Spring 2017

IFIS model-plus: a web-based GUI for visualization, comparison and evaluation of distributed hydrologic model outputs

Andre Della Libera Zanchetta
University of Iowa

Recommended Citation

Della Libera Zanchetta, Andre. "IFIS model-plus: a web-based GUI for visualization, comparison and evaluation of distributed hydrologic model outputs." MS (Master of Science) thesis, University of Iowa, 2017.
https://doi.org/10.17077/etd.irk6eh9d.

IFIS MODEL-PLUS
A WEB-BASED GUI FOR VISUALIZATION, COMPARISON AND EVALUATION OF DISTRIBUTED HYDROLOGIC MODEL OUTPUTS

by

Andre Della Libera Zanchetta

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Civil and Environmental Engineering in the
Graduate College of
The University of Iowa

May 2017

Thesis Supervisor: Assistant Professor Ricardo Mantilla Gutierrez

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Andre Della Libera Zanchetta

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Civil and Environmental Engineering at the May 2017 graduation.

Thesis Committee:

Ricardo Mantilla Gutierrez, Thesis Supervisor

Ibrahim Demir

Witold F. Krajewski

Larry Weber

To my parents, my friends and Lizbeth, who were always there to support me.

ACKNOWLEDGMENTS

I would like, first of all, to recognize the value of my supervisor, Professor Ricardo Mantilla (PhD), for making my work a success. More than providing all guidance with excellency for my academic development as his graduate student, Ricardo also offered the intimacy and personal concern to make me consider him more than an advisor, but also a friend - a close one. Secondly, I would like to express my gratitude for Professor Ibrahim Demir (PhD) with all the support with the use of the tool developed by him – IFIS – which is a central element of this work, and all the constructive suggestions offered during all the process of development of this thesis. But this work have never been successful without the valuable help of many others members of IIHR – Hydroscience and Engineering, mainly: Felipe Quintero Duque, who taught me almost all the details of the cyber infrastructure with which I dealt during most of the activities I developed related to this work – he is someone to be called a Professor for sure; Samuel Debionne, who, while being responsible for maintaining ASYNCH and real-time instances of the hydrological model – fundamental elements of this work – was always open to possible improvements to the tool that would potentially benefit my activity and to discuss general topics related to technology; and Radek Goska, whose readiness to help and to suggest improvements with database-related issues was immeasurably helpful for the establishment of the tool developed in this theses. This work would not have gone so far if they were not who they are. Finally, I want to thank Professors Witold Krajewski and Larry Weber not only for accepting being part of my Thesis Committee, which was my great honor, but, as directors of the IFC - Iowa Flood Center – and of IIHR (respectively), for the opportunity to be part of the these groups. There are no words to describe the gratitude I feel for this experience.

ABSTRACT

This work explores the use of hydroinformatics tools to provide a user friendly and accessible interface for executing, and visualizing the output of, distributed hydrological models for Iowa. It uses an IFIS-based web environment for graphical displays and it communicates with the ASYNCH ODE solver to provide input parameters and to gather modeling outputs. The distributed hydrologic models used here are based on the segmentation of the terrain into hillslope-link hydrologic units, for which water flow processes are represented by sets of nonlinear ordinary differential equations. This modeling strategy has shown promising results in modeling extreme flood events in the state of Iowa – USA, but the usage and evaluation of outputs from hillslope-link models (HLM) has been limited to a restrict group of academics due to the demand of high processing capability and the number of customized tools needed to visualize model outputs. HLM-based models provide abundant output information on rainfall-runoff processes of the hydrological cycle, including estimates of discharge for all streams in the state of Iowa, and water storage on all conceptual vertical layers of soil.

The interfaces and methodologies developed in this thesis respond to the constant demand for communicating effectively water-related information from academic communities to the public using hydroinformatics tools to provide an accessible portal to the information generated by complex hydrological models. It also facilitates model development and evaluation by allowing rapid development of what-if scenarios. Features included visualization and comparison between outputs of different models. This work represents a significant advance in this direction and the results have been made publicly available online under the URL http://ifis.iowafloodcenter.org/ifis/sc/modelplus/.

PUBLIC ABSTRACT

The State of Iowa faces the environmental threat of extreme flooding events. A case in point is the historical event of June 2008, which involved flooding of all major rivers in Eastern Iowa including the Iowa-Cedar, Turkey, Wapsipinicon and Maquoketa Rivers. It affected important urban centers, including Cedar Rapids and Iowa City. The floods caused a considerable amount of property damages and long term loss of economic activity. Motivated by such occurrence, the Iowa Flood Center was established in 2009 with the objective of developing flood-related studies and projects that would benefit the State of Iowa and contribute to preparedness and mitigation plans.

Some of the work developed by the IFC since its creation includes the HLM-ASYNCH hydrological modeling framework, which had the novelty of being able to provide rainfall-runoff and runoff-routing simulations for the entire State of Iowa in real-time. However, due to the complexity of such system, few tools have been developed so far to represent and evaluate its outputs through an accessible user interface, restricting its effective use to academic members of IFC.

This thesis proposes a web interface for a set of HLM-ASYNCH pre-defined models based on IFIS for 1) triggering model execution and provide output visualization and evaluation for past flood events and 2) make real-time-generated information accessible to general public through visualization of the model output, comparison between multiple models and evaluation of its results with respect to observed data from multiple sources. The interface has been published to the web under the URL http://ifis.iowafloodcenter.org/ifis/sc/modelplus/.

TABLE OF CONTENTS

LIST OF TABLES ix

LIST OF FIGURES x

CHAPTER 1 - INTRODUCTION AND BACKGROUND 1

- 1.1 - Motivation 1
- 1.2 - An Overview of the core IFIS System 3
- 1.3 - An Overview of HLM-ASYNCH framework 5
  - 1.3.1 - Framework Description 5
  - 1.3.2 - ASYNCH System Structure and User Interface 11
- 1.4 - Thesis Contribution 12
- 1.5 - Outline and Contents 13

CHAPTER 2 - TERMINOLOGY AND DEFINITIONS 14

- 2.1 - System Structural Components 14
- 2.2 - Data Density 18

CHAPTER 3 - IFIS MODEL-PLUS SYSTEM STRUCTURE 19

- 3.1 - Artefacts Distribution 19
- 3.2 - Real-time System 21
  - 3.2.1 - Workflow 21
  - 3.2.2 - Data repository 22
- 3.3 - Requester System Workflow 24

3.3.1 - Workflow 24

3.3.2 - Data repository 26

CHAPTER 4 - IFIS MODEL-PLUS CURRENT TOOLS 27

4.1 - SC-Products 27

4.2 - SC-Representations 32

4.3 - SC-Evaluations 49

4.4 - Control Panel 53

CHAPTER 5 - Use Cases and Applications 54

5.1 - Overview 54

5.2 - Flood of 2016 56

5.2.1 - Event Description 56

5.2.2 - Runset Setup 57

5.2.3 - Models Results 58

5.3 - Flood of 2008 64

5.3.1 - Event Description 64

5.3.2 - Model Setup 66

5.3.3 - Model Results 66

CHAPTER 6 - CONCLUSION 75

CHAPTER 7 - FUTURE DEVELOPMENTS 77

REFERENCES 79

APPENDIX.. 82

Appendix 1 - Flow quantile regression parameters 82

Appendix 2 - Algorithm for initial state estimation.. 83

LIST OF TABLES

Table 1 – Summary of sc-models of real-time sc-runset. 22

Table 2 – Flow classification with respect to estimated annual exceedance probability.. 32

Table 3 – Flow discharge classification for the hillslope-link i at time t. 37

Table 4 – Flood classification criteria for the hillslope-link i at the moment t. 45

Table 5 – Monthly constant evaporation rates assumed by HLM-ASYNCH models. 54

LIST OF FIGURES

Figure 1 – Screenshots of tools available in IFIS. 4

Figure 2 – Sample of a drainage network representation 6

Figure 3 – Segmentation of Iowa water domain 7

Figure 4 – Decomposition of a hillslope-link pair with n conceptual soil layer in which water flow is governed by ODEs. 10

Figure 5 – Entity-Relationship diagram of conceptual components of the system. 17

Figure 6 – General data flow between the components of the system. 20

Figure 7 – Flow diagram of the procedures executed on an hourly base for updating the real-time sc-runset. 23

Figure 8 – Flow diagram of the procedures executed each time the request for execution of an sc-runset is performed. 25

Figure 9 – Examples of 24-hours cumulative distributed rainfall representation 34

Figure 10 – Examples of 24-hours cumulative distributed runoff representation 35

Figure 11 – Representations of the Top Layer saturation variable 38

Figure 12 – Representation of Distributed Soil Water Column 39

Figure 13 – Representations of the Distributed Flow Discharge Classification 41

Figure 14 – Example of hydrograph available in NWS-AHPS portal 43

Figure 15 – Representations of the Distributed Flood Discharge Classification 46

Figure 16 – An example of Forecast Stage Hydrograph 47

Figure 17 – Composition of Flow Discharge and Flood Severity Classifications 48

Figure 18 – Example of stage hydrographs. 49

Figure 19 – Example of Nash-Sutcliffe Coefficient representation. 51

Figure 20 – Instantaneous flow discharge classification 52

Figure 21 – Interfaces 53

Figure 22 – Identification of selected locations used on evaluation. 55

Figure 23 – Impacts of the flood event on Cedar River in 2016 57

Figure 24 – Effects of rainfall prior to the flood events of 2016 on soil moisture modeled by TL-Standard 58

Figure 25 – Snapshots of 6-hour accumulation precipitation of rainfall event that covered almost entire Iowa from on September 15th and September 16th. 59

Figure 26 – Precipitation-flood process modeled by TL-Standard for the 2016 floods ... 60

Figure 27 – Nash-Sutcliffe indicating locations were the TL-Standard performed better for the simulation of de flood of 2016. 62

Figure 28 – Representation of 24-hours Distributed Cumulative Surface Runoff 63

Figure 29 – Magnitude of differences in discharge between TL-Low Percolation 63

Figure 30 – Massive damages caused by flood events of 2008 65

Figure 31 – Sequence of rainfall events that affected the entire state of Iowa on the days previous and during the Flood of 2008. 67

Figure 32 – Effects on soil moisture of consecutive rainfalls in a short period of time registered during flood events of 2008 modeled by TL-Standard sc-model 68

Figure 33 – Composite representation of Flow Discharge / Flood Severity Classifications 69

Figure 34 – Evaluation hydrographs of TL-Standard sc-model results for the 2008 flood season 70

Figure 35 – Nash-Sutcliffe coefficient map of TL-Standard sc-model for 2008 flood season simulation. 71

Figure 36 – The hydrograph of one of the locations classified with low Nash–Sutcliffe in the western region of the state of Iowa for the TL-Standard model output. 71

Figure 37 – Nash-Sutcliffe coefficient map of TL-Low Percolation sc-model for 2008 flood season simulation 72

Figure 38 – Evaluation hydrographs of TL-Low Percolation sc-model results for the 2008 flood season 73

Figure 39 – Zoom screenshot of comparison between TL-Low Percolation and TL-Standard of Flow Classification results 74

CHAPTER 1 - INTRODUCTION AND BACKGROUND

1.1 - Motivation

Iowa is located in the Midwest region of the United States and it is bounded by the Mississippi River (east) and the Missouri River (west). It covers a total area of 145,765 km^2. A set of conditions, which include the predominance of humid continental climate and relatively flat terrain, result in the persistent threat of moderate and extreme floods statewide.

Zogg (2014) classifies the so called Great Flood of 1993 as the most impacting weather related event in Iowa history. It resulted in 17 fatalities and around $2.7 billion in damages. Such devastation was wide spread and all 99 counties were classified as Federal Disaster Area. The same author places the Flood of 2008 as the second most significant flood event in the state, as it caused the river water levels to exceed previously existing record high levels across the eastern region of Iowa, mainly within Cedar and Iowa River basins, and resulted on total statewide damage estimated on $10 billion. Other significant historical events occurred in 1851 (The Great Flood of 1851), 1876 (The Rockdale Flood), 1952 (The Missouri River Flood), and 1965 (The Mississippi River Flood).

Following the 2008 event, the Iowa Flood Center (IFC) was established as an academic research unit under the College of Engineering of the University of Iowa, and hosted at IIHR - Hydroscience & Engineering, with the purposes of developing hydrological models for 1) real-time forecasting of floods, 2) defining flood plain inundation maps, 3) establish community-based programs to improve flood monitoring and prediction along Iowa's major waterways, and 4) develop flood related research and activities.

Over the last 7 years, different activities and projects led to the expansion of the physical and cyber infrastructure of the IFC. In particular, the need to make flood related information accessible to the public lead IFC to the development of the Iowa Flood Information System (IFIS) online portal (Demir and Krajewski, 2013; Demir *et al*, 2015). IFIS allows the public to access flood-related geospatial information, such as streamflow data, precipitation estimates, and soil moisture measurements from sensors maintained both by the United States Geological Survey (USGS) and by IFC. It also communicates forecasts for water levels at a limited number of locations. IFIS was implemented in such a way that its functionalities can be extended in IFIS-like portals that contain the main functionalities, and real-time information presented on the original IFIS system. Extensions of IFIS look like independent interface systems and are called **IFIS Special Cases**.

As part of IFC's efforts to provide augmented flood forecasting capabilities for the state of Iowa, a physically-based distributed hydrological model was developed and implemented to provide real-time statewide flood forecasts. The hydrological modeling framework is called the Hillslope-Link Model (HLM). HLM inputs and outputs are organized as directed tree data structures to represent the surface water drainage network, and it follows the assumption that water flows between segments and soil layers are properly represented by Ordinary Differential Equations (ODEs).

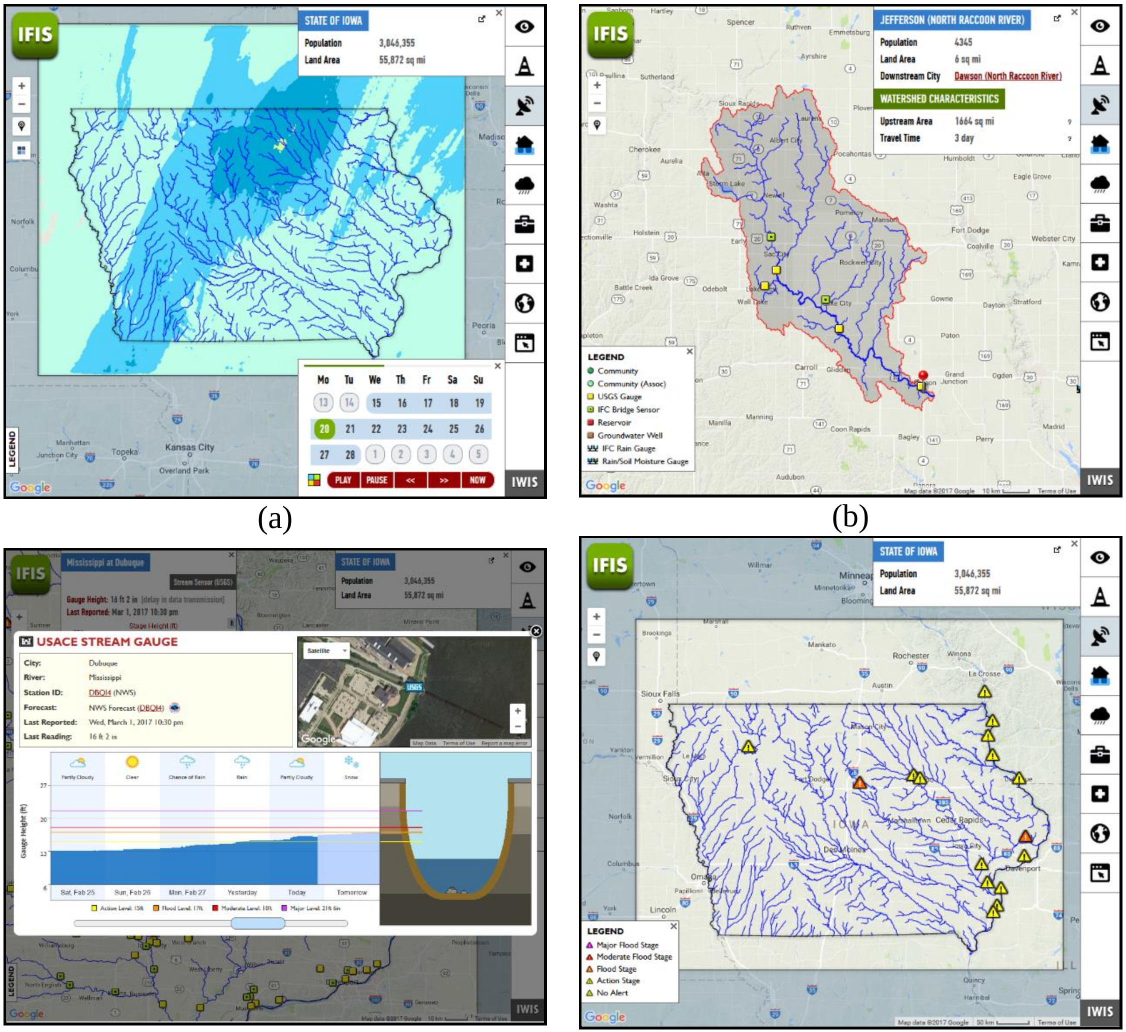
In addition, a computational framework to numerically solve directed-tree ODE systems was implemented using multiprocessing parallelization capabilities of the High Processes Computer (HPC) available at the University of Iowa. This numerical solver optimizes the execution of HLM model instances for relatively large drainage networks. The numerical solver is called ASYNCH (Small, 2012), and consequently hydrological models following HLM framework that are solved using this novel HPC infrastructure are named **HLM-ASYNCH** models.

IFC maintains instances of HLM-ASYNCH models that are being continuously executed using real-time precipitation data for the entire State of Iowa, however access to most model outputs is still limited to IFC members mainly due to the data format in which it is generated by the numerical solver implementation. This work is focused on proposing a web-interface for intuitively visualizing, comparing and evaluating results of HLM-ASYNCH models using an extension of the IFIS infrastructure and tools through the implementation of an IFIS Special Case that we call **IFIS MODEL-PLUS**.

1.2 - An Overview of the core IFIS System

IFIS (http://ifis.iowafloodcenter.org) is an Iowa-focused, one-stop web platform designed to be an information dissemination portal with the "general public" as the target audience, integrating data and resources from several sources, including from National Weather Service (NWS), USGS, U.S. Army Corps of Engineers (USACE) and from own IFC (Krajewski *et al*, 2016).

The system is structured following a Hydroinformatics approach in a hydrological context. It organizes flooding relevant spatial information for riverine communities using the river network and corresponding basins boundaries. IFIS uses Google Maps Application Programming Interface (API), integrated with custom made Javascript and JQuery algorithms to present temporally variable and dynamically updated data, including stage hydrographs (recorded by bridge water level sensors), and soil water saturation conditions (registered by soil moisture sensors) (Figure 1).



STATE OF IOWA
Population 3,046,355
Land Area 55,872 sq mi

JEFFERSON (NORTH RACCOON RIVER)
Population 4345
Land Area 6 sq mi
Downstream City Dawson (North Raccoon River)

WATERSHED CHARACTERISTICS
Upstream Area 1664 sq mi
Travel Time 3 day

LEGEND
- Community
- Community (Assoc)
- USGS Gauge
- IFC Bridge Sensor
- Reservoir
- Groundwater Well
- IFC Rain Gauge
- Rain/Soil Moisture Gauge

Mississippi at Dubuque
Gauge Height: 16 ft 2 in [delay in data transmission]
Last Reported: Mar 1, 2017 10:30 pm

USACE STREAM GAUGE
City: Dubuque
River: Mississippi
Station ID: DBQI4 (NWS)
Forecast: NWS Forecast (DBQI4)
Last Reported: Wed, March 1, 2017 10:30 pm
Last Reading: 16 ft 2 in

LEGEND
- Major Flood Stage
- Moderate Flood Stage
- Flood Stage
- Action Stage
- No Alert

(a) (b)

(c) (d)

Figure 1 – Screenshots of tools available in IFIS. (a) The representation of animated large scale rainstorms, (b) restriction of available data for a specific watershed, (c) stage hydrographs for a specific stream gage and (d) icons for current flood alerts.

Among the tools developed in IFIS for enhancing the user experience when dealing with large scale spatial and temporal information is the animation of sequential georeferenced images. By sequentially replacing co-geolocated images that capture different instants in time (e.g.: current rainfall), the user has the experience of seeing an animation describing how a spatial field of a hydrological variable of interest evolved in recent past or in future forecasted scenarios. Another important layer of information includes geolocated sites where water level is monitored and classified with thresholds for current flood impacts as Action, Flood, Moderate or Major Flood (Figure 1d).

A central repository for storing and sharing the information needed by IFIS and other IIHR systems is separately implemented and maintained. It uses PostgreSQL as the database system and PHP scripts for external communication mainly through web services approach. Due to the availability of such repository of tools and real-time updated information, an IFIS Special Case was considered an ideal framework for the development of the tool proposed in this work.

1.3 - An Overview of HLM-ASYNCH framework

1.3.1 - Framework Description

A natural river network can be, in most of cases, represented by a directed-tree data structure, in which channels (in this work named ‘links’) correspond to directed edges in the flow direction, and channel junctions correspond to tree-nodes (Figure 2).

Prior to the development of this work, the delineation of the drainage network of Iowa was performed trough an automated partitioning of geomorphological features of the terrain using a 90 meters resolution Digital Elevation Model (DEM). The terrain decomposition into hillslope-link units follows the strategy proposed by Mantilla and Gupta (2005). The resulting product includes contributing rivers located outside of Iowa (mainly flowing from southern Minnesota and southeastern South Dakota regions into Iowa’s territory) and excluded the rivers bordering the state, Mississippi (east) and Missouri (west). The domain is composed by 419,157 hillslope-link units covering a total area of 165,676 km². Within the scope of this work the domain is referred as the **Iowa water domain** (Figure 3).

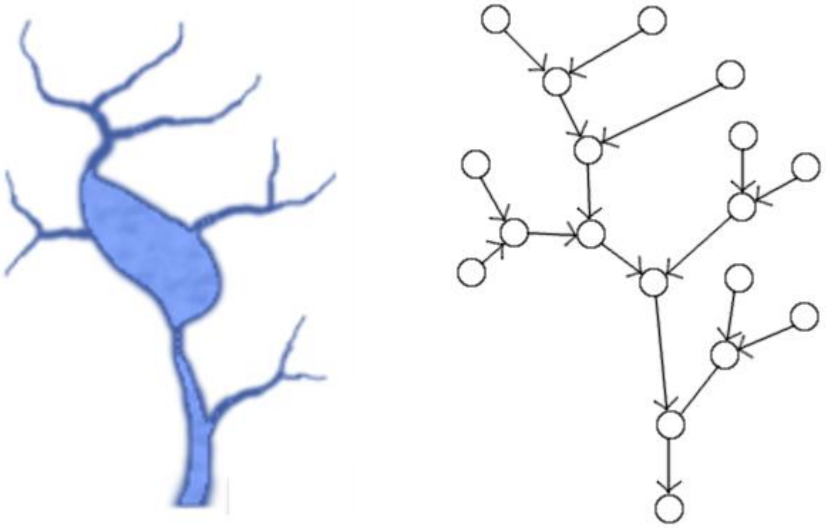
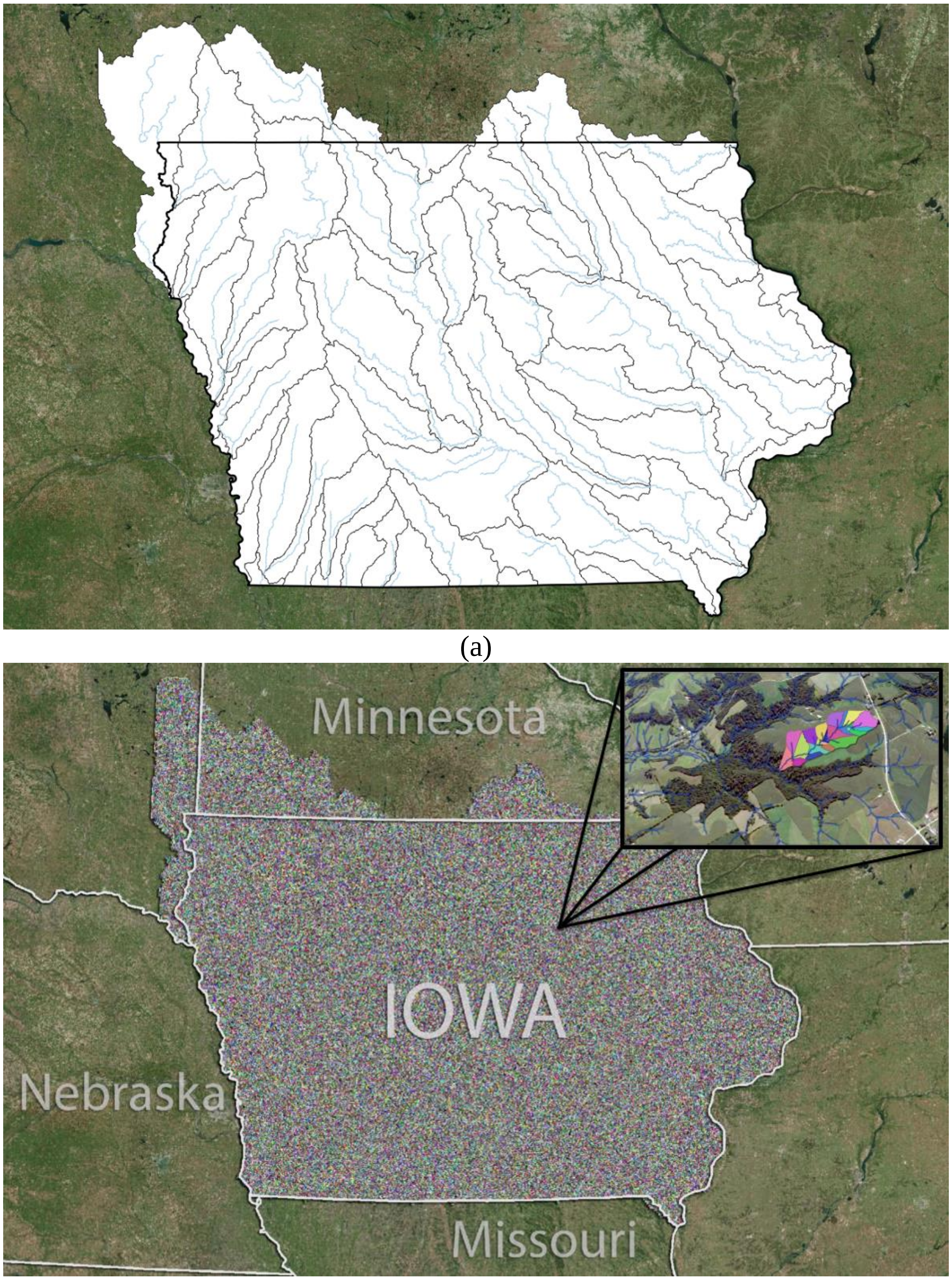


Figure 2 – Sample of a drainage network representation (a) as seen in nature and (b) as a directed tree data structure.

