TOWARDS REAL-TIME CONTINENTAL SCALE STREAMFLOW SIMULATION IN CONTINUOUS AND DISCRETE SPACE

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ABSTRACT: The National Weather Service (NWS) forecasts floods at approximately 3,600 locations across the United States (U.S.). However, the river network, as defined by the 1:100,000 scale National Hydrography Dataset-Plus (NHDPPlus) dataset, consists of 2.7 million river segments. Through the National Flood Interoperability Experiment, a continental scale streamflow simulation and forecast system was implemented and continuously operated through the summer of 2015. This system leveraged the WRF-Hydro framework, initialized on a 3-km grid, the Routing Application for the Parallel Computation of Discharge river routing model, operating on the NHDPPlus, and real-time atmospheric forcing to continuously forecast streamflow. Although this system produced forecasts, this paper presents a study of the three-month nowcast to demonstrate the capacity to seamlessly predict reach scale streamflow at the continental scale. In addition, this paper evaluates the impact of reservoirs, through a case study in Texas. Validation of the uncalibrated model using observed hourly streamflow at 5,701 U.S. Geological Survey gages shows 26% demonstrate PBias ≤ [25%], 11% demonstrate Nash-Sutcliffe Efficiency (NSE) ≥ 0.25, and 6% demonstrate both PBias ≤ [25%] and NSE ≥ 0.25. When evaluating the impact of reservoirs, the analysis shows when reservoirs are included, NSE ≥ 0.25 for 56% of the gages downstream while NSE ≥ 0.25 for 11% when they are not. The results presented here provide a benchmark for the evolving hydrology program within the NWS and supports their efforts to develop a reach scale flood forecasting system for the country.

(KEY TERMS: continental scale river dynamics; streamflow prediction; surface water hydrology; flood forecasting.)

INTRODUCTION

The art and science of flood forecasting is imperfect and has a long history that dates to the early settlements along the Nile River where farmers planted crops along its nutritious river banks (Sutcliffe and Parks, 1999). Although the quantitative impacts of floods have changed significantly since then (e.g., loss of crops for an individual farmer...


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compared to billions of dollars in municipal infrastructure damage), the ability to accurately forecast flood events with an appropriate lead time and at a relevant spatial scale has always been a sought after achievement. Floods within the United States (U.S.) are the nation’s largest natural disasters with respect to annual cost (approximately $8 billion per year) and are responsible for an average of 85 losses of life each year with trends suggesting an increase in these totals (U.S. Flood Loss Report—Water Year 2014. http://www.nws.noaa.gov/ohc/summaries/WY2014.pdf, accessed July 31, 2017). Both of these costs are a result of several factors that include steady and rapid urbanization within the floodplain (Ogden et al., 2011; Vogel et al., 2011; Gilroy and McCuen, 2012), extreme synoptic and convective precipitation events (Arnberg-Nielson, 2012; Kunkel et al., 2012; Mahoney et al., 2013), and gaps in the communication of flood risk at an appropriate temporal and spatial scale (Kellens et al., 2013; Morss et al., 2015; Sharif et al., 2015). These risks are exacerbated in areas, such as the central Texas corridor and Colorado Front Range, where moist seasonal weather patterns combine with steep topography to produce flash floods (typically characterized as rapid responses in streamflow within 0-3 h) (Morss et al., 2015; Zhao and Li, 2015; Nielsen and Schumacher, 2016).

The effects of floods are mitigated through planning, education, and the real-time distribution of flood information. On the planning side, water practitioners develop watershed scale hydrologic models (McDonnell et al., 2007; Wagener et al., 2010; Hodges, 2013) and statistically characterize observational records (Helsel and Hirsch, 2002; Vogel et al., 2011; Salas and Obeysekara, 2014) to facilitate thousands of watershed scale engineering studies that contribute to the National Flood Insurance Program (NRC, 2009). Although this has led to the development of the “100-year” flood inundation map along thousands of rivers and creeks across the country, a majority of the river miles within the U.S. lack such a map. Moreover, while “100-year” flood inundation maps aid in the planning of flood response by communicating risk to the public and emergency response community (Merz et al., 2007), they do not provide real-time spatial or temporal intelligence on imminent flood events.

In the U.S., the National Weather Service (NWS) is operationally responsible for issuing flood forecasts and warnings to the public (McEnery et al., 2005; Seo et al., 2013; Clark et al., 2014). This service is supported by local Weather Forecast Offices (WFOs) and regional River Forecast Centers (RFCs) that rely on myriad observations, numerical weather prediction (NWP) models, hydrologic and hydraulic models, and peer-to-peer communication. Although distributed modeling capabilities have evolved in recent decades, a substantial portion of the nation’s flood forecasting system relies on the Sacramento Soil Moisture Accounting (SAC-SMA) model developed in the 1970s (Burnash et al., 1973). The product of this system, communicated through the Advanced Hydrologic Prediction Service, is a set of flood forecasts at approximately 3,600 locations across the country. This approximates to one forecast for every 1,500 river kilometers, as depicted in Figure 1, and results in a disparity between where water flows and where forecasts are available. For reference, the U.S. has 5.34 million river kilometers, as defined by the 1:100,000 (1:100K) scale National Hydrography Dataset-Plus (NHDPlus) (McKay et al., 2012). At this scale, the NHDPlus divides the country’s river network into approximately 2.7 million river segments, or “reaches,” that have corresponding drainage catchments. This rich geospatial dataset has enabled water practitioners and researchers to seamlessly track the movement of water through a complete channel network and has resulted in several scientific studies.

