

Sec. 15. NEW SECTION. 466C.1 IOWA FLOOD CENTER.

1. The state board of regents shall establish and maintain in Iowa City as a part of the state university of Iowa an Iowa flood center. In conducting the activities of this chapter, the center shall work cooperatively with the department of natural resources, the department of agriculture and land stewardship, the water resources coordinating council, and other state and federal agencies.

2. The Iowa flood center shall have all of the following purposes:
   a. To develop hydrologic models for physically based flood frequency estimation and real-time forecasting of floods, including hydraulic models of flood plain inundation mapping.
   b. To establish community-based programs to improve flood monitoring and prediction along Iowa's major waterways and to support ongoing flood research.
   c. To share resources and expertise of the Iowa flood center.
   d. To assist in the development of a workforce in the state, knowledgeable regarding flood research, prediction, and mitigation strategies.

Fig. 1. Excerpts from the bill of the State of Iowa legislature that established the Iowa Flood Center in 2009.

The timing of this report is particularly appropriate, as the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), in collaboration with other federal agencies, is embarking on the development of a new-generation, nationwide hydrologic model [National Water Model (NWM)] to facilitate streamflow and flood forecasts "everywhere." According to available information (Maidment 2017), the NWM will be based on the Weather Research Forecasting Hydro (WRF-Hydro) modeling system and will provide forecasts for some 2.7 million locations, with elements of the national hydrography system known as NHD Plus (McKay et al. 2012; David et al. 2009, 2011). The NWM went online in August 2016.

In the meantime, the IFC system has been operational for about five years, estimating flows at over 420,000 locations used for issuing forecasts at about 2,000 points, including 1,000 communities. The IFC model operates on a higher-resolution river network, providing IFC researchers with considerable expertise in addressing the logistical and scientific difficulties of running such a system. We will discuss some of these difficulties after presenting the IFC system.

FLOOD MONITORING. To improve monitoring of water levels in Iowa's streams and rivers and to provide water surface elevation observations, IFC researchers have developed and deployed over 230 bridge-mounted stream-stage sensors (Fig. 2). The sensors use ultrasonic sensing technology and provide data in near–real time using cell-modem-based communication (Fig. 3). IFC staff installed the sensors at bridges that provide existing easy access to water. (In Iowa, there are some 25,000 bridges from which to choose.)

The network complements the existing system of streamflow gauges deployed and maintained by the U.S. Geological Survey (USGS). There are 149 USGS gauges in Iowa, with which the agency measures stage and estimates discharge and provides rating curves, that is, the relationships between the two. The USGS also operates some 100 gauges that provide stage-only information in real time. Combined, the IFC and USGS operate nearly 500 stream gauges in Iowa, reporting stage in real time.

The IFC stream-stage sensors are autonomous in the sense that the power supply and communication systems are integrated into one box. A battery with a 5-yr life expectancy recharges via solar panel. Data loggers ensure that occasional difficulties in obtaining a cell phone connection do not cause data loss; data are sent during the next successful connection. The sensors' ultrasonic technology is less accurate than radar-based distance measurement, but also less expensive. Modest inaccuracies related to air density are not a major problem for the situations that matter most—flood warnings (Fig. 4). Kruger et al. (2016) provide a detailed system description.

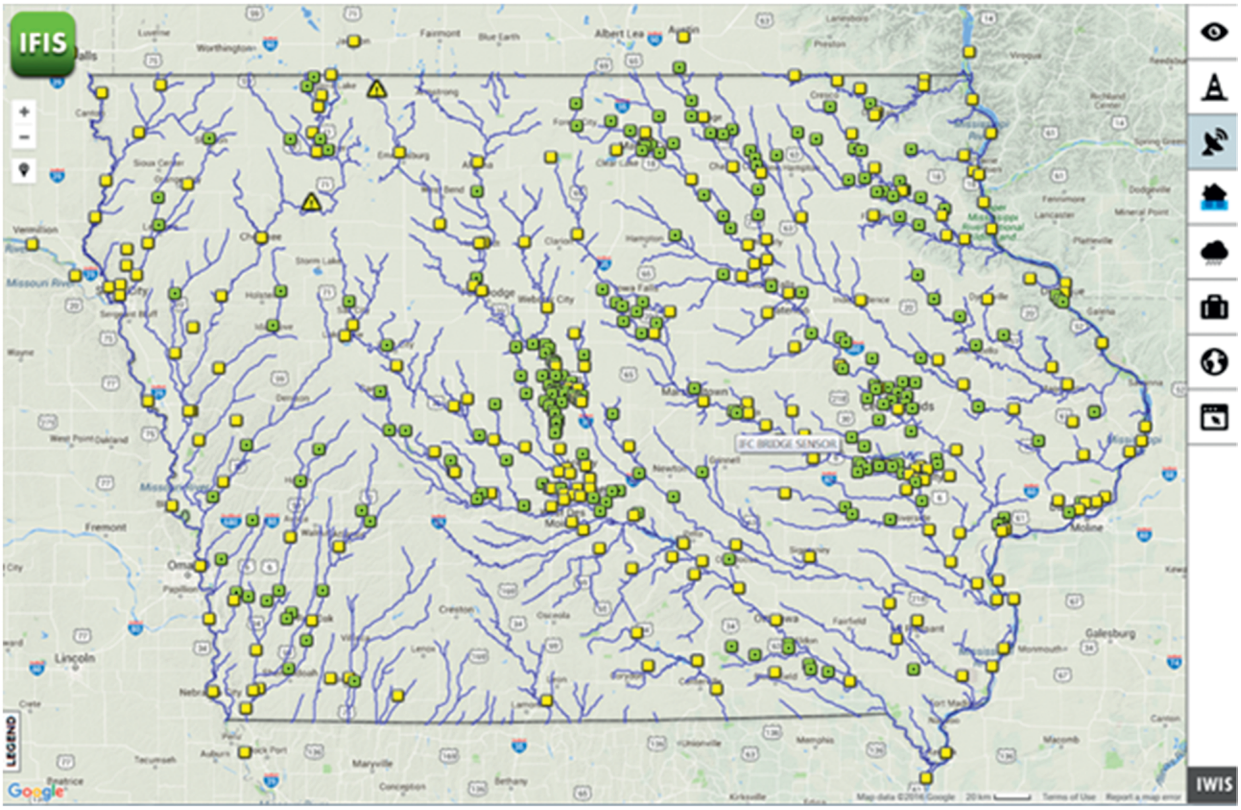


Fig. 2. Stream gauge network in the state of Iowa. The yellow squares denote locations of the USGS gauges and the green squares are the locations of the IFC bridge-mounted ultrasonic stage sensors.

FLOOD MAPPING. *Community flood inundation map libraries.* During the 2008 Iowa floods, many communities were unable to make effective response plans using NWS river stage forecasts made at USGS stream gauging stations. Specifically, communities could not relate forecasted river stages to flood elevations, depths, or inundation extents. To better communicate flood forecast data, the IFC has developed libraries of flood inundation maps that "translate" forecasted river stages into estimated flood extents and depths. The maps are readily available online via IFIS.

The IFC used hydrodynamic modeling software to simulate river and floodplain flows for conditions ranging from near bankfull to above the 0.2% annual chance flood event. Researchers use the best available information to describe the river and floodplain geometry: Iowa's statewide Light Detection and Ranging (LiDAR) topographic dataset (Iowa LiDAR Consortium 2016) is used to describe overbank topography; as-built plan sets are used to describe bridges, low-head dams, and other obstructions; and IFC-performed river surveys using single-and multibeam sonar technologies are used to map bathymetry (Fig. 5).

Model boundary conditions are based on observed data and rating curves at USGS stream gauging stations. Simulations are performed for steady flow conditions at 6-in. intervals in river stage, from near bankfull to the upper limit of the USGS rating curve. The simulations are available online as community map sets, approximating many potential inundation conditions in each community (Fig. 6). The IFC has also developed inundation maps for annual exceedance probability flows, which are based on the IFC's own statistical analysis of the gauge record, assuming a log-Pearson type III distribution consistent with the United States Interagency Advisory Committee on Water Data (USIACWD 1982). Inundations based on the USGS rating curves inform decisions about flood response during an event and allow users to consider "what if" scenarios. Annual exceedance inundation data help individuals and communities understand and plan for their long-term flood risks.

We calibrated and validated IFC inundation models using measured water surface profiles and high-water marks measured by IFC engineers, provided by the community, or reported in USGS flood investigation studies (e.g., Linhart and Eash 2010).