Water flows, in and out of hillslope-link units, can be modeled under multiple assumptions of vertical soil layers as illustrated in Figure 4, as long as all processes can be properly described using ODEs (Mantilla and Gupta, 2005). In such context, flows on the same drainage network, can be characterized using different assumptions and configurations regarding soil layers. Governing equations and optimal parametrizations can be assumed leading to different conceptual models to explain and simulate internal hillslope-link water transport processes, including infiltration, percolation, runoff evaporation and storage (Mantilla, 2007).

The current standard hillslope-link conceptual model used by IFC assumes the representation of soil column with three different layers: the surface, the upper one (named "Top Layer") and the lower one (named "subsurface"), each one acting as a storage component generating runoff in rates that vary in time. It requires a time series of high resolution precipitation (5-minute to hourly) and low resolution evapotranspiration rates (daily or monthly) affecting each hillslope-link. It is known as Top Layer model and may also be referred by its numerical code in the modeling framework **HLM-ASYNCH-254**.


(a)

(b)

Figure 3 – Segmentation of Iowa water domain in (a) contained and contributing HUC-8 watersheds and (b) in 419,157 hillslope-link units.

The governing equations of the Top Layer model are given by

$$
\begin{aligned}
&\frac{dq}{dt} = \frac{1}{\tau}\left(\frac{q}{q_r}\right)^{\lambda_1}\left(-q + c_2\left(q_{pc} + q_{sc}\right) + q_{in}(t)\right) \\
&\frac{ds_p}{dt} = c_1 p(t) - q_{pc} - q_{pt} - e_p \\
&\frac{ds_t}{dt} = q_{pt} - q_{ts} - e_t \\
&\frac{ds_s}{dt} = q_{ts} - q_{sc} - e_s \\
&\frac{dV_p}{dt} = c_1 p(t) \\
&\frac{dV_r}{dt} = q_{pc} \\
&\frac{dq_b}{dt} = \frac{v_B}{L}\left(A_h q_{sc} - 60\,.\; q_b + q_{b,in}(t)\right)
\end{aligned}
\tag{1}
$$

where $p(t)$ is the precipitation rate (in mm/hr) at moment t, $e_{p(t)}$ is the evaporation rate (in mm/hr) at moment t, $q_{in(t)}$ is the total discharge entering the channel from the directly upstream hillslope-links channels on moment t (in m³/s), $q_{b,in}(t)$ is the total of the directly upstream hillslope-links channels at moment t, q is the channel discharge, s_p is the water column stored in the ponds on surface (in m), s_t is the water column stored in top layer (in m), s_s is the water column stored within the subsurface (m), V_p is the total fallen precipitation from time 0 to t (m³), $V_r(t)$ is the total volume of water transported as runoff (m³), q_b is the base flow. $\frac{1}{\tau}$ is a simplification for

$$\frac{1}{\tau} = \frac{60 \cdot v_r \cdot \left(A_{up} \,/\, A_r\right)^{\lambda_2}}{(1-\lambda_1) \cdot L \cdot 10^{-3}}. \tag{2}$$

Internal water fluxes to a hillslope-link system are given by the flow from surface (ponded) to channel $q_{pc} = k_2 \cdot s_p$ (in m/min), from top layer to subsurface $q_{ts} = k_i \cdot s_t$, from the subsurface to the channel $q_{sc} = k_3 \cdot s_s$ (in m/min) and from surface to top layer $q_{pt} = k_t \left(1 - \frac{s_t}{T_l}\right)^3 s_t$ (in m/min).

Each hillslope-link in the Top Layer Model is characterized by the parameters of total area draining into the link (A_{up}, in km²), channel length (L, in km) and area of hillslope (A_h in km²). Additional global parameters required are related to the channel reference velocity (v_r, in m/s), exponent of channel velocity discharge (λ_1, dimensionless), exponent of channel velocity area (λ_2, dimensionless), constant velocity of water on the hillslope (v_h, in m/s), infiltration from subsurface into channel (k_3, in 1/min), percentage of percolation from top layer to subsurface (β, dimensionless, varying from 0 to 1), total hillslope soil depth (h_b, in m), total topsoil depth (S_L, in m), surface to top layer infiltration addictive, multiplicative and exponent factors (A, B and α, respectively, all dimensionless) and channel base flow velocity (v_B, in m/s).

Further explanations concerning e_p, e_t, e_s, evapotranspiration rates (all dependent on input potential evapotranspiration), k_2, k_i, k_t, c_1, c_2, q_r and A_r variables can be found in Small (2015).

As it could be observed, each hillslope-link, at a time t for a simulation started at time 0, is characterized by the volume of water stored in the channel, in the hillslope ponded surface, in the porosity of the top layer, and in the porosity of the subsurface. In addition, two equations keep track of accumulated precipitation and accumulated surface runoff generated by the hillslope-link system. The set of all this information, for all hillslope-link systems on a simulation for a time t, is known as "the state" of a model instance at time t. The state of a model at time 0 is a required input (commonly referred as the "initial state" or "initial condition").

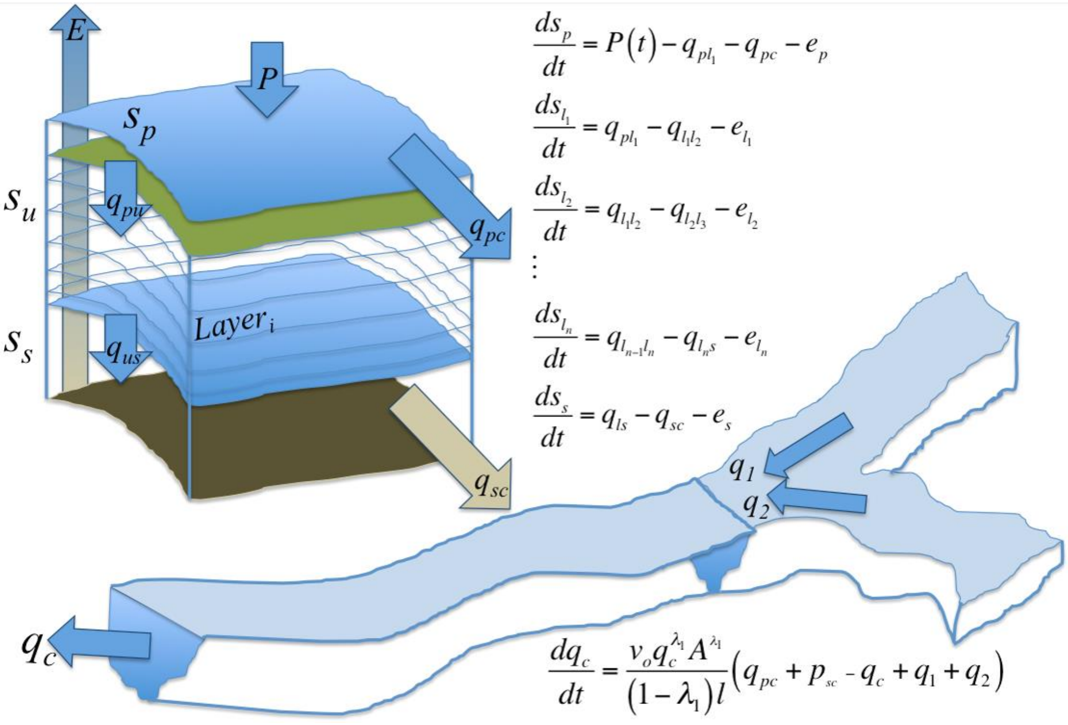


Figure 4 – Decomposition of a hillslope-link pair with n conceptual soil layer in which water flow is governed by ODEs.

The applicability of the conceptual model has been continuously evaluated and improved (Cunha *et al.*, 2012; Seo *et al.*, 2013, Ayalew *et al.*, 2014; Quintero *et al.*, 2016).

To exemplify the flexibility of ASYNCH framework on supporting more representations of the hillslope-link unit, one can refer to a simpler conceptual model in use at IFC named Constant Runoff Model, identified by the numerical code **HLM-ASYNCH-190** (more information may be obtained in Small (2015)).

The computational resources needed for solving the set nearly 3 million ODEs in Equation 1 which are linked by a sparse directed-tree would be unfeasible using non-optimized numerical solvers or not using high processing computer systems. For that purpose, the ODE numerical solver ASYNCH was developed and it is now briefly described on Chapter 1.3.2.

1.3.2 - ASYNCH System Structure and User Interface

ASYNCH is a parallel numerical solver for systems of nonlinear ODEs. It has been implemented in C programming language and uses Message Passing Interface (MPI) (see Pacheco, 1997) with a compiling system specific for Unix-like systems. Despite of being possible to execute the framework on personal computers for relatively limited sizes of watersheds on an acceptable time interval, the full potential of the tool is reached when it is executed on high performance computing clusters, in which effective parallel processing can be used.

ASYNCH's user interface is based on command line instructions, in which the user is requested to provide a set of structured files describing all input information. The main input file of such a set is named "global file" and summarizes references for all the others. As conceptual hydrological model-dependent inputs, it is necessary to provide a set of global parameters, which are constant for every hillslope-link (the Top Layer model, for instance, presents 12 global parameters: v_r, v_b, $\lambda_1, \lambda_2, v_h, k_3, \beta, h_b, S_L, A$, B and α), hillslope-link specific parameters (3 for the Top Layer model: L, A_{up} and A_h) and an initial state for the system, which is constituted of values for the states of each and every hillslope-link (in the Top Layer model, the state of a hillslope-link system comprises value for q, s_p, s_t, s_s, s_{prec}, v_r and q_b) (for a brief description of the Top Layer model, refer to Chapter 1.3.1).

The output of the models can be presented in different formats: a single text file describing the final state of the entire system, a set of **snapshots** (binary files describing intermediate states of the entire system during the execution of the simulation), tuples on one (or more) database describing specific states of specific links, or combinations of them

(Small and Debionne, 2017). Each “snapshot” can be used as an input for the initial state for the execution of other models.

Despite of allowing extraordinary flexibility, such a complex mixed file/database-based system for input and output, associated to the Unix command line system as unique user interface, results in an overall *user-unfriendly* system. The processes of setting up the inputs is relatively time-consuming and highly subject to errors, even for simplistic simulations, and the steps of evaluating and visualizing model outputs are not standardized, requiring that each user of ASYNCH implements his/her own set of tools for processing the obtained data.

With the objective of simplifying the hydrological modeling with HLM-ASYNCH in large scale using available data in IIHR repository, a web system based on IFIS structure was considered an accessible and intuitive alternative user interface for the solver.

1.4 - Thesis Contribution

Despite of the fact that IFIS already presents relevant part of the products from HLM-ASYNCH instances executed in real-time (e.g. water level forecast for a limited number of sites), a lot more information is produced that could be made available either for the public or for research groups. It includes, maps of soil moisture of surface layers, water stored in soil, surface runoff production, and flow discharge (amongst others). This work proposes an IFIS Special Case focused on visually exploring all output information provided by HLM-ASYNCH model instances, potentially providing insights for future implementations of new tools IFIS tools for either the public or academics.

The features present in the proposed tool include: 1) an interface for starting the execution of groups of hydrological simulations for periods in the past in which enough input data is available in IIHR repository; 2) visualization of interpretations of individual model outputs for both past and real-time simulations; 3) comparisons of results obtained from different model configurations; and 4) evaluation of obtained results through comparison of observed data.

1.5 - Outline and Contents

Chapter 2 presents the definition of specific terminologies used to describe the project and a conceptual structure of the system is provided. In Chapter 3 the overall system architecture and the workflow of the main procedures are presented. The current implemented functionalities of the system are described in Chapter 4. Chapter 5 presents two applications of the model to describe real state-scale flood events. General conclusions are discussed in Chapter 6 and considerations regarding future developments of the tool are summarized in Chapter 7.

CHAPTER 2 - TERMINOLOGY AND DEFINITIONS

2.1 - System Structural Components

All data structures that are part of the IFIS-Model Plus design are named with the prefix "sc-" as an acronym for "Specific Concept". A diagram representing the inter relationship of such conceptual components is given in Figure 5.

One of the most recurrent questions that is asked while hydrological simulations are performed is "what would be the output of a model if a different set of parameters or input data is assumed?" To answer such type of question, hydrologists usually define a specific period for which enough input data is available and, for such interval of time, run a set of different model instances. From the multiple outputs obtained, comparisons between the models results and evaluations taking into consideration observed data are performed.

The data structure used by IFIS-Model Plus reproduces such experimental modeling approach. Every time a user is about to evaluate the performance of a set of hydrological models, he or she must create an **sc-runset**. An sc-runset is defined by a title, an initial and a final simulation date. The sc-runset can be thought of as an isolated sandbox associated to a unique pre-defined rainfall-flood event of interest to be modeled.

Each sc-runset is composed by a set of **sc-sources** (sc-sources are components that provide **sc-products,** described below). Among the sc-sources, a set of sc-models must be defined by the user and a set of **sc-references** is automatically associated to the sc-runset. All data provided by the sc-sources is limited to the time interval between the initial and final simulation dates of the sc-runset.

An **sc-model** represents the instance of an HLM model executed for the rainfall-flood event delimited by the sc-runset and is composed by all information associated to a model instance, including: ASYNCH input files, ASYNCH output files, sc-products and sc-results. Each sc-model is associated to one conceptual hydrological model (Top Layer or Constant Runoff Model – definitions in Chapter 1.3.1) and is customizable thought its global variables.

In the context of an sc-model, an **sc-product** is the data imported from one snapshot or one forecasting generated as an output of the sc-model execution. It contains the data of one of the states of the conceptual hydrological model associated to the sc-model. For instance: an sc-model of a Top Layer conceptual hydrological model generates 7 types of sc-products, each one associated to a state in the (hillslope-link system: q, s_p, s_t, s_s, s_{prec}, v_r and q_b). The set of currently supported sc-products by IFIS-Model Plus is presented in Chapter 4.1.

Sc-references are sources of information that provide data used for evaluation purposes. Usually they represent web services for distribution of stream gages-observed data. Each sc-reference is associated to one type of sc-product, which is the specific information provided by the sc-reference after being imported in the backend component of the system. For example: the sc-reference that represents the USGS web service for sharing historical discharge data has as sc-products the sparse instantaneous discharge registered for the rainfall-event represented by the sc-runset.

An **sc-result** is a generic expression to designate representations derived from sc-products. It includes sc-representations, sc-evaluations and sc-representations compound.

Sc-representations are the translation of the binary data contained in one or more sc-product files into visual artefacts to be displayed in the interface. An sc-representation may express the data from a single sc-model or from a comparison between the outputs produced by two different sc-models in the same sc-runset. A list of currently supported sc-representations in the system is presented in Chapter 4.2.

Sc-evaluations are visual elements that express the comparison between sc-products from an sc-model and sc-products from an sc-reference. Here a close match between the compared values are indicators of an sc-model performance. A list of currently supported sc-evaluations in the system is presented in Chapter 4.3.

Sometimes, it is interesting to represent the data in different types of sc-products from different sc-models in the same visual artefact. Representations of this type are named **sc-representations compound.** For logically representing such type of composition, different sc-models from the same sc-runset are associated in an **sc-model combination** object. Sc-model combinations are composed only by sc-representations compound. An exceptional type of sc-runset is named "Realtime", as it is continuously updated by new outputs provided by the model instances executed sequentially by IFC (as described in Chapter 3.2).

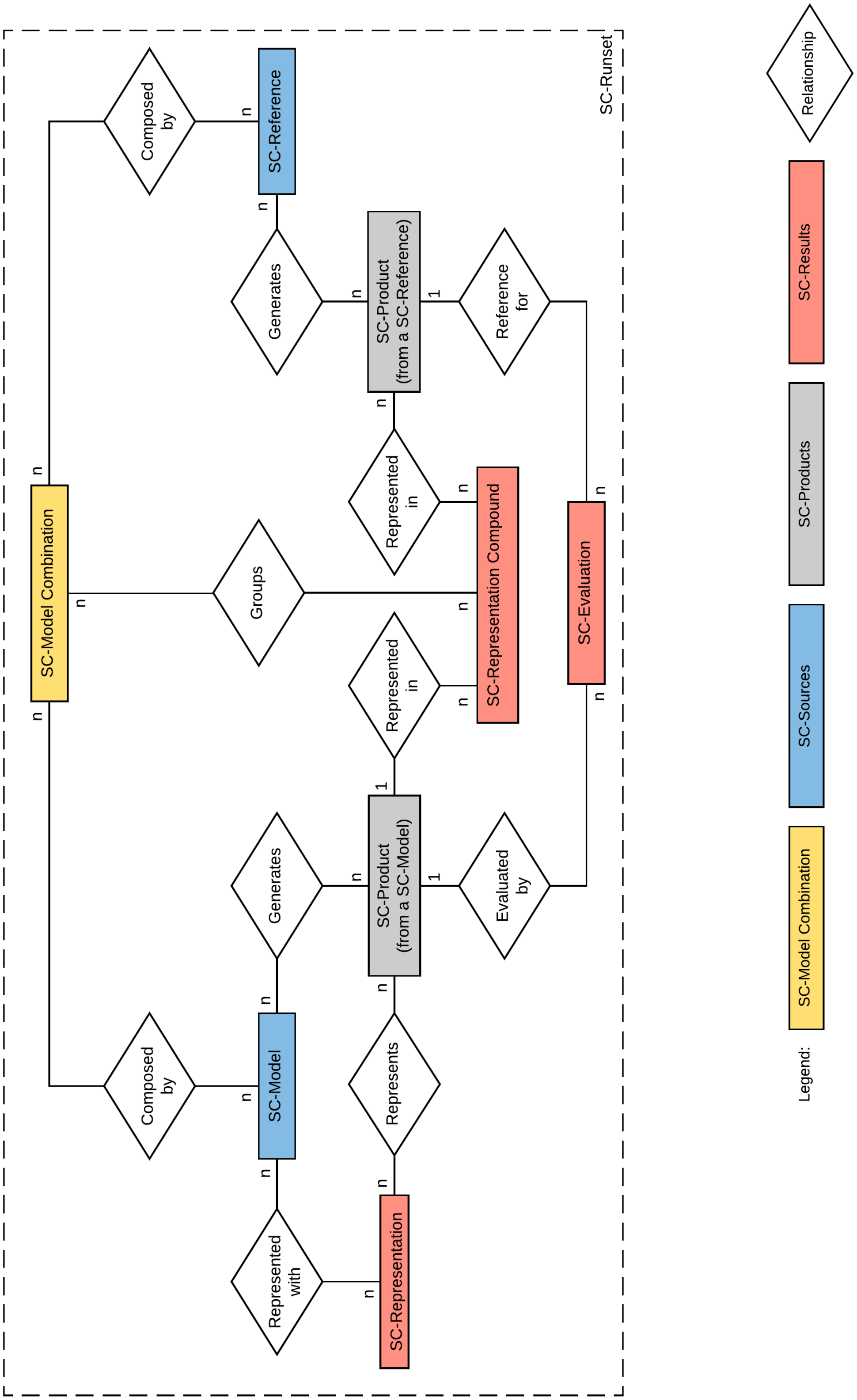


Figure 5 – Entity-Relationship diagram of conceptual components of the system.

2.2 - Data Density

Sc-products can be classified as **dense** or **sparse** based on the total number of hillslope-link units in the Iowa Water Domain for which values exist. This distinction is necessary for certain optimizations of the system and to distinguish which sc-representations apply.

Dense sc-products and sc-representations

A dense sc-product or sc-representation is a type of data that is available for all hillslope-links on the Iowa water domain at most of the time. Usually it is related to output data of sc-models, but it can be also related to data originated from other models that can be considered an sc-reference for evaluation, such as soil moisture maps generated by specialized satellite programs which include the entire domain of the Iowa water domain on its coverage area, for example the Level 3 and Level 4 data products generated by NASA-Soil Moisture Active Passive (SMAP) satellite (Entekhabi *et al*, 2014).

Usually dense sc-products are stored in the format of serialized binary vector files and representations of dense information are presented using raster images.

Sparse sc-products and sc-representations

A sparse sc-product or sc-representation is data that is available only for specific hillslope-links on the Iowa water domain. Usually it is related to observed data, such as stage levels registered by bridge sensors or soil moisture data from specific instruments, but it can also be related to specific sc-model outputs, such as discharge forecasts.

Usually special representations of sparse information are presented using punctual data and they are stored in the file system as files of serialized dictionary structures with hillslope-link ids as keys.

CHAPTER 3 - IFIS MODEL-PLUS SYSTEM STRUCTURE

3.1 - Artefacts Distribution

The IFIS Model-Plus system is composed of three main components identified as the frontend, the backend and the backend-HPC. Each one is executed in a different server and performs interdependent the communication described in Figure 6. Such modularization follows the software principle of Separation of Concerns (SoC), in which groups of logically related elements with high cohesion are structurally separated from one another (Laplante, 2007).

The backend-HPC component is a set of supplementary Bash scripts located on the **HPC** cluster system designed to trigger single runs of models instances and to submit the output information generated by HLM-ASYNCH to server IIHR-54. Algorithms residing in IIHR-54 process output data to generate the corresponding sc-representations.

The backend component is composed of a set of Python and Bash scripts implemented with the objective of processing the files generated by HLM-ASYNCH model. They request external data provided by external components and generate the necessary representation files that will be later displayed to the user through the web frontend. The elements of the backend component are located on the server **IIHR-54** with high storability and processing capability.

The frontend component is composed of a web system implemented using PHP as server-side programming language and Javascript with complementary libraries such as JQuery, Google Maps API and Baidu EChart as client-side programing language. It is currently hosted the **IIHR-50** server, which is designed for providing HTTP access and thus no heavy processing and storage capability is expected on it.

One external component of the system of the system is the **UIowa Data Center**, in which the real-time instances of HLM-ASYNCH model are executed. The outputs of the model are continuously replicated into the IIHR-54 internal file and database systems. Its location outside the computational domains of the IIHR cyber infrastructure is justified by the requisite of high resilience associated to real-time generation of data.

Products generated by companies other than IIHR/IFC are classified as another generic external component named **Third party**, which usually share its data through Web Services. The current implementation of IFIS Model-Plus only supports data provided by USGS web services related to river discharge information.

The two main workflows of the system are described in more detail in the following sections.

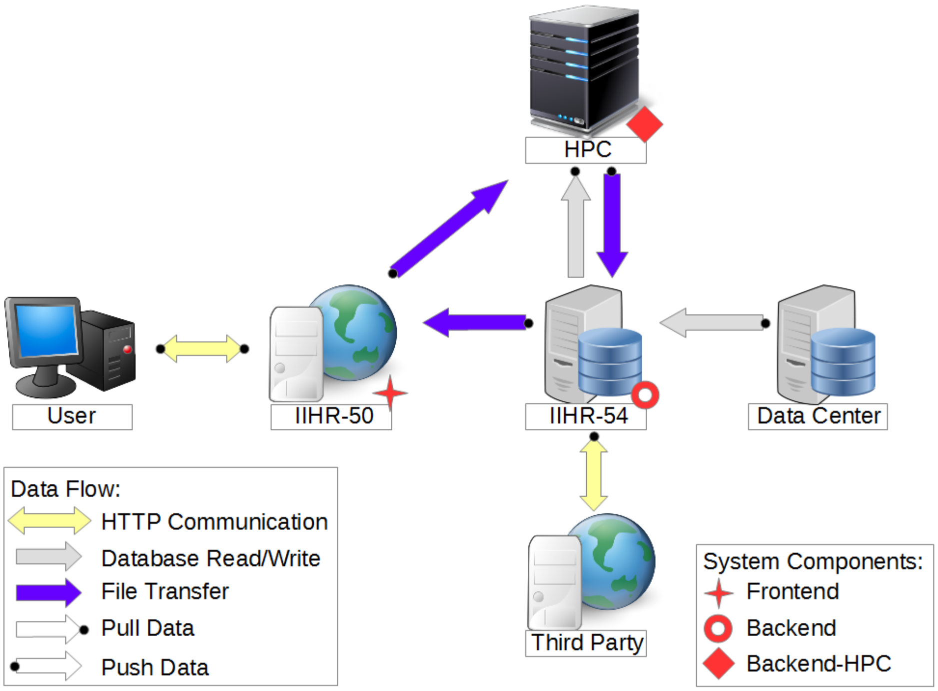


Figure 6 – General data flow between the components of the system.

3.2 - Real-time System

3.2.1 - Workflow

IIHR has currently defined one HLM-ASYNCH model as its standard. It uses the Top Layer conceptual configuration and spatially constant parameters. For this runset, five model instances are executed, on an hourly or minute basis, taking into consideration different combinations of initial conditions and rainfall data products. Two of the model instances have the objective of generate real time estimation of relevant water parameters in all Iowa water domain), one uses as rainfall input the quantitative precipitation estimation (QPE) estimated by National Oceanic and Atmospheric Administration – Multi-Radar/Multi-Sensor System (NOAA-MRMS), and the other receiving as rainfall input the QPE from IFC-Rain products. The other three sequentially executed model instances are set up to produce 10-days forecasts of flow discharge for 1,426 specific points of interest, most of them locations in which a rating curve is available. The three forecast scenarios considered are: no-further rain, occurrence of uniform 2-inches rainfall in 24 hours and occurrence of rainfall precipitation forecasted by NOAA-High Resolution Rapid Refresh (HRRR). All the three forecast models are named What-If (WI) and assume as initial condition for their hourly execution the last system global conditions generated by the model instance that receives IFC-Rain QPE. Each model instance executed is associated to an sc-model contained in the real-time sc-runset. A summary of such sc-models is presented in Table 1.

In order to generate a continuously updated set of representations of the outputs of this set of HLM-ASYNCH instances and make them available to the public through the web interface, every hour a script is automatically launched to execute the workflow presented in Figure 7.

Table 1 – Summary of sc-models of real-time sc-runset.

