Large Scale High Resolution Flood Inundation Mapping in Near Real-time

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Abstract

Most flood forecasting frameworks are based on point discharge measurements at discrete locations, which limits their capability to provide spatio-temporal information of flood inundation extents over large sales and at high spatial resolution. This paper features coupling of a spatially distributed hydrologic model Soil and Water Assessment Tool (SWAT) with a 2D hydrodynamic model LISFLOOD-FP for flood inundation mapping over the entire Ohio River Basin in United States. This large scale, high-resolution application of SWAT provides streamflow estimates for nearly 100,000 NHDPlus reaches/streamlines over the 491,000 km^2 drainage area of the Ohio River Basin. SWAT-simulated streamflow outputs are set at multiple input locations of LISFLOOD-FP and routed along the streams to generate corresponding flood inundation maps. To test the predictive capability of this framework, it is first calibrated by executing with historical hydro-climatic data over the past 80 years (1935-2014). Post-calibration evaluation suggests that simulated daily streamflow from SWAT has average Nash-Sutcliffe Efficiency score of 0.4-0.7 when compared against observed records across the basin, and the modeled inundation area from LISFLOOD-FP has more than 70% agreement with the corresponding 100-year Federal Emergency Management Agency (FEMA) reference flood maps along the main river channels. Such satisfactory model performance proves the suitability of the proposed framework to be implemented in a cyber-infrastructure, enabling the near real-time dissemination of streamflow and inundation extents through an open-access web interface.

1. Introduction

Disseminating scientifically-driven disaster predictions to the emergency responders and the public with precision and speed has been a long-standing concern. Accordingly, there is a growing need to develop advanced flood warning and inundation mapping systems (Kauffeldt et al., 2016; Schumann et al., 2013). Conventionally, the data recorded at streamflow (river discharge) gauging stations are used to generate information on historical flooding and future prediction through various statistical/stochastic methods (Bourdin et al., 2012). While importance of such in-situ observations is inevitable, they do not help assessing local level details of flood inundation area and associated risks where there is no gauge station.

Hydrologic-Hydraulic models can potentially supplement such data demand; however, modelers typically deal with only tens to hundreds of km^2. With the advancements in numerical weather prediction, simulation techniques for surface-subsurface hydrologic processes and high performance computational resources, there have been some current initiatives to design large scale flood modeling frameworks, including Coastal and Inland Flooding Observation and Warning project (CI-FLOW; NOAA, 2014) and the National Flood Interoperability Experiment in the United States (NFIE; Maidment, 2015); studies by Thielen et al. (2009), Pappenberger et al. (2012), Paiva et al. (2011, 2013), Alfieri et al. (2013) and Winsemius et al. (2013) highlight some other recent attempts, specifically focusing on Europe, parts of Africa and South America, or the entire globe as a whole. Numerous models exist in practice, all with equally good functionality; but majority of the modeling packages come with a "black-box" configuration which can be executed only for research purposes in a stand-alone desktop environment. Hence, how suitable is a model's structure to be executed at high resolution and for large domain is a controlling factor affecting the choice of model as the component of an operational system. In addition, how individual models represent physical processes for runoff generation, streamflow routing and flood propagation, as well as the model adaptability inside a cyber-enabled high performance computational platform deserve major considerations. All these factors lead to a wide scope for testing different model combinations which serve the purpose of flood prediction at large scales, both with accuracy and efficiency.

This paper evaluates a new flood inundation modeling framework consisting of a spatially distributed hydrologic model Soil and Water Assessment Tool (SWAT), being loosely coupled with a 1D/2D coupled hydrodynamic model LISFLOOD-FP. The proposed SWAT and LISFLOOD-FP coupling presented here should be considered as a prototype of an actual flood forecasting system. In future, an open-access web-interface will be designed enabling dynamic near real-time visualization of the resulting flood inundation maps generated by the proposed framework. This can eventually lead to a new frontier of more skillful operational disaster management system, leveraging efficient resource allocation by the field level first responders.

2. Study Domain

To demonstrate the capabilities of the proposed framework, the entire Ohio River Basin (ORB), with a total drainage area of 490,000 km^2 that drains through eleven states within the contiguous United States (Figure 1), is chosen as the study area.

