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Real-Time Flood Forecasting for River Crossings

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MATC

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16. Abstract

We have developed a generic prototype of a flood-forecasting model transferable to other locations around the Midwest to provide monitoring and forecasting flood potential at critical infrastructure points, such as bridges, where streamflow gauges are not available. A real-time web-based visualization platform to display the model predictions has been implemented. The platform will display the river network upstream from a point of interest and a time control slider that will allow exploring the evolution of flows everywhere in the network over the past several days, and about a week into the future. The model uses in-house developed radar-rainfall maps updated every 5 minutes with the spatial resolution of about 0.5 km currently covering the Iowa domain and extending some 100 km into the neighboring states. For future rainfall, we use predictions for the National Weather Service High-Resolution Rapid Refresh (HRRR) forecasting system. The system provides hourly accumulation products for up to 20 hours ahead. Our system expands the forecasting capabilities of the current NWS by providing predictions at locations that have not been historically gauged.

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Mid-America Transportation Center (MATC)
Nebraska Transportation Center (NTC)

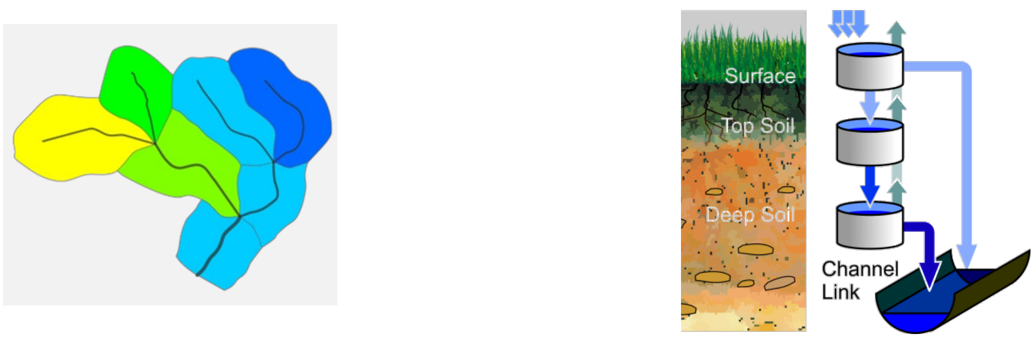
Disclaimer

Abstract

We have developed a generic prototype of a flood-forecasting model transferable to other locations around the Midwest to provide monitoring and forecasting flood potential at critical infrastructure points, such as bridges, where streamflow gauges are not available. A real-time web-based visualization platform to display the model predictions has been implemented. The platform will display the river network upstream from a point of interest and a time control slider that will allow exploring the evolution of flows everywhere in the network over the past several days, and about a week into the future. The model uses in-house developed radar-rainfall maps updated every 5 minutes with the spatial resolution of about 0.5 km currently covering the Iowa domain and extending some 100 km into the neighboring states. For future rainfall, we use predictions for the National Weather Service High-Resolution Rapid Refresh (HRRR) forecasting system. The system provides hourly accumulation products for up to 20 hours ahead. Our system expands the forecasting capabilities of the current NWS by providing predictions at locations that have not been historically gauged.

Chapter 1 Preliminaries: The Iowa Flood Center HLM Hydrological Model

The Iowa Flood Center hydrological model, Hillslope-Link Model (HLM), is a distributed hillslope-scale rainfall-runoff model that partitions Iowa into over three million individual control volumes following the landscape decomposition outlined in Mantilla and Gupta (2005). The model is parsimonious, using ordinary differential equations to describe transport between adjacent control volumes. This characteristic reduces the computational resources needed by capturing the most essential features of the rainfall runoff transformation; it uses only a few parameters to obtain acceptable results. The model partitions the river network into river links (the portion of a river channel between two junctions of a river network) and the landscape into hillslopes (adjacent areas that drain into the links).