SC-Model Code	HLM-ASYNCH Product	Lead time	Time base	Snapshot source
254-MRMS	Dense system snapshot	0 (current)	1 hour	254-MRMS
254-IFC	Dense system snapshot	0 (current)	5 minutes	254-IFC
IFC-WI-NoRain	Sparse discharge forecast	10 days	1 hour	254-IFC
IFC-WI-2in24h	Sparse discharge forecast	10 days	1 hour	254-IFC
IFC-WI-QPF	Sparse discharge forecast	10 days	1 hour	254-IFC

3.2.2 - Data repository

The most recent QPF made available by NOAA-HRRR project and QPE products for the region of the state of Iowa generated both by IFC and by NOAA-MRMS is maintained and continuously updated at the Data Center. The data is aggregated into the hillslope-link systems for the Iowa water domain and is used as rainfall data input for each model. Forecasts of discharge regulation of three considered reservoirs in Iowa (Saylorville Lake Reservoir, Lake Red Rock and Coralville Lake) are also continuously ingested into the database to be used as internal boundary conditions in the models. The initial state of each instance of the models is the last snapshot produced by a previously executed instance (Table 1), on a way to obtain continuity of the modeling process.

Third party references retrieved for every execution of the workflow include current sparse water stage and sparse annual exceedance-probability classification, both provided by different USGS web services (see Chapter 4.1).

The model outputs are continuously copied into the IIHR-54 file and database system, from where they are imported to the respective sc-models. This data is removed after 11 days and the corresponding generated representations are removed after 30 days.

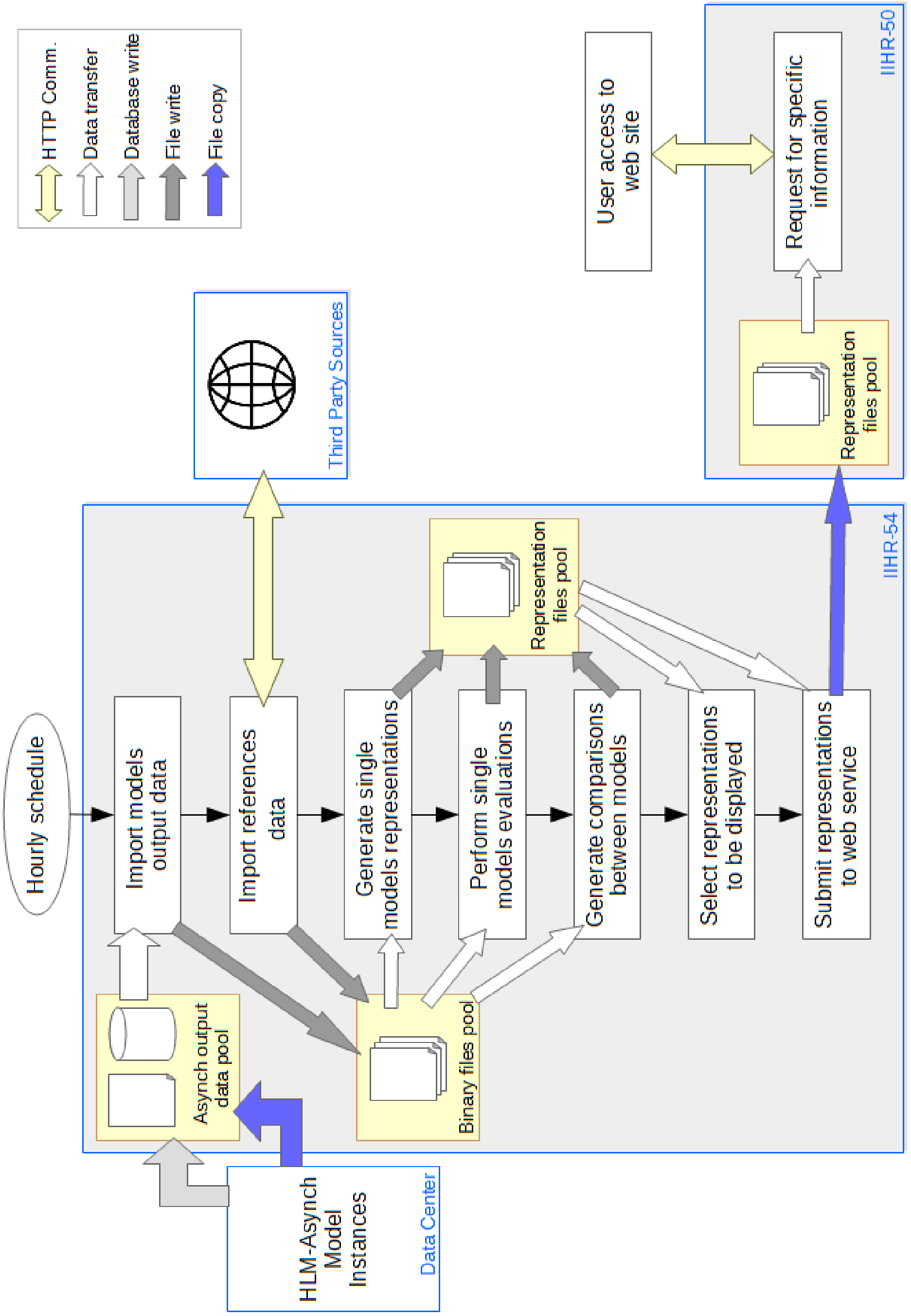


Figure 7 – Flow diagram of the procedures executed on an hourly base for updating the real-time sc-runset.

3.3 - Requester System Workflow

3.3.1 - Workflow

Despite of the major interest on the information related to current state and forecasting of river network, an additional interest emerges on the simulation of past rainfall-runoff and flood scenarios for model performance evaluation, model inter-comparison and general flood related research questions.

In order to provide a method for intuitively allow users to reproduce past significant large scale hydrological events in Iowa using HLM-ASYNCH conceptual models and rain data available on IFC databases, a subsystem of IFIS Model-Plus, named Requester, was created. It collects, fills and organizes all the necessary input files for the execution of a set of HLM-ASYNCH model instances, each one with an arbitrarily defined set of parameters and settings, for the fixed period of 20 days. The Requester component executes ASYNCH runs for each of the defined HLM-ASYNCH model instances defined in the interface, and after all runs are completed, it executes the procedures necessary to generate individual representations, comparison and evaluations of the model outputs. The last step is the submission of the generated representations to the web service to be displayed back to the user. The workflow started at the moment the user submits a request for the execution of an sc-runset is shown on Figure 8.

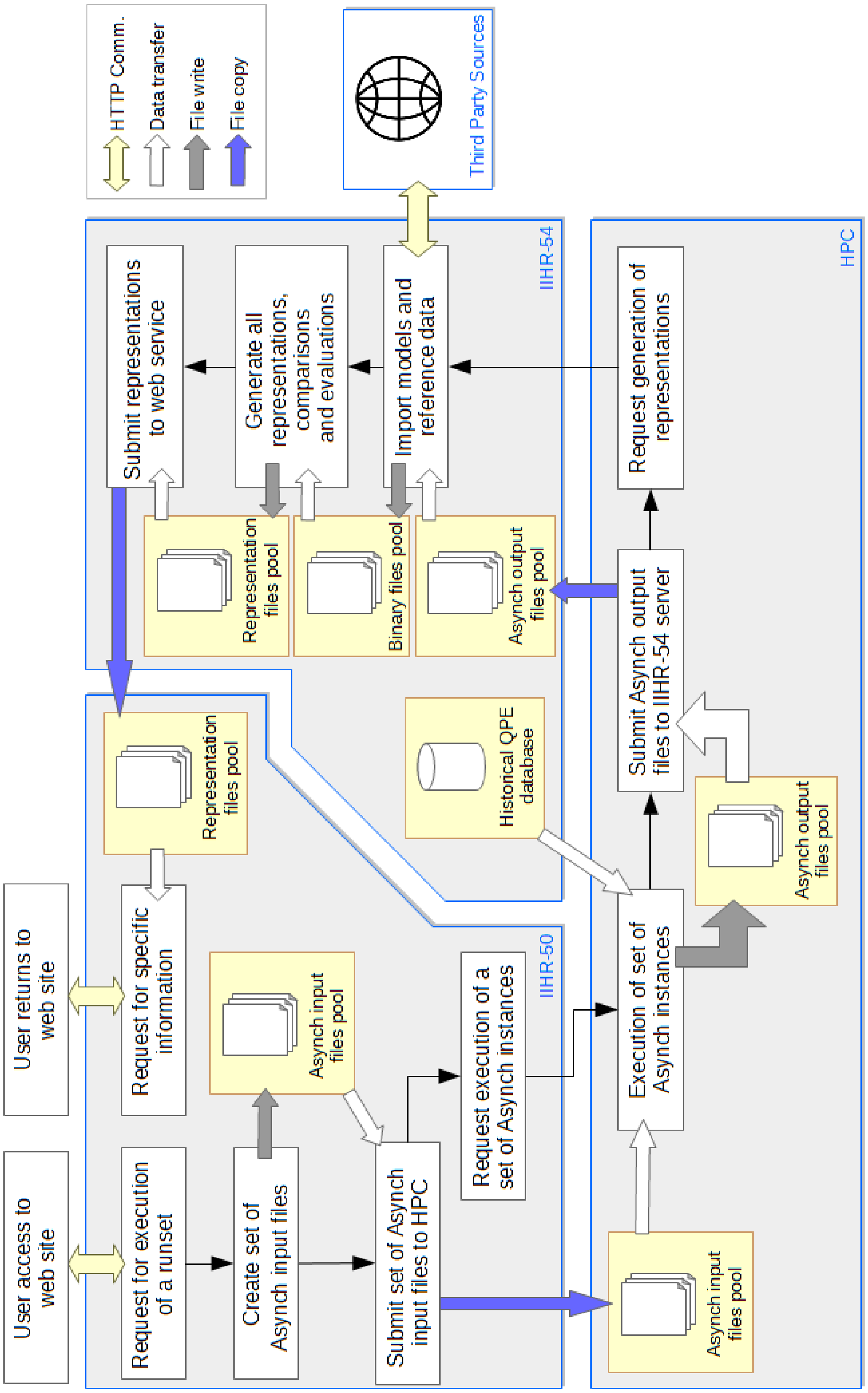


Figure 8 – Flow diagram of the procedures executed each time the request for execution of an sc-runset is performed.

3.3.2 - Data repository

One of the requisites of the Requester subsystem is to be intuitive and require limited inputs from users. It was defined that user options for triggering model executions would be limited to the date of the simulations within the sc-runset and basic specifications of each of the sc-models (regarding its respective HLM conceptual model, the respective set of global parameters and the QPE data source for input data). For filling such requisite, a data repository for model inputs must be set in advance to include the information not provided by the final user but necessary for ASYNCH runs.

A database with historical QPE produced in the context of NOAA-MRMS project was replicated, from previously existing IIHR data repositories, into IIHR-54 server, from which HLM-ASYNCH model instances being executed on HPC retrieve the rainfall data.

A set of initial states of Top Layer hydrological conceptual model for every 10-days interval, for years 2008 and 2016, was established through an algorithm based on spatial regression of estimated base flows, which is described in the Appendix 2. In each execution, the simulation starts from the snapshot in such repository that is closer to the initial date of the sc-runset.

No historical of anthropogenic-controlled reservoirs discharge is considered, so that the discharge in the hillslope-links in which such dams are present are modeled through the standard governing equation of the conceptual model.

After the completion of the entire workflow, both the ASYNCH output files and the imported binary files of the sc-runset are removed for disk space saving reasons.

CHAPTER 4 - IFIS MODEL-PLUS CURRENT TOOLS

IFIS Model-Plus is designed to be a flexible system of modular components that can be modified or expanded with relatively small efforts. In this chapter, the currently supported and implemented components are presented.

4.1 - SC-Products

In the following subsections, the expression “an sc-product” refers to the data produced by an sc-model instance or retrieved from an sc-reference to represent water-related conditions in the Iowa water domain over a one-hour time interval.

All products, as well as additional sources of data, are structurally associated to the set of hillslope-links in the Iowa water domain for them to be imported into IFIS-Model Plus as sc-products. Therefore a mapping function (often a look up table) between the data set and the hillslope-links within the Iowa water domain is needed. Currently supported sc-products include:

Distributed Instantaneous Discharge

An sc-product of Distributed Instantaneous Discharge contains values for the instantaneous discharge for the link in each hillslope-link at the Iowa water domain, in units of cubic meters per second for a given moment in time. This data can be used to generate representations for Flow Discharge Classification, Flood Severity Classification and Hydrographs.

Distributed Instantaneous Base Flow

In HLM-ASYNCH-254, base flow is the portion of the discharge in the link that reached the channel after infiltration into the ground and percolation trough the subsurface.

Because its flow velocity is in a lower order of magnitude when compared with the water flowing through the surface (runoff), such information is relevant to provide insights related to which percent of the instantaneous flow is expected to stand for longer time and which can be considered an intermittent condition (“flood wave”).

An sc-product of Distributed Base Flow contains a value of discharge, in cubic meters per second for each hillslope-link system. In the current version of the system, no representation is related to this information.

Distributed Instantaneous Ponded Equivalent Water Depth

Sc-products of this type record the amount of water in the surface of the hillslope in each hillslope-link of the system for a specific moment in time. Ponded water accumulated during a precipitation event will flow to the link as surface runoff or will infiltrate into the soil (in equivalent water depth, in meters). Except for moments just following rainfall events, this value is close to zero (negligible volume of pounded water).

In the present implementation of the system no representation considers such information, but it has the potential to be used in exploring the potential of runoff generation in future versions.

Distributed Instantaneous Top Layer Equivalent Water Depth

This sc-product provides the amount of water stored in the porous void spaces in the Top Layer region of the soil for each hillslope-link in the Iowa water domain in a given moment in time. The unit used is the equivalent water depth (in meters).

Sc-products of Distributed Instantaneous Top Layer Equivalent Water Depth are presented in the interface by the Distributed Top Layer Water Saturation sc-representation.

Distributed Instantaneous Subsurface Equivalent Water Depth

Sc-products of Distributed Instantaneous Subsurface Equivalent Water Depth store, for each hillslope-link in the Iowa water domain in a given moment in time provide the amount of water stored in the porous void spaces in the region of soil between the Top Layer (subsurface) and deeper soils in equivalent water depth (in meters).

Sc-representations of distributed soil water content depend on this data.

Distributed Accumulated Precipitation

An sc-product of Distributed Accumulated Precipitation contains the total amount of precipitation that affected each of the hillslope-link systems in the Iowa water domain since the beginning of the model simulation (in units of millimeters of equivalent water column).

The difference between two sc-products of distributed accumulated precipitation, one for a given time t_1 and the other for given time t_2, both produced by the same sc-model and with $t_2 > t_1$, results in values for the accumulated precipitation estimated within the time interval of $\Delta t = t_2 - t_1$. When using time windows with Δt equal to 3 hour, 6 hour, 12 hours and 24 hours, it is possible to generate representations of the accumulated rainfall within such time intervals.

Distributed Accumulated Runoff

An sc-product of Distributed Accumulated Runoff contains the total amount of surface runoff, in units of millimeters of equivalent water column, that each of the hillslope-link systems in the Iowa water domain produced since the beginning of the model simulation represented by the sc-model component.

In this work, surface runoff is understood as the water that, after being accumulated in the surface pounds of a hillslope, flowed directly into its respective associated river link (i.e., without passing through infiltration/percolation processes).

As explained for the Distributed Accumulated Precipitation sc-roduct, the cumulative runoff generated within a time interval can be easily calculated as the difference between of products generated in two different moments of time.

Sparse Forecast Discharge

Due to the extensive number of hillslope-link systems in which Iowa territory was segmented, the amount of resources, in terms of data storage and processing capabilities, estimated for generating distributed discharge forecasts is considered a potential limiting factor. For such a reason, one of the output options of HLM-ASYNCH is the generation of discharge forecasts (in the format of time series data) for a limited number of sites. Generally, the selected locations correspond to flow gages or specific communities of interest. Other potential sources for this type of sc-product are agencies that generate their own forecasts of river discharge. These sources can be considered either as sc-models or as sc-references.

Thus, a Sparse Forecast Discharge sc-product stores a discharge time series, associated to a hillslope-link unit and it is assumed to be valid for that specific moment in time. Each time series is represented as a list of time (in epoch timestamp) and instantaneous discharge (in cubic meters per second) pairs.

It is applied in the composition of hydrographs both for comparing potential rainfall scenarios and evaluating forecasting capabilities.

Sparse Instantaneous Water Stage

Usually provided by sc-references that represent sets of USBS (Ultrasonic Stream Bridge Sensors), an sc-product of sparse instantaneous water stage type contains the information related to the water stage registered, in units of inches, on all locations associated to the sc-source for a specific moment.

This data is used in the composition of stage hydrographs with reference values. They are converted into discharge through rating curves for the evaluation of model performance through discharge-dependent methods such as Nash-Suticliffe.

Sparse Instantaneous Water Discharge

Specific flow sensors (usually stage gages for which the respective rating curve is established) provide, directly or indirectly, estimations on instantaneous water discharge for a specific river segment. An sc-product of this type stores information of instantaneous discharge data registered by stream gages provided by the USGS or the USACE.

Such information is particularly necessary for specific evaluating techniques of the models, such as the Nash-Sutcliffe. In addition, after being converted into stage values through regression of rating curves, these values are used to generate reference stage data for visual evaluation using hydrographs.

Sparse Instantaneous Daily Exceedance-Probability Classification

For specific long-term monitored river segments in which appropriate flow frequency analysis has been performed, observed or modeled instantaneous flow values can be expressed as their respective exceedance probability of occurrence. Such conversion is performed through the usage of flow-duration curves (USDA, 2007).

Using this methodology, for each long-term monitored river segment a set of flow thresholds values can be defined considering the respective annual exceedance probability of occurrence to be established a simple flow classification method. USGS – Water Watch portal, for instance, presents real-time conditions of its monitored locations considering the thresholds of probability of exceedance presented in Table 2. IFIS Model-Plus classification applies the same set of thresholds to classify the value of a river flow in a specific moment in time. IFIS Model-Plus uses a technique recently developed by Perez et al (2017) to provide discharge thresholds at ungauged locations. Thus, an sc-product of Sparse Instant Annual Exceedance-Probability Classification registers the exceedance of probability class to which the instant flows of each monitored site is associated. Both direct and evaluating representations of such data are produced in the system.

Table 2 – Flow classification with respect to estimated annual exceedance probability.

Criteria	**USGS WaterWatch Flow classification**	**IFIS Model-Plus sc-product value**
$q_{it} < Q(10\%)_i$	Much below normal	1
$Q(10\%)_i < q_{it} < Q(25\%)_i$	Below Normal	2
$Q(25\%)_i < q_{it} < Q(75\%)_i$	Normal	3
$Q(75\%)_i < q_{it} < Q(90\%)_i$	Above normal	4
$q_{it} > Q(90\%)_i$	Much above normal	5

4.2 - SC-Representations

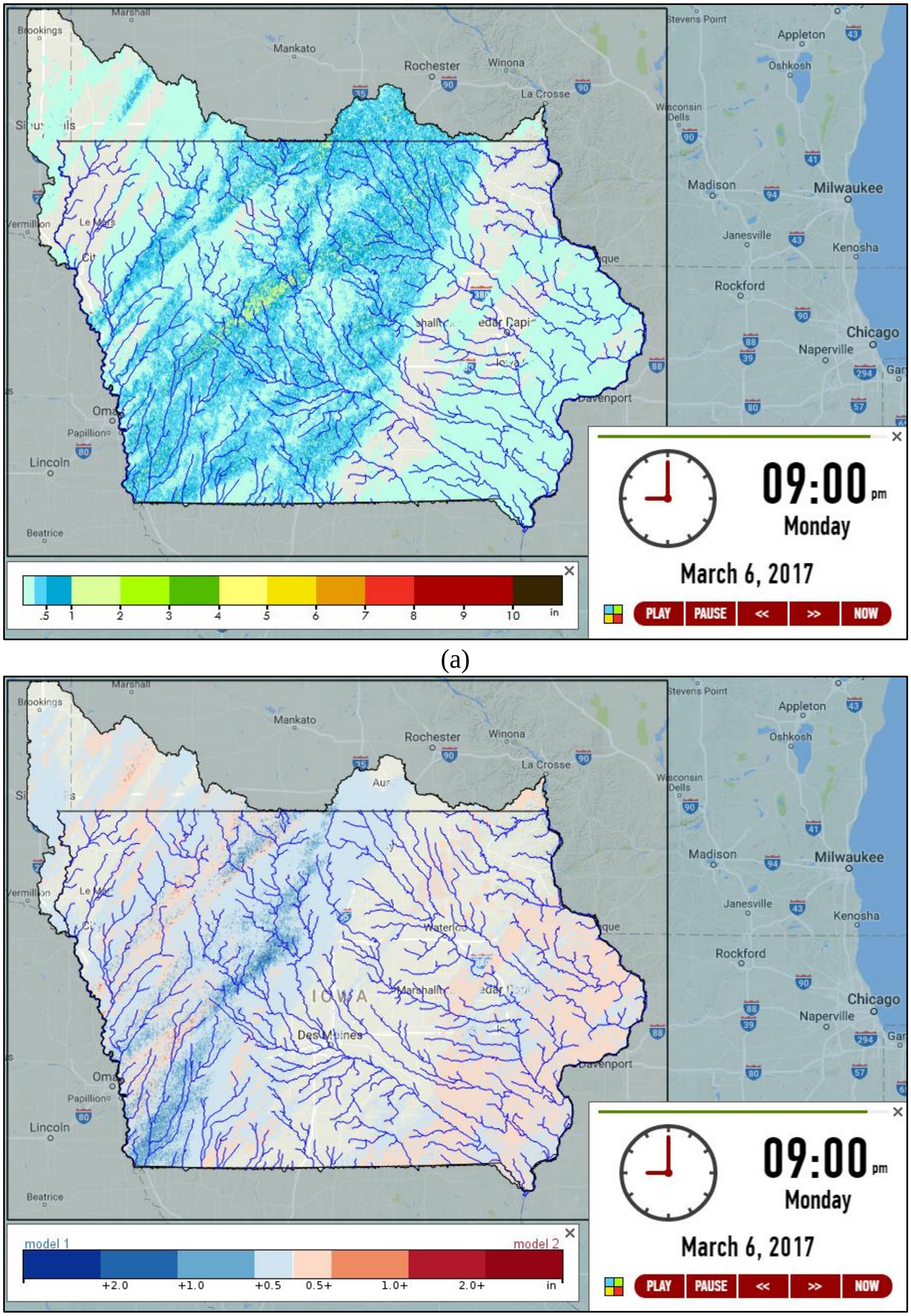
All distributed representations are displayed as raster images of 1744 x 1433 pixels with an approximately resolution of 341m/pixel. The decision for using this specific resolution comes from the previously implemented functionality for representing sequential images as an overlay on the state of Iowa available on IFIS Special Cases. Sparse representations are represented as dots on the Iowa map with specific functionalities activated as response for mouse clicks over each icon. The representations included in the current distribution of IFIS Model-Plus are,

Distributed Cumulative Precipitation

There are five different types of representations related to Distributed Cumulative Precipitation, each one related to different accumulation periods of rainfall of 3-hours, 6-hours, 12-hours, 24-hours as moving windows and fix window accumulation of daily time intervals. The difference between 24-hours and Daily time intervals is the segmentation of time between images in the animated sequence - while the 24-hours representation provides the accumulated precipitation in the past 24 hours from any rounded hour in a day, daily time interval provides the accumulated between the midnight of a specific day and the midnight of the following day. When representing the output of a single sc-model, the color code follows the standard adopted by IFIS for representing rainfall intensities (Figure 1a) and a value interval from 0.5 to 10 inches (Figure 9a). The comparisons between precipitations registered by two sc-models represents the direct difference of cumulative values for up to 2 inches difference (Figure 9b).

Distributed Cumulative Surface Runoff

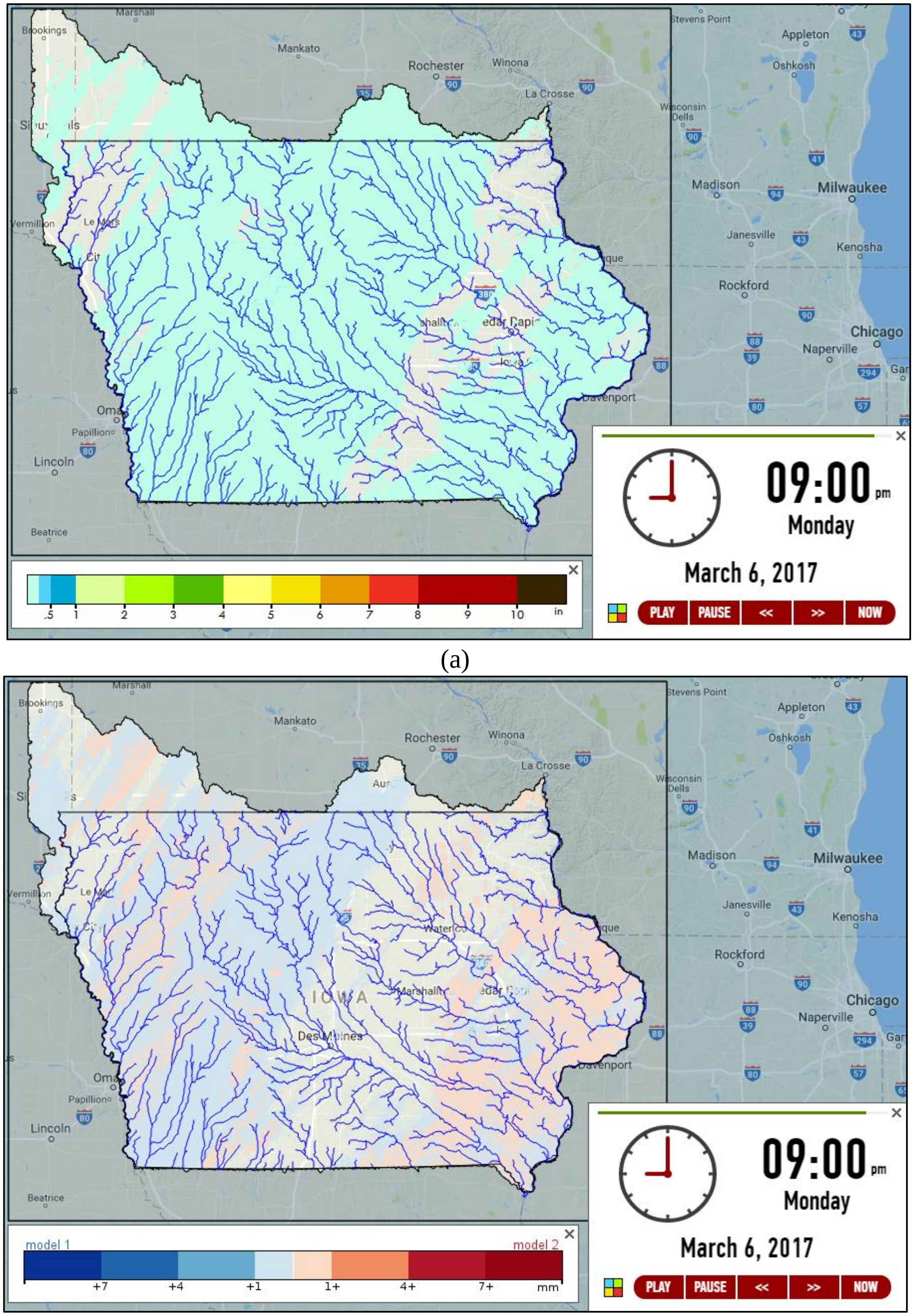
It represents the accumulated volume of water (in equivalent water column) that reached a specific hillslope-link after being partitioned into the surface runoff component of the hydrological cycle. As the volume of produced runoff follows a close order of magnitude as Distributive Cumulative Precipitation, similar time intervals of accumulations of 24, 12, 6, and 3 hours are presented in equivalent color codes for both representations of runoff output from single sc-models (Figure 10a) and the comparison between the cumulative runoff output of two sc-models (Figure 10b).