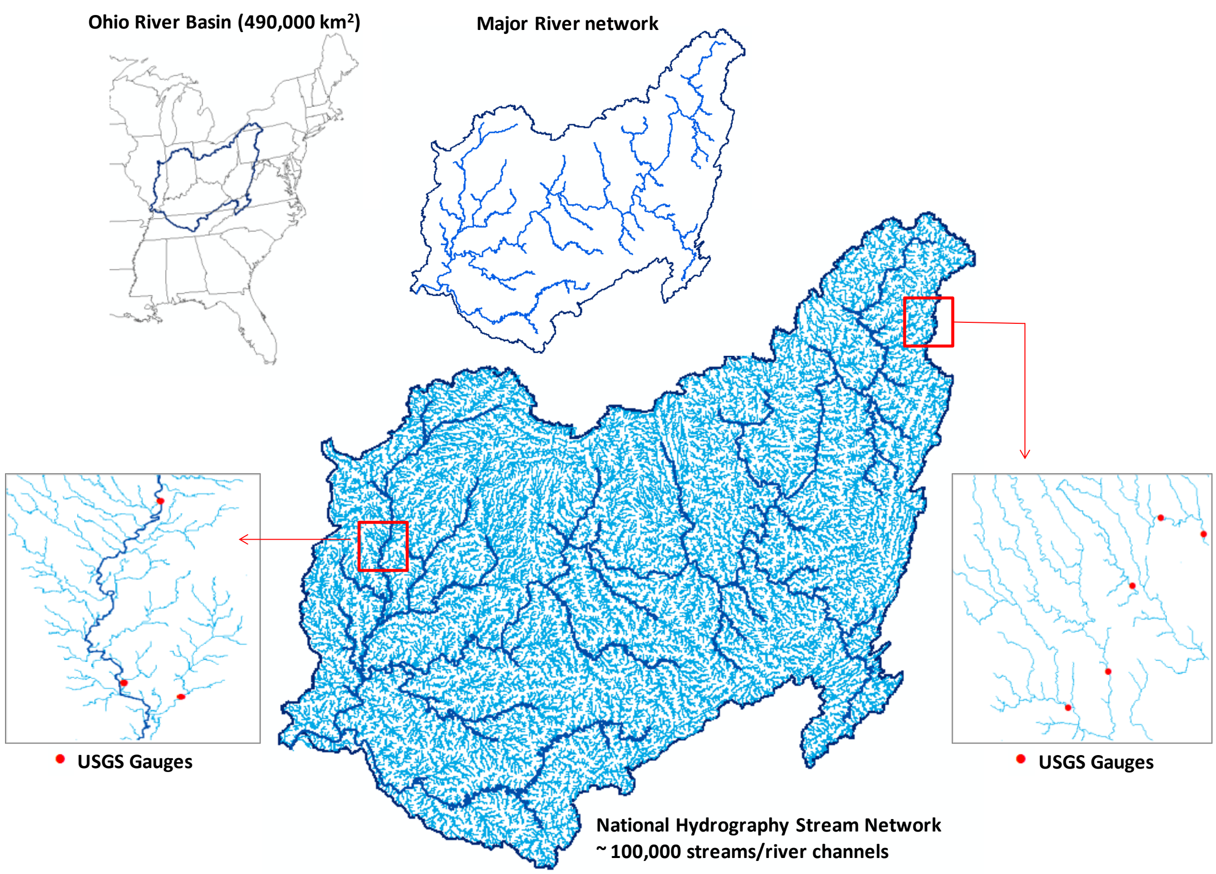

Figure 1. Extent of Ohio River Basin with 100,000 ~NHDPlus stream network.

Figure 1 also shows the position of United States Geological Survey's (USGS) streamflow gauge stations in two smaller domains within the ORB, which explicitly depicts the possible vastly ungauged regions lacking a prediction support system in case of flood occurrences.