(a) (b)

Figure 1.1 (a) illustration of landscape decomposition into hillslopes and decomposition of the river network into channel link and (b) vertical soil profile and control volumes included in the hydrological model

Mass conservation equations give rise to the system of coupled nonlinear ordinary differential equations that represent changes in the water storage in the hillslope surface (s_{surf}), top soil (s_{tops}), and deep soil (s_{deeps}) given by,

$$\begin{cases} \frac{ds_{surf}(t)}{dt} = p(t) - q_{runoff}(t) - q_{infil}(t) - e_{surf}(t) & (1.1) \\ \frac{ds_{tops}(t)}{dt} = q_{infil}(t) - q_{percol}(t) - e_{tops}(t) & (1.2) \\ \frac{ds_{deeps}(t)}{dt} = q_{percol}(t) - q_{baseflow}(t) - e_{deeps}(t) & (1.3) \end{cases}$$

Fluxes in, across, and out of the vertical hillslope control volumes include precipitation $p(t)$, overland runoff q_{runoff}(t), infiltration into the topsoil q_{infil}, percolation from the topsoil into the deeper soils q_{percol}(t), baseflow into the channel $q_{baseflow}$(t), and evaporation from the ponded, topsoil, and deep soil layers (e_{surf}(t), e_{tops}(t), and e_{deeps}(t), respectively). The model assumes percolation flux is a linear function of the amount of water stored at time t in the topsoil $q_{percol}=k_{percol}\cdot s_{tops}$ and the baseflow is a linear function of the water stored in deep soil $q_{baseflow}=k_{baseflow}\cdot s_{deeps}$. Overland runoff is a power function of the water stored on the hillslope surface (consistent with Manning's equation) given by,

$$q_{runoff} = k_{runoff} s_{surf}^{1.67} \tag{1.4}$$

and infiltration is a nonlinear function of soil moisture content (s_{tops}/T_{tops}), where T_{tops} is the thickness of the topsoil layer (i.e., A-horizon) and a linear function of hydraulic head s_{surf} given by,

$$q_{infil} = k_{dry}\left(1 - \frac{s_{tops}}{T_{tops}}\right)^{\phi} s_{surf} \tag{1.5}$$

where k_{dry} corresponds to the case of dry soil and, similarly to k_{runoff}, k_{percol}, and $k_{baseflow}$ can be interpreted as time constant (residence time) of the respective storage component. The hillslope area (a_h) for the elements in the distributed model is on average 0.05 km², and link length (l_{link}) is on average 400 m. Note that $a_h/(2l_{link})$ is the hillslope length. The exponent φ is a nonlinearity introduced by the change in the potential matric of the soil column as soil moisture changes with time.

The HLM should be thought of as a modeling system rather than a single specific model. As the equations describing hillslope-scale processes are separated from the numerical solver, it is rather easy to explore different mathematical descriptions for water fluxes. For example, one can consider such simplifications as constant runoff coefficient or water transport velocity, or as an alternative, one can formulate these components based on the available physical characteristics.

Water transport through the river network is nonlinear and governs how channel links propagate flows through the river network. Formulated in the context of a mass conservation equation developed by Gupta and Waymire (1998), it uses the water velocity parameterization given by Mantilla (2007) as,

$$\frac{dq_{link}(t)}{dt} = \frac{v_0 q_{link}^{\lambda_1}(t) A^{\lambda_2}}{(1-\lambda_1)l}\left[a_h\left(k_{runoff} s_{surf}^{1.67}(t) + k_{baseflow} s_{deeps}(t)\right) - q_{link}(t) + q_1(t) + q_2(t)\right] \tag{1.6}$$

Where q_{link} = discharge from link at time t

a_h = total hillslope area draining to link

$q_1(t)$ and $q_2(t)$ = incoming flows of the upstream tributaries

A = upstream basin area

λ_1, λ_2, and v_0 = global parameters of the water velocity component of the model;

$\lambda_1 = 0.2$; $\lambda_2 = -0.1$; and $v_0 = 0.3$

The model can capture the main features of the hydrographs including the maximum stage. We used the model in several studies (e.g., Ayalew et al. 2014; Cunha et al. 2012). We also discuss the model performance in Krajewski et al. (2017). The model is driven by radar-rainfall estimated from Level II NEXRAD data from seven WSR-88D weather radars covering the state of Iowa. The maps of rainfall intensity have spatial resolution of about 0.25 km^2 and are updated every five minutes. The algorithms are described in Krajewski et al. (2013) and Seo and Krajewski (2015).