(a)

(b)

Figure 9 – Examples of 24-hours cumulative distributed rainfall representation for (a) a single sc-model using IFC Rain product and (b) its comparison with another using NOAA-MRMS rain product.



(a)

(b)

Figure 10 – Examples of 24-hours cumulative distributed runoff representation for (a) a single sc-model using IFC Rain product and (b) its comparison with another using NOAA-MRMS rain product.

Distributed Top Layer Water Saturation

Provides an estimative of the Water Saturation, defined as the ratio between the water volume and pore space volume, in the Top Layer (from surface to soil depth S_L). This estimative is based on the output data of the sc-product Distributed Instantaneous Top Layer Equivalent Water Depth (s_t) and it assumes a soil porosity (ϕ) of 50% uniform in space, so that

$$WS_t = \frac{s_t}{\phi * S_L} \, . \tag{3}$$

This information is presented as a raster color-coded in values ranging from 0% for total dry (beige color) to 100% for total saturated soil (blue color) as shown in Figure 11a. A corresponding comparison representation is calculated as the ratio between the percentage of saturation of one model with respect to the percentage of saturation of another. For instance, if a hillslope-link has value of 62% for this variable in one model and in the other model it presents the value of 21%, the map will represent in the class of "3x", meaning that one value is approximately three time higher than the other (Figure 11b).

This is one of the most important model variables to keep tracking, as it determines conditions that lead to intensified surface runoff, and subsequent flooding, for a particular watershed.

Distributed Soil Water Column

This variable represents an estimation of the total equivalent water column stored in the soil. It's calculated as the sum of instantaneous Top Layer and subsurface equivalent water depth sc-products. It is predominantly characterized by the long-term accumulation of rainfall in the soil and it provides valuable insights on the potential for baseflow production. In addition, it has shown to reveal inconsistencies and artifacts in radar-data derived rainfall products. A case in point is the consistent underestimation of total rainfall from products rainfall estimates derived from the Sioux Falls radar that covers the north west corner of Iowa (Figure 12a). Both single model and comparisons are represented in color codes of equivalent water depth in millimeters (Figure 12).

Distributed Flow Discharge Classification

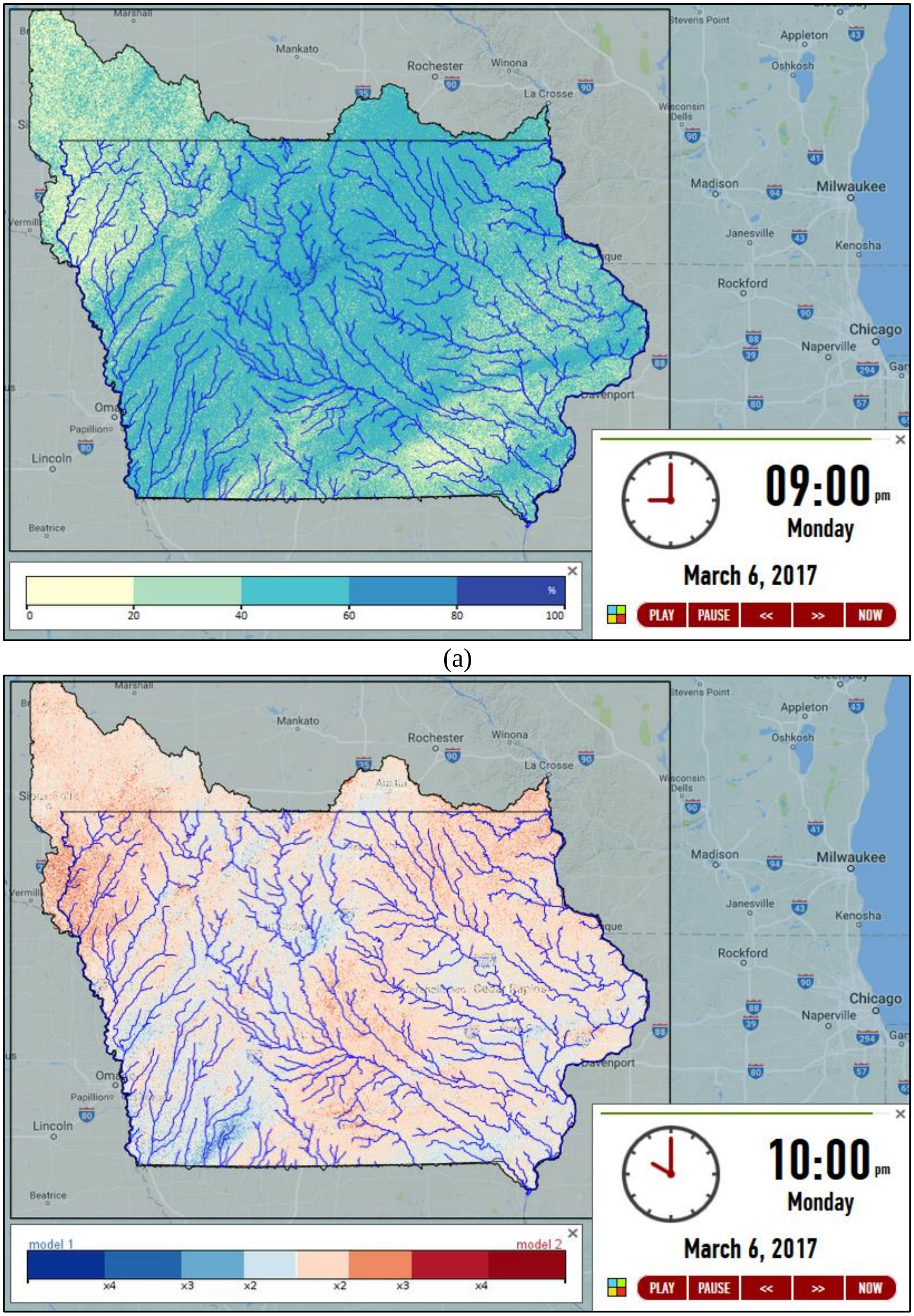
An instantaneous flow discharge is classified in one of five categories using its daily probability of exceedance in the river link in which it was observed or modeled, as presented in Table 3. For a matter of compatibility, the thresholds were established following the USGS standard (Table 2).

Table 3 – Flow discharge classification for the hillslope-link i at time t.

Criteria	IFIS Model-Plus Flow Classification
$q_{it} < Q(10\%)_i$	Very low
$Q(10\%)_i < q_{it} < Q(25\%)_i$	Low
$Q(25\%)_i < q_{it} < Q(75\%)_i$	Normal
$Q(75\%)_i < q_{it} < Q(90\%)_i$	High
$q_{it} > Q(90\%)_i$	Bankfull

While for long term monitored locations the discharge values for each quantile are usually obtained from previous observed time series analysis, for ungauged river links, in which estimations of instantaneous discharge values are available from outputs of sc-models, a non-empirical method for classification is needed.

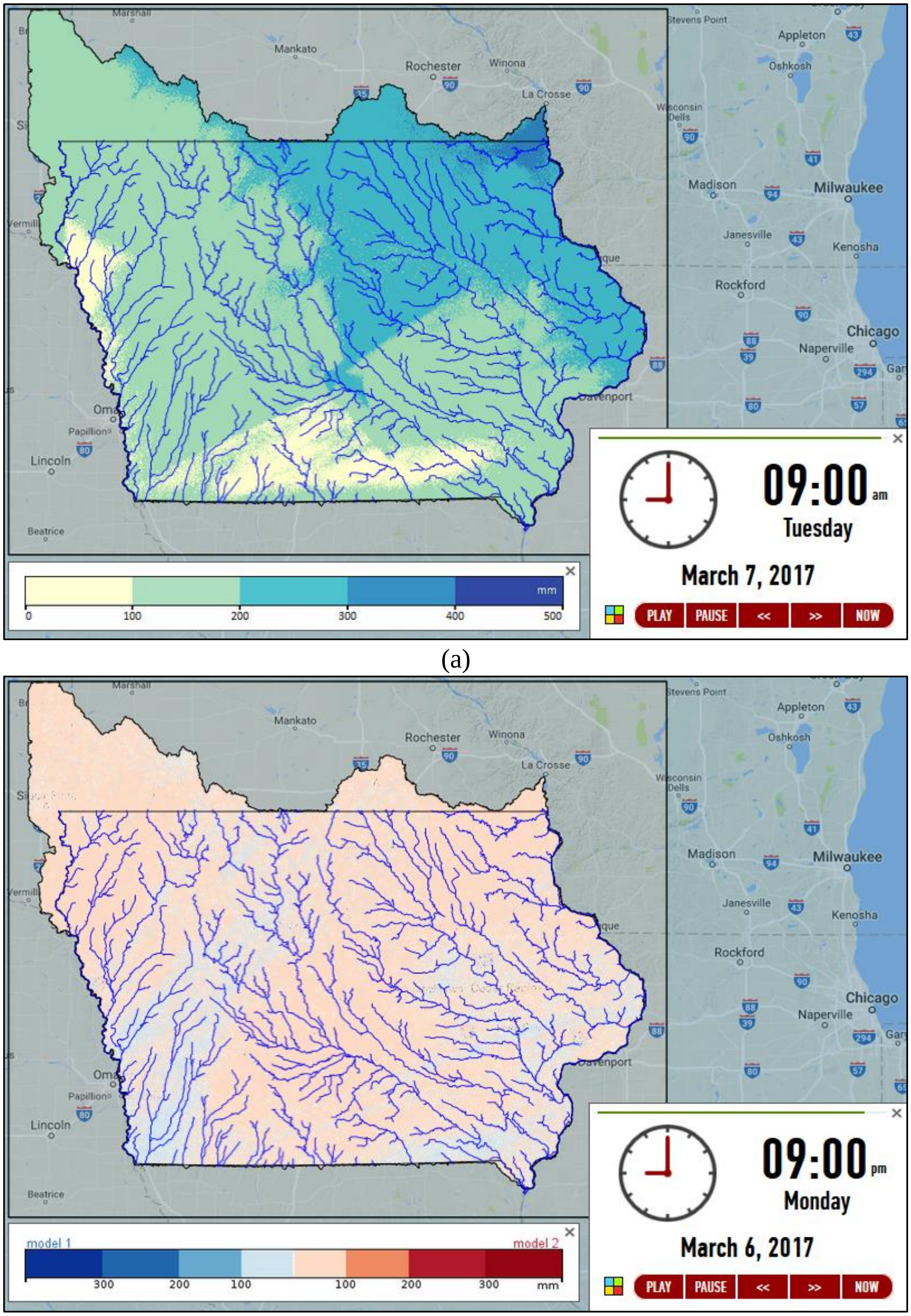
The current implementation of IFIS Model-Plus uses the multi-scaling framework proposed by Perez *et al.* (2017) to estimate a daily probability of exceedance for each river link in the Iowa water domain and, from such distribution, determine the discharges related to the respective thresholds of probabilities of exceedance. Their method determines the flow quantile $Q_{p,m,i}$, for a probability of exceedance p on the location l in the month m, in



(a)

(b)

Figure 11 – Representations of the Top Layer saturation variable for (a) a single sc-model and for (b) the comparison of two sc-models.



(a)

(b)

Figure 12 – Representation of Distributed Soil Water Column for (a) a single sc-model and for (b) the comparison of two sc-models output.

which only mean monthly discharge $\overline{Q_{m,l}}$ is known, by

$$Q_{p,m,i} = \alpha_{p,m} \, \overline{Q_{m,p,l}}^{\Theta_{p,m}}, \tag{4}$$

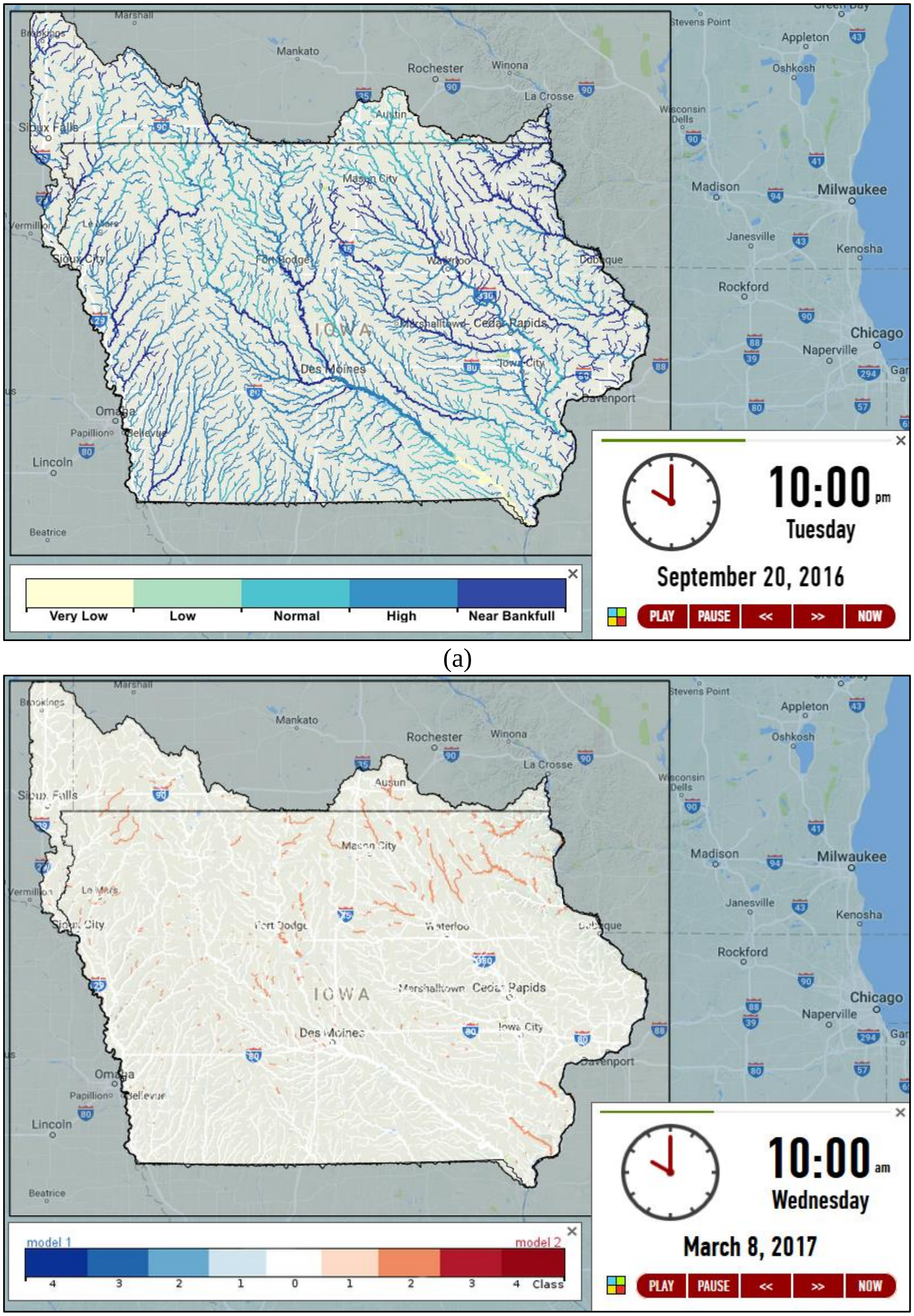
where $\alpha_{p,m}$ and $\Theta_{p,m}$ are parameters estimated from temporal data analysis of a nearby set of gauged locations. Using 84 gauged sites within the State of Iowa, the same authors established the parameter $\alpha_{p,m}$ and $\Theta_{p,m}$ for the region for p ranging from 0.01 to 0.99. The values applied in this work are summarized in Appendix 1.

The value of $\bar{Q}$ for each river link was defined using the long-term water balance equation given by

$$\bar{Q} = (\bar{P} - \bar{E})A \tag{5}$$

in which $\bar{P}$ and $\overline{ET}$ are the mean annual precipitation (estimated from PRIMS products Oregon State University, 2016) and the mean annual evapotranspiration (obtained from estimations for years 1983 to 2006 developed by Zhang *et al*, 2010), respectively, and A is the upstream drainage area of the river link.

The representation of the distributed flow discharge classes is performed through color coded raster images with the drainage network of links of Horton order 4 and more. In the representation of a single sc-model data, different shades of blue with the darker shades indicating higher flow classes are used (Figure 13a). For comparisons between two sc-models, the difference between the classes defined for each link is represented with colors ranging from intense blue if one class is much higher in one point to intense red if the opposite case (Figure 13b).



(a)

(b)

Figure 13 – Representations of the Distributed Flow Discharge Classification for (a) a single sc-model and for (b) the comparison of two sc-models.

Flood Severity Classification

The NWS has developed thresholds of water surface levels for each monitored location that define objectively the degree of flood threat an observation data. According to NWS (2012), the thresholds correspond to: *Bankfull stage* (above which the rise of water level would result in overflow of the natural stream bank). *Action Stage* (above which it is required mitigation actions from respective authorities in preparation for impacts caused by eventual hydrologic activities that result in water surface rising), and *Flood Stage* (above which it is expected effective impacts on live, commerce and property). If the water surface of a monitored location overpasses its established Flood Stage, the classification switches to the severity of the flood also taking into consideration pre-established water level thresholds. A situation of flood, by its time, can be classified based on its severity in *Minor Flood* (when some public threat such blockage of roads is expected, but minimal property damage), *Moderate Flood* (when a restricted level of property damage is expected and limited evacuation of people is necessary) or *Major Flooding* (when extensive property damage is expected and evacuation of people is necessary).

These thresholds are usually displayed as part of the background in hydrographs present in real-time monitoring portal, such as the NWS – Advanced Hydrologic Prediction Service (AHPS) (Figure 14).

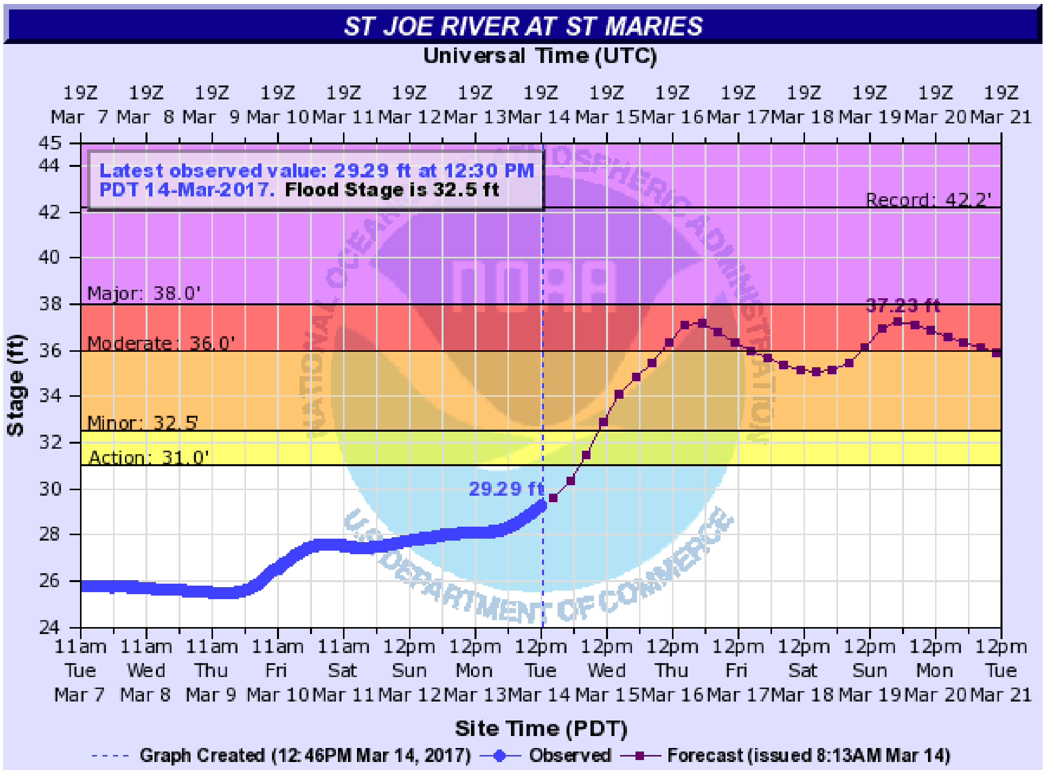


Figure 14 – Example of hydrograph available in NWS-AHPS portal, in which Action Stage, Flood Stage, Moderate Stage and Major Stage thresholds are presented as colored regions of horizontal axis.

One limitation of such classification is that it is currently available only for monitored gages. In order to expand the capability of classification of flood states to all hillslope links in the Iowa water domain, for each gage in Iowa with defined Action stage and flood classification thresholds, it was estimated the respective mean annual probability of exceedance values of such water levels. A regression, taking into consideration the respective mean annual flood (it is: the flow with period of return of 2.33 years - based on Leopold (1968)) was performed to find estimates for quantiles in the probability of exceedance distribution that best describe such thresholds. Resulting threshold quantiles are presented in Table 4.

Using a similar methodology applied on Flow Discharge Classification, but with annual values for α and θ, discharge thresholds for equivalent action and flood classification stages were defined for each hillslope-link system in the Iowa water domain. The classification of the flood condition in a hillslope-link unit is performed by the comparison of its instant discharge values, estimated by a hydrological model instance, with the flood thresholds defined for it. The final representation is given by a color-coded raster image with the drainage network of links of Horton order 4 or more.

In the representation of a single sc-model data, the colors associated to different flood situations can be estimated, with yellow for above Action stage, orange for above Minor Flooding, red for Moderate Flooding and dark purple for Major Flooding, while light blue is reserved for the rest of the drainage network in which no flooding conditions are estimated (Figure 15a). In the case of comparisons between the outputs of two sc-models, the difference between the classes are defined for each link, ranging from intense blue if one class is much higher in one point to intense red if the opposite (Figure 15b), while white reserved for hillslope-links with equal classification.

The main advantage of such method of visualization comes from the perception of how fast the crest of a flood is moving through a river network and the visual identification of hillslope-links that contribute the most to the formation of the flooding scenario. This representation has the potential of providing insights on understanding the genesis of floods and how widespread the consequences of flooding are across the state.

Table 4 – Flood classification criteria for the hillslope-link i at the moment t.

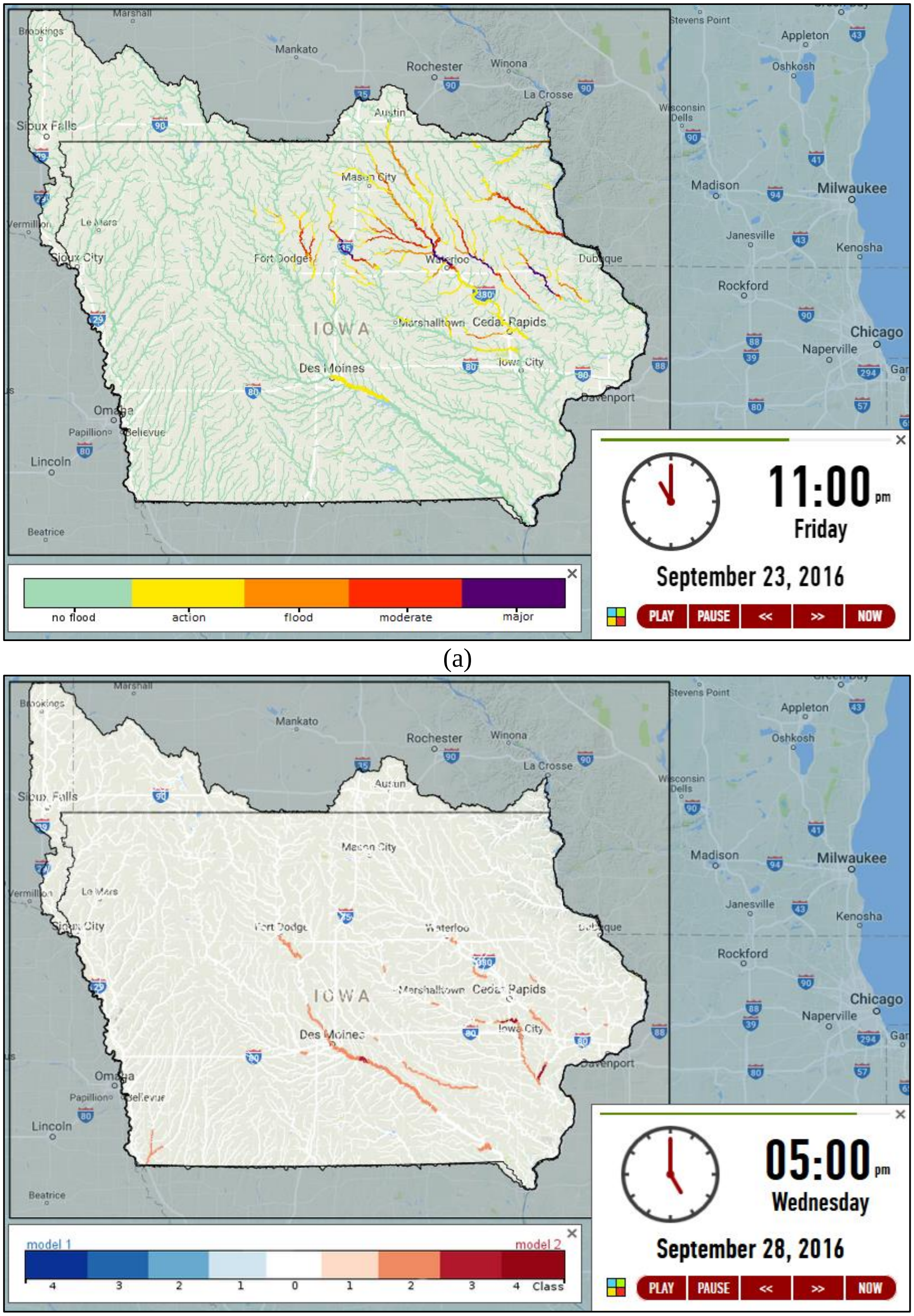
Criteria	Flood classification	IFIS Model-Plus label
$q_{it} < 0.4\ Q_{2.33,i}$	No Flood	No Flood
$0.4\ Q_{2.33,i} < q_{it} < 1.0\ Q_{2.33,i}$	Above Action Stage	Action
$1.0\ Q_{2.33,i} < q_{it} < 1.5\ Q_{2.33,i}$	Minor Flooding	Flood
$1.5\ Q_{2.33,i} < q_{it} < 2.7 Q_{2.33,i}$	Moderate Flooding	Moderate
$q_{it} > 2.7\ Q_{2.33,i}$	Major Flooding	Major

Flow Discharge Classification / Flood Severity Classification

The combined representation of flow discharge and flood severity classification assumes that the stage values that represent the different quantiles used for flow discharge levels are generally lower than the minimum stage registered for the lower flood alert level threshold (Action stage), so both classifications could be overlaid to represent more naturally the gradient of elevations of water in a single map. An example is provided in Figure 17a.