![FIGURE 1. 3,600 National Weather Service Forecast Points (in purple) and a Subset of the 2.7 Million National Hydrography Dataset-Plus (NHDPlus) River Reaches (stream order 2 and above). Although not pictured, Alaska is included in the 3,600 forecast points while Hawaii has none. The box on the right shows the detailed NHDPlus network as a set of connected river reaches (blue) and catchments (green).](image-url)
which reference the NHDPlus as an adequate geospatial framework for streamflow simulation (Cooter et al., 2010; Booth et al., 2011; David et al., 2013).

As computers, geospatial datasets and sensor networks evolve, the ability to seamlessly model the water cycle in real-time expands and enables scientists to answer many questions that were not possible before (Wagener et al., 2010; Hodges, 2013). In fact, NASA’s North American Land Data Assimilation System (NLDAS) is a prime example of the continuous operation of multiple near real-time gridded land surface models (LSMs) covering the contiguous U.S. at a 1/8th degree resolution (Mitchell et al., 2004; Xia et al., 2012). However, in 2011, Wood et al. (2011) challenged the hydrologic science community to go beyond this scale and support the infrastructure development of “hyperresolution” hydrologic models on the spatial scale of 1 km. Concurrently, because of the increasing pressures on the nation’s critical water resources, the National Oceanic and Atmospheric Administration (NOAA) erected the National Water Center (NWC) on the campus of the University of Alabama in Tuscaloosa as an instantiation of the Integrated Water Resource Science and Services (IWRSS) consortium (Cline, 2009) which includes NOAA, the U.S. Geological Survey (USGS), U.S. Army Corps of Engineers, and Federal Emergency Management Agency. Among the missions of the NWC, one is to provide timely and real-time “street level” flood forecasts to the public.

As such, the focus of this paper revolves around the challenge made by Wood et al. (2011) and the mission of the NWC by describing the geospatial and hydrologic framework used during the 2015 National Flood Interoperability Experiment (NFIE), which included the continuous operation of a continental scale streamflow simulation and forecasting system from May 2015 to August 2015. Although this effort was motivated by real-time, “street level” flood forecasting at the continental scale, the purpose of this study was to demonstrate the capacity to support real-time streamflow prediction at the continental scale and at the resolution of the NHDPlus reaches and catchments, which in turn could be used to support “street level” flood forecasting. This paper is accompanied by a companion paper, Maidment (2016), which introduces the high-level conceptual framework for NFIE. In contrast, this paper provides a detailed technical description of the modeling framework used to operate the real-time streamflow simulation system. This system leverages the Weather Research and Forecasting Model Hydrological modeling extension package (WRF-Hydro) and the Routing Application for the Parallel Computation of Discharge (RAPID) to simulate streamflow along 2.7 million NHDPlus river reaches. This study will present a streamflow analysis of the three-month nowcast, covering the temporal extent of the experiment, and provide a case study in Texas evaluating the influence of reservoir operations. The following sections start with a brief review of existing flood forecasting and hydrologic modeling capabilities within the U.S. and is followed by an overview of NFIE and the model configurations used during the demonstration effort. Finally, an evaluation of simulated streamflow is presented and discussed within the context of the NWS’ evolving hydrology program.

EXISTING FORECASTING AND MODELING CAPABILITIES

Within the U.S., the NWS is the entity responsible for forecasting flood events and issuing flood warnings for the protection of life and property (Weather-Ready Nation. https://www.weather.gov/media/news/WRN_Pilot_Projects_Final.pdf, accessed July 31, 2017). This operation is carried out daily by 122 local WFOs and 13 regional RFCs (McEnery et al., 2005; Seo et al., 2013; Clark et al., 2014). Using a suite of hydrologic datasets, observations and models, NWS personnel assimilate the best available information in near real-time and issue flood forecasts at approximately 3,600 locations or forecast points across the country (including Alaska but not Hawaii). This is enabled by the modeling of hydrologic conditions across 3,600 subbasins, herein referred to as forecast basins, with an average size of 1,000 km². These forecast basins cover the majority of the country with gaps in the western desert and along coastal estuaries. Although forecasting operations within each RFC differ, the outlets of the forecast basins (i.e., the forecast points) function as a basis for operational forecasts in that they are the locations where flood forecasts are routinely issued across the country.