An important aspect of our modeling approach is the avoidance of calibration. Instead, we rely on detailed information on the physical properties we model. This includes the topography, land use and land cover, soil properties, and details of the main forcing, i.e., precipitation. Comparing simulation results to streamflow observations across Iowa validates the model formulation and parameterization. Therefore, we can view the model as data-intensive and calibration-free when used in forecast-mode. This in turn implies the model will work better with more detailed, relevant, and accurate data, including model states and physical domain characterization as well as the driving inputs. The model is fully automatic in the sense that no corrections are applied to the model as it moves forward in time once initial and boundary conditions are imposed.

The model predicts the streamflow fluctuations associated with storm events over the catchment of interest using current observations of rainfall, and rainfall forecasts. The effect of storms on river ways is usually delayed for a time ranging from days to weeks. Each point of interest in the landscape (bridge, culvert) can then be categorized according to the maximum warning time. The web interface will provide a visual tool to show when a particular location will be impacted, and it will provide an inundation map associated to the particular peak flow expected for that location. Inundation maps are more effective tools in communicating the effects of flooding than crest stages at specific locations.

Chapter 2 Incorporate Critical Bridges as Forecast Locations into the Forecasting System

The hydrological model that is the basis for the flood forecasting system provides predictions everywhere in the river network, however, not all points in the river network can be compared against observation. The Iowa Flood Center has developed an inexpensive stream level gauge that uses a sonic device to monitor rivers in real time. We have used a few locations where these instruments have been installed to test the performance of the model predictions at relevant bridge crossings. The locations shown in Figure 2.1 have been selected for continuing monitoring of model performance at road crossings

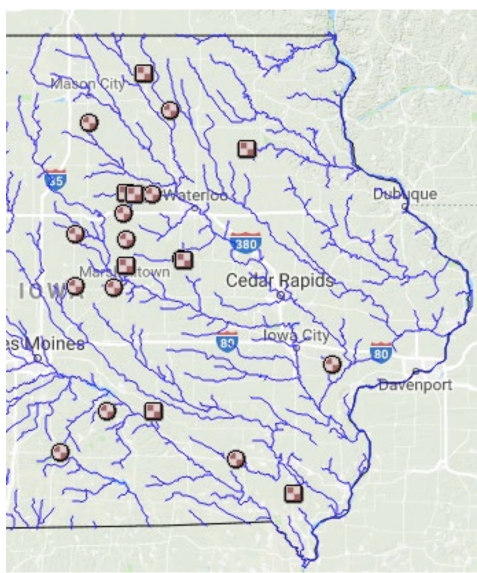


Figure 2.1 Road Crossing locations where IFC sensors have been installed being used as prototype testing sites

2.1 Comparison of Hydrographs at River Crossings

An interface has been developed to compare stage observations at the road/river crossing. A synthetic rating curve developed as part of a parallel project was used to determine river elevations from estimated discharges. In Figure 2.2 an example is shown for the stage hydrograph at the US218 crossing over Spring Creek. The black line is observation and the green hydrographs is the model estimated fluctuation. The interface allows visualizing of the performance of the model in a quick and real-time fashion as streamflow fluctuations occur. A full presentation of model evaluation at the selected locations is beyond the scope, however, our current developments serve as a test case that shows that any location of interest can be incorporated into the system and monitored continuously.

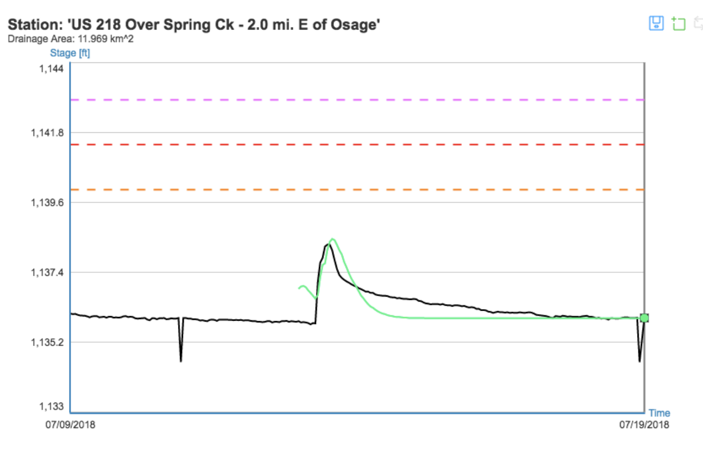


Figure 2.2 Comparison of the observed stage hydrograph at the US218 crossing over Spring Creek. The black line is observation and the green hydrographs is the model estimated fluctuation.