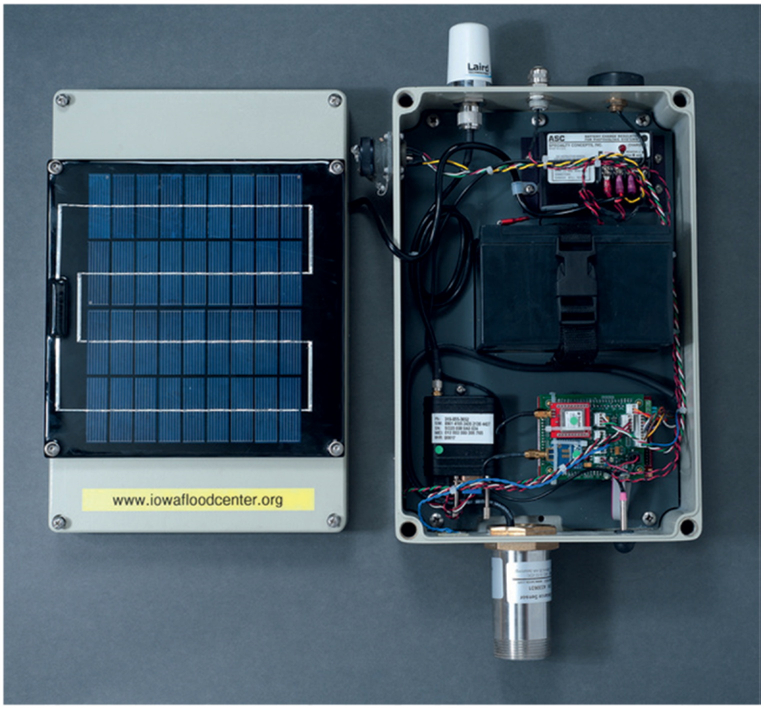


Fig. 3. A photo showing an ultrasonic stage measuring sensor. The solar panel charging the battery is shown on top of the cover on the left. Cell modem and GPS antennas are visible on the top of the box. A sonic sensor protrudes the box at the bottom.

grant was directed toward updating and developing Iowa's floodplain mapping data. The goal was to create data consistent with standards established by the Federal Emergency Management Agency (FEMA), to create Flood Insurance Studies (FISs) and Flood Insurance Rate Maps (FIRMs) to be used in management of the National Flood Insurance Program (NFIP). The IFC was contracted to complete the work. A supplemental grant from the Iowa Natural Heritage Foundation allowed the IFC to expand the project from the FEMA-required 1% and 0.2% to include 50%, 20%, 10%, 4%, 2%, and 0.5% annual exceedance floodplain boundaries and depth grids.

We calculate drainage areas greater than one square mile from a 3-m-resolution, bare-Earth digital elevation model (DEM), derived from Iowa's statewide LiDAR topographic dataset using Esri ArcGIS software. IFC research staff digitized Iowa streams draining greater than 24 acres to create a new stream centerline dataset, which they used to alter the DEM and estimate drainage area data for use in hydrologic calculations.

The IFC creates hydraulic model geometries from the 1-m-resolution DEM and a statewide land cover map (Homer et al. 2007) using the HEC-GeoRAS

Depending on geometric complexity and community needs, IFC researchers use different software packages to solve equations governing flood flows. Investigators use solvers for two-dimensional or coupled one-dimensional/two-dimensional shallow water equations, such as Sedimentation and River Hydraulics Two-Dimensional model (SRH-2D; Lai 2008) or MIKE FLOOD (DHI 2014), to simulate complex floodplain flows. Use of the Hydrologic Engineering Center's River Analysis System (HEC-RAS; USACE 2016) backwater analysis is often beneficial for communities seeking to leverage IFC data for flood insurance or engineering design applications.

The IFC makes these inundation map libraries publicly available online through IFIS. To date, the IFC has published over 5,000 inundation maps for 20 Iowa communities, and it adds about three communities each year.

Iowa statewide floodplain mapping program. Following the 2008 Iowa floods, a $15 million U.S. Department of Housing and Urban Development

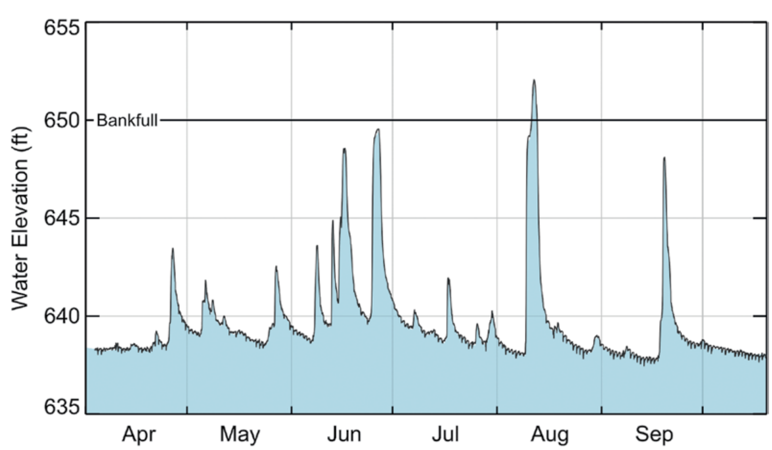


Fig. 4. An example of time series of stage measurements at English River near Kalona, Iowa, taken in 2015. An IFC bridge-mounted sensor is collocated there with a USGS stream gauge. The blue outline and the black line show USGS and the IFC stage measurements, respectively. The little "wiggles" seen in black are due to the diurnal cycle changes of air temperature that affect air density and consequently introduce small errors in the IFC measurements.

toolset (USACE 2011) in ArcGIS. Staff use HEC-RAS software to perform steady backwater calculations on each stream individually, applying a uniform flow downstream boundary conditions. Per FEMA standards, backwater effects from receiving streams are disregarded. They then export the water surface profiles back into ArcGIS, where they are intersected with the DEM to develop depth grids and flood boundary polygons. Flood boundary and depth data from all study streams are aggregated and used to create mapping products organized by Hydrologic Unit Code watershed or county boundaries. The maps generated with this steady-state approach do not necessarily represent the area of flooding under transient conditions at the same level of flow.

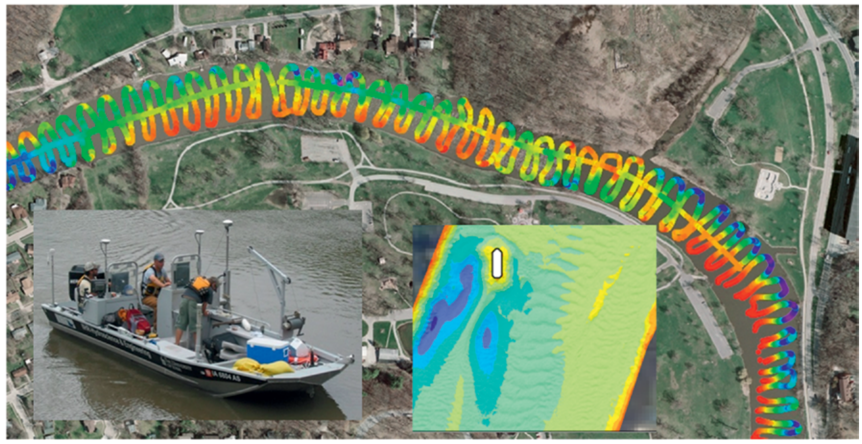


Fig. 5. Bathymetry data collection in preparation for open-channel flow modeling in the Iowa River. A swath of color-coded distance to the bottom is shown following the path taken by the research boat with sonar devices on board. Red is shallow and blue is deeper.

All floodplain boundary and depth grid data are made publicly available through Google Maps–based interfaces at www.iowafloodmaps.org. To date, project data for 75 of Iowa's 99 counties have been or are currently being reviewed and used by FEMA to develop new FIRMs. Stakeholders for floodplain management and conservation activities are also using the data. See Gilles et al. (2012) for additional process details.

REAL-TIME FLOOD FORECASTING SYSTEM. Major components of the IFC's real-time flood forecasting system include rainfall and evapotranspiration inputs and a rainfall–runoff distributed model with streamflow routing. The model is data intensive, but not calibrated. Streamflow predictions are communicated to the public via IFIS. The forecasting system makes hydrograph predictions for all streams in Iowa, but the IFC only outputs predictions for some 2,000 points on the river network. These include over 1,000 communities and other "points of interest," such as river crossings by major roads. This discussion begins with rainfall.

Rainfall. The IFC forecasting system is driven by radar-based rainfall data produced in near–real time. Statewide rainfall intensity and accumulation maps are updated every 5 min processing Level II data from the seven Next Generation Weather Radar (NEXRAD) radars covering Iowa (Fig. 7). We use radar-rainfall estimation algorithms based on a Hydro-NEXRAD implementation documented in Krajewski et al. (2013). In data quality control, automated algorithms identify and remove nonprecipitation radar echoes using three-dimensional structure of reflectivity and polarimetric signature (e.g., Seo et al. 2015b). Individual radar data are synchronized at 5-min nominal times using a simple advection extrapolation (e.g., Seo and Krajewski 2015) and merged onto a common grid of approximately 500 m (for more details, see Seo et al. 2011; Krajewski et al. 2013). The composite reflectivity maps are converted to rain rate using the common NEXRAD Z–R relation; dual polarization variables such as differential reflectivity and specific differential phase change are not yet used for rain rate estimation.

We calculate rainfall accumulation products at 5-min, hourly, daily, and two-week intervals, based on the advection correction method that mitigates radar temporal sampling errors (Seo and Krajewski 2015). The IFC rainfall estimates have been used and evaluated in numerous atmospheric and hydrologic studies (e.g., Seo et al. 2013; Smith et al. 2013; Villarini et al. 2014; Seo et al. 2015a; Cunha et al. 2015).