One of the models used to guide flood forecasts is the SAC-SMA model (Burnah et al., 1973). This model is coupled with a routing scheme to issue forecasts at the 3,600 forecast points. During a flood event, a forecaster will readily adjust antecedent soil moisture conditions, and run the lumped SAC-SMA model based on specified model inputs (e.g., current and forecasted precipitation and air temperature). Although this procedure provides a robust methodology, studies have shown that there are limitations to using lumped basin models as basin scale parameters fail to capture local hydrologic processes at the catchment scale (Beven, 1989; Singh and Frevert, 2005; Chaney et al., 2016). In recent years, the NWS developed a distributed version of SAC-SMA, and
enhanced it by accounting for frozen soils and vegetated canopy cover. The enhanced version of the model is referred to as the SAC-Heat Transfer Evapotranspiration (Koren et al., 2010) and is run within the Hydrology Laboratory-Research Distributed Hydrologic Model (HL-RDHM) framework. As with SAC-SMA, HL-RDHM is used by some RFCs in operation.

Although the forecasting system within the NWS has evolved over the years, many other advances have been made with respect to continental scale hydrologic simulation and they are partially a result of demands and advances within the atmospheric science community (Putnam, 2003). In contrast to watershed scale modeling efforts within hydrologic sciences, gridded three-dimensional models, like the Weather Research and Forecast (WRF) model, have been implemented over large domains within the atmospheric science community (Maurer, 2007; Gula and Peltier, 2012; Hodges, 2013; Rassmusen et al., 2014). Because land surface feedback has been demonstrated as a primary driver of local and regional weather phenomena, sophisticated LSMs have been actively developed on the order of tens to hundreds of kilometers (Liang et al., 1994; Mitchell, 2005; Oleson et al., 2010; Niu et al., 2011; Wood et al., 2011; Archfield et al., 2015; Clark et al., 2015). Although higher resolution LSMs have followed, many still employ parameterization schemes to represent subgrid scale hydrologic processes (Wood et al., 2011; Archfield et al., 2015; Chaney et al., 2016). In fact, Archfield et al. (2015) notes that scaling the application of LSMs from tens of kilometers to the catchment scale remains a challenge due to the disparate requirements and perspectives of the existing hydrologic modeling communities: catchment (local scale), land surface (regional scale), and global water security (global scale).

Parallel to the development of LSMs, several studies have focused on the development of large scale river routing models (Oki et al., 2001; Lohmann et al., 2004; Miguez-Macho and Fan, 2012; David et al., 2013; Krajewski et al., 2017; Tavakoly et al., 2016). The models developed have varied in sophistication based on routing scheme yet all demonstrate the capacity to route streamflow over large domains. In an effort to maintain spatial consistency among atmosphere, landscape, and river network, and because of insufficient data available as vector blue lines (i.e., river polylines), most of these large scale modeling efforts have been based in the gridded domain routing from one channel grid cell to the next (David et al., 2013; Hodges, 2013). However, the emergence of the NHDP (McKay et al., 2012) and other Geographic Information System (GIS) datasets have now made it possible to develop large scale river routing models on vector blue lines (Beighley and Gummadi, 2011; Paiva et al., 2011; David et al., 2013; Liu and Hodges, 2013; Tavakoly et al., 2016).

As demonstrated in David et al. (2013) and Tavakoly et al. (2016), one such model is the light-weight and computationally efficient RAPID river routing model which has been implemented, among other domains, over the Texas Gulf Coast and Mississippi River basins. The development of these models has presented an opportunity to systematically link atmospheric and land surface processes, over large domains, to catchment scale hydrologic and hydraulic processes.

In a recent collaboration between NASA, NOAA, and others, the National Centers for Environmental Prediction implemented a real-time version of the NLDAS system and extended the land surface flux outputs to streamflow through a gridded terrain and channel routing scheme (North American Land Data Assimilation System [NLDAS], http://www.emc.ncep.noaa.gov/mmb/nldas, accessed July 31, 2017). Although the implementation of NLDAS has demonstrated the capacity to readily operate large scale hydrologic models (i.e., LSMs coupled with terrain and river routing), the resolution of the system is too coarse in space (approximately 13 km resolution) for operational flood forecasting at the catchment scale. One model addressing this scale gap is the community WRF-Hydro modeling system (Gochis et al., 2015). Originally developed as a high-resolution hydrologic modeling extension to the widely used WRF atmospheric model, WRF-Hydro permits the dynamic coupling of coarse-resolution vertical water fluxes, simulated by a numerical weather model and LSM, with spatially explicit modeling of high-resolution hydrologic routing processes. WRF-Hydro is used in operations for flood and water supply forecasting in the U.S. and abroad, as well as a number of research applications (Senatore et al., 2015; Yucel et al., 2015; Arnault et al., 2016).