Before the start of this project our real-time forecasting system provided forecasts in the form of a flood potential index for 1600 riverine communities in Iowa. We have updated our databases to include the location of critical bridges and have restructured our forecasting system to provide forecasts at such locations.

The incorporation of new points of interest into our system is a major milestone on our overall goal of creating a flexible system that can be transferred to other states in the Midwest. The other major development that we have been investigating is the availability of information for the four states involved in MATC.

First, the river network that drains the four states that support MATC. In Figure 2.3 a coarse version of the river network over the four states is shown. The river network has been organized into our databases to provide a mechanism to implement the hydrological model using a realistic representation of the river network. A recent paper by Krajewski et al. 2017 illustrates the key ingredients that go into model configuration. Note that the "water domain" of the four states includes rivers in Wyoming and Colorado. The network does not include rivers that drain into the Missouri River as it enters Nebraska or the Mississippi River as it enters Iowa. Our forecasting system does not model those major streams because they are heavily regulated and fluctuations are not controlled by natural processes but by more predictable river management policies and rules.

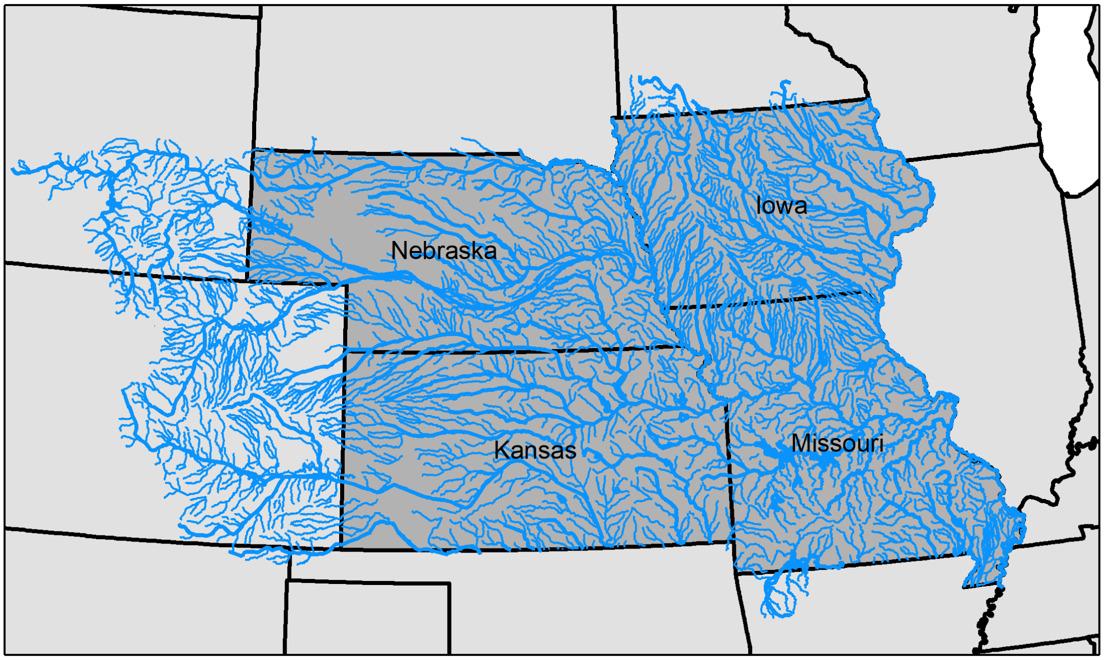


Figure 2.3 River network for the four states that support MATC. An accurate representation of the drainage network system is the most fundamental aspect of model implementation using the technologies developed by the Iowa Flood Center.

Second, in order to validate any hydrological model implemented for a particular region is the availability of streamflow gauges. Figure 2.4 shows locations that are gauged in the four states that support MATC. There are over 500 USGS gauging sites that can be used in model validation sites. The information for these sites have been incorporated into our databases for future activities related to model development and model validation.