Precipitation (3h) / Flow Discharge Classification / Flood Classification

The composition on a single representation of the information presented on both Distribute Cumulative Precipitation (3 hours interval), Flow Discharge Classification and Flood Severity Classification maps through overlaying provides a powerful visual tool for understanding the cause-effects relationship between rainfall and flooding, especially when used in animated sequences. A simple example is given by Figure 17b and complete sequences can be found on Chapter 5.



(a)

(b)

Figure 15 – Representations of the Distributed Flood Discharge Classification for (a) a single sc-model and for (b) the comparison of two sc-models.

Forecast Stage Hydrographs

The system allows the representation of sparse data generated by different sc-models in one single graph for hydrograph comparison. In Figure 16, the multiple forecast scenarios feature of the real-time flood forecasting system is shown. The figure shows the output of the HLM-ASYNCH-254 model using IFC Rainfall for the gage station on Boone River, from which two forecast scenarios spawn: the case of occurrence of a uniform rainfall of 2 inches intensity in the interval of one day and the case of no occurrence of rainfall. Note that a flood threshold would be crossed under the former scenario only.

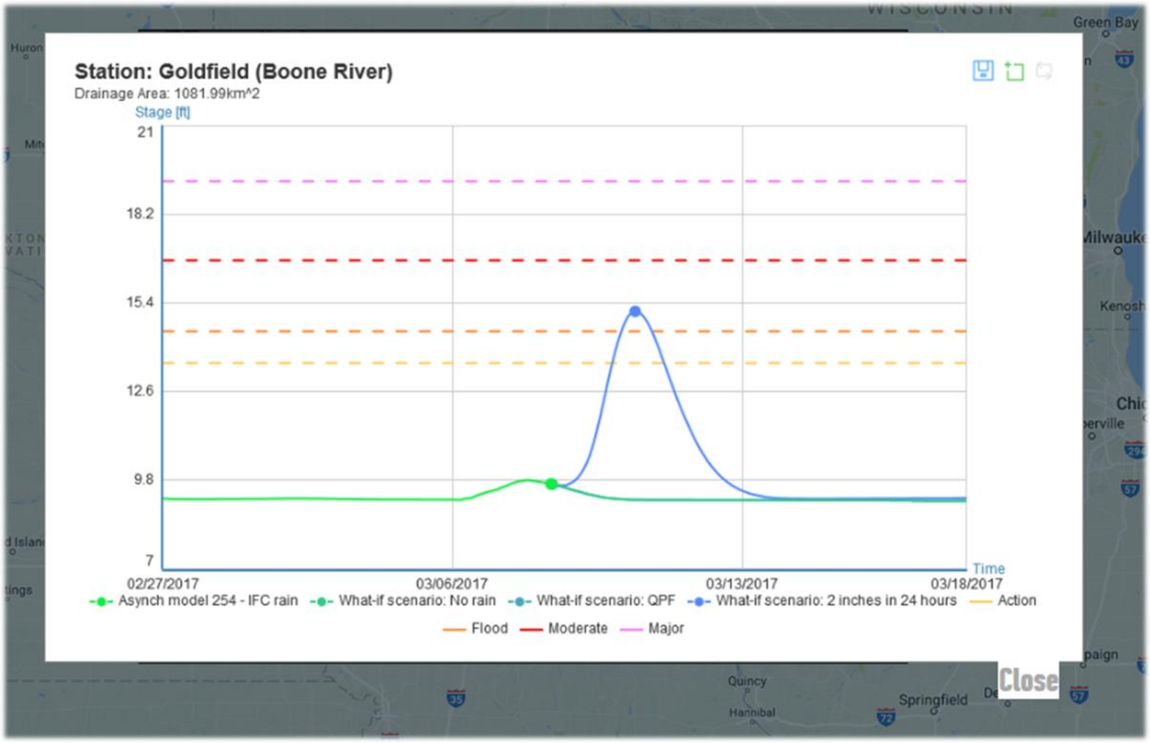
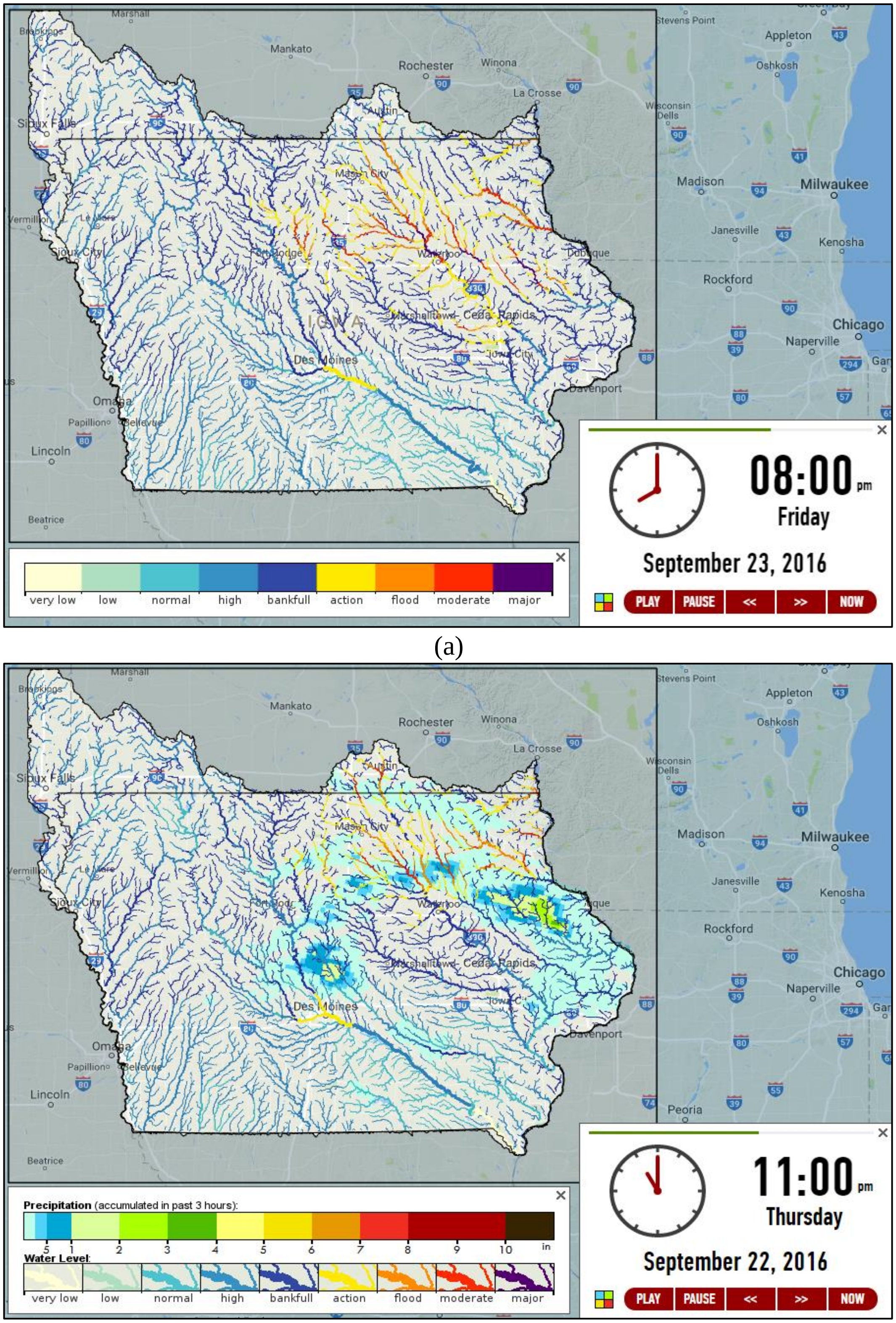


Figure 16 – An example of Forecast Stage Hydrograph, in which three possible future scenarios of stage level are presented after the last moment of data modeled by an sc-model.



(a)

(b)

Figure 17 – Composition of Flow Discharge and Flood Severity Classifications allows identify (a) a major flood in central-east region of the state at the same time that south rivers are in lower levels, which is explained by (b) the previous day rainfall distribution.

4.3 - SC-Evaluations

Stage Hydrographs

Stage hydrograph is a two-dimensional graph in which the stage on a segment of river is plotted with respect to time (Hornberger *et al*, 2014). It provides a simplified mechanism to perform visual comparisons between the data generated by an sc-model that provides sc-products of Sparse Instantaneous Water Discharge and the data provided by an sc-reference with Sparse Instantaneous Water Stages sc-product. Due to the need of converting discharge values (from the sc-model) into respective stage values, only the sc-reference locations with associated rating curves provide stage hydrographs. Baidu E-Charts library is used to create the dynamic representations used for this evaluation. An example of generated hydrograph for one single model is shown in Figure 18.

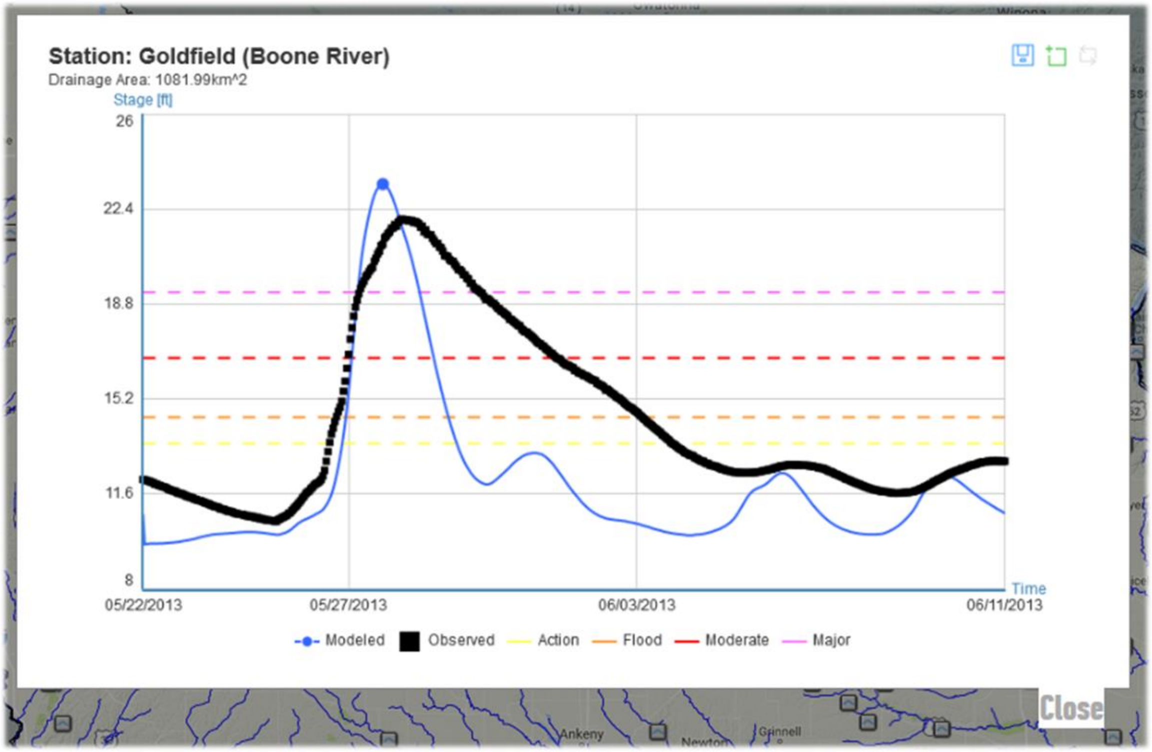


Figure 18 – Example of stage hydrographs.

Nash-Sutcliffe Coefficient

The efficiency coefficient proposed by Nash and Sutcliffe(1970) (in this work named E_{NS}) is a well-established methodology for evaluating hydrological models performance based on the comparison of modeled and observed discharge values. It is defined by the estimation of E_{NS} for a limited and equally time-spaced set of values of size T trough the equation

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

in which Q_m^t is the modeled discharge at moment t, Q_o^t is the observed discharge at moment t and $\overline{Q_\mathrm{o}}$ is the average of observed discharges values in the interval between $t = 1$ and $t = T$.

This evaluation method is implemented in IFIS Model-Plus through the definition of an evaluated sc-model, which must have Distributed Instantaneous Water Discharge as one of its sc-products (Q_m^t), and an “observed” sc-reference, which must present Sparse Instant Discharges or Sparse Instantaneous Water Stages as one of its sc-products (Q_o^t and $\overline{Q_\mathrm{o}}$). If the chosen sc-reference presents the Sparse Instantaneous Water Stages sc-product (as it is the most common scenario for bridge sensors), its values are converted into discharge through inverse rating curves associated to a given location (if no rating curve is available, the location is not evaluated).

Since the availability of data for estimating N_{SE} is limited by the locations associated to the chosen sc-reference (sparse source of data), such evaluation is also sparse and coincides with the locations of the references. An example of such evaluation is given in Figure 19.

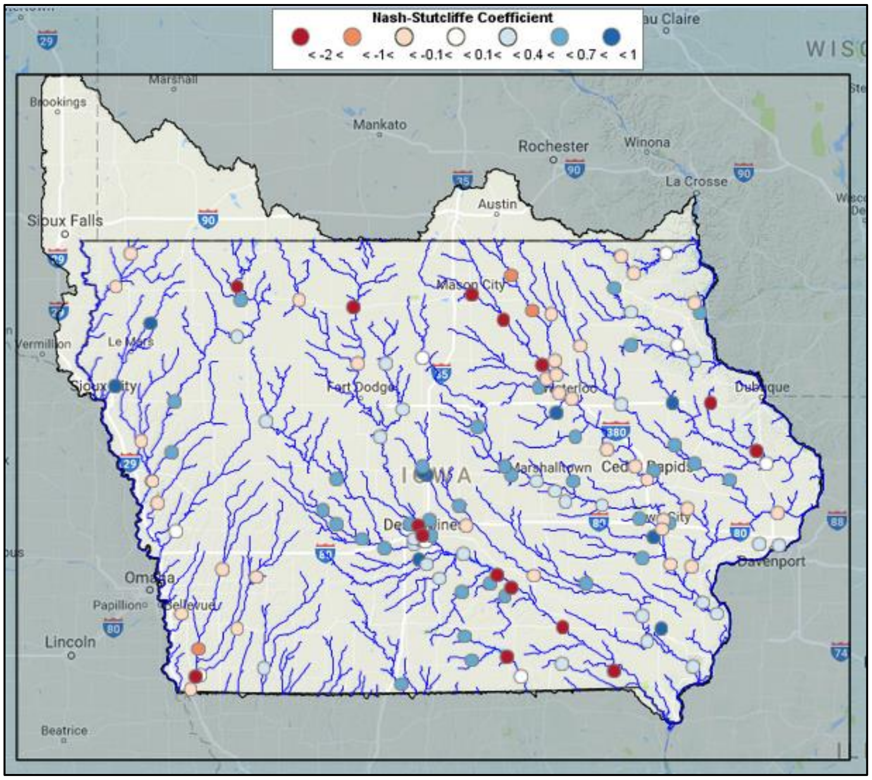
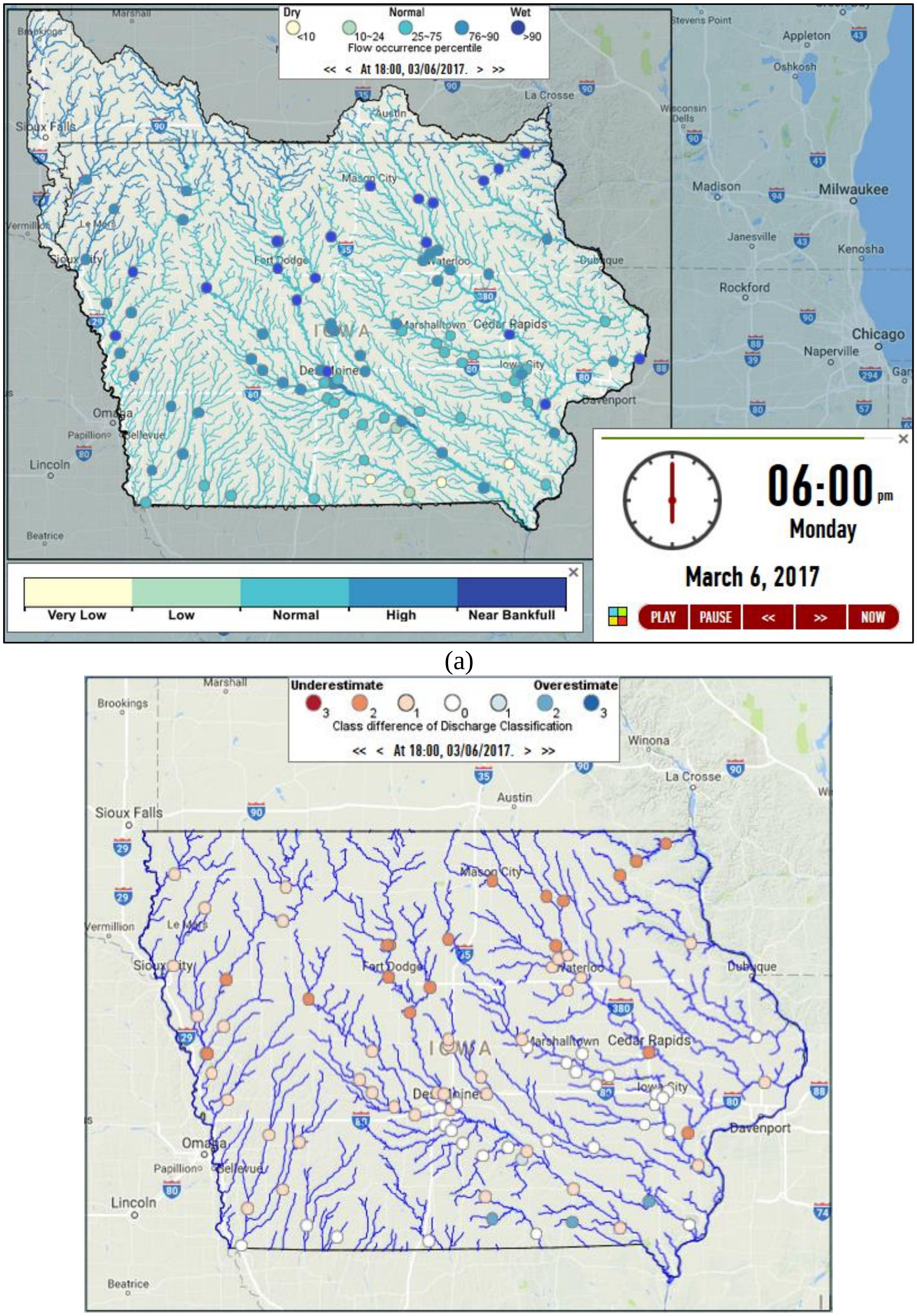


Figure 19 – Example of Nash-Sutcliffe Coefficient representation.

Discharge Flow Quantile Classification

As presented in Chapter 4.3, subsection Flow Discharge Classification, IFIS Model-Plus implements a methodology for classifying the instantaneous flow discharge of a link with respect to estimation of the monthly probability of exceedance. The classes used in such method can be assumed as equivalent to the classes used by USGS WaterWatch portal (Chapter 4.1, subsection Sparse Instantaneous Annual Exceedance-Probability Classification), as the former was conceived as an intent to replicate the outputs of the latter on a distributed perspective.

Thus, for a specific moment in time, taking the USGS WaterWatch data as an sc-reference, the flow classification of an sc-model output can be evaluated as the difference between the classes assigned by each source (Figure 20).



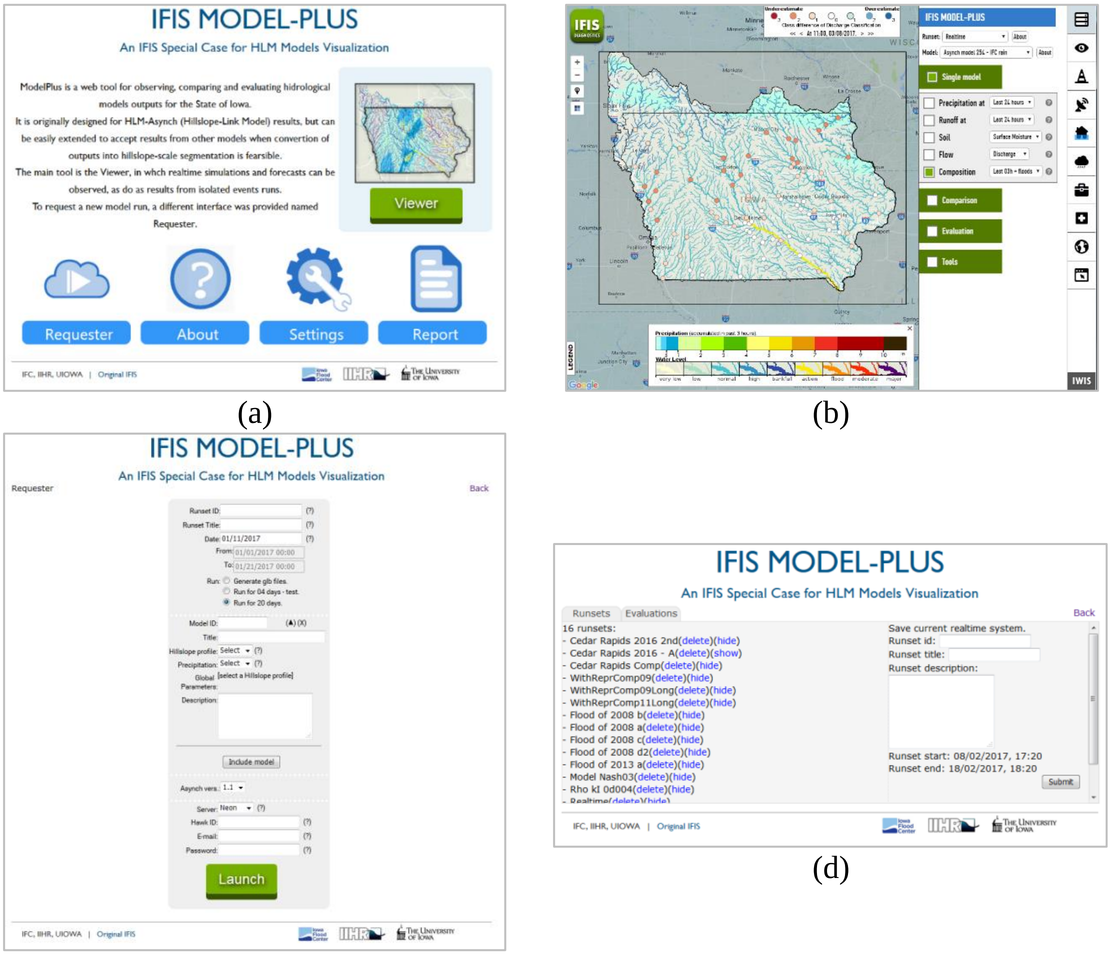
(a)

(b)

Figure 20 – Instantaneous flow discharge classification of (a) both sc-model (distributed-rivers) and sc-reference (dots) and (b) its evaluation compact.

4.4 - Control Panel

The opening web page to the IFIS Model-Plus system (Figure 21a) gives users access to the main functionalities of the system. The “Viewer” button triggers the IFIS Special Case, which provides visual access to all available information of published sc-runsets (both real-time and stand-alone ones), as shown in Figure 21b. The “Requester” functionality directs the user to the form in which stand-alone model runs can be triggered, creating sc-runsets and starting the workflow described in Chapter 3.3.2 (Figure 21c). “Settings” functionality allows administrative users of the system to perform basic manipulations on published sc-runsets, such as deleting or hiding them (Figure 21d).



ModelPlus is a web tool for observing, comparing and evaluating hidrological models outputs for the State of Iowa.
It is originally designed for HLM-Asynch (Hillslope-Link Model) results, but can be easily extended to accept results from other models when convertion of outputs into hillslope-scale segmentation is fearsible.
The main tool is the Viewer, in whch realtime simulations and forecasts can be observed, as do as results from isolated events runs.
To request a new model run, a different interface was provided named Requester.

(a)

Runset: Realtime ▾ About
Model: Asynch model 254 - IFC rain ▾ About
☐ Precipitation at Last 24 hours ▾
☐ Runoff at Last 24 hours ▾
☐ Soil Surface Moisture ▾
☐ Flow Discharge ▾
☑ Composition Last 03h + floods ▾

(b)

Runset ID: (?)
Runset Title: (?)
Date: 01/11/2017 (?)
From: 01/01/2017 00:00
To: 01/21/2017 00:00
Run: ○ Generate glb files.
○ Run for 04 days - test.
● Run for 20 days.
Model ID: (▲) (X)
Title:
Hillslope profile: Select ▾ (?)
Precipitation: Select ▾ (?)
Global Parameters: [select a Hillslope profile]
Description:
Asynch vers.: 1.1 ▾
Server: Neon ▾ (?)
Hawk ID: (?)
E-mail: (?)
Password: (?)