NATIONAL FLOOD INTEROPERABILITY EXPERIMENT

Conceptual Framework

The NFIE was organized in part as a demonstration effort by the NWS and Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) to demonstrate the nation’s capacity to provide flood forecasts for each of the 2.7 million NHDPlus river reaches. As part of this demonstration, an experimental streamflow simulation system
was set up and run between May 23, 2015 and August 23, 2015 (i.e., the simulation period). To support this endeavor, a high-level conceptual framework was devised to organize and coordinate the various efforts within NFIE and is presented in detail in Maidment (2016). This framework is also briefly presented here to provide context for the streamflow simulation system discussed in the following sections.

The conceptual framework for NFIE has five main components: NFIE-Geo, NFIE-Hydro, NFIE-River, NFIE-Response, and NFIE-Services. NFIE-Geo refers to the geospatial framework and datasets needed to support continental scale streamflow simulation. NFIE-Hydro refers to the continental scale streamflow simulation system and its individual model components. NFIE-River refers to the datasets and methods for converting streamflow to water level and inundation extent. NFIE-Response refers to the framework needed to coordinate and plan flood response. And finally, NFIE-Services refers to the suite of Web services that support the four other components of NFIE. Each component can be seen in Figure 2 with arrows indicating how each component supports the other(s).

This paper will only focus on NFIE-Geo and NFIE-Hydro where NFIE-Hydro refers to a loosely coupled continental scale implementation of the WRF-Hydro framework and the RAPID river routing model. In this implementation, a suite of atmospheric forcing datasets are used to drive WRF-Hydro which provides 3-km gridded simulations of surface and subsurface runoff to RAPID. Using a Muskingum channel routing scheme, RAPID simulates streamflow and operates on the NFIE-Geo river network. The following section will begin by describing the core modeling layers within NFIE-Geo, and the subsequent sections will describe the NFIE-Hydro streamflow simulation system and the model configurations used during the experiment. The authors would like to note that although the goal of NFIE is to provide reach scale flood forecasts at the continental scale, this paper will only discuss reach scale streamflow simulation as forecasting ahead in time requires a discussion on precipitation forecasts which is beyond the scope of this study. Furthermore, flood modeling is treated as a distinct topic related to NFIE-River and NFIE-Response and will not be discussed here as part of the analysis.

Building a Consistent Geospatial Framework

As conveyed abstractly through Figure 3, a consistent geospatial framework is needed to support continental scale streamflow simulation. This framework is needed to integrate (1) continuous atmospheric and hydrologic phenomena, (2) continuous terrain and landscape processes, and (3) discrete geospatial features. Within the U.S., the NHDPlus catchment and reach features provide a geospatial framework through which continuous grids can be spatially aggregated at the catchment scale while discrete point and polygon features can be referenced at the reach scale; one can think of this like a hydrologic addressing system for the country. As such, NFIE-Hydro leverages the NHDPlus dataset to aggregate gridded surface and subsurface runoff (output from WRF-Hydro) at the catchment scale to drive flow (using RAPID) through NHDPlus reaches. Because the evolution of the NHDPlus dataset is ongoing, the modeling framework discussed herein pertains to the 1:100K resolution NHDPlus Version 2 dataset (NHDPlusV2).

The NHDPlus dataset enables both the addressing of water-related features through referencing (i.e., location of a feature along a river) and tracing of water through the landscape using a collection of related drainage catchments and river reaches, both indexed by a unique and common “ComID” identifier. Contained within the NHDPlusV2 dataset is a geodatabase of related GIS features, attributes, and tables. The reach features, within the “NHDFlowline” layer, are organized by 21 Vector Processing Units (VPU) which comprise of 12 major drainage areas within the contiguous U.S. as seen in Figure 4. These drainage areas are herein referred to as NFIE modeling regions and do not include areas outside of the contiguous U.S. as NHDPlus reaches are not available in these areas. As described by McKay et al. (2012), the “NHDFlowline” layer is comprised of river reaches, defined by their junctions, and represent
several feature types such as “artificial path,” “canal/ditch,” “coastline,” “connector,” “pipeline,” and “stream/river”; an artificial path represents the reaches contained within the area of a water body. If the reach has a flow direction (a majority do), it is indicated through the “FLOWDIR” field as “with digitized.” For the purposes of this continental scale simulation, only reaches indicating “stream/river,” “artificial path,” and “connector” in the “TYPE” field and “with digitized” in the “FLOWDIR” field were preserved within NFIE-Geo as hydraulics within canals, coastlines, and pipelines were not included in this modeling effort.

Within the NHDPlusV2 tables is the information necessary to trace upstream and downstream through the river network. Each “with digitized” river reach has an upstream and downstream node defined at the ends of the reach and its identifiers are contained within the “FromNode” and “ToNode” fields of the related “PlusFlowlineVAA” table. As part of the development of NHDPlus, each node in the network was processed in a manner that ensures one is able
to trace and navigate through the network even if there exists a gap in the geographic representation of the features. For example, in areas where rivers disappear underground or where reaches are disconnected as a result of the digitizing process, river reach features may not be connected in space but will maintain network connectivity through the “FromNode” and “ToNode” attributes. This is also the case along the U.S. border where reaches are not defined; a reach flowing out of the U.S. will be connected to a reach flowing in at another location. Together, this information is used to build network connectivity and is provided as input to the RAPID model.