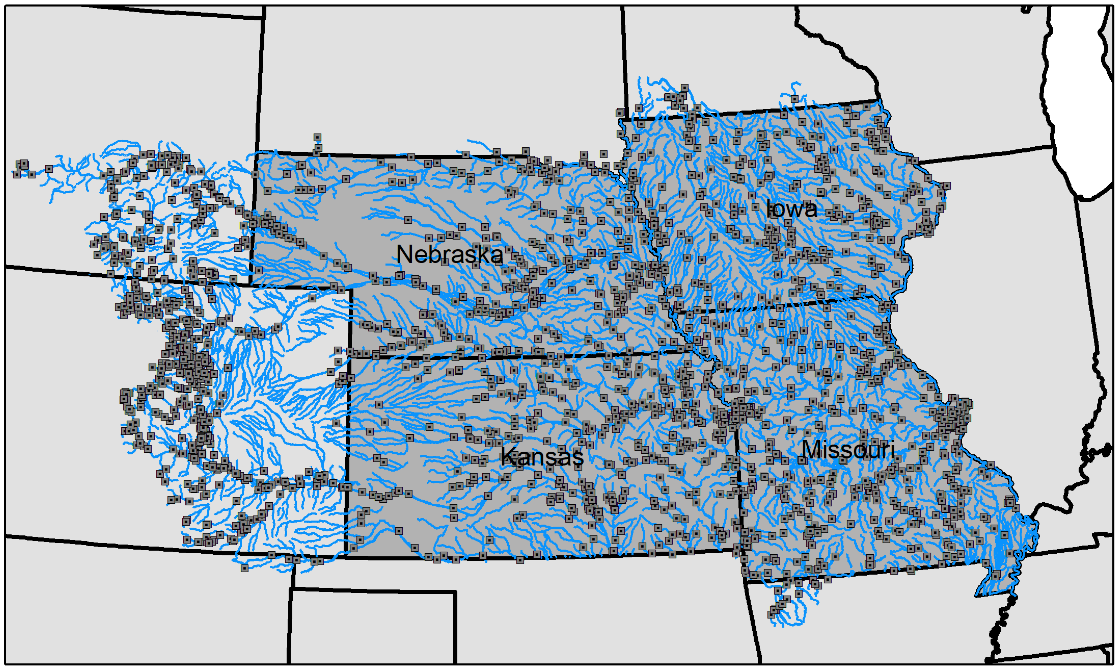


Figure 2.4 Location of USGS gauges in the four states four states that support MATC. All states are well covered by gauging sites which provide a significant set of points for model evaluation.

Third, and finally, we have verified the availability of real-time precipitation products over the four states that support the MATC. The national MRMS product is available over the four states and the initial reports of accuracy are promising. Although validation and implementation activities are beyond the scope of the report, we are encouraged by the availability of all the elements needed for the implementation of our tools across the Midwest.