(c)

16 runsets:
- Cedar Rapids 2016 2nd(delete)(hide)
- Cedar Rapids 2016 - A(delete)(show)
- Cedar Rapids Comp(delete)(hide)
- WithReprComp09(delete)(hide)
- WithReprComp09Long(delete)(hide)
- WithReprComp11Long(delete)(hide)
- Flood of 2008 b(delete)(hide)
- Flood of 2008 a(delete)(hide)
- Flood of 2008 c(delete)(hide)
- Flood of 2008 d2(delete)(hide)
- Flood of 2013 a(delete)(hide)
- Model Nash03(delete)(hide)
- Rho kI 0d004(delete)(hide)
- Realtime(delete)(hide)

Save current realtime system.
Runset id:
Runset title:
Runset description:
Runset start: 08/02/2017, 17:20
Runset end: 18/02/2017, 18:20

(d)

Figure 21 – Interfaces include (a) main page, (b) viewer, (c) requester and (d)settings.

CHAPTER 5 - Use Cases and Applications

5.1 - Overview

To illustrate the use of the tool proposed in this work, two sc-runsets were created using the Requester subsystem for two events associated to high precipitation and flooding scenarios: the most recent floods of September 2016 and the historic floods of June 2008.

In these examples, all sc-models associated to the sc-runsets use the Top Layer Model (HLM-ASYNCH-254) as the base conceptual hydrological model (refer to Chapter 1.3.1 for a brief description). Two sets of parameters were considered: the standard adopted by IFC, with global parameters given by v_r= 0.33 m/s, v_b= 0.75 m/s, λ_1= 0.20, λ_2= -0.1, v_h= 0.02 m/s, k_3=2.042·10^{-6} min^{-1}, β=0.02, h_b= 0.5m, S_L=0.1m, A=0.0, B=99 and α=3.0, and an experimental set that assumes the same global parameter values as the IFC standard, except by the value of β=0.004 (this change reduces the percolation rate from the Top Layer into the subsurface). Sc-models assuming the first set of parameters are referred in this work as TL-Standard and as TL-Low Percolation when assuming the second set (TL as acronym for Top Layer).

The rainfall products applied for all simulations were generated in the scope of NOAA-MRMS project and retrieved from internal IIHR database repository. Evapotranspiration was defined as constant for each month with values presented in Table 5.

Table 5 – Monthly constant evaporation rates assumed by HLM-ASYNCH models.

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Inches/ month	19	18	30	32	48	77	121	112	52	20	15	13

The historical data of water release from reservoirs was not included in this simulations, therefore all links associated to Iowa dams are modeled as simple natural channels.

For evaluating results, some locations in which a USGS stream gage is available were arbitrarily selected, as identified in Figure 22.

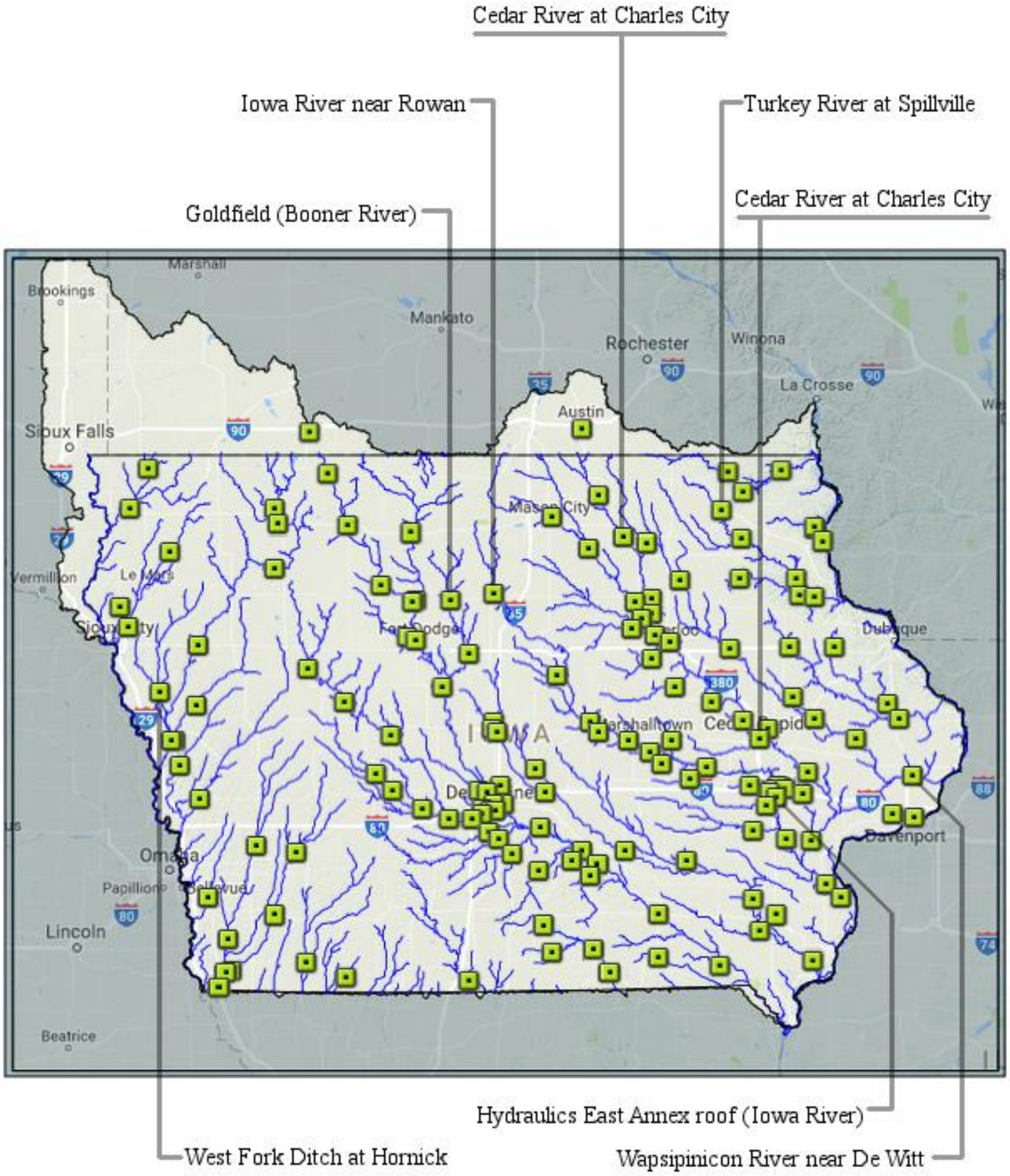


Figure 22 – Identification of selected locations used on evaluation.

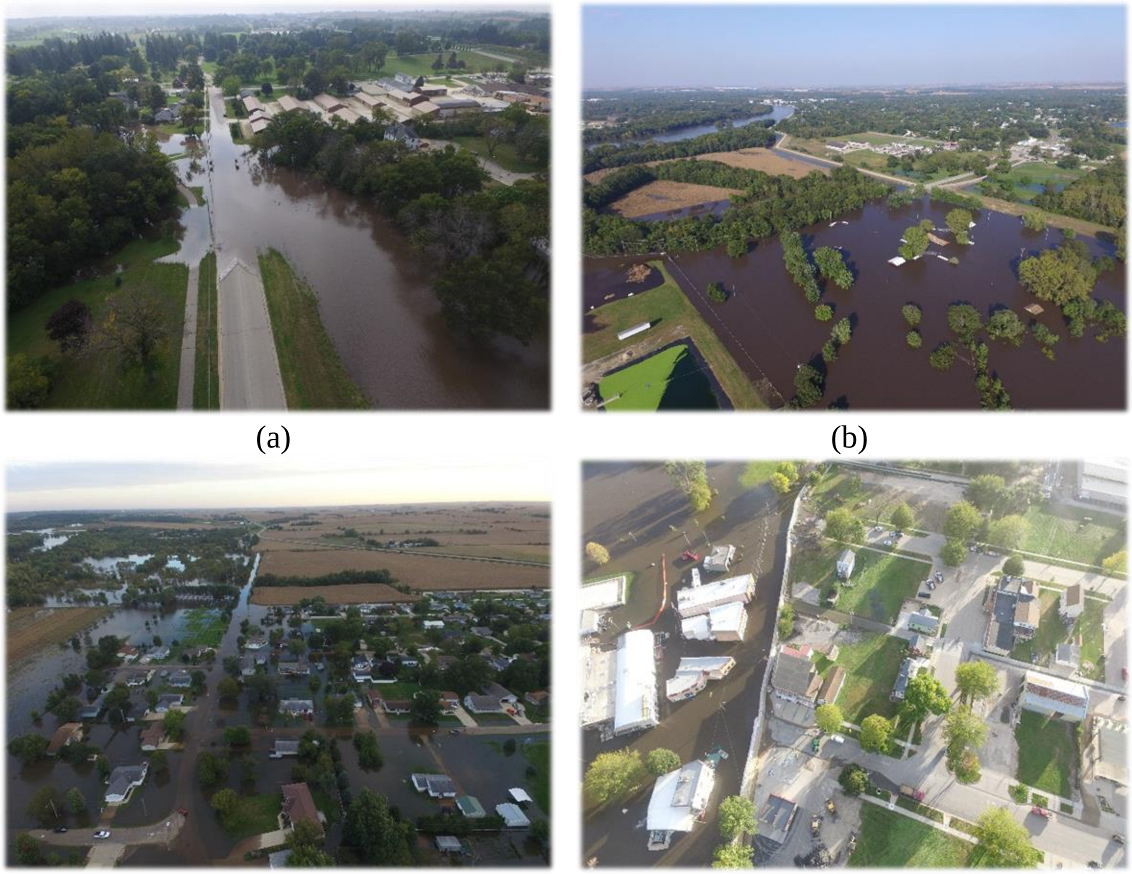
5.2 - Flood of 2016

5.2.1 - Event Description

The Cedar River Basin was affected by a major flood event in September of 2016, causing thousands of residents to voluntarily evacuate their residences and temporarily close roads and commercial establishments in cities like Cedar Falls, Waverly, Vinton and Cedar Rapids.

Climate conditions that resulted in this scenario include a wet summer, with the months of July and August recording precipitation levels above average (NWS, 2016), followed by to the occurrence of two intense rainfall events. The first one on September 16th, widely spread across the territory of the state and which caused the soil to become saturated, and the second was a cluster of storms on September 21st and September 22nd, which impacted the northern headwater regions of the watershed. These events generated high volumes of runoff.

The cities of Waverly, Cedar Falls, Waterloo and Evensdale were affected by the flood crest in September 24th (Figure 23a and Figure 23b). About 115 kilometers downstream the Cedar River, the cities of Vinton, Palo and Cedar Rapids were affected on September 27th, with minimal impacts in the later one due to the implementation of mitigation strategies, such as the wide use of sandbags and HESCO barriers as levees (Figure 23c and Figure 23d). Despite the magnitude and widespread of these floods, the author of this work is unaware of death causalities due to this event.



(a) (b)

(c) (d)

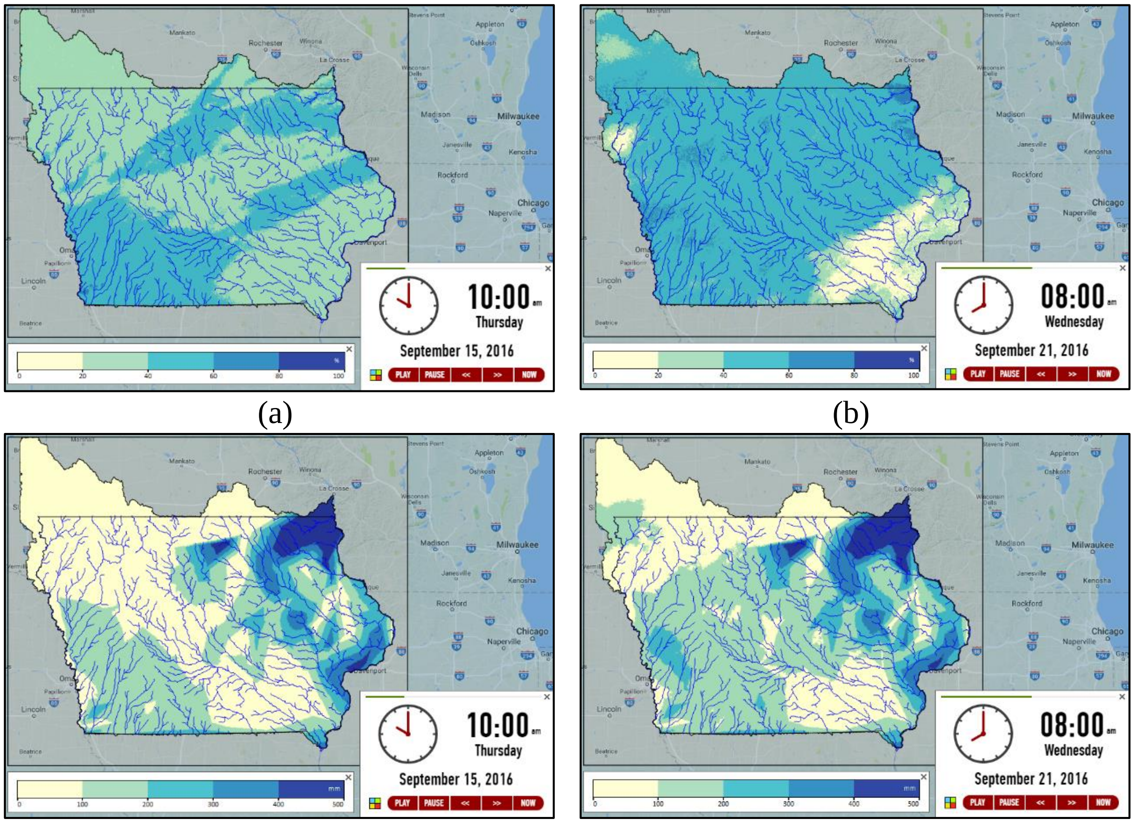
Figure 23 – Impacts of the flood event on Cedar River in 2016 included (a) the closing of roads in Waverly, (b) total submersion of buildings in Evensdale, (c) isolation of residences in Palo and (d) partial inundation of commercial zones in Cedar Rapids, reduced by the effective usage of mitigation techniques. Source: IFC archive.

5.2.2 - Runset Setup

Both TL-Standard and TL-Low Percolation sc-models were included in this sc-runset. The initial condition for both models was defined trough the algorithm described in Appendix 2 with base flow established from a data analysis involving the entire year of 2016 (bf_start = January 1st, 2016 and bf_end = December 31st, 2016) and a top layer assumed to be relatively dry (2.2 cm of stored water column equivalent). The simulation was performed for the time interval from September 11th to October 1st of 2016. Ideally, the initial condition would be established from a "warm up" run, but due to time limitations it was decided to use the simpler base flow initial conditions set up.

5.2.3 - Models Results

Representations of soil moisture-related outputs illustrate how significant the Top Layer portion of the soil got affected by the first rainfall event (September 16th, 2016), changing from an average of 40% (Figure 24a) to an average of 50% across the entire domain (Figure 24b), while the central-north region of the state (headwaters of Cedar River) exhibited high levels of water in the soil in the beginning of the simulation (Figure 24c), soils got even more saturated after the precipitation event (Figure 24d).



(a) (b)

(c) (d)

Figure 24 – Effects of rainfall prior to the flood events of 2016 on soil moisture modeled by TL-Standard include increase of (a)(b) Top Layer water saturation and (c)(d) subsurface equivalent water column.

Representations of accumulated rainfall for September 16th, 2016, show that it was a wide spread event across the entire Iowa water domain with considerable intensity, moving from the north-west to the south-east extremes of the state (Figure 25).

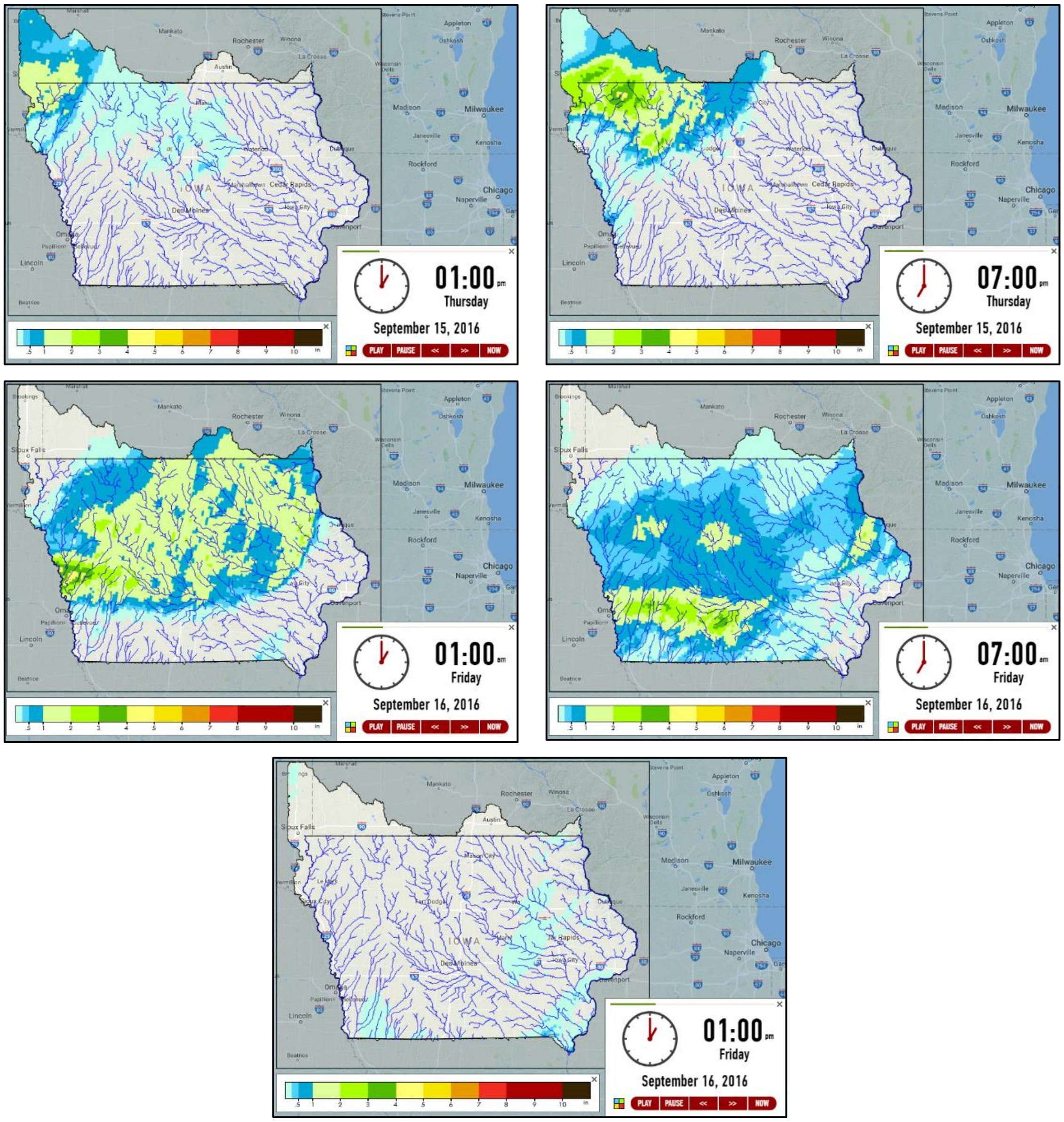


Figure 25 – Snapshots of 6-hour accumulation precipitation of rainfall event that covered almost entire Iowa from on September 15th and September 16th.

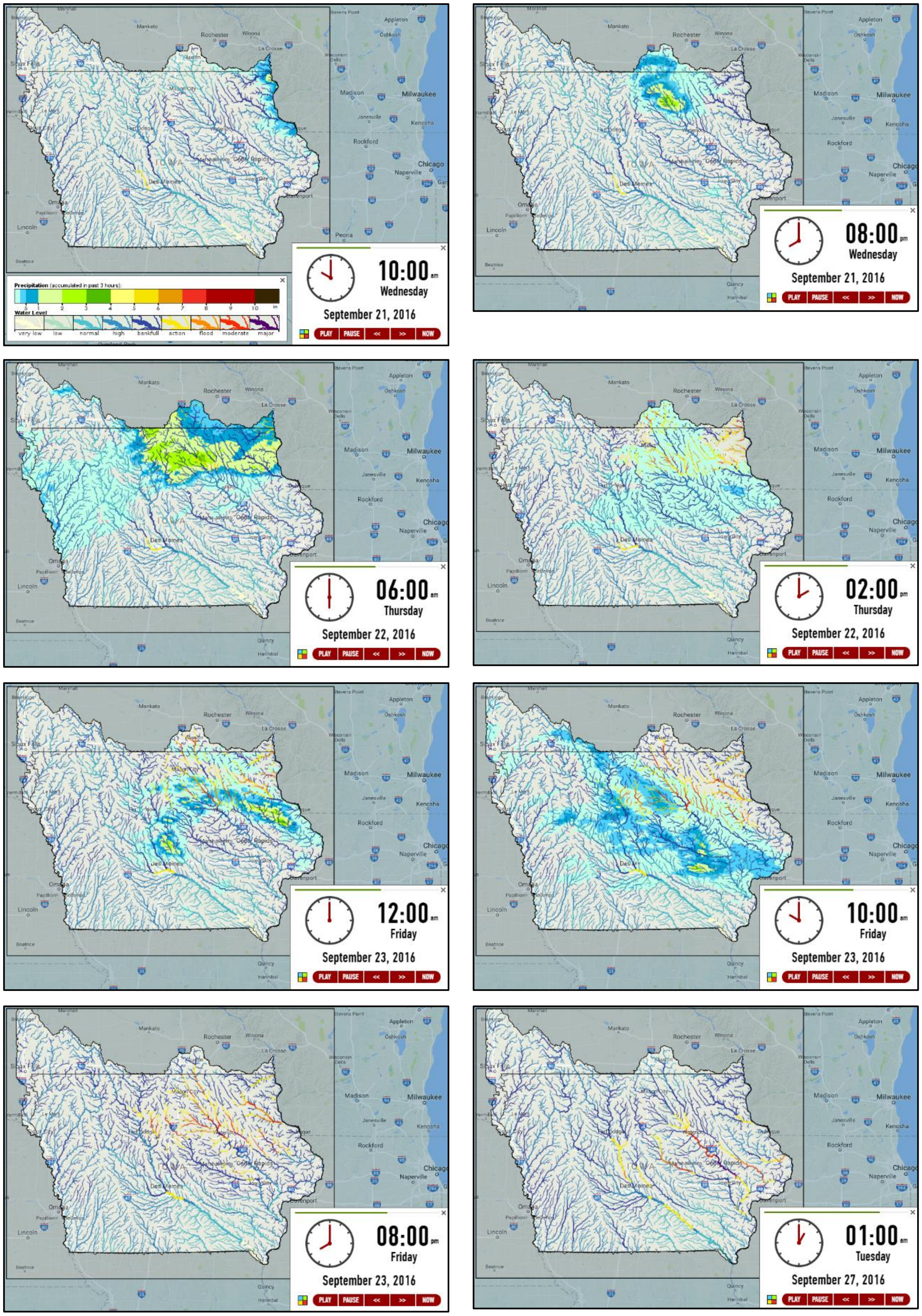


Figure 26 – Precipitation-flood process modeled by TL-Standard for the 2016 floods from the formation of the rainfall to the major flood crest approaching Waterloo on the evening of September 23rd. Later, on September 27th, the crest reaches Cedar Rapids.

The second cluster of storms, on September 21st (responsible for saturating the top layer of the soil) and September 22nd (which generated a considerable amount of runoff), resulted in the precipitation of up to 7 inches in some locations of the headwaters of Cedar River, which generated flood crests in the smaller branches of the watershed network. The crests propagated downstream at the same time precipitation moved south, potentially maintaining the intensity of the flood (Figure 26). The crest of the flood in Cedar River, approaches the city of Waterloo on the evening of September 23rd and reached Cedar Rapids by September 27th, dates compatible with the observed events.

The evaluation of the model revealed higher performance, according to the Nash-Sutcliffe coefficient method, in the northern and eastern region of the state (Figure 27). Regions where higher precipitation intensities were registered coincide with places where the models performed best. The high difference between observed and model values, as presented in the hydrographs for evaluation, is an indication that the initial conditions assumed were drier than the real conditions. Such hypothesis is supported by the high variability in the soil water column at the beginning of the simulation (Figure 24b).

The fact that even with an inappropriate initial condition set the results were acceptable in regions were precipitation was more intense suggests high resilience and power of normalization of the conceptual model driven by the rainfall input.

Maps of comparisons of runoff produced by both models indicate that the headwaters of the Cedar River basin, were rainfall was more intense, was the region in which the difference between the two outputs was more significant, with the TL-Low Percolation generating more runoff (Figure 28). Such difference affects directly the discharge, as it can be explored by the comparison of hydrographs (Figure 29).