Although the majority of river reaches in the NHDPlus dataset are associated with an immediate drainage area or catchment feature through the “ComID” field, there are instances where river reaches do not have catchments and instances where catchments do not have river reaches. During the digitization process of NHDPlus, the length of some river reaches was smaller than 30 m and did not have a catchment delineated since the resolution of the flow accumulation grid used to derive the catchment was 30 m. There were also instances where reaches did not connect to one another and resulted in the addition of small reaches to ensure continuity from upstream to downstream. In these situations, reaches were not given catchments as they were only used as symbolic connections between reach features. Conversely, there are also catchments that do not have associated river reaches in instances where there are noncontributing areas as is the case in the northwest part of the Brazos River basin in Texas. Although these details seem irrelevant to a continental scale modeling framework, these artifacts are critical to the processing of the river network and its connection to the landscape processes (i.e., runoff) and were thus taken into account when assigning runoff from the WRF-Hydro grid to the NHDPlus reaches. This process is discussed in more detail in the following section.

In addition to defining the primary drainage network, one must also account for lakes and reservoirs that reside along rivers. Within the NHDPlus dataset, many waterbodies are contained in the “Waterbody” layer and vary in size. While large waterbodies were included in the vertical land surface fluxes of WRF-Hydro (waterbodies larger than the 3 km land cover grid), lake routing and reservoir operations were not systematically accounted for within the RAPID model due to data constraints (e.g., lack of lake/reservoir geometries, operation rules, etc.). However, because NWS RFCs routinely issue flow forecasts downstream of major reservoirs (some, not all), NWS forecast basins and forecast points were included in NFIE-Geo along with the NHDPlus catchments, reaches, and waterbodies. As described in more detail in the following section, NWS forecast points co-located with major reservoirs were used to study the impact of reservoir releases through a case study in Texas.

Lastly, as the USGS maintains the streamflow monitoring network for the country, the locations of reporting USGS gages (reporting during the simulation period) were also included in NFIE-Geo to provide points at which streamflow estimates could be evaluated against observations. Although the coordinates of USGS observation points represent the approximate location of the physical gage, these coordinates may not align with the NHDPlus representation of the river channel. As such, the NHDPlus provides an attribute within its “GageLoc” layer that links the gage to the “ComID” field of the related NHDPlus river reach; the “FLComID” field. This layer not only maintains the geographic representation of the gage but also allows one to connect the observations to the outputs of the model. Table 1 lists the NFIE-Geo layers that were used to support the NFIE-Hydro streamflow simulation system.

### Description of NFIE-Hydro Streamflow Simulation System

The NFIE-Hydro component of NFIE refers to the continental scale streamflow simulation system.

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRF-Hydro grid</td>
<td>NFIE</td>
<td>Model grid defining land surface model computations</td>
</tr>
<tr>
<td>Catchment</td>
<td>NHDPlus Version 2</td>
<td>Unit used to spatially aggregate gridded runoff</td>
</tr>
<tr>
<td>NHDFlowline</td>
<td>NHDPlus Version 2</td>
<td>River network used to route streamflow</td>
</tr>
<tr>
<td>Water body</td>
<td>NHDPlus Version 2</td>
<td>Feature used to represent lakes and reservoirs</td>
</tr>
<tr>
<td>Forecast basin</td>
<td>NWS</td>
<td>Modeling unit used to derive NWS streamflow forecasts</td>
</tr>
<tr>
<td>Forecast point</td>
<td>NWS</td>
<td>Point where NWS streamflow forecasts are valid</td>
</tr>
<tr>
<td>Reporting gage</td>
<td>USGS</td>
<td>Point where streamflow along river is observed</td>
</tr>
</tbody>
</table>

producing streamflow for 2.7 million NHDPPlus river reaches. This includes (1) the assimilation of atmospheric forcing from NWP models and precipitation datasets, (2) the WRF-Hydro framework running the Noah-MP LSM, and (3) the RAPID river routing model operating on the NHDPPlus river network. In this section, (2) and (3) will be discussed with (1) discussed in the following section. For reference, Figure 5 depicts the high-level workflow used within NFIE-Hydro to simulate streamflow.

WRF-Hydro is a distributed hydrologic modeling system that conforms to the WRF modeling framework (Gochis et al., 2015). WRF-Hydro can seamlessly couple with WRF and provide a modeling solution that dynamically solves the feedback between land surface and atmosphere or run in an offline mode where a user provides predefined gridded atmospheric forcing. In addition to the forcing options, WRF-Hydro includes a number of LSM options, on-the-fly regridding tools, and multiple process-based modules simulating spatially distributed hydrology. For this implementation, version 3 of WRF-Hydro was used which has the capacity to model several hydrologic processes: (1) vertical land surface flux on a grid through the implementation of an LSM (e.g., Noah, Noah-MP), (2) lateral subsurface flow on a high-resolution routing grid, (3) lateral overland flow on a high-resolution routing grid, (4) channel flow on a high-resolution channel grid, (5) lake/reservoir flow through lake/reservoir objects, and (6) groundwater flow through conceptual bucket objects (Gochis et al., 2015). Due to computational constraints and the desire to route streamflow through defined reach features (as opposed to channel grid cells), module (1) was the only module within WRF-Hydro implemented for NFIE. To route streamflow, the RAPID model was implemented outside of WRF-Hydro and loosely coupled through an area