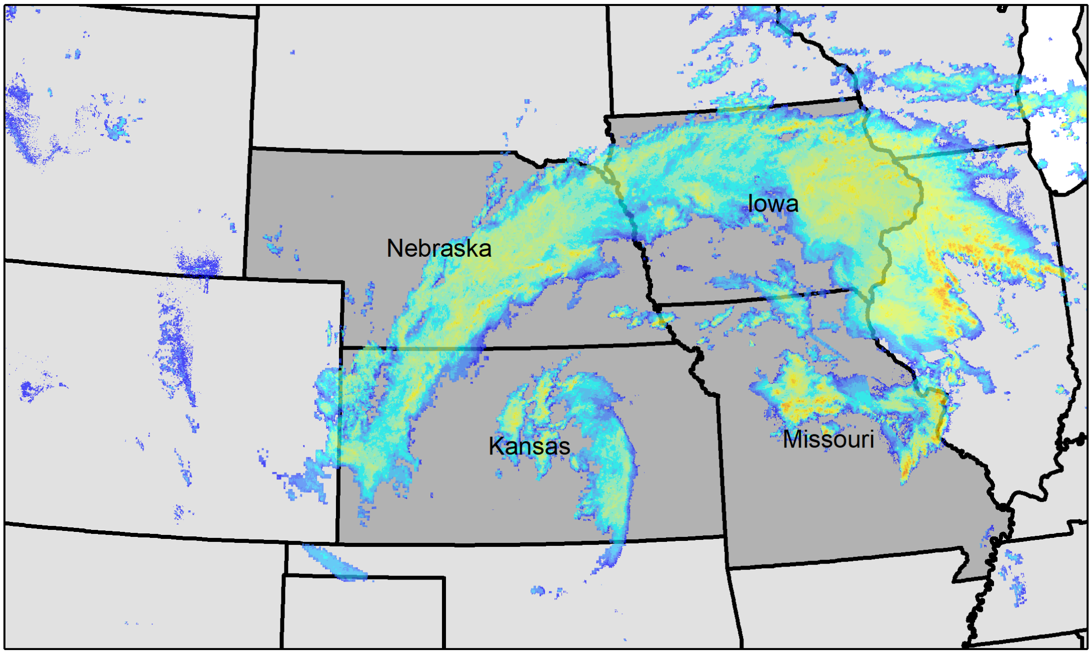


Figure 2.5 A view of the national radar-based rainfall product MRMS over the four states that support the MATC. Coverage of rainfall using the array of NEXRAD radars is the second most important ingredient needed to configure the hydrological models developed at the Iowa Flood Center.

Chapter 3 Implementation of Web Based Graphical User Interface for the Evolution of Forecasted Floods

We have implemented hydroinformatics tools to provide a user friendly and accessible interface for executing and assessing the output of real-time flood forecasts using distributed hydrological models. The main result is the implementation of a web system that uses an Iowa Flood Information System (IFIS)-based environment for graphical displays of rainfall-runoff simulation results for both real-time and past storm events. It communicates with ASYNCH ODE solver to perform large-scale distributed hydrological modeling based on segmentation of the terrain into hillslope-link hydrologic units. The cyber-platform also allows hind-cast of model performance by testing multiple model configurations and assumptions of vertical flows in the soils. The scope of the currently implemented system is the entire set of contributing watersheds for the territory of the state of Iowa. The interface provides resources for visualization of animated maps for different water-related modeled states of the environment, including flood-waves propagation with classification of flood magnitude, runoff generation, surface soil moisture and total water column in the soil. Additional tools for comparing different model configurations and performing model evaluation by comparing to observed variables at monitored sites are also available. The user-friendly interface has been published to the web under the URL http://s-iihr50.iihr.uiowa.edu/ifis/sc/test1/ihmis/dev/frontend/code/site/.

3.1 Visualization of Flood Level Estimates

The Iowa Flood Information System has been expanded and reorganized with an extended set of tools for evaluation of flood forecasts. Our interface reports the estimated flood condition at all points in the river network. Color indicators are used to provide a visual representation of the level of rivers as seen in Figure 3.1. The interface shows five colors in the river network associated to flood levels with the lowest being yellow, which indicates that water is close to the river bank, and purple indicating that a major flood is occurring at the locality. Rainfall is color coded independently and the two legends are shown simultaneously.