3. Methodology

3.1 Model Descriptions

SWAT (Neitsch et al., 2011; Arnold et al., 2012) is a physically-based, semi-distributed hydrologic model, being recognized as a principal tool in various national level governmental projects in United States, such as the U.S. Department of Agriculture's CEAP (Conservation Effects Assessment Project) initiative, as well as the U.S. Environmental Protection Agency's BASINS (Better Assessment Science Integrating Point and Non-point Sources) project. Based on topography, land use, soil information and stream network, SWAT model divides a basin into a number of smaller sub-basins and then into Hydrologic Response Units (HRUs) where surface runoff is estimated either using the Soil Conservative Service (SCS) curve number or Green-Ampt infiltration method. SWAT provides two options to simulate in-stream routing, including the Muskingum K-X and the Variable Storage Area method (Neitsch et al., 2011). LISFLOOD-FP is a 1D/2D coupled hydrodynamic model to simulate spatial flood inundation extents (Bates and De Roo, 2000; Horritt and Bates, 2001). Flood wave propagating downstream through the channel is simulated in the model using 1D continuity and momentum equations. When the bankfull flow depth is reached, flow between two cells in the floodplain is taken as a function of the free surface height difference between those cells based on 2D continuity and momentum equations (Horritt and Bates, 2001)

3.2 Conceptual Design of the Modeling Framework

The proposed flood inundation modeling framework is shown in Figure 2. Digital elevation model (DEM) at 30 m spatial resolution is obtained from the USGS National Elevation Dataset (USGS-NED, 2015), land use dataset from the USGS's National Land Cover Database of year 2011 (USGS-NLCD, 2015) and soil information from the State Soil Geographic Database (STATSGO) are used to represent the geospatial heterogeneity. A high-resolution stream network (nearly 100,000 streams/rivers across the entire extent of ORB) from the National Hydrography (NHDPlus) database is ingested in the model. The output is the discharge (streamflow; volume/unit time of model simulation) at each stream's downstream node where it meets another stream. However, in order to bring the water balance simulated by the model at a reasonably representative state, the model parameters need to be optimized through calibration process, using daily streamflow records from selected USGS gauge stations as the reference (Figure 3). In this model initiation/calibration stage, climate data from the National Climatic Data Center (NCDC) for 112 weather stations over a period of past 80 years (1935-2014) are used to force the model.