Evapotranspiration. While the IFC's main interest is in high flow (flood) prediction, it is also important to keep track of the water removed from soil storage. A week of warm dry weather can remove a considerable amount of water from the soil through both evaporation and plant transpiration, thus making "room" for future rainfall. Considering threshold-type behavior of the runoff generation mechanism, proper accounting for evapotranspiration (ET) is important, although its rates are smaller than those of rainfall.

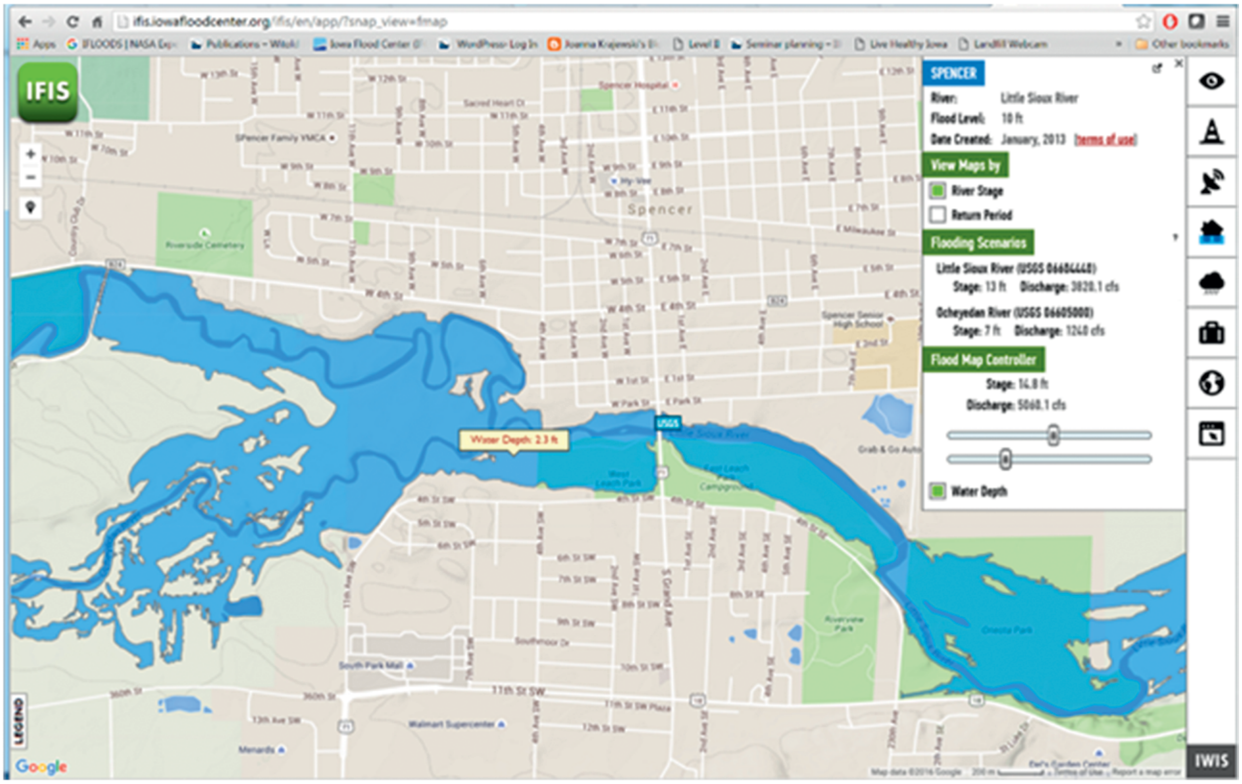


Fig. 6. Community inundation map for Spencer, Iowa. The town is located at the confluence of the Little Sioux River and the Ocheyedan River. The IFC maps allow exploring varied flow from the two rivers and checking water depth at an arbitrary location in the inundated area.

To date, the IFC has been using a simple climatology based on 12 years of North American Land Data Assimilation System (Mitchell et al. 2004). This approach captures the seasonal effects but fails to account for year-to-year and day-to-day variability. The effects of properly accounting for daily fluctuations of evaporation do not seem to significantly influence the IFC's ability to forecast the largest floods, but they do hinder the ability to capture precisely smaller streamflow oscillations created by smaller storm systems. The IFC is working on a more time- and place-specific ET estimation method.

Landscape decomposition. Before discussing modeling partitioning of rainfall into runoff, a description of the structure of the hydrologic model is needed. The IFC's approach decomposes the landscape into channels and hillslopes (Mantilla and Gupta 2005) based on topography data from the USGS DEM data. The IFC uses the well-known D8 algorithm (O'Callaghan and Mark 1984) to calculate flow directions and pruning algorithms to "extract" the river drainage network from proper analysis of the DEM data (e.g., Mantilla and Gupta 2005). We also implemented a method of digital delineation of areas that drain into specific segments (links) of the surface drainage network (see Fig. 8 for a schematic).

This landscape decomposition results in a unique hydrologic model structure that is not based on a regular grid of simple geometric shapes. Instead, landscape drainage areas are polygons characterized with respect to basic attributes such as area, slope, length, etc. The links, when connected, constitute a tree-like river network structure. These links also have major attributes such as length, slope, and average width. Proper indexing of the links ensures that the IFC model can track the water as it moves downstream.

To predict discharge, estimated rainfall needs to be partitioned into several components, including infiltration and near-surface groundwater recharge, surface and near-surface runoff feeding the stream and rivers, and ET. Rainfall conversion to runoff takes place, in the model and in nature, at hillslopes, and the landscape is drained by a system of gullies, streams, creeks, and rivers. Water moves at vastly different velocities (two orders of magnitude) on the hillslope surface and in the channels.

The above model has its theoretical roots in the scaling properties observed to characterize river

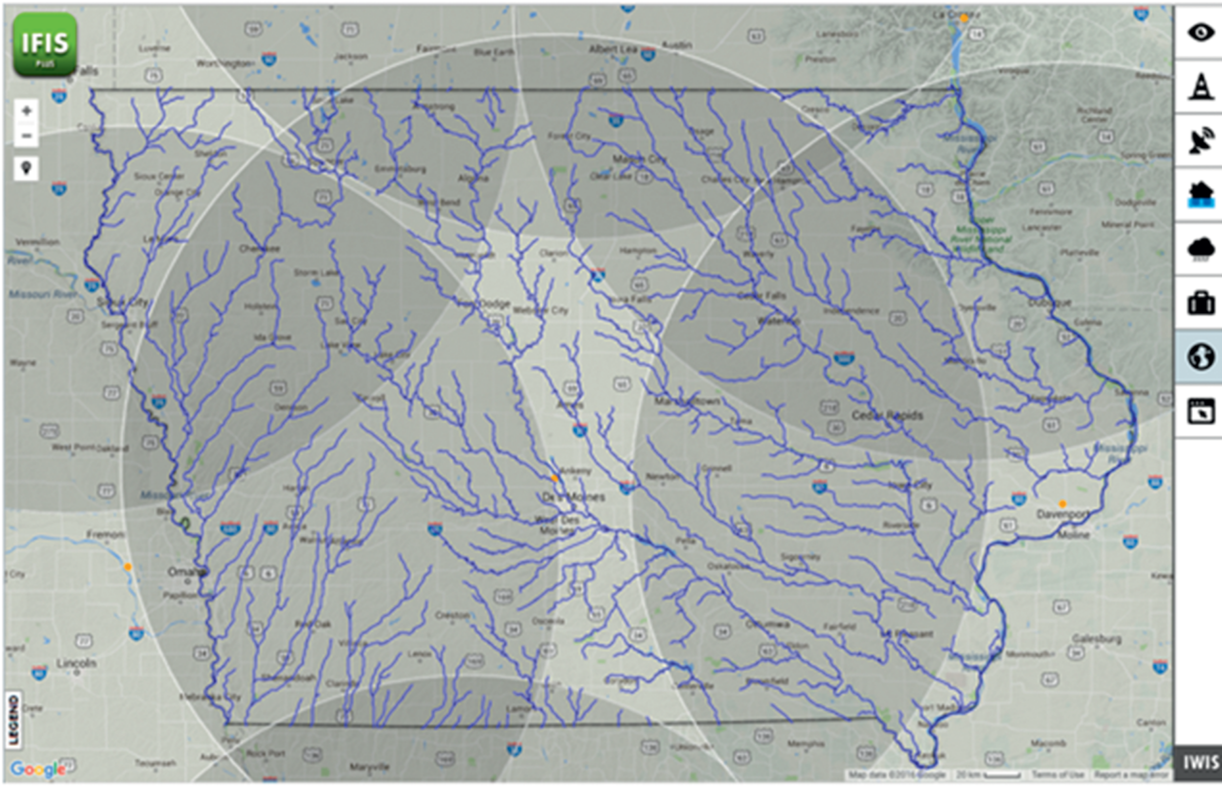


Fig. 7. WSR-88DP radar coverage of Iowa. The circles shown correspond to 230-km range. Seven radars cover the state.

networks and processes operating on them (see, e.g., Gupta et al. 1996; Rinaldo and Rodríguez-Iturbe 1996; Menabde and Sivapalan 2001; Gupta 2004; Mantilla et al. 2006; Mantilla et al. 2011; Ayalew et al. 2014a,b).