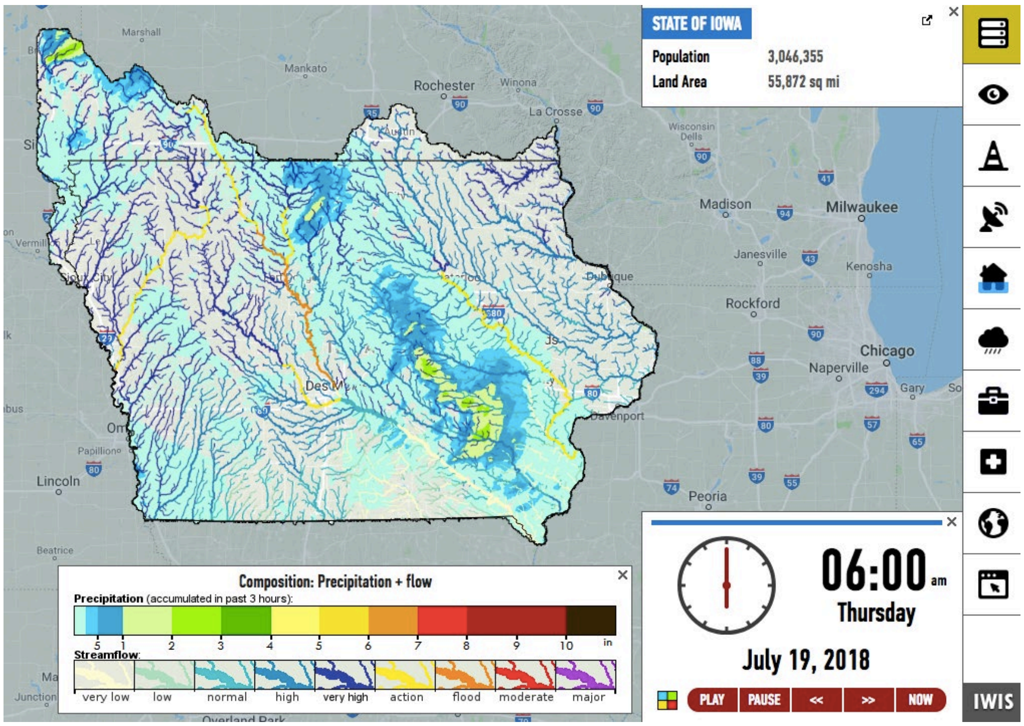


Figure 3.1 Color coded flood levels estimated for the river network in Iowa. The map also shows the current 3-hour accumulation of rainfall over the state.

Integration between models and GIS systems may be performed adopting a loose, tight or embedded coupling approach. In a loose approach, the implementation of the mathematical model and the GIS tools are presented in two different platforms with independent user interfaces that communicate to each other through files. Tight coupling is characterized by the sharing of a user interface and a data model between the hydrological model and the GIS toolset. In an embedded approach, the geo-spatial information system and the hydrological model share the same runtime environment and the GIS components are capable of performing intra-simulation modifications (Bhatt, 2014). The computational power requirements for solving hydrological simulations on a state scale for Iowa and the interest in presenting a web-based user interface lead to the adoption of a loose coupling approach for our tool. The entire tool is composed of a set of components distributed among three different servers, each one performing groups of procedures with logically high cohesion - a modularization that follows the software principle of Separation of Concerns (SoC; Laplante and Phillip, 2007).

The frontend component is composed of a web system implemented using PHP as the server-side programming language and Javascript with complementary libraries such as JQuery (for general enhancements on user experience), Google Maps API (for geospatial data presentation), and Baidu EChart (for plotting dynamic and interactive graphs) as main client-side programing languages. The server in which it is stored is designed to optimize the response for user HTTP external requests, so the data provided for this component is expected to be reduced in size and optimized for querying.

The backend is split into two components. The simulation component consists of a set of Linux bash scripts designed for responding to the frontend requests of new simulations and to trigger the expected HLM-Asynch hydrological model runs. It is stored on a High Performance Computing cluster which provides an MPI environment with processing cores of 56 parallel nodes.

Streamflow forecasts are typically made for specific locations and the forecast is presented to stakeholders in the form of hydrographs. Our flood forecasting model allows us to query current and future streamflow at all locations in the river network, which can be translated into maps and animations of flood evolution in the river network. We anticipate that this type of graphical representation will provide planners and first responders with a more intuitive tool to manage, prioritize, and respond to road closures as the flood evolves.

Chapter 4 Implementation of a Comprehensive Evaluation System

A key question is "how accurate are the estimates from hydrological models?" To this end we have collected information from gauged sites by the USGS to compare our hydrographs to direct observations. These data allow us to compute error metrics for the estimated hydrographs at sites where observations are available.

4.1 Tools for Real-Time and Retrospective Model Evaluation

As a flood-focused tool, only the discharge component of model outputs is initially being evaluated. Two different traditional methods were implemented for such: Nash-Sutcliffe coefficients spatial location and hydrograph plotting.