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**FIGURE 5.** High-Level Workflow Used to Run the RAPID Model within NFIE-Hydro. WRF-Hydro runoff and estimated reservoir releases are used to drive the RAPID model, which operates on the NFIE-Geo river network. RAPID, Routing Application for the Parallel Computation of Discharge; MRMS/HRRR, Multi-Radar/Multi-Sensor System/High-Resolution Rapid Refresh; Noah-Multi-Physics (MP) LSM; RFC, River Forecast Center.
weighted catchment-based regridding process (i.e., mapping of WRF-Hydro gridded runoff to NHDPlus catchments).

For NFIE, the Noah-MP LSM was initialized within WRF-Hydro on a 3-km Lambert Conformal Conic grid covering the contiguous U.S. Noah-MP is a one-dimensional LSM that builds on the widely used Noah model and solves the energy and moisture fluxes along the land surface boundary through an explicit representation of vegetated canopy cover and a multilayer snowmelt process (Niu et al., 2011). Land surface and soil classifications for the Noah-MP model were, respectively, obtained from the 2011 National Land Cover Database and 1-km NRCS State Soil Geographic (STATSGO) database and regridded to fit the 3-km model domain. Because subsurface and groundwater modules were not used within WRF-Hydro, subsurface runoff was assumed to come from vertical drainage from the bottom of the Noah-MP soil column (assumed to be 2 m thick across the domain). Similarly, since WRF-Hydro’s overland routing modules were not used, surface runoff was assumed to come from the infiltration excess flow at the surface of the Noah-MP soil column. Other datasets used within Noah-MP and WRF-Hydro, such as vegetation structure, are referenced in Gochis et al., 2015 and provided by the well-documented WRF Preprocessing System (WPS) (WRF Preprocessing System Version 3.8: Updates. http://www2.mmm.ucar.edu/wrf/users/wpsv3.8/updates-3.8.html, accessed July 31, 2017). Although it is possible to calibrate the parameterization schemes within WRF-Hydro and Noah-MP, no calibration was performed for NFIE due to the limited temporal scope of the experiment.

Runoff from the WRF-Hydro grid cells is routed through the NFIE-Geo river network using the RAPID river routing model (David et al., 2011a, b). The RAPID model routes water volumes through defined river segment features using the Muskingum method. As indicated in Figure 5, inputs to the RAPID model include a network connectivity file, runoff file (i.e., surface and subsurface volumes), a pair of Muskingum parameter files and optional forcing files which represent locations where users can interrupt the flow routing scheme and provide user defined flow (e.g., in cases where reservoir releases are available). At these locations, the model uses defined flow to route water downstream instead of the internally computed upstream flow (David et al., 2011a). A depiction of the computational modeling unit within RAPID is seen in Figure 6 and demonstrates how surface and subsurface runoff is mapped from the WRF-Hydro/Noah-MP grid cells to the NHDPlus catchments. NHDPlus connectivity from catchment to river reach is then used to define lateral inflow into the channel. This flow is combined with either the current volume of the target reach (routed upstream flow or user defined flow), and routed to the next downstream segment.

As alluded to in the previous section, the network connectivity file is derived from the “FromNode” and “ToNode” fields contained within the NHDPlus “PlusFlowlineVAA” table using a customized geoprocessing tool within ArcGIS. The Muskingum k parameter values are derived from the geometry of the individual reaches using an arbitrary 1 km/hr wave celerity while the Muskingum x parameter is maintained at a constant value of 0.3 as prior studies have demonstrated minimal influence of this parameter on the routing process (Koussis, 1978; David et al., 2013). The locations of forcing inputs (used for the case study in Texas) were extracted from a national layer of NWS forecast points by intersecting the point features with NHDPlus waterbodies.

Finally, runoff files were generated using customized ArcGIS geoprocessing tools to produce spatially averaged catchment runoff. To support this effort, the 3-km gridded domain of WRF-Hydro was converted to a set of polygon features and then intersected with NHDPlus catchment features to produce a “weight table”; areas were derived using the Albers Equal Area projection to ensure proper area calculations. For each time step, output from WRF-Hydro (a 1 h time step for NFIE), gridded runoff was regridded to catchment runoff. Using the related catchment and reach “ComIDs,” catchment runoff was associated with its corresponding river reach and used to define lateral inflow to the RAPID model. It is important to note that catchment runoff is connected to the routing scheme at the upstream node of each river reach and flow output from the model represents flow at the downstream node.