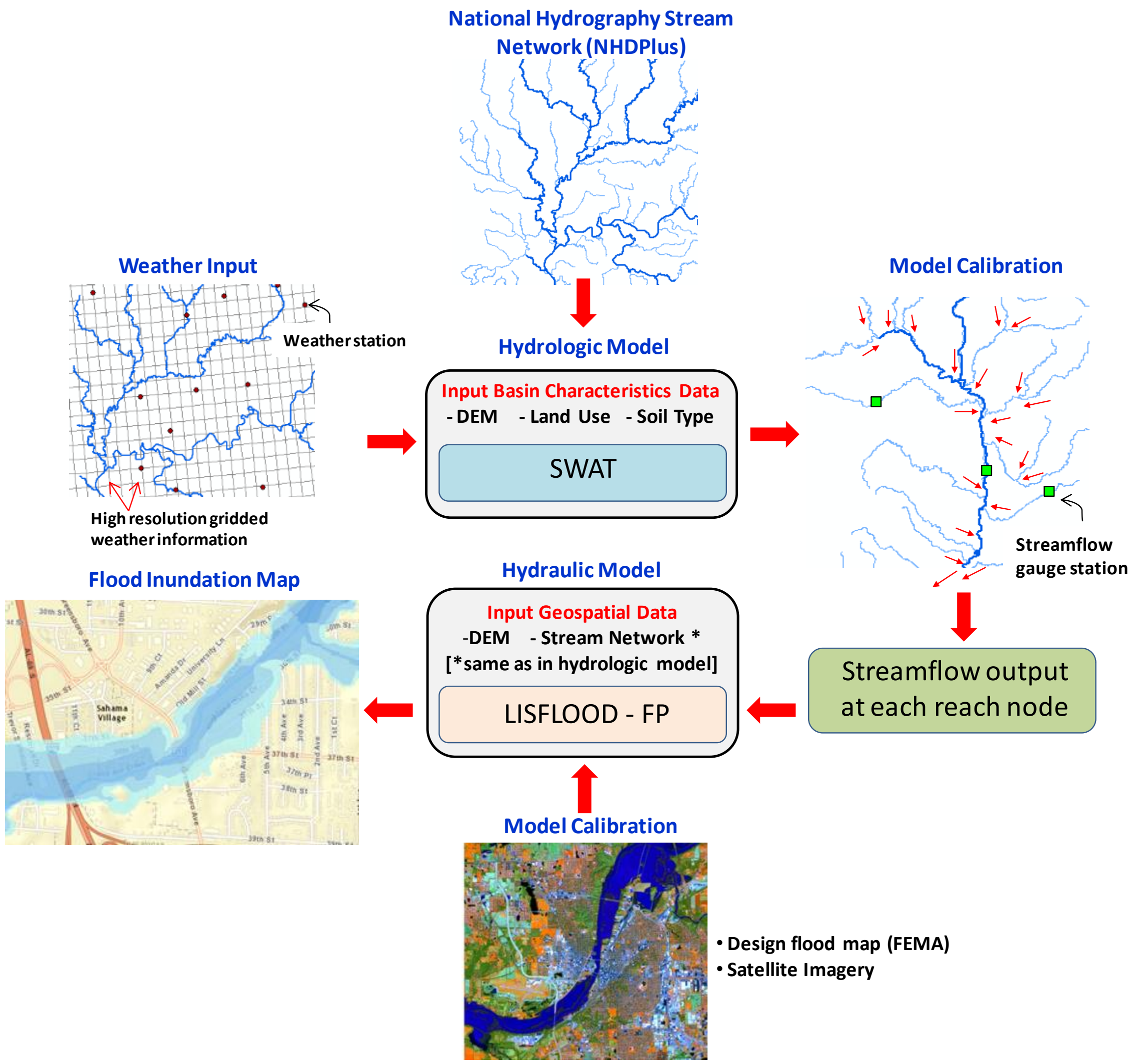

Figure 2. Proposed SWAT and LISFLOOD-FP modeling framework.

LISFLOOD-FP is set with the same NHDPlus stream network as in the SWAT model. Streamflow output time-series from SWAT or a design flow with certain return period calculated from thereof can be fed into LISFLOOD-FP at several stream locations. Taking the SWAT based outputs as input boundary conditions, LISFLOOD-FP uses its own algorithm (section 3.1) for simulating channel and floodplain propagation of water. It is noteworthy that the aforementioned integration between the two models is manual or loosely coupled, since a dynamic message passing interface has not been designed yet. However, LISFLOOD-FP needs to go through several iterative runs with different sets of roughness values (Manning's *n*; the major parameter for this model) until it produces maximum fitness with a reference map (such as 100 year flood map from the U.S. Federal Emergency Management, FEMA).