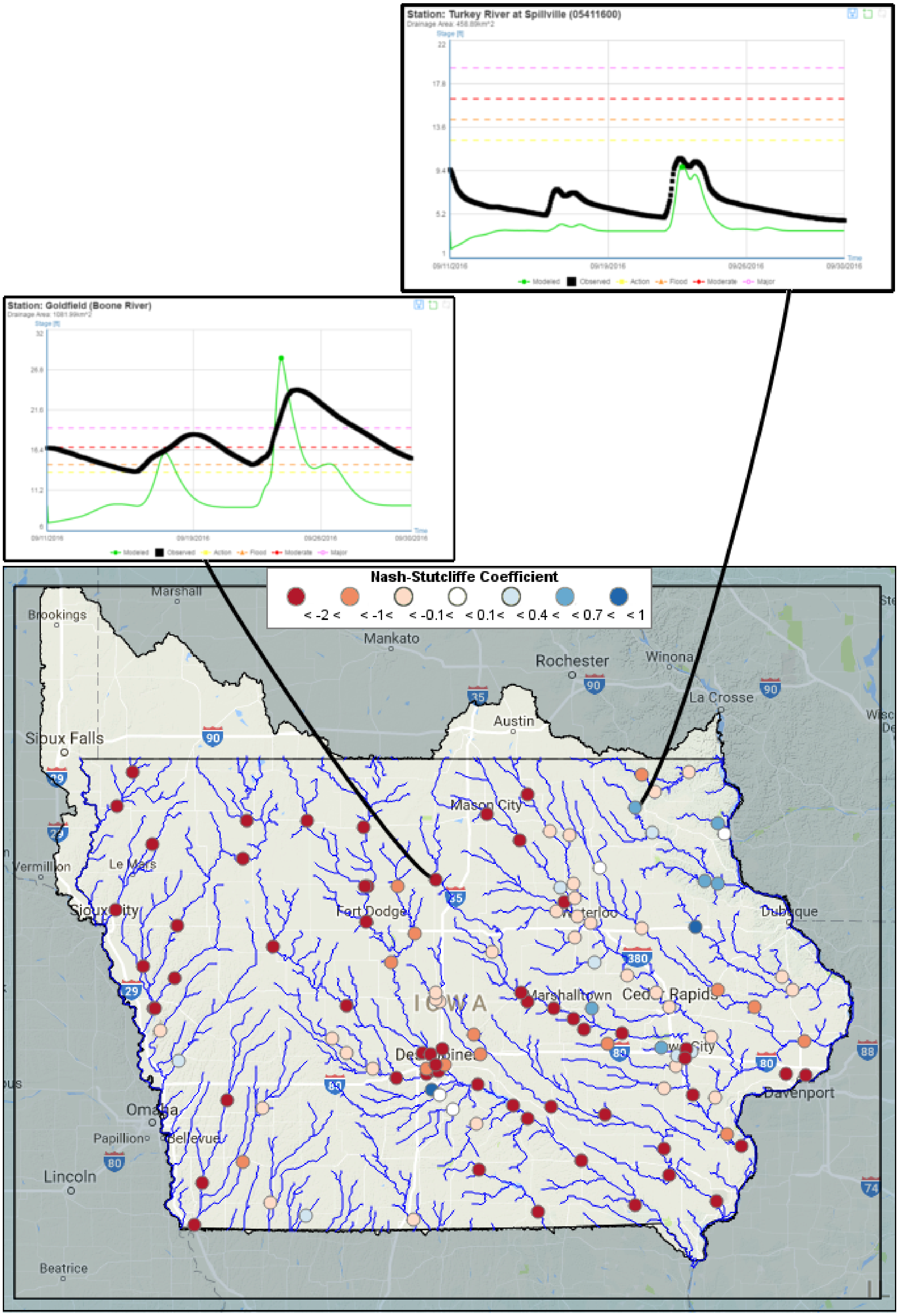


Figure 27 – Nash-Sutcliffe indicating locations were the TL-Standard performed better for the simulation of de flood of 2016.

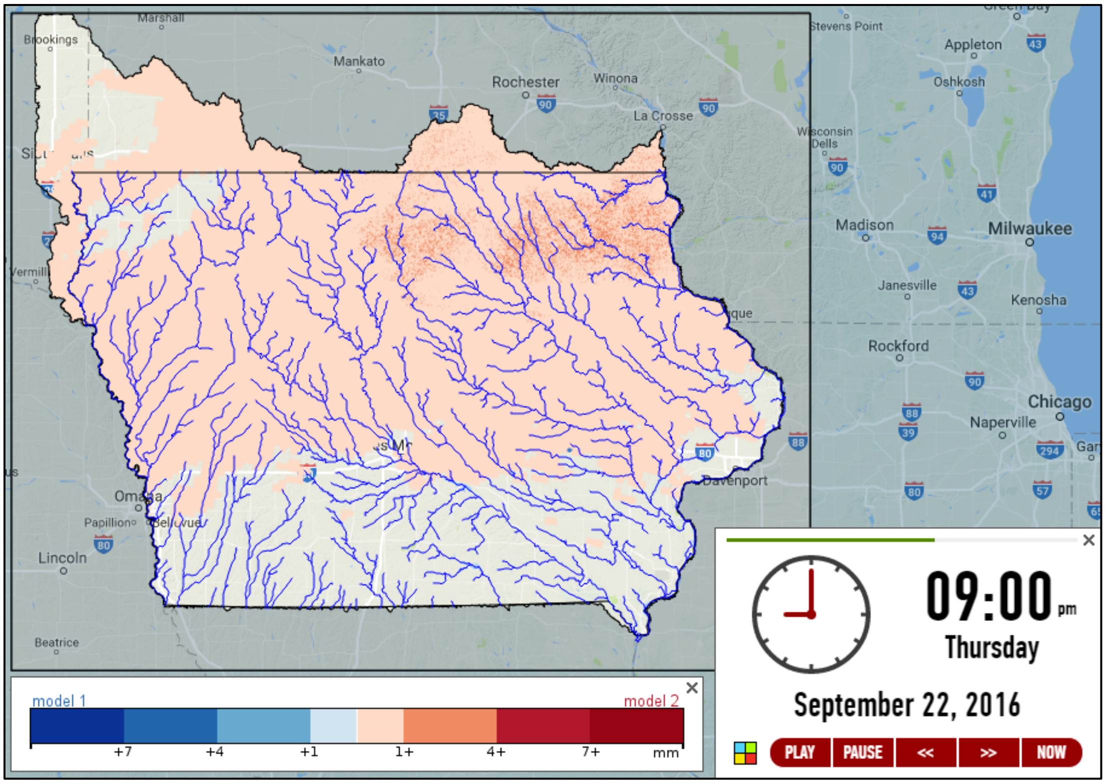
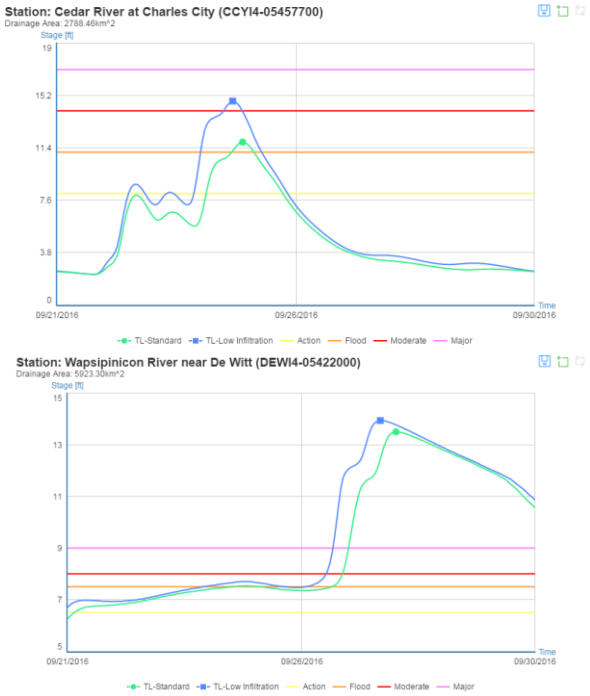


Figure 28 – Representation of 24-hours Distributed Cumulative Surface Runoff reveals higher differences in the headwaters of Cedar River Basin, with TL-Low Percolation (model 2) generating runoff water column equivalent of more than 1mm.



(location: north-east of Iowa)

(location: extreme east of Iowa)

Figure 29 – Magnitude of differences in discharge between TL-Low Percolation (blue line) and TL-Standard (green line) is directly related to differences in runoff.

5.3 - Flood of 2008

5.3.1 - Event Description

A heavier than normal snowpack during the winter of 2007-2008 followed by prolonged and intense periods of precipitation in the months of May and June (9.03 inches registered average rainfall in Iowa statewide) contributed to the flooding event of highest proportion in the records of Iowa River and Cedar River Basins (USGS, 2010). This event was part of a series of extreme floods registered in the Midwest during the months of January to June of 2008. Of those, the events that took place in the last month of the period were the most severe and widespread.

In June 2008, 62 stream gages in eastern region of Iowa registered flow discharges classified as exceeding the 100-year record, 41 of them recording new historical maximums. Floodwaters forced more than 35,000 Iowans to evacuate their residencies in different counties, 83 of which were declared state disaster areas (USGS 2010).

The USGS bridge sensor 05452000 (Salt Creek) recorded the beginning of a Major Flooding scenario of 50-years interval in Iowa River Basin on May 30th, followed by historical peaks in gages 05449500 (Iowa River near Rowan) on June 9th and on June 13th at 05451500 (Marshalltown). USGS gages 05453520 (close to Coralville) and 05454500 (Iowa City) recorded the peak flows in June, 15th.

Similarly, the first peak of the flood observed in Cedar River Basin was registered on May 30th at USGS gage 05464220 (Wolf Creek), followed by the record of the crest being registered at Waverly on June 10th and with maximum discharge recorded in Cedar Rapids at the bridge sensor 05464500 on June 13th at 10:15am (the other sensor in Cedar

Rapids, code 05464500, did not record the peak due to the fact that the water level overpassed the structure of the bridge in which it is positioned).

(a)

(b) (c)

Figure 30 – Massive damages caused by flood events of 2008 included (a) downtown of Cedar Rapid on June 13th (Source: Iowa Civil Air Patrol), (b) commercial buildings at Coralville on Saturday 14th (Credits: Dave Schwarz / Iowa City Press-Citizen) and (c) Iowa City water treatment plant on 15th, 2008 (Credits: Corey Schjoth / Iowa City Press-Citizen).

5.3.2 - Model Setup

Both TL-Standard and TL-Low Percolation sc-models were included in this sc-runset. The simulation was performed within the time interval from May 27th to October June 17st of 2008. The initial condition for both models was defined trough the algorithm described in Appendix 2 with base flow established from a data analysis involving the 10-days prior to the beginning of simulated interval (bf_start = May 16st, 2008 and bf_end = May 26st, 2008). The top layer was assumed to be relatively wet (5cm of stored water column equivalent). Ideally, the initial condition would be established from a "warm up" run, but due to time limitations it was decided to use the simpler base flow initial conditions set up.

5.3.3 - Model Results

Representations of 24-hours Distributed Cumulative Precipitation show the sequence of six relatively high intensity rainfall events that affected the entire state of Iowa in an interval of three weeks (May 28th, May 30th, June 3rd, June 5th, June 8th, June 12th and June 15th of 2008) (Figure 31). The recurrent rainfall maintained high levels of saturation on the top layer portion of the soil for the entire period (Figure 32).

Combined representations of Flow Discharge and Flood Severity Classifications (Figure 33) reveal the propagation of the flood crests across the river network, with the timing modeled by TL-Standard matching the observed data in the Cedar River and Iowa River watershed. This is confirmed by the evaluation stage hydrographs for gages in these locations (Figure 34). In Figure 35, it is shown that, according to Nash-Sutcliffe efficiency method, the performance of the model was high in the central and eastern regions of the state, with poor performance registered in specific locations in west (Figure 36).

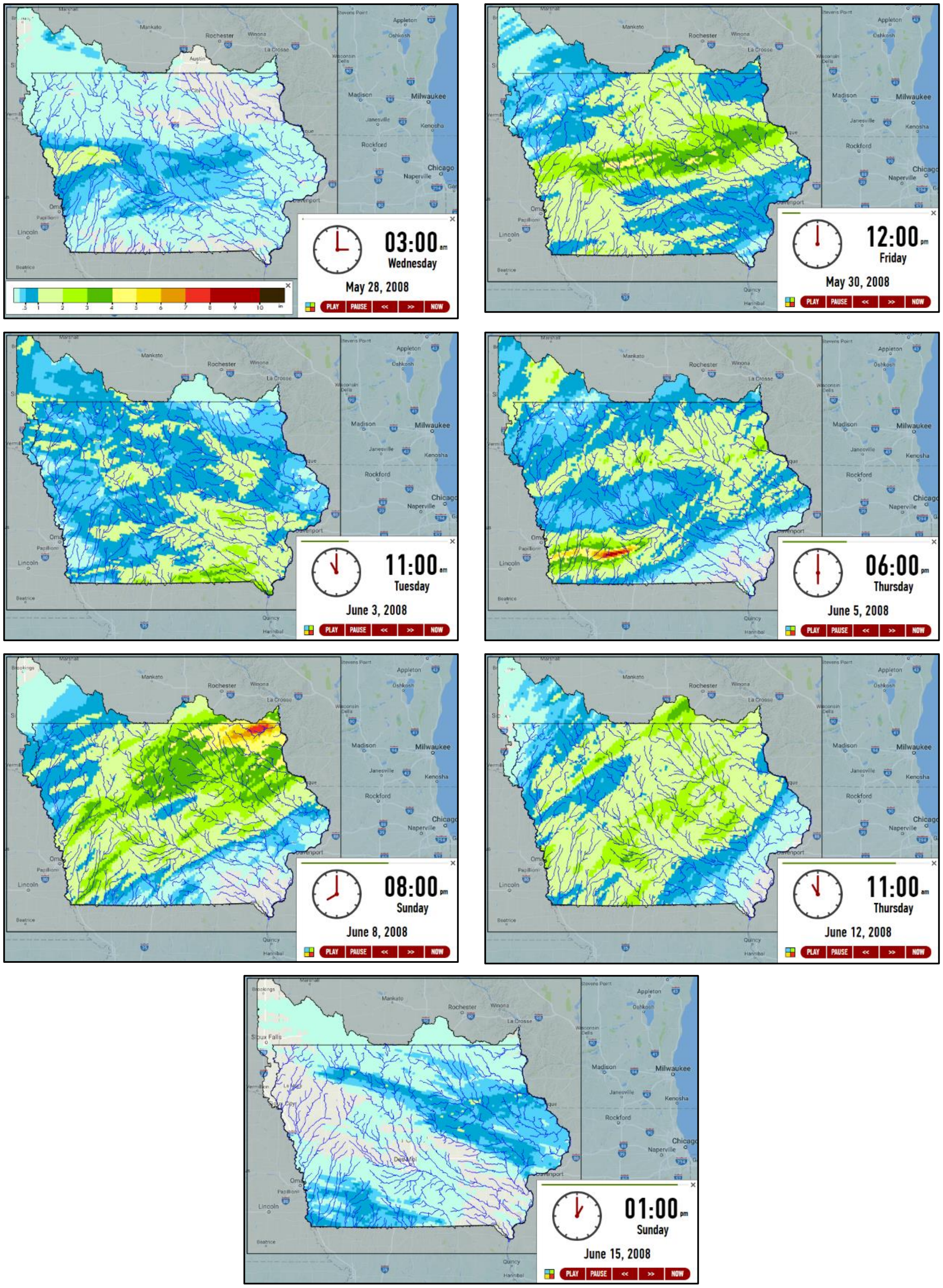


Figure 31 – Sequence of rainfall events that affected the entire state of Iowa on the days previous and during the Flood of 2008.

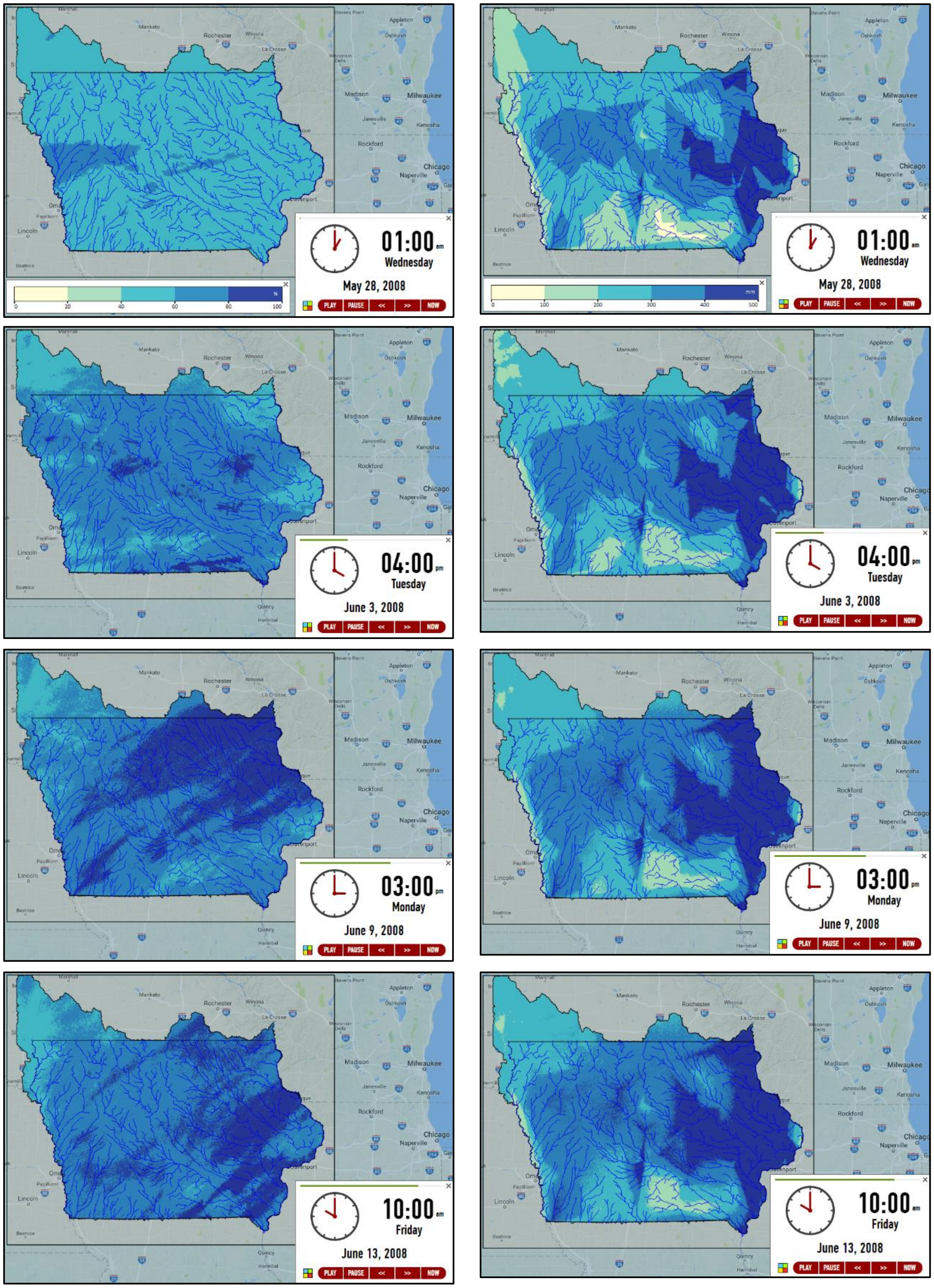
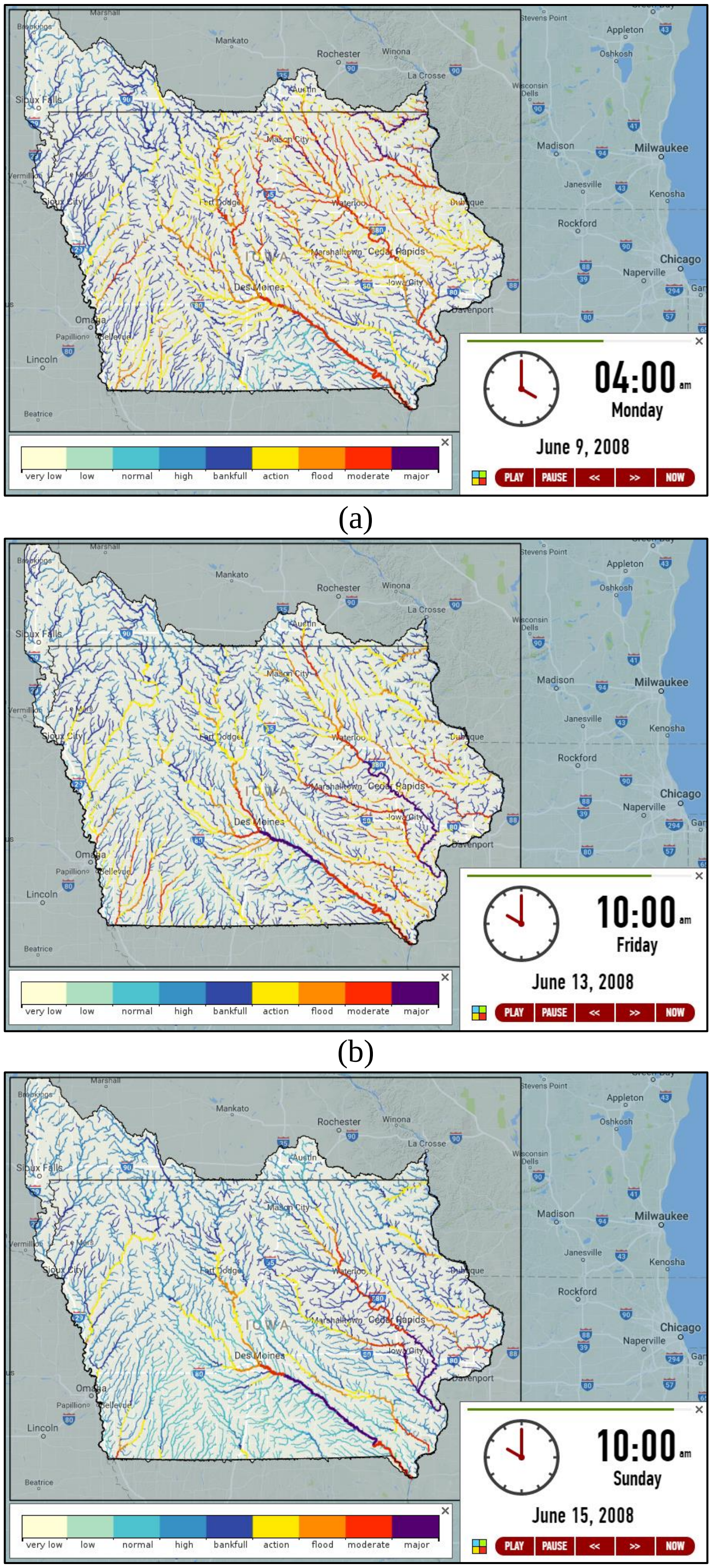


Figure 32 – Effects on soil moisture of consecutive rainfalls in a short period of time registered during flood events of 2008 modeled by TL-Standard sc-model: (left) maintenance of high saturation levels in the top layer of the soil during the entire simulation interval and (right) continuous increase of the soil water column.

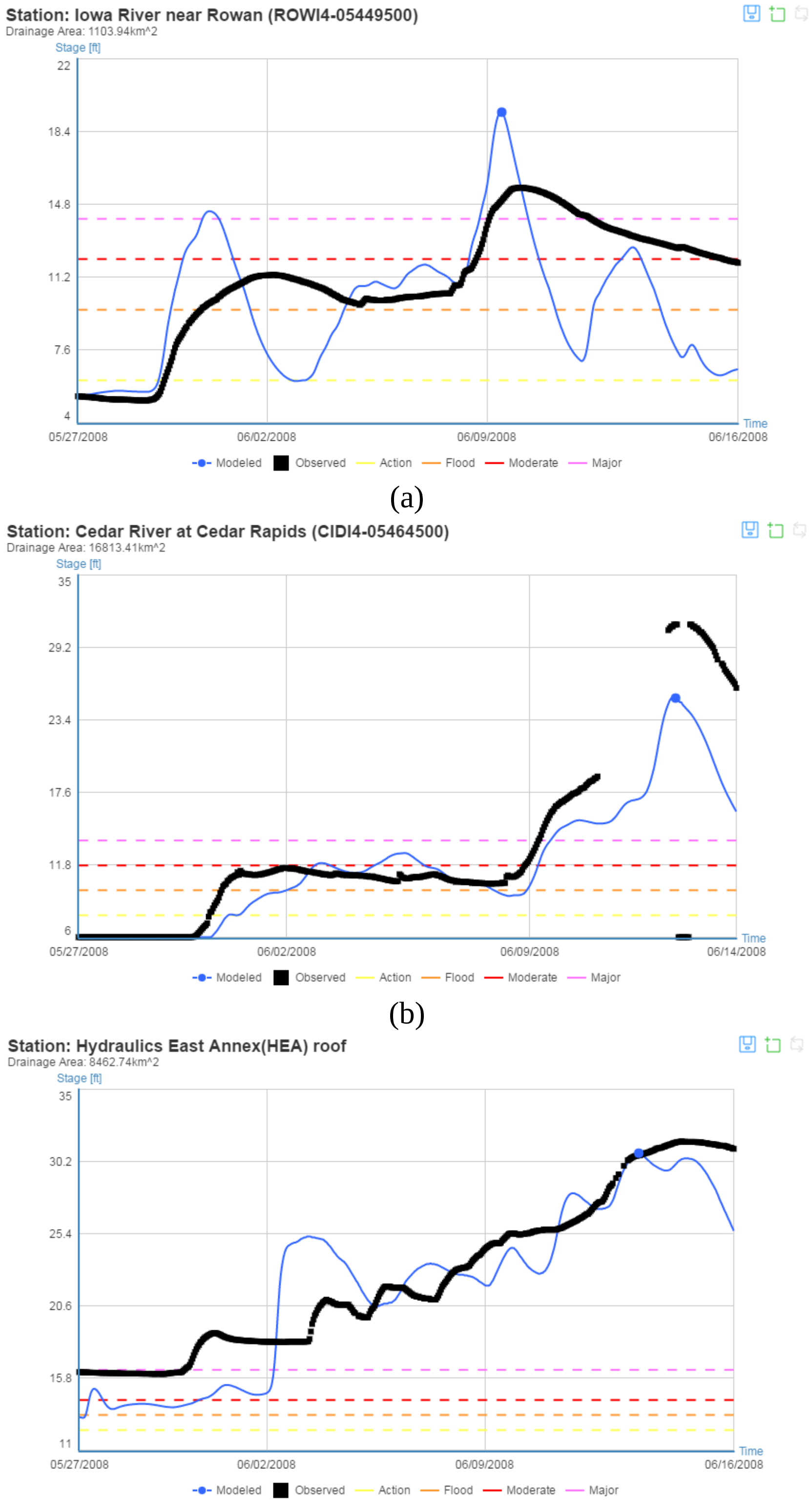


(a)

(b)

(c)

Figure 33 – Composite representation of Flow Discharge / Flood Severity Classifications reveals the flood crests modeled by TL-Standard in (a) Rowan on June 9th, in (b) Cedar Rapids and Des Moines on June 13th and in (c) Iowa City on June 15th, 2008.



(a)

(b)

(c)

Figure 34 – Evaluation hydrographs of TL-Standard sc-model results for the 2008 flood season for gages at (a) Rowan, (b) Cedar Rapids and (c) Iowa City.