ANALYTICAL METHODS AND EVALUATION

NFIE-Hydro Model Configuration

As depicted in Figure 7, between May 23 and August 23, 2015, NFIE-Hydro (i.e., a loosely coupled and uncalibrated implementation of WRF-Hydro and RAPID) was run continuously every 3 h using 15-h forecasts from the High-Resolution Rapid Refresh (HRRR) model (Bytheway and Kummerow, 2015; Pinto et al., 2015). The HRRR model is an operational NWP model supported by NOAA and is operated on a 3-km grid with hourly outputs (The High-Resolution Rapid Refresh [HRRR]. http://ruc.noaa.gov/hrrr/, accessed July 31, 2017); HRRR is currently the highest resolution NWP model run in real-time at the
continental scale. Because of its resolution and spatial and temporal coverage, the output from HRRR was used in NFIE to provide atmospheric forcing to WRF-Hydro (e.g., precipitation, temperature, wind, etc.); the full list of forcing variables needed to run WRF-Hydro is available in Gochis et al., 2015. Before initializing the next model run (3 h ahead), WRF-Hydro was run for the previous 10 h (herein referred to as a “spin cycle”) to update the initial conditions of the Noah-MP and RAPID state variables before the subsequent forecast. In contrast to each forecast, these spin cycles used HRRR analysis fields (i.e., initial conditions for HRRR forecasts) in combination with hourly precipitation from the Multi-Radar/ Multi-Sensor System (MRMS); HRRR analysis fields provided estimates of real-time atmospheric conditions and MRMS provided spatially consistent precipitation estimates (Zhang et al., 2016). MRMS precipitation is a 1-km operational dataset that assimilates radar, satellite, NWP models and gage information (Multi-Radar/Multi-Sensor System [MRMS]. http://www.nssl.noaa.gov/projects/mrms, accessed July 31, 2017). Since it is an assimilated and blended product, MRMS precipitation was assumed to match observations more closely than the existing precipitation fields in the HRRR analysis cycles. As such, gridded precipitation from MRMS was regridded to match the 3-km NFIE-Hydro grid and used to drive WRF-Hydro for each spin cycle. Prior to the summer experiment simulation period for NFIE, initial state variables for Noah-MP were derived from a five-year WRF-Hydro simulation using 1/8th degree atmospheric forcing from the NLDAS-2 dataset.

Using the same operational procedure as above, the RAPID model was run every 3 h for 15 h into the future. Before initializing the subsequent simulation (3 h ahead), the outputs from the WRF-Hydro spin cycle were used to update the streamflow conditions of the RAPID model. Although WRF-Hydro was initialized using a five-year simulation, the initial conditions of the RAPID model were not and started at 0 m³/s on May 23, 2015. Once initialized, both WRF-Hydro and RAPID ran continuously for three months through August 22, 2015. The complete modeling process resulted in 3 h updates of 15-h WRF-Hydro forecasts of land surface conditions (e.g., runoff) and 15-h RAPID forecasts of streamflow at 2.7 million NHDPlus river reaches. Because of limited data availability, reservoir releases were not accounted for within the continental scale RAPID simulations. However, as mentioned previously, estimated reservoir releases, available through the NWS, were used.
FIGURE 7. Depiction of Model Cycling within NFIE-Hydro Configuration. Both WRF-Hydro and RAPID were run every 3 h with a 10-h spin cycle to update initial conditions. The arrows along the bottom of the figure depict the atmospheric forcing used while spinning up the NFIE-Hydro initial conditions and the graph at the top depicts the forcing used to drive the 15-h forecasts. The initial conditions for the first NFIE-Hydro run (indicated as "Present" in the graph) were derived from a five-year retrospective simulation using atmospheric forcing from NLDAS. Leading up to the first run, HRRR analysis fields were used in conjunction with MRMS precipitation. The two blue arrows at the bottom of the figure represent the 10-h spin cycles and the purple arrows at the top represent the 15-h forecasts. NLDAS, North American Land Data Assimilation System.

in a case study in Texas to evaluate the impact of reservoirs (discussed in following section).

Model Domain, Case Study, and Analytical Methods

Although lake, reservoir, and lateral flow routing processes were not accounted for within NFIE-Hydro (among other hydrologic processes), this paper provides a preliminary evaluation of streamflow at 5,701 USGS gages as seen in Figure 9. Of the 9,322 high-quality gages within the GAGES-II dataset (Falcone, J.A., GAGE-II, Geospatial Attributes of Gages for Evaluating Streamflow [digital spatial dataset]. http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml, accessed July 31, 2017), only 5,701 had records during the simulation period. Of the 5,701 reporting gages, 1,145 are considered “reference” gages or gages minimally impacted by anthropogenic development and infrastructure (Falcone). Using the RAPID output from the 10-h NFIE-Hydro spin cycles, a three-month hourly streamflow simulation was analyzed to evaluate model skill across the contiguous U.S.