Runoff generation. As stated above, runoff generation takes place at hillslopes, which constitute the spatial support for the model elements. They are irregular-shaped polygons with surface area on the order of 0.1 km^2; the channels form a fractal tree-like river network structure (urban areas being the exception). The soil properties, land use and cover, and near-surface soil saturation determine the split between runoff and infiltration immediately following a rainfall event. We model these processes as mass conservation equations. By keeping track of the amount of water moving from the land surface to the top soil to deeper soil horizons for each hillslope, we obtain a system of coupled nonlinear ordinary differential equations that represent changes in the water storage in those elements (Fig. 9). Fluxes in, across, and out of the vertical hillslope-based control volumes include precipitation, overland runoff, infiltration into the topsoil, percolation from the topsoil into the deeper soils, base flow into the channel, and evaporation from the ponded topsoil and deep soil layers, respectively.

The model assumes that percolation flux is a linear function of the amount of water stored at a given time in the topsoil and that base flow is a linear function of the water stored in deep soil. Overland runoff is a power function of the water stored on the hillslope surface (consistent with Manning's equation), and infiltration is a nonlinear function of soil moisture content and a linear function of hydraulic head. The parameters of the model can be interpreted as time constant (residence time) of the respective storage component. The hillslope area for the elements in the distributed model is on average 0.3 km^2, and link length is on average 600 m. Nonlinearity of the model is introduced by varying the matric potential of the soil column as soil moisture changes with time.

Routing. Once water is in the channels, its velocity is determined by the opposing forces of gravity and drag due to channel resistance, impacted by channel cross-section geometry, slope, and the roughness characteristics, often not known in sufficient detail. It is a common practice to use a simpler water routing scheme, referred to as hydrologic routing, to overcome this problem. In this case, water transport

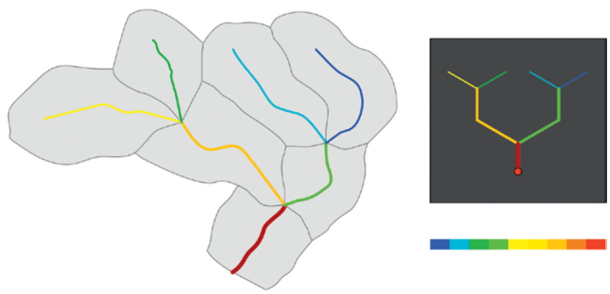


Fig. 8. Landscape decomposition into hillslopes and channel links. Colored areas drain to the respective links. A tree-like structure results when indexing the links.

through the river network is nonlinear and governs how channel links propagate flows through the river network. This is formulated in the context of a mass conservation equation, using the water velocity parameterization in which a two-factor power law describes velocity changes with increasing discharge and increasing drainage area (Ayalew et al. 2014a). The parameters of this model are global for large areas and can be determined from USGS data. The model is parsimonious, using ordinary differential equations to describe transport between adjacent control volumes in the channel network. This feature reduces the computational resources needed by capturing the most essential aspects of the water routing; it uses only a few parameters to obtain acceptable results.

Numerical solver. Mathematically, the IFC streamflow forecasting model is a system of ordinary differential equations organized on a tree topology. The system is stiff but sparse. The stiffness originates from the fact that there are several time scales involved in streamflow response to rainfall. At small scale, that is, a single hillslope or a small basin with the surface area of few square kilometers, it will respond within minutes to hours; a large basin, on the order of 10,000 km^2, may take a week. The sparseness results from the fact that there is no "communication" between hillslopes, only between hillslopes and the nearby channel link; thus, the equations can be integrated independently. The solution sequence and the one-way coupling become important as the water moves down the network, while the system of equations to be solved simultaneously decreases. The IFC developed an efficient numerical solver that allows updates of the streamflow forecasts throughout in the state every 10–15 min, using modest computational resources.

Calculations for the model are performed using the asynchronous (ASYNCH) software package developed by the IFC. ASYNCH contains a novel numerical solver for systems of differential equations interconnected in a tree structure (Small et al. 2013). The model applies continuous-output Runge–Kutta methods to the equations at each hillslope, allowing for asynchronous time stepping. This software runs on a distributed memory system, performing calculations in parallel. Simulation results can be produced in several formats and can be uploaded to a database for analysis or display. Forcings, such as precipitation or ET, can be read from various file formats or pulled from a Structured Query Language (SQL) database.

Model performance and validation. Model evaluation effort is an ongoing activity. This report presents only a glimpse of early evaluation results [examples of model-simulated hydrographs compared to observed hydrographs are included in Ayalew et al. (2014a,b), Cunha et al. (2012), Seo et al. (2013), Moser et al. (2015), and Quintero et al. (2016)]. While the model makes predictions "everywhere," observational references exist at only a limited number of points. In Iowa, 150 USGS gauges have established rating curves, a tool necessary for assessing discharge prediction. Also, the IFC focuses on the warm season performance due to seasonal cycle of floods in Iowa (e.g., Villarini et al. 2011). The IFC may revise this strategy in the future because of unexpected significant flooding significant flooding during the 2016 winter.

Another caveat is that, until recently, the IFC did not use rainfall forecasts [quantitative precipitation forecasts (QPFs)] in its discharge predictions. Thus, the evaluation includes hydrograph simulations forced by observed rainfall only. An evaluation based on

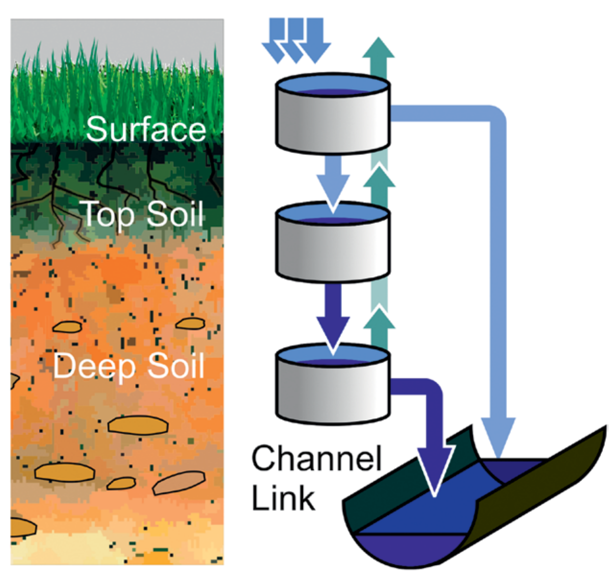


Fig. 9. A schematic of the hillslope-based water flux and storage accounting.

comparisons of model simulations against hydrograph of discharge observations is conceptually simple and provides an incomplete assessment of the forecasting system. Quintero et al. (2016) discusses a more comprehensive framework. These issues aside, numerous metrics play a special role in flood forecasting applications. In addition to standard measures such as correlation coefficient or root-mean-square difference, these include the time-integrated volume of river flow, peak value, time to peak, duration over a threshold, and more. This illustration uses only two measures, that is, annual peak and Nash–Sutcliffe (NS) efficiency index (Nash and Sutcliffe 1970). Nash–Sutcliffe efficiency can range from $-\infty$ to 1, with values above zero indicating predictive performance better than the mean of observations.

The components forcing the hydrologic model are primarily long-term rainfall datasets of the IFC radar product, which are postprocessed to correct data gaps and consistently use the same estimation algorithm. We exclude the winter months to avoid problems of rainfall estimation from frozen precipitation. The ET forcings are monthly spatially averaged values derived from climatology. The model is initialized assuming that the upper soil layer is partially saturated at the beginning of the simulations for each year. Subsurface storage is calculated to match the baseflow conditions observed at the initialization time.

We obtained the model simulations from 1 April to 1 October between 2009 and 2014, during which time the number of available gauges used in the analyses increased from 121 to 150. Figure 10 shows a comparison of the largest peak flow in the year observed at all gauged locations as the simplest measure directly related to floods. Figure 11 addresses NS efficiency index. The overall average value across all gauges is over 0.5, with better performance in wet years. (Year 2012 experienced a severe drought in Iowa.) Some gauges show NS efficiency as high as 0.8 or higher (not shown). The maps also show that the model performs better when forced by rain-gauge-corrected Stage IV radar-rainfall product rather than the IFC radar-only product. Clearly, several factors affect the model performance, including the accuracy of the rainfall estimation algorithm at multiple scales, the ability of the model to mimic the runoff generation processes, and the ability to simulate channel flow. All these factors have a spatial component that is reflected in a map of the annual performance of the model (Fig. 11). The model produces acceptable results in most Iowa rivers, with the exception of those in the western part of the state. With the IFC's calibration-free modeling approach, researchers can easily detect these locations where issues occur. The hypothesis is that there is much more regulation of surface water resources, including water diversions and irrigation, in western Iowa than in the rest of the state.