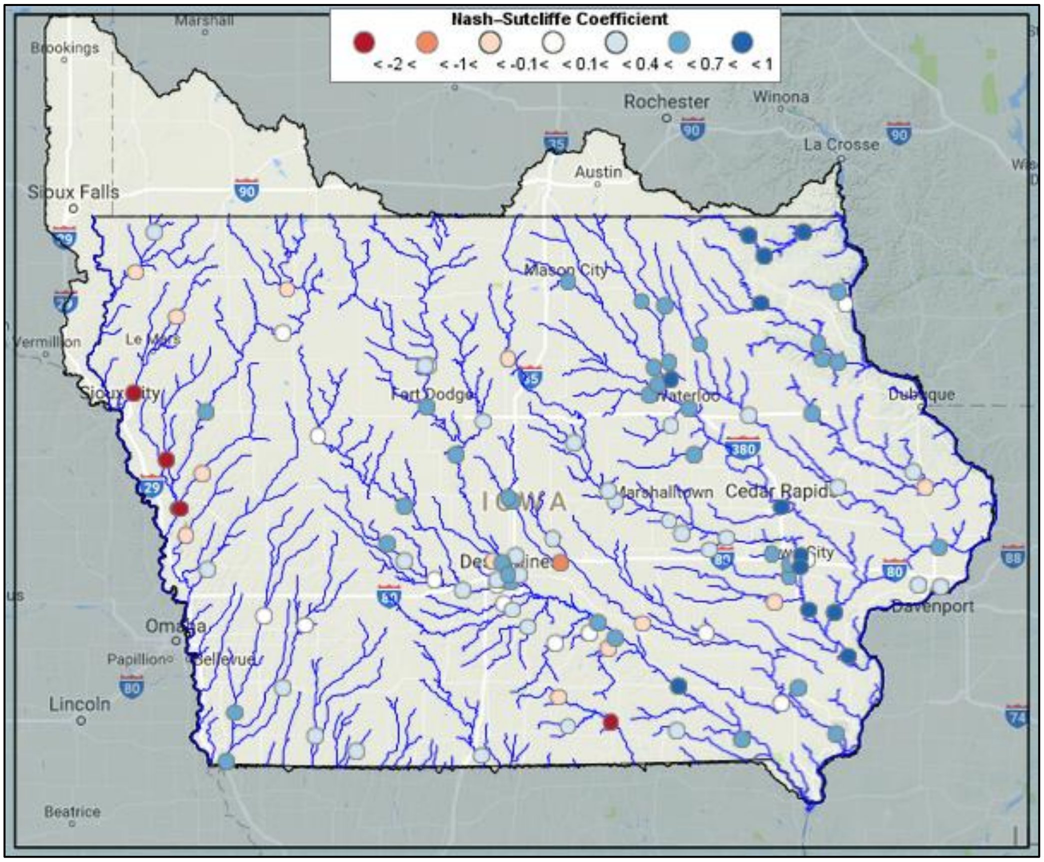


Figure 35 – Nash-Sutcliffe coefficient map of TL-Standard sc-model for 2008 flood season simulation.

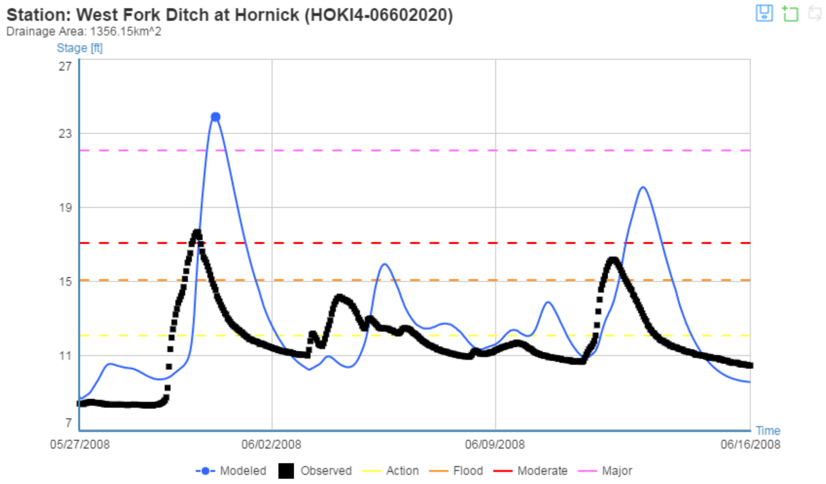


Figure 36 – The hydrograph of one of the locations classified with low Nash–Sutcliffe in the western region of the state of Iowa for the TL-Standard model output.

The TL-Low Percolation sc-model presented, according to Nash-Sutcliffe efficiency method, a better performance in modeling the rainfall-runoff processes of the event in the central and eastern region of the state when compared to the TL-Standard, but also presented more locations with unacceptable results in the western area (Figure 37).

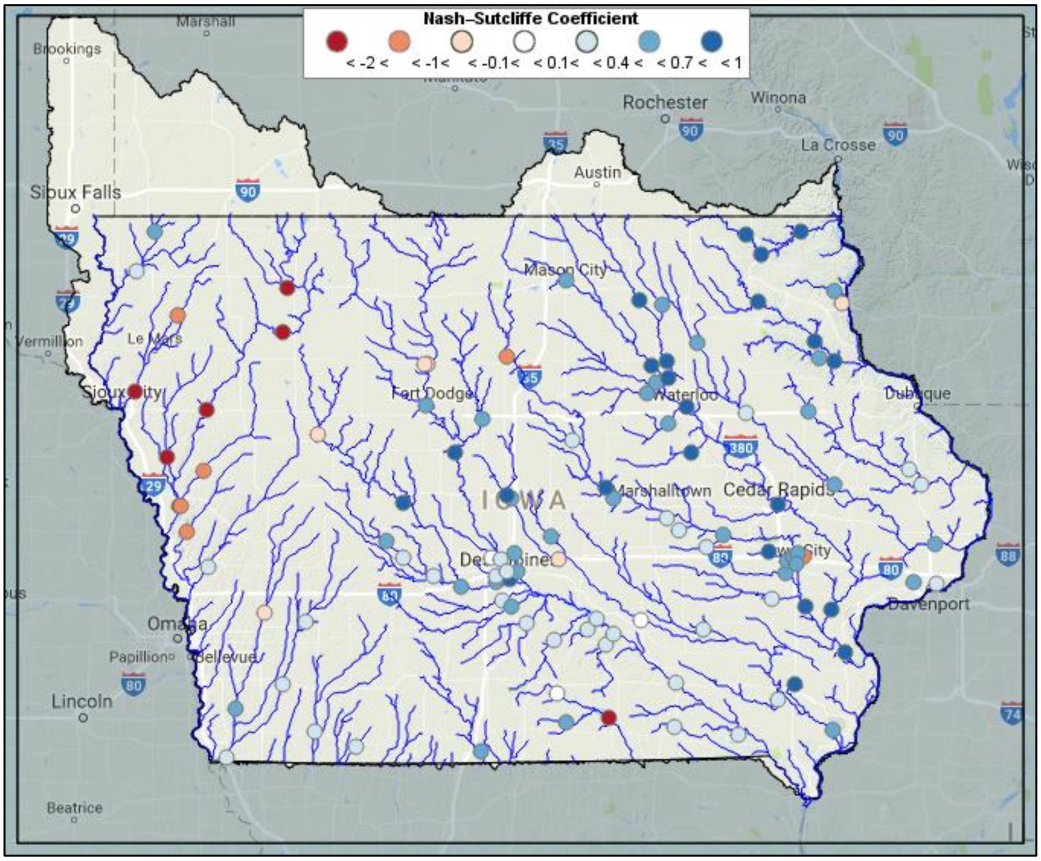
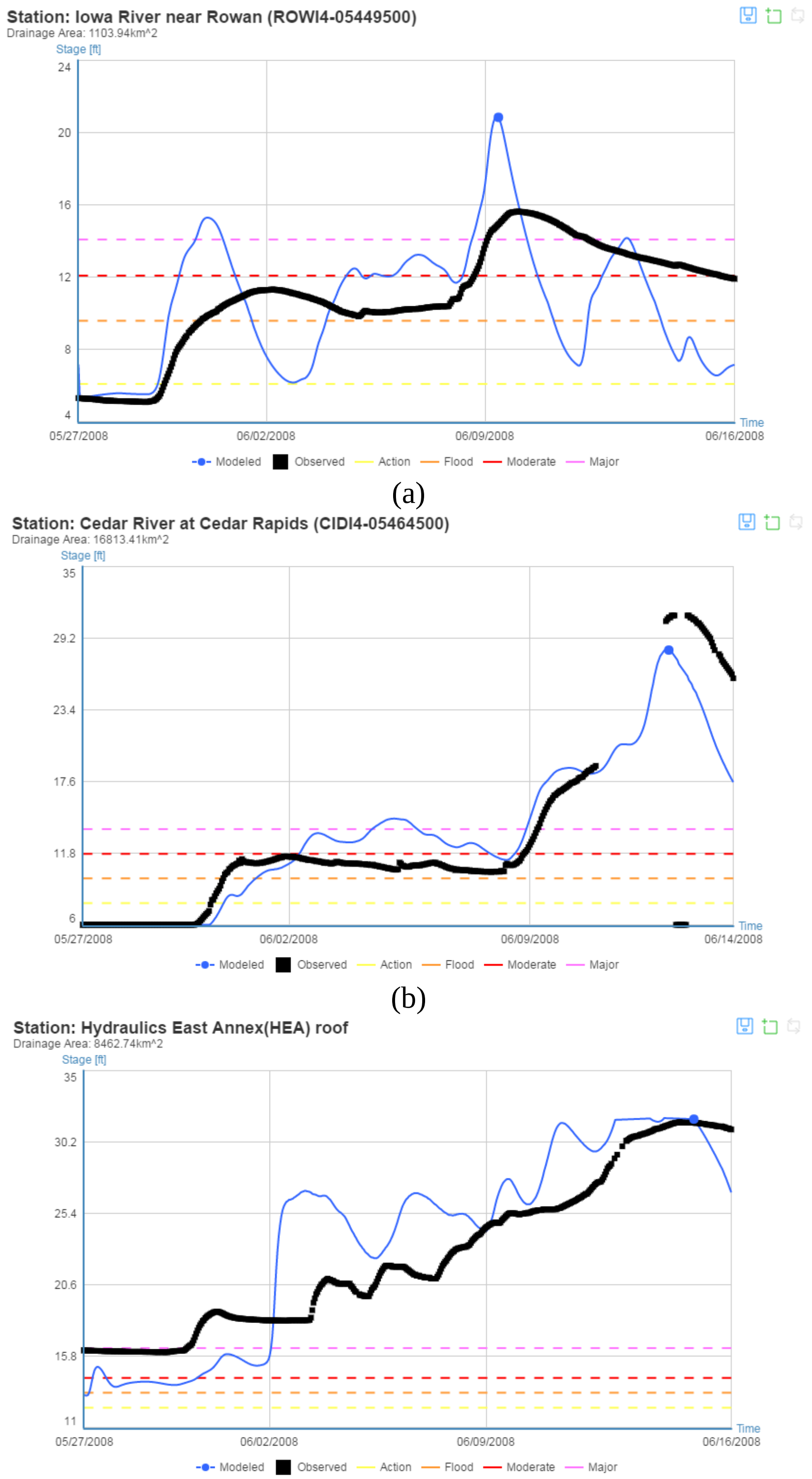


Figure 37 – Nash-Sutcliffe coefficient map of TL-Low Percolation sc-model for 2008 flood season simulation.

As expected, the reduction of the coefficient related to infiltration increased the generation of runoff, which increase the discharge levels. Locations in which peak discharge was overestimated got more distant from the observed (Figure 38a), while the opposite can be observed at places with underestimated discharge (Figure 38b and Figure 38c).



(a)

(b)

(c)

Figure 38 – Evaluation hydrographs of TL-Low Percolation sc-model results for the 2008 flood season for gages at (a) Rowan, (b) Cedar Rapids and (c) Iowa City.

A curious observation comes on the comparison between flow classification levels. While higher order streams presented higher flows in TL-Low Percolation sc-model when compared to TL-Standard, the opposite was observed in lower order streams (Figure 39).

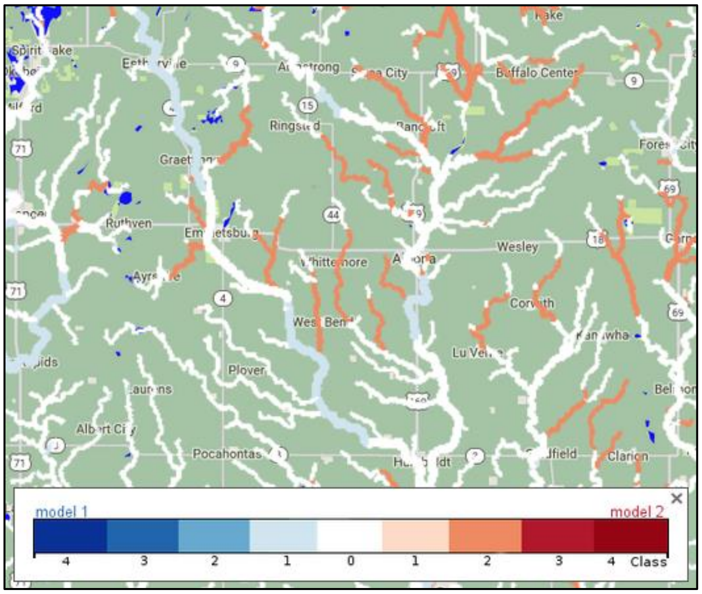


Figure 39 – Zoom screenshot of comparison between TL-Low Percolation and TL-Standard of Flow Classification results, in which the first (model 1) is presented in blue when its classification is higher than the latter (model 2), and red when overestimated.

CHAPTER 6 - CONCLUSION

From obtained results, it was possible to assert that Hydroinformatics approaches may provide automated ways to explore the outputs of distributed hydrological models, facilitating the access to real-time and event-based simulation results. This work resulted in the implementation of a web portal with a set of visualization tools that is publically available.

The potential of the developed tool to provide a user friendly interface for both triggering multiple executions of HLM-ASYNCH model instances for the state of Iowa and for producing cognitive representations of model outputs has been demonstrated. The major contributions of the work are summarized as follows:

- The tool developed allows users to access the information produced in real-time (on an hourly interval), by of the IFC instances of HLM models that are continually executed at the University of Iowa Data Center for the Iowa Water Domain. It allows accessing estimations of current water discharge in ungauged channels through simple web connections. In addition to the representation of the output of the models, the associated evaluation tools implemented here provide an easy way to assert the reliability of the results generated. The comparison between different maps can be used as a tool for evaluating the influence of different rainfall products and model assumptions in the resulting estimation of runoff and streamflow for different forecasting scenarios.
- The use of IFIS Special Case as a framework for creating Iowa-driven Hydroinformatics tools based on animation of space-temporal data proved to be effective. The integration of proposed tools with previously developed features on IFIS

promoted a fast association of the information presented in both real-time modeled and observed state of rivers discharge in the state of Iowa.

- The subsystem for triggering executions of multiple instances of HLM models, each instance taking specifically defined assumption, allows a significant reduction of time in setting up hydrological modeling experiments. The automated composition of geo-located maps of the outputs and its associated evaluation may be used as tools for increasing the performance of the already implemented real-time system for forecasting flood events through the state of Iowa.
- The flexibility of the system structure provides high capability of expansion of represented variables, making it possible to implement, in relatively short time, real time information systems based on distributed models for purposes other than those directly related to floods, such as estimation of water temperature and water quality.

CHAPTER 7 - FUTURE DEVELOPMENTS

The current version of the system is operational and is being executed on an internal server at IIHR. Future enhancements of the system can be separated in: 1) extension of existing supported import data, 2) inclusion of additional sources of information, 3) addition of new structural features, and 4) improvements to existing features.

Future versions of the system are expected to be able to import distributed evapotranspiration estimates and distributed forecast discharge data. In the case of evaporation fields, recent studies conducted at IIHR have shown promise that a more careful treatment of the variable would improve the accuracy of hydrological models, and the case of distributed forecast discharge data is a required to generate representations of distributed forecast scenarios.

Several additional sources of data are yet to be included. For instance: IFC bridge sensors can be included as sc-references for sparse river stage data and forecasts of water stage produced by USGS as additional sc-models. HLM-ASYNCH 190 is also expected to be supported as an option for new model set up on the Requester subsystem.

Among the future additional structural features to be implemented, the representation of distributed forecast flow discharge and flood severity classification, presented as temporal sequence of past modeled flow discharge and flood classification is considered in higher priority. Methodologies to represent evapotranspiration processes are also of interest to provide a tool to generate more accurate estimates for such parameter.

Features to be improved include the optimization of the process steps for generating representations to reduce the user experience of long waiting time between triggering models and obtaining results. Initial planning includes exploring parallelization capabilities within the available HPC Clusters, as several internal procedures are not concurrent.

REFERENCES

Ayalew, T.B.; Krajewski, W.F.; Mantilla, R.; Small, S.J. Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge. Advances in Water Resources - Elsevier, 2014, 64, 9–20.

Cunha, L.K.; Mandapaka, P.V.; Krajewski, W.F.; Mantilla, R.; Bradley, A.A. Impact of radar rainfall error structure on estimated flood magnitude across scales: An investigation based on a parsimonious distributed hydrological model. Water Resources Research - AGU, 2012, 48, W10515.

Small, S.; Debionne, S. Asynch Documentation. [Online] 2017. https://media.readthedocs.org/pdf/asynch/latest/asynch.pdf (accessed Mar 21, 2017).

Demir, I.; and Krajewski, W.F. Towards an adaptive flood information system: Integrated data access, analysis and visualization. Environmental Modeling & Software - Elsevier, 2013, 50, 77–84.

Demir, I.; Conover, H.; He, Y.; McEniry, M.; Krajewski, W.F.; Seo, B.-C.; Goska, R.; Petersen, W. Data enabled field experiment planning, management and research using cyberinfrastucture. Journal of Hydrometeorology – American Meteorological Society, 2015, 16, 1155–1170.

Demir, I., and Beck, M. B., ‘GWIS: A Prototype Information System for Georgia Watersheds’, Paper 6.6.4, in Proceedings of Georgia Water Resources Conference: Regional Water Management Opportunities, 2009, April 27-29, UGA, Athens, GA, USA.

Demir, I., Jiang, F., Walker, R. V., Parker, A. K., and Beck, M. B., ‘Information Systems and Social Legitimacy: Scientific Visualization of Water Quality’, in Proceedings of IEEE Int. Conference on Systems, Man, and Cybernetics, 2009, October 11-14, p1093-1098, October 11-14, San Antonio, TX, USA.

Domeneghetti, A.; Castellarin, A.; Brasth, A. Assessing rating-curve uncertainty and its effects on hydraulic model calibration. Hydrology Earth System Sciences, 2012, 16, 1191–1202.

Entekhabi, D.; Das, N.; Njoku, E.; Yueh, S.; Johnson, J.; Shi, J. Algorithm Theoretical Basis Document L2 & L3 Radar/Radiometer Soil Moisture (Active/Passive) Data Products. Jet Propulsion Laboratory – California Institute of technology. [Online] 2014. https://smap.jpl.nasa.gov/system/internal_resources/details/original/ (accessed Mar 21, 2017).

Quintero, F.; Krajewski, W.F.; Mantilla, R.; Small, S.; Seo B.-C. A spatial-dynamical framework for evaluation of satellite rainfall products for flood prediction. Journal of Hydrometeorology. Journal of Hydrometeorology – American Meteorological Society, 2016, 17, 2137-2154.

Perez, G.; Mantilla, R.; Krajewski, W.F. Estimating annual and monthly scale-invariant flow duration curves for the State of Iowa. Submitted to Journal of Hydrologic Engineering – ASCE. 2017.

Hornberger, G.M.; Wiberg, P.L.; Raffensperger, J.P.; D'Odorico, P. 2014. Elements of physical hydrology – 2nd edition. John Hopkins University Press: Baltimore, 2014. ISBN 1-4214-1396-5.

Krajewski, W.F.; Ceynar, D.; Demir I.; Goska, R.; Kruger, A.; Langel, C.; Mantilla, R.; Niemeier, J.; Quintero, F.; Seo, B.-C.; Small, S. J.; Weber, L. J.; Young, N. C. Real-time Flood Forecasting and Information System for the State of Iowa. Bulletin of the American Meteorological Society, 2017. 98, 539–554.

Linhart, S. M.; Eash, D. A. Floods of May 30 to June 15, 2008, in the Iowa River and Cedar River Basins, Eastern Iowa. Open-File Report 2010-0090. United States Geological Survey: Reston, 2010. https://pubs.usgs.gov/of/2010/1190/pdf/of2010-1190.pdf (accessed Mar 21, 2017).

Leopold, L. B. Hydrology for urban land use planning – a guidebook on the hydrologic effects of urban land use. U.S. Department of the Interior: Washington, 1968. U.S. Geological Survey Circ. 544, 18p. 8 figs.

Mantilla, R.; Gupta, V.K. A GIS Framework to Investigate the Process Basis for Scaling Statistics on River Networks. Geoscience and Remote Sensing Letters - IEEE. 2005, 2(4):404–408.

Mantilla, R. Physical basis of statistical scaling in peak flows and stream flow hydrographs for topologic and spatially embedded random self-similar channel networks. 2007. PhD thesis, University of Colorado.

Nash, J. E.; Sutcliffe, J. V. River flow forecasting through conceptual models, Part I - A discussion of principles. Journal of Hydrology – Elsevier. 1970, 10, 282–290.

NWS - National Weather Service. National Weather Service Manual 10-960 - Operations & Services - NDS 10-9 Hydrologic Services Program - 10-950 Definitions and General Terminology. [Online] 2012. http://www.nws.noaa.gov/directives/sym/pd01009050curr.pdf (accessed Mar 21, 2017).

NWS – National Weather Service. Climate Reports: August 2016 & summer 2016. [Online] 2016. http://www.weather.gov/dvn/Climate_Monthly_08_2016 (accessed Mar 21, 2017).

OSU - Oregon State University. PRISM Climate Group. [Online] 2016. http://www.prism.oregonstate.edu/normals/ (accessed Mar 21, 2017).

Pacheco, P. S. Parallel programming with MPI. Morgan Kaufmann Publishers, Inc.: San Francisco, 1997. ISBN 1-5586-0339-5.

Small, S. J.; Jay, L. O.; Mantilla, R.; Curtu, R.; Cunha, L. K.; Fonley, M.; Krajewski, W. F. An asynchronous solver for systems of ODEs linked by a directed tree structure. Advances in Water Resources - Elsevier. 2013, 53, 23-32.

Seo, B.-C.; Cunha, L. K.; Krajewski, W. F. Uncertainty in radar-rainfall composite and its impact on hydrologic prediction for the eastern Iowa flood of 2008. Water Resources Research – AGU, 2013, 49, 2747–2764.

Small, S. J. ASYNCH Documentation and User's Guide. IIHR: Iowa City, 2015. Not published.

USDA – United States Department of Agriculture. Stream Restoration Design (National Engineering Handbook 654) – Chapter 5 – Stream Hydrology. [Online] 2007. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17781.wba (accessed Mar 21, 2017).

Zhang, K.; Kimball, J. S.; Nemani, R. R.; Running, S. W. A continuous satellite-derived global record of land surface evapotranspiration from 1983 to 2006. Water Resources Research – AGU, 2010, 46(9), 1–21.

Zogg, J. The Top Five Iowa Floods. National Weather Service - Des Moines. [Online] 2014. http://www.crh.noaa.gov/Image/dmx/hydro/HistoricalIowaFloods_Top5.pdf (accessed Mar 21, 2017).

APPENDIX

Appendix 1 - Flow quantile regression parameters

Values for $\alpha_{p,m}$ and $\Theta_{p,m}$ used in this work. Source: Perez *et al* (2017)

	$p = 0.10$		$p = 0.25$		$p = 0.75$		$p = 0.90$	
m	α	θ	α	θ	α	θ	α	θ
Jan	0.0053	0.2356	0.0224	0.1528	0.3498	0.0139	0.7555	-0.0066
Feb	0.0107	0.1918	0.0557	0.0798	0.7357	-0.0201	2.1725	-0.0575
Mar	0.0482	0.1232	0.1287	0.1126	0.9872	0.0692	3.5533	0.0059
Apr	0.0447	0.1784	0.1268	0.1484	0.8391	0.1099	2.5471	0.04716
May	0.0452	0.1726	0.1407	0.1418	1.0259	0.0828	3.6464	-0.0012
Jun	0.0180	0.2868	0.0628	0.2382	0.7813	0.1253	3.2410	0.0335
July	0.0059	0.3534	0.0217	0.2930	0.2370	0.2092	1.1379	0.1042
Aug	0.0022	0.4173	0.0085	0.3347	0.1232	0.1966	0.6263	0.1020
Sep	0.0013	0.4458	0.0056	0.3459	0.1392	0.1535	0.6585	0.0785
Oct	0.0021	0.3742	0.0084	0.2865	0.2288	0.1152	0.8602	0.0498
Nov	0.0061	0.2688	0.0176	0.225	0.3710	0.0639	0.8150	0.0492
Dec	0.0045	0.2715	0.0192	0.1931	0.3953	0.0310	0.9378	-0.0038

Appendix 2 - Algorithm for initial state estimation

Terms:

bf_start : date of start of time interval from which baseflow will be retrieved
bf_end : date of end of time interval from which baseflow will be retrieved
ws : USGS WaterData webservice
domain : Iowa water domain
h-link: hillslope-link system

This algorithm was developed at IIHR by Walter Navarro in 2014. It assumes that

1) the minimum instant discharge value registered by a gage in an interval of time can be taken as the base flow of that location for such period;
2) the ration between base flow and drainage area (named C2) can be estimated for ungagged links by the spatial regression of such relationship estimated from gaged channels;
3) the water saturation in the top layer of the soil is equal for all hillslope-links and must be provided by the user as input;
4) the water column in the subsurface of a hillslope-link is a function of its C2 and the k3 parameter in Top Layer conceptual hydrological model (Chapter 1.3.1).

A pseudo-code of the procedure is given by:

```
Given:
  bf_start as initial date of base flow data analysis
  bf_end as final date of base flow data analysis
  top_layer_wc equivalent water column stored in the top layer
Establish constant k3 = 0.0000020425;
Create a grid of dimensions 900 x 550 geo-located as a bounding box for the domain;
List all stream gages inside the domain from the ws;
For each of such stream gages:
       Retrieve series of time-discharge within interval [bf_start, bf_end] from ws;
       Identify the minimum discharge value observed in retrieved time series;
       Associate such minimum discharge as base flow of respective h-link;
       Define C2 as the ratio between the base flow and the h-link’s upstream area;
       Set the value of C2 to the grid cell respective to the h-link location;
Interpolate the values in the grid;
For each h-link in the domain:
       Identify the grid cell respective to its location;
       Retrieve value of such cell as C2;
       Define state of equivalent water column in ponds on surface as 0.0;
       Define state of equivalent water in top layer as top_layer_wc
       Define state of equivalent water in subsurface as C2 / k3 * 0.06 / 1000
       Define state of discharge as C2 * h-link’s upstream area;
       Define state of base flow discharge equal to state of discharge;
       Define state of accumulative precipitation and accumulative runoff as 0;
       Associate all such states to the h-link;
Save file with all states of all h-links.
```