The evaluation by Nash-Sutcliffe coefficient has the objective of providing insights on the visual distribution of the efficiency of a model simulation. For each evaluated site in a simulation that goes from time *t*=1 to *t*=T, where T is the simulation period, an efficiency coefficient E_{NS} is calculated using the classical methodology presented by Nash and Sutcliffe (1970), which is given by

$$E_{NS} = 1 - \frac{\sum_{t=1}^{T}\left((Q_m^t)^2-(Q_o^t)^2\right)}{\sum_{t=1}^{T}\left((Q_o^t)^2-(\overline{Q_o})^2\right)} \qquad (4.1)$$

where Q_m^t = discharge model result for time t

Q_o^t = observed discharge for time t

$\overline{Q_o}$ = mean of observations registered from time t=1 to t=T

The E_{NS}value translated into classes ranging from -2 (bad performance) to 1.0 (perfect matching) and then the E_{NS} value for all sites is plotted simultaneously in a map. This approach permits a fast observation of potential regionalization of performance of a model but does not provide information regarding the time variance of efficiency. In order to do that, the user can access model hydrographs in which both observations and models are presented. Because the tool is focused on flood event scenarios, water stage is used instead of traditional discharge and conversions are performed using pre-defined rating curves. An additional and element of the plotting is the set of threshold lines for stages classified by the National Weather Service (NWS) as action, flood, moderate flood, and major flood (NWS, 2016). Examples of usage of the NS index can be seen in figure 4.1

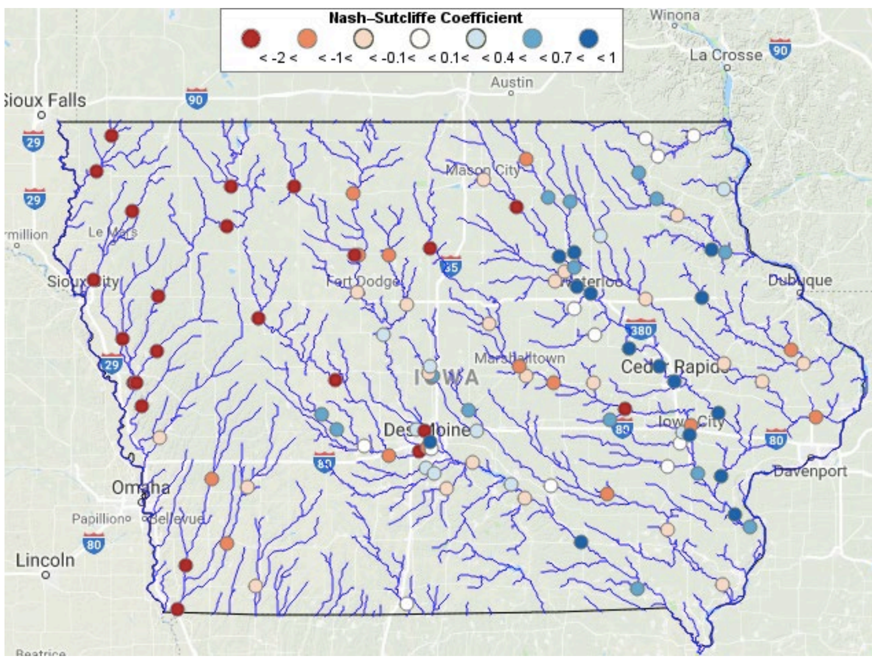


Figure 4.1 Color coded NS indexes for model simulations in the state of Iowa.

Chapter 5 Conclusions

An important aspect in providing a safe, efficient, and effective transportation system is anticipating natural hazards that can lead to road closures. Extreme floods can lead to bridge overtopping and to compromising the structural integrity of river overpasses, including box culverts. The flood forecasting model and information system proposed here provides a tool to anticipate potential hazardous situations related to floods. It would allow the activation of action plans to minimize the impact on the overall transportation system. The forecasting model can be used in real time to anticipate floods and to look at past flooding scenarios to determine if all the actions taken were appropriate or can be improved. Our forecasting system will contribute to improving safety and minimizing risk associated with increasing multi-modal freight movements on the U.S. surface transportation system by *enhancing safety* and providing warning of potential road closures.

As part of this project, we have provided a prototype forecasting web platform with four specific innovations. 1) Forecasts at critical river/road intersections, 2) Spatial animated maps of flood evolution into the future, and 3) a measure of forecast accuracy at the newly incorporated forecast bridges. Our developments give us confidence that we can continue moving forward in developing a forecasting system that is transferable to other locations in the Midwest. As floods continue to be the most costly disaster in the nation it becomes critical that tools are developed to better predict them.

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