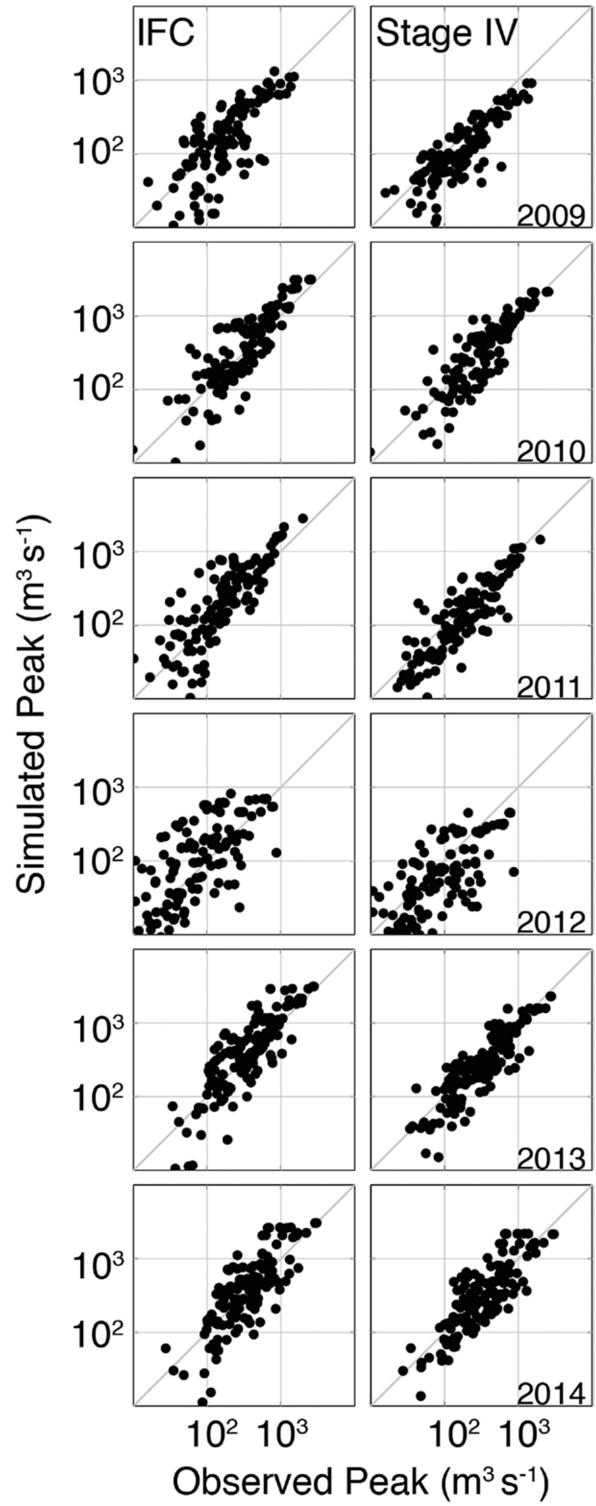


Fig. 10. Comparison of annual peaks, observed vs simulated. The number of dots corresponds to the number of USGS stream gauges used in the analysis.

COMPUTATIONAL ORGANIZATION. The IFC flood forecasting system consists of four interconnected computational subsystems (Fig. 12): IFC Central Database, IFC Forecasting Model, IFC Rainfall System, and IFIS. Although information is exchanged between each subsystem, they operate independently. A failure at one subsystem does not cause failure at another, although a delay in data transfers may occur.

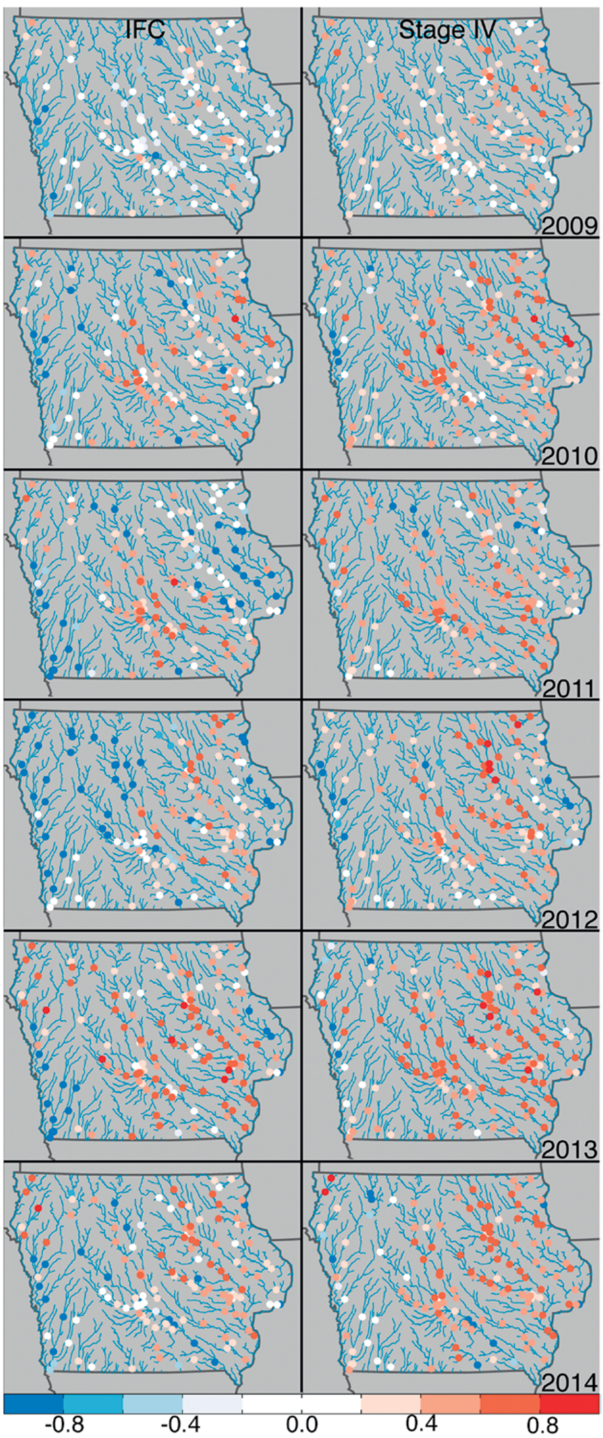


Fig. 11. Maps of NS efficiencies obtained when forcing the model with two different rainfall products.

IFC central database. This subsystem serves as a central repository for data exchanged between the other three subsystems, as well as additional information needed by the subsystems. The IFC Central Database runs a PostgreSQL database and uses PHP (PHP: Hypertext Preprocessor) scripts for communication between the IFC Rainfall System and the IFIS.

Data stored in the IFC Central Database can be divided into two main collections. The first collection generally pertains to data related to the domain and is not modified with any regularity. This includes rainfall rasters, hillslope-link decompositions, hillslope parameters, and IFIS object information. The second collection consists of data grown over time and includes stream gauge and IFC stream-stage sensor data, precipitation estimates, and streamflow forecasts.

IFC forecasting model. This subsystem performs the computations for streamflow forecasting. The program running here is a mixture of C and Python. Computations are performed using the IFC's ASYNCH numerical solvers, and PostgreSQL's libpq library is used for access to the IFC Central Database. Every 15 min, rainfall estimates are pulled from the IFC Central Database and the corresponding 10-day streamflow forecasts for the state are pushed into the IFC Central Database. The IFC Central Database maintains a small history of these forecasts for review.

Each day, a snapshot of the model records the current value of every modeled state; this is stored on the local file system of the Forecasting Model. We use the snapshot to restart the model in the event of a system failure.

The distributed hydrological model uses a 90-m DEM to decompose Iowa into hillslopes and channel links. A system of four differential equations at each of 420,000 hillslopes is solved for each forecast. The channels at the hillslopes are interconnected according to a tree structure, but the model equations are independent at each hillslope.

While the system calculates discharge hydrographs for all 420,000 links, communicating this information directly to the general public would be impractical and meaningless in most locations. Instead, it issues forecasts for over 1,000 Iowa communities located near streams and rivers. Still, since the great majority of those communities lack stream gauges, providing discharge is still not particularly meaningful. To overcome this difficulty, the IFC developed a flood potential index based on scaling principles using long-term streamflow observations and calculating mean flood discharge as a function of drainage area. The index rescales the discharge so that values greater than the mean annual flood (peak flow) indicate imminent flood potential. Therefore, the system presents flood potential as existing (for index > 1) and potentially severe (if index > 2). Similarly, for the locations where there are stage-only measurements, the system cannot convert model-forecast discharge into stage without a rating curve. For those locations, the IFC also provides the index displayed only as a function of time color bar.

For those locations and times where the NWS forecast is available (received in real time as a web service), the system displays only the NWS forecast. For those locations where a rating curve is available, but the NWS forecast is not available, the system displays the IFC forecast.

IFC rainfall system. The Iowa Flood Center acquires real-time streaming radar Level II data (e.g., Kelleher et al. 2007) through the Unidata Local Data Manager (LDM) technology and processes them to create updated rain rate maps every 5 min over a domain somewhat larger than the state of Iowa with spatial resolution of about 500 m. The maps have latency that ranges from 5 to 10 min, of which only 5 min is due to processing time. The maps are available in three formats: first, as images displayed and animated at the Iowa Flood Information portal; second, as binary files used as input to the rainfall–runoff model; and third, as tables in the IFC Central Database. Codes also calculate rainfall accumulation maps as daily and cumulative products that can be viewed by the general public for up to two weeks.