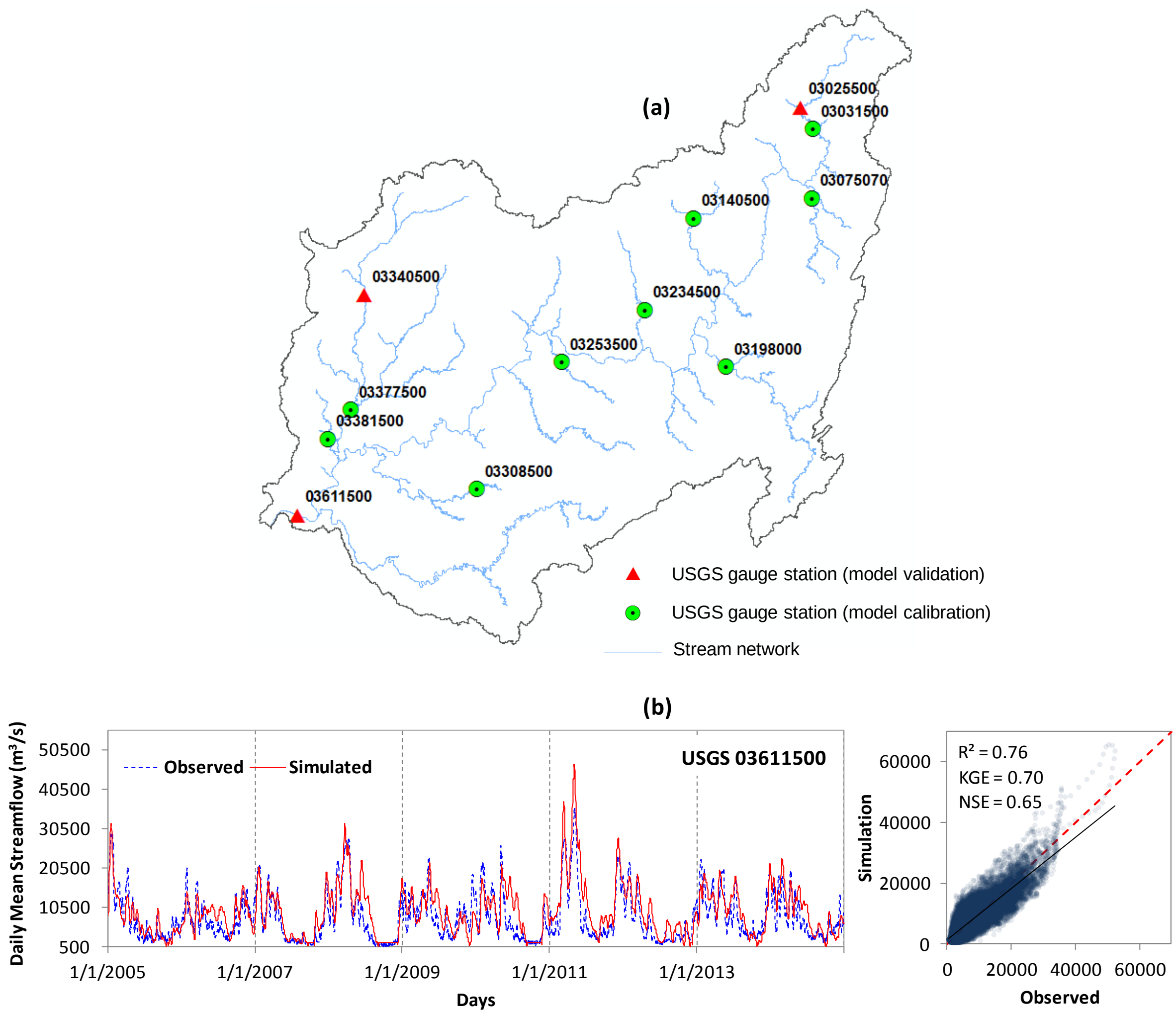

Figure 3. (a) SWAT calibration and validation locations (numbers correspond to respective USGS station IDs); (b) evaluation of model performance at a near-outlet gauge station.

4. Results

Performance of the calibrated SWAT model is evaluated by comparing the simulated streamflow with observed data at three separate gauge stations which are not included in the calibration process (Figure 3a). The goodness of fit scores (Correlation (R^2), Kling-Gupta Efficiency (KGE) and Nash-Sutcliffe Efficiency (NSE); Figure 3b) are found in the range of 0.4-0.72 and 0.55-0.7 for the calibration and validation locations respectively. These fitness statistics are within the acceptable range as suggested by Moriasi et al. (2007). To reduce the parameter uncertainty and equifinality in such large scale model applications, an alternative approach of using remotely sensed soil moisture data, along with streamflow records, in a spatially-distributed calibration scheme (e.g. Rajib et al., 2016) can also be used.