The rainfall estimated over Iowa used to drive the streamflow forecasting model is a radar-only product. The system does not use rain gauge data, as Iowa does not have a high-quality, uniformly distributed network.

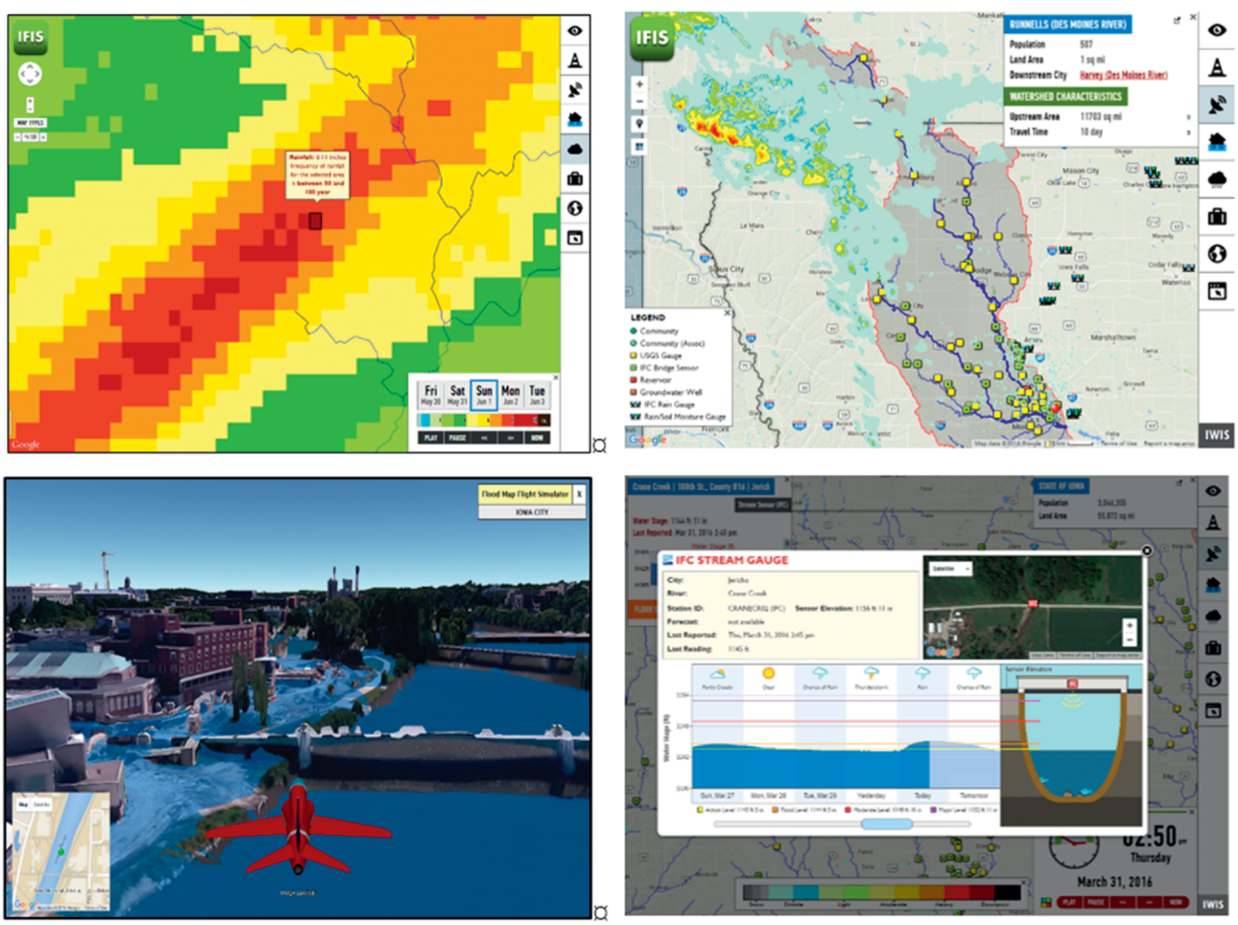


Fig. 12. Screenshots of various tools from the IFIS. The upper left shows probabilistic interpretation of observed daily rainfall. Users can interrogate any pixel and get information on the expected recurrence interval of the given value. The upper right shows a passing storm within a hydrologic context of basin boundaries that correspond to the community of interest. The lower left allows examination of the inundation maps in 3D environment directly from the browser. The lower right shows a cartoonish depiction of the hydrograph obtained from IFC stage sensor data.

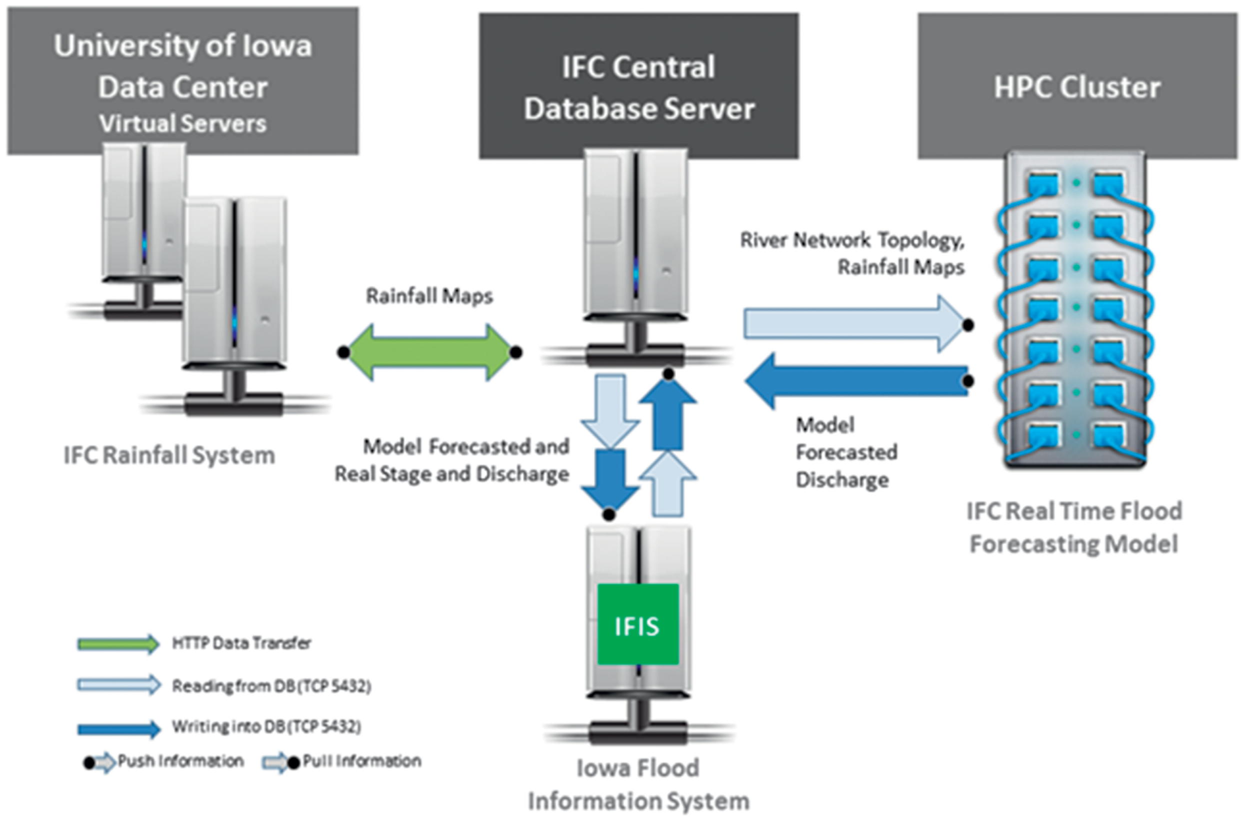


Fig. 13. General computing and data flow architecture of the IFIS modeling system. The University Data Center is a disaster-proof facility where the university keeps sensitive data including the university's hospital and clinics patient records.

Iowa Flood Information System. The IFIS (http://ifis.iowafloodcenter.org) serves as an information dissemination system, with the general public as the target audience. The system has been online since 2011 and undergoes frequent enhancements and improvements. It is a one-stop web platform to share flood-related data and information in an interactive system (Demir and Krajewski 2013). It has over 250,000 users. The IFIS is a modular and integrated system based on the latest web technologies. It integrates data and resources from many sources, including the IFC, NWS, USGS, and U.S. Army Corps of Engineers.

IFIS is optimized for speed and has an intuitive, jargon-free, and modern design with a short learning curve. Custom tools are used to visualize large-scale atmospheric and hydrological real-time data, precomputed objects such as flood inundation maps (Fig. 13), and streamflow forecasts. Information is displayed within a hydrologic context that includes the river network and basin boundaries delineated in a familiar Google Maps environment. It is within IFIS where all the components the IFC has developed come together. In particular, the system allows flood forecasting as inundation maps. While the maps are not computed in real time and are based on steady-state flow assumption, they provide enough georeferenced context to be useful.

From the informatics perspective, IFIS relies on a hybrid of file and computing servers, including a high-performance computing cluster, codes and scripts in different programming languages, data streams through web services, relational databases, and web-based visualization tools. The system processes over 50 GB of hydrological and meteorological data per day from radars and sensors in Iowa. See Fig. 13 for the general architecture of IFIS with connections between systems, data exchange routes, and other details.

DISCUSSION AND FUTURE PLANS. While the IFC provides real-time routine forecasts, it remains an academic research center. As such, it is organized to conduct a wide range of research related to floods. The IFC provides information based on its own tools, but IFC researchers also have a keen interest in concepts, models, and products developed by other groups, and they explore their value for use in Iowa. In this sense, IFC researchers serve as "technical agents" for the state. For example, the IFC is ingesting in real time the Multi-Radar/Multi-Sensor rainfall product developed at the National Severe Storms Laboratory and currently produced at the National Centers for Environmental Prediction (NCEP; Zhang et al. 2016). This input now replaces Stage IV products that the IFC used in parallel with the IFC's own radar rainfall to see the differences in streamflow prediction. Since the IFC model has not been calibrated, we are able to discern problems due to the input as related to the model structure. Several other activities enhancing the value of the IFC system are underway. We discuss them below.

Quantitative precipitation forecasting. Thus far, we have discussed streamflow predictions based on integrating model equations with forcing provided only up to the time of the forecast's issuance (apart from a few minutes delay). Clearly, the forecast skill can be extended by using good QPF to drive the model. However, warm season convective rainfall, the main driver of flooding in the upper Midwest and other areas of the world, is particularly poorly forecasted (Fritsch and Carbone 2004; Sun et al. 2014). Using poor QPF is a good way to lose credibility with the public, and thus, the IFC has tried hard to avoid it. We have engaged with colleagues at Iowa State University to explore the potential for assimilating radar reflectivity data into the initial conditions of a 12-h forecast simulation of the WRF system. Results are reported in Moser et al. (2015).

Rating curve development. To take full advantage of the 230 IFC bridge-mounted stream-stage sensors, corresponding site-specific rating curves are needed to translate discharge into stage and vice versa. The IFC is working with regional agency partners on a pilot project to explore inexpensive ways of developing the rating curves. Investigators are surveying channels at 10 IFC sensor sites that are collocated with USGS gauges where discharge is measured and rating curves exist. We are exploring two methodologies that use hydraulic principles to derive rating curves. The results are promising; although investigators are finding, as expected, that the "synthetic" rating curves are not as accurate as those derived by the USGS, they still add value to stage-only observations. To develop such rating curves statewide will require one-time visits to survey the stream upstream and downstream from each sensor. The IFC looks forward to reporting the final results.

Data assimilation. Assimilating stage and discharge data from IFC sensor locations would help the model track actual streamflow (e.g., Liu et al. 2012). Such data assimilation to correct the states of the model requires rating curves. The IFC has developed a data assimilation procedure based on minimization of mean square deviation between the model forecasts and the observed discharge but is not yet using it operationally. Tests indicate the benefits of the procedure, to no surprise, but a comprehensive evaluation remains to be done. It is clear that as the number of stream gauges and the corresponding rating curves increases, the forecasting skill will also improve, in some cases considerably.

Relation to the National Water Model. The National Water Model (Maidment 2017) will use the spatially distributed structure based on the NHD Plus digital resources. At highest resolution, these resources constitute small basins that range in size from 0.03 to 7.9 km^2 and average 1.6 km^2 over Iowa (Quintero and Krajewski 2016, manuscript submitted to *J. Amer. Water Resour. Assoc.*). Since they are based on DEM processing, in principle they "fit" the IFC model structure. The difference is that the IFC model further resolves the NHD Plus units. At scales larger than the NHD Plus, the two models should integrate to the same points on the river network, for example, the locations of USGS stream gauges. In addition to resolution, the two models differ with respect to runoff generation and routing components. However, the IFC model should be considered more as a modeling *system* than a fixed model. The architecture is flexible, and researchers have already demonstrated that they can run simulations using WRF-Hydro runoff and IFC routing (M. ElSaadani 2016, personal communication).

Because of these features, the IFC model presents an opportunity for the NWC to test its approach in Iowa, where there is an alternative model using a similar, but sufficiently different, approach. A unique feature of the IFC model is that it has not been calibrated. Contrary to the dominant culture in the hydrologic model development community and the past practice of the NWS, we claim that large-scale, high-resolution distributed models cannot be calibrated. There are simply too many degrees of freedom and too many sources of uncertainty (see Gupta 2004; Fatichi et al. 2016). Therefore, tuning model parameters must be replaced with changing the model components and/or structure. This is easier if alternative components are available. These need to include the inputs, rainfall in particular, and processes. The evaluation frameworks need to include different diagnostic components and model response tracking strategies. The IFC is developing both. Working together, the NWC and IFC could leverage the ~5 years of IFC operation and the many novel aspects of the IFC model. Such collaboration would offer the opportunity to intercompare model structures, components, and forcings for a "regional assessment" of water resources forecasting approaches in the Midwest with broader application to the rest of the United States.

ACKNOWLEDGMENTS. The authors would like to acknowledge the wisdom and foresight of the Iowa legislators who, in the aftermath of the 2008 catastrophe, recognized the expertise resident at the University of Iowa and established the IFC and provided funding for its operation. We also acknowledge all our colleagues at the IFC as well as collaborators at Iowa State University and at state and federal agencies operating in Iowa. The authors would like to use this opportunity to thank Dr. Louis Uccellini, Director of NWS, for visiting the IFC in October 2014. He called IFC a "tremendous resource." Following the lead author, the coauthors are listed in alphabetical order.

REFERENCES

Ayalew, T. B., W. F. Krajewski, and R. Mantilla, 2014a: Connecting the power-law scaling structure of peak-discharges to spatially variable rainfall and catchment physical properties. *Adv. Water Resour.*, **71**, 32–43, doi:10.1016/j.advwatres.2014.05.009.

——, ——, ——, and S. J. Small, 2014b: Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge. *Adv. Water Resour.*, **64**, 9–20, doi:10.1016/j.advwatres.2013.11.010.

Budikova, D., J. S. M. Coleman, S. A. Strope, and A. Austin, 2010: Hydroclimatology of the 2008 Midwest floods. *Water Resour. Res.*, **46**, W12524, doi:10.1029/2010WR009206.

Cunha, L. K., P. V. Mandapaka, W. F. Krajewski, R. Mantilla, and A. A. Bradley, 2012: Impact of radar-rainfall error structure on estimated flood magnitude across scales: An investigation based on a parsimonious distributed hydrological model. *Water Resour. Res.*, **48**, W10515, doi:10.1029/2012WR012138.

——, J. A. Smith, W. F. Krajewski, M. L. Baeck, and B.-C. Seo, 2015: NEXRAD NWS polarimetric product evaluation for IFloodS. *J. Hydrometeor.*, **16**, 1676–1699, doi:10.1175/JHM-D-14-0148.1.

David, C. H., D. Gochis, D. R. Maidment, W. Yu, D. N. Yates, and Z.-L. Yang, 2009: Using NHDPlus as the land base for the Noah-distributed model. *Trans. GIS*, **13**, 363–377, doi:10.1111/j.1467-9671.2009.01169.x.

——, D. R. Maidment, G.-Y. Niu, Z.-L. Yang, F. Habets, and V. Eijkhout, 2011: River network routing on the NHDPlus dataset. *J. Hydrometeor.*, **12**, 913–934, doi:10.1175/2011JHM1345.1.

Demir, I., and W. F. Krajewski, 2013: Towards an adaptive flood information system: Integrated data access, analysis and visualization. *Environ. Modell. Software*, **50**, 77–84, doi:10.1016/j.envsoft.2013.08.009.

——, H. Conover, Y. He, M. McEniry, W. F. Krajewski, B.-C. Seo, R. Goska, and W. Petersen, 2015: Data enabled field experiment planning, management and research using cyberinfrastucture. *J. Hydrometeor.*, **16**, 1155–1170, doi:10.1175/JHM-D-14-0163.1.

DHI, 2014: MIKE FLOOD 1D-2D modeling user manual. 162 pp. [Available online at www.dhigroup.com.]

Fatichi, S., and Coauthors, 2016: An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. *J. Hydrol.*, **537**, 45–60, doi:10.1016/j.jhydrol.2016.03.026.

Fritsch, J. M., and R. E. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Bull. Amer. Meteor. Soc.*, **85**, 955–965, doi:10.1175/BAMS-85-7-955.

Gilles, D., N. C. Young, H. Schroeder, J. Piotrowski, and Y. Chang, 2012: Inundation mapping initiatives of the Iowa Flood Center: Statewide coverage and detailed urban flooding analysis. *Water*, **4**, 85–106, doi:10.3390/w4010085.

Gupta, V. K., 2004: Emergence of statistical scaling in floods on channel networks from complex runoff dynamics. *Chaos Solitons Fractals*, **19**, 357–365, doi:10.1016/S0960-0779(03)00048-1.

——, S. L. Castro, and T. M. Over, 1996: On scaling exponents of spatial peak flows from rainfall and river network geometry. *J. Hydrol.*, **187**, 81–104, doi:10.1016/S0022-1694(96)03088-0.