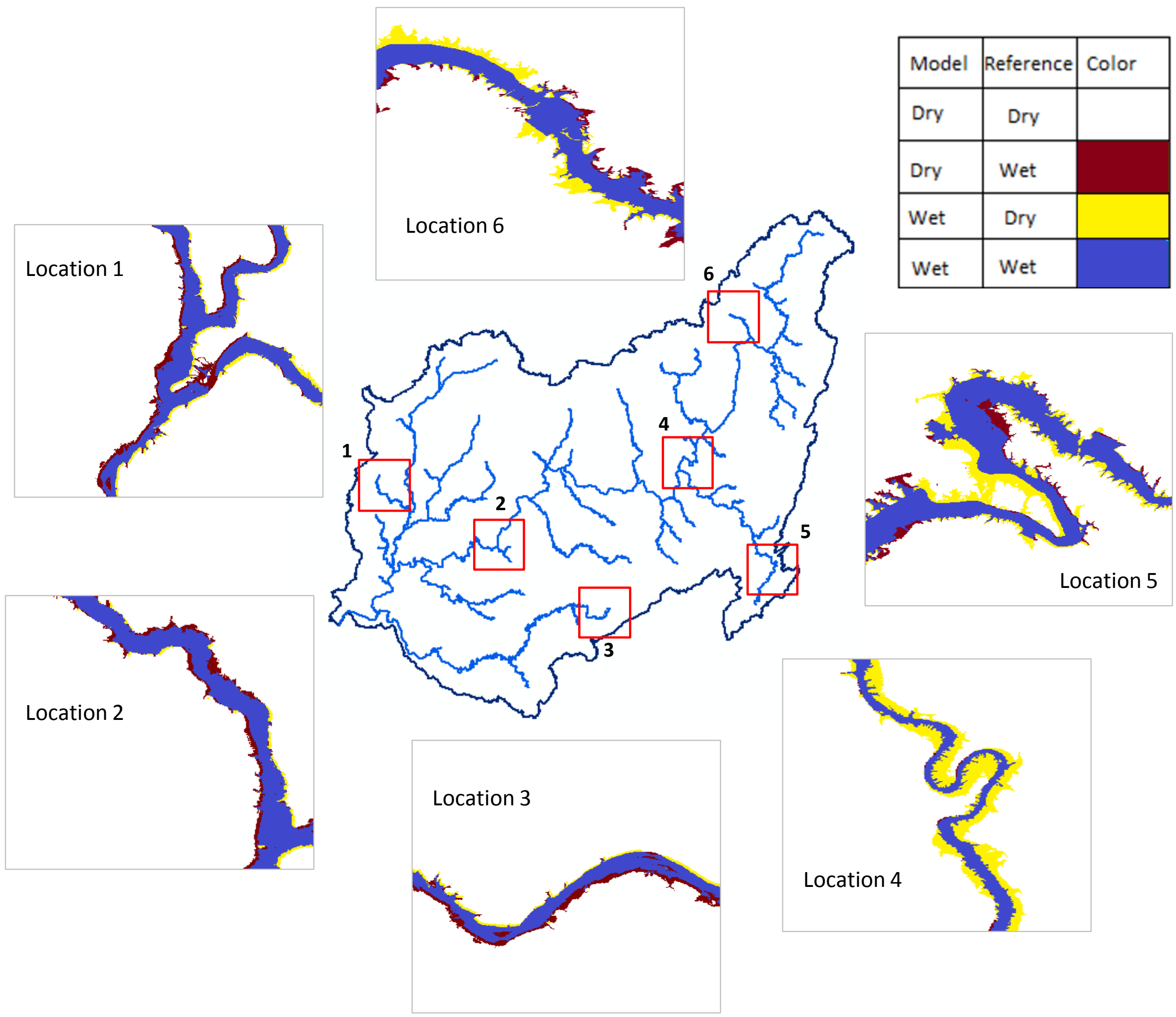

Figure 4. Evaluation of model generated 100 year flood inundation with corresponding FEMA reference.

For the evaluation purposes, SWAT simulated 80 year streamflow along the 100,000 NHDPlus reaches are used to calculate 100-year design flow for each reach by assuming the annual maximum series to follow the Log Pearson Type III distribution. The calculated design flows at the headwater reaches are applied as input for the LISFLOOD-FP model following the scheme shown Figure 2. Considering that the land use and topography vary significantly across ORB, the entire basin is divided into six regions (not shown here) based on the clustering of the major river tributaries, therefore, enabling better calibration of the model with representative Manning's *n* values. Such sub-division of ORB for hydrodynamic simulation also facilitates parallel execution using high performance computational resources in Purdue University's Carter cluster. Different combinations of channel and floodplain *n* values (0.01-0.05 and 0.03-0.15 respectively) are tested for the respective segments in iterative simulations of the model until the model generated inundation map matched well with the 100 year reference flood map from FEMA. Overall, the illustrations in Figure 4 suggest reasonable performance by the SWAT and LISFLOOD-FP framework over such a large scale. Further evaluation of modeled inundation extents is necessary based on satellite imagery of actual flood events over the past years.

5. Summary and Future Work

This paper presents a prototype of integrated hydrologic and hydraulic modeling approach to enable high resolution flood inundation mapping at regional to continental scale. The performance of the proposed SWAT and LISFLOOD-FP modeling framework as presented in this paper shows promise in delivering streamflow and flood inundation maps along the high resolution National Hydrography (NHDPlus) stream network than what is possible by using only gauged location on major river reaches.

Following similar structure, such large scale high resolution modeling initiatives can be tested for other major river basins in the United States as well. To help disseminate the prediction information, an open-access dynamic web-interface is currently being developed with the functionalities of visualizing streamflow at each of the NHDPlus reaches, corresponding flood inundation maps and inundation depths in near real-time. As the next step forward, this modeling system can be run with near real-time as well as short/medium range weather forecasts under the auspices of a national operational forecasting system.

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