——, R. Mantilla, B. M. Troutman, D. Dawdy, and W. F. Krajewski, 2010: Generalizing a nonlinear geophysical flood theory to medium-sized river networks. *Geophys. Res. Lett.*, **37**, L11402, doi:10.1029/2009GL041540.

Homer, C., and Coauthors, 2007: Completion of the 2001 National Land Cover Database for the conterminous United States. *Photogramm. Eng. Remote Sensing*, **73** (4), 337–341.

Iowa LiDAR Consortium, 2016: Iowa LiDAR Project—LAS and ASCII files. Iowa Department of Natural Resources Natural Resources Geographic Information System metadata, accessed 17 March 2016. [Available online at ftp://ftp.igsb.uiowa.edu/GIS_library/Projects/Iowa_LiDAR/Block_data/Lidar_LAS_ASCII.html.]

Kelleher, K. E., and Coauthors, 2007: Project CRAFT: A real-time delivery system for NEXRAD level II data via the internet. *Bull. Amer. Meteor. Soc.*, **88**, 1045–1057, doi:10.1175/BAMS-88-7-1045.

Krajewski, W. F., A. Kruger, S. Singh, B.-C. Seo, and J. A. Smith, 2013: Hydro-NEXRAD-2: Real-time access to customized radar-rainfall for hydrologic applications. *J. Hydroinform.*, **15**, 580–590, doi:10.2166/hydro.2012.227.

Kruger, A., W. F. Krajewski, J. J. Niemeier, D. L. Ceynar, and R. Goska, 2016: Bridge-Mounted River Stage Sensors (BMRSS). *IEEE Access*, **4**, 8948–8966, doi:10.1109/ACCESS.2016.2631172..

Lai, Y., 2008: SRH-2D version 2: Theory and user's manual. U.S. Bureau of Reclamation, 97 pp. [Available online at www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/Manual-SRH2D-v2.0-Nov2008.pdf.]

Linhart, S. M., and D. A. Eash, 2010: Floods of May 30 to June 15, 2008, in the Iowa River and Cedar River basins, eastern Iowa. USGS Open-File Rep. 2010-1190, 99 pp. [Available online at http://pubs.usgs.gov/of/2010/1190/pdf/of2010-1190.pdf.]

Liu, Y., and Coauthors, 2012: Advancing data assimilation in operational hydrologic forecasting: progresses, challenges and emerging opportunities. *Hydrol. Earth Syst. Sci.*, **16**, 3863–3887, doi:10.5194/hess-16-3863-2012.

Maidment, D. R., 2017: Conceptual framework for the National Flood Interoperability Experiment. *J. Amer. Water Resour. Assoc.*, doi:10.1111/1752-1688.12474, in press.

Mantilla, R., and V. K. Gupta, 2005: A GIS numerical framework to study the process basis of scaling statistics in river networks. *IEEE Geosci. Remote Sens. Lett.*, **2**, 404–408, doi:10.1109/LGRS.2005.853571.

——, ——, and O. J. Mesa, 2006: Role of coupled flow dynamics and real network structures on Hortonian scaling of peak flows. *J. Hydrol.*, **322**, 155–167, doi:10.1016/j.jhydrol.2005.03.022.

——, ——, and B. M. Troutman, 2011: Scaling of peak flows with constant flow velocity in random self-similar networks. *Nonlinear Processes Geophys.*, **18**, 489–502, doi:10.5194/npg-18-489-2011.

McKay, L., T. Bondelid, A. Rea, C. Johnston, R. Moore, and T. Deward, 2012: NHDPlus version 2: User guide. Horizon Systems Corp., 182 pp. [Available online at ftp://ftp.horizon-systems.com/nhdplus/NHDPlusV21/Documentation/NHDPlusV2_User_Guide.pdf.]

Menabde, M., and M. Sivapalan, 2001: Linking space–time variability of river runoff and rainfall fields: A dynamic approach. *Adv. Water Resour.*, **24**, 1001–1014, doi:10.1016/S0309-1708(01)00038-0.

Mitchell, K. E., and Coauthors, 2004: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res.*, **109**, D07S90, doi:10.1029/2003JD003823.

Moser, B., W. A. Gallus Jr., and R. Mantilla, 2015: An initial assessment of radar data assimilation on warm season rainfall forecasts for use in hydrologic models. *Wea. Forecasting*, **30**, 1491–1520, doi:10.1175/WAF-D-14-00125.1.

Mutel, C., 1998: *Flowing through Time: A History of the Iowa Institute of Hydraulic Research*. University of Iowa, 299 pp.

——, 2010: *A Watershed Year: Anatomy of the Iowa Floods of 2008*. University of Iowa Press, 250 pp.

Nash, J. E., and J. V. Sutcliffe, 1970: River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.*, **10**, 282–290, doi:10.1016/0022-1694(70)90255-6.

O'Callaghan, J. F., and D. M. Mark, 1984: The extraction of drainage networks from digital elevation data. *Comput. Vision Graph. Image Process.*, **28**, 323–344, doi:10.1016/S0734-189X(84)80011-0.

Quintero, F., W. F. Krajewski, R. Mantilla, S. Small, and B.-C. Seo, 2016: A spatial–dynamical framework for evaluation of satellite rainfall products for flood prediction. *J. Hydrometeor.*, **17**, 2137–2154, doi:10.1175/JHM-D-15-0195.1.

Rinaldo, A., and I. Rodríguez-Iturbe, 1996: Geomorphological theory of the hydrological response. *Hydrol. Processes*, **10**, 803–829, doi:10.1002/(SICI)1099-1085(199606)10:6<803::AID-HYP373>3.0.CO;2-N.

Seo, B.-C., and W. F. Krajewski, 2015: Correcting temporal sampling error in radar-rainfall: Effect of advection parameters and rain storm characteristics on the correction accuracy. *J. Hydrol.*, **531**, 272–283, doi:10.1016/j.jhydrol.2015.04.018.

——, ——, A. Kruger, P. Domaszczynski, J. A. Smith, and M. Steiner, 2011: Radar-rainfall estimation algorithms of Hydro-NEXRAD. *J. Hydroinform.*, **13**, 277–291, doi:10.2166/hydro.2010.003.

——, L. K. Cunha, and W. F. Krajewski, 2013: Uncertainty in radar-rainfall composite and its impact on hydrologic prediction for the eastern Iowa flood of 2008. *Water Resour. Res.*, **49**, 2747–2764, doi:10.1002/wrcr.20244.

——, B. Dolan, W. F. Krajewski, S. Rutledge, and W. Petersen, 2015a: Comparison of single and dual polarization based rainfall estimates using NEXRAD data for the NASA Iowa Flood Studies Project. *J. Hydrometeor.*, **16**, 1658–1675, doi:10.1175/JHM-D-14-0169.1.

——, W. F. Krajewski, and K. V. Mishra, 2015b: Using the new dual-polarimetric capability of WSR-88D to eliminate anomalous propagation and wind turbine effects in radar-rainfall. *Atmos. Res.*, **153**, 296–309, doi:10.1016/j.atmosres.2014.09.004.

Small, S. J., J. O. Laurent, R. Mantilla, R. Curtu, L. K. Cunha, M. Fonley, and W. F. Krajewski, 2013: An asynchronous solver for systems of ODEs linked by a directed tree structure. *Adv. Water Resour.*, **53**, 23–32, doi:10.1016/j.advwatres.2012.10.011.

Smith, J. A., M. L. Baeck, G. Villarini, D. B. Wright, and W. F. Krajewski, 2013: Extreme flood response: The June 2008 flooding in Iowa. *J. Hydrometeor.*, **14**, 1810–1825, doi:10.1175/JHM-D-12-0191.1.

Sun, J., and Coauthors, 2014: Use of NWP for nowcasting convective precipitation: Recent progress and challenges. *Bull. Amer. Meteor. Soc.*, **95**, 409–426, doi:10.1175/BAMS-D-11-00263.1.

USACE, 2011: HEC-GeoRAS: GIS Tools for Support of HEC-RAS using ArcGIS. U.S. Army Corps of Engineers, 244 pp. [Available online at www.hec.usace.army.mil/software/hec-georas/documentation/HEC-GeoRAS_43_Users_Manual.pdf.]

——, 2016: HEC-RAS: River analysis system, user's manual. U.S. Army Corps of Engineers, 790 pp. [Available online at www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%20Users%20Manual.pdf.]

USIACWD, 1982: Guidelines for determining flood flow frequency. Bulletin 17-B of the Hydrology Subcommittee, U.S. Interagency Advisory Committee on Water Data, 183 pp. [Available online at http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf.]

Villarini, G., J. A. Smith, M. L. Baeck, and W. F. Krajewski, 2011: Examining flood frequency distributions in the Midwest U.S. *J. Amer. Water Resour. Assoc.*, **47**, 447–463, doi:10.1111/j.1752-1688.2011.00540.x.

——, B.-C. Seo, F. Serinaldi, and W. F. Krajewski, 2014: Spatial and temporal modelling of radar rainfall uncertainties. *Atmos. Res.*, **135–136**, 91–101, doi:10.1016/j.atmosres.2013.09.007.

Zhang, J., and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation: Initial operating capabilities. *Bull. Amer. Meteor. Soc.*, **97**, 621–637, doi:10.1175/BAMS-D-14-00174.1.