In addition, this study also performs a detailed analysis of streamflow at 367 USGS gages within the Texas Gulf Coast basin where flash floods frequently occur along the Central Texas corridor; see Figure 8a. This corridor, which runs from San Antonio to Dallas parallel to the Balcones escarpment, is known as "Flash Flood Alley." Of the 367 reporting gages within the basin, 60 are considered reference gages and are depicted in Figure 8d. To demonstrate the effect of reservoirs, RAPID was rerun over the same threemonth period using (1) WRF-Hydro runoff from the spin cycles and (2) estimated reservoir releases from the NWS West Gulf River Forecast Center (WGRFC). Reservoir release time series were obtained for 72 reservoirs within the study domain as seen in Figure 8b. Although many major reservoirs exist (around 200), NWS estimates for reservoir releases were only available at 72 major reservoirs; this represents 15% of the total number of NWS forecast points within the
basin and about one-third of the major reservoirs in Texas. Of the 367 gages used for comparison, 112 of these gages are located downstream of the 72 reservoirs included in the RAPID simulation; see Figure 8d. The downstream trace from each of these reservoirs has been symbolized in purple in Figure 8c. These traces represent approximately 5% of the total river kilometers in the basin. For all these gage subsets (summarized in Table 2), the following metrics were used to analyze simulated hourly streamflow: (1) percent bias (PBIAS), (2) hourly Nash-Sutcliffe Efficiency (NSE), and (3) hourly Pearson correlation.

**Evaluation of Retrospective Simulation**

Correlation and NSE of hourly streamflow are shown in Figure 9. Figures 9a and 9c show statistics for all 5,701 reporting gages while Figures 9b and 9d show statistics for the 1,145 reference gages. Although neither WRF-Hydro nor RAPID were

<table>
<thead>
<tr>
<th>Gage Subset</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continental scale</td>
<td>5,071</td>
</tr>
<tr>
<td>All reporting gages</td>
<td></td>
</tr>
<tr>
<td>Gages impacted by anthropogenic influences</td>
<td>4,556</td>
</tr>
<tr>
<td>Reference gages</td>
<td>1,145</td>
</tr>
<tr>
<td>Texas case study</td>
<td></td>
</tr>
<tr>
<td>All reporting gages</td>
<td>367</td>
</tr>
<tr>
<td>Gages impacted by modeled reservoirs</td>
<td>112</td>
</tr>
<tr>
<td>Reference gages</td>
<td>60</td>
</tr>
</tbody>
</table>

Note: Observed flow from these gages is provided by the USGS.
calibrated for NFIE, Figures 9a and 9b depict strong correlation in the Pacific Northwest, Rocky Mountains, Central U.S., and Eastern U.S. (0.50-1.0), and moderate correlation in the Rocky Mountains, Central U.S., and Eastern U.S. (0.50-0.75). In contrast, one can see weak correlation (less than 0.50) in the arid Southwest and Northern Plains. While correlation statistics can be used to diagnose adequate representation of model processes, they are not sufficient for demonstrating model skill. Moriasi et al. (2007) suggest that daily streamflow simulations demonstrating PBias $\leq 25\%$ and NSE $\geq 0.50$ can be considered satisfactory for hydrologic modeling. However, because this analysis is based on uncalibrated simulations of hourly streamflow, we have relaxed the Moriasi criteria by adjusting the NSE metric, NSE $\geq 0.25$, to provide a benchmark for future studies. As such, Figures 9c and 9d show the locations where simulations meet the PBias $\leq 25\%$ criteria and plot NSE for these gages in varying shades of blue. As one can see in Figure 9c, most of the country does not meet this criteria, however, parts of East Texas, the Arkansas River basin, the Ohio River basin, and Northeast do. Although the influence of reservoirs across the contiguous U.S. is a primary source of error, reference gage statistics in Figure 9d suggest sources of error linked to space, climate, and hydrography, as the spatial patterns are similar to that of the complete dataset. Of the 4,556 impacted gages and 1,145 reference gages, 266 (5.8%) and 75 (6.6%) met both the bias and NSE criteria, 1,165 (25.6%) and 297 (26.0%) met only the bias criteria and 479 (10.5%) and 123 (10.7%) met only the NSE criteria; these results are tabulated in Table 3.

FIGURE 9. Pearson Correlation and NSE of NFIE-Hydro Hourly Streamflow Simulations to Observed Streamflow. Parts (a) and (b) show gages that demonstrate correlation $\geq 0.5$ while (c) and (d) show gages that have PBias $\leq 25\%$ and positive NSE. The maps on the left show statistics at 5,701 USGS gages (including reference gages) and the maps on the right show statistics at the 1,145 reference gages. The gray circles in the background depict gages with weak correlation and unsatisfactory NSE. PBias, percent bias; NSE, Nash-Sutcliffe Efficiency.
<table>
<thead>
<tr>
<th></th>
<th>All Reporting Gages (n = 5,701)</th>
<th>Gages with Anthropogenic Influence (n = 4,556)</th>
<th>Reference Gages with Minimal Anthropogenic Influence (n = 1,145)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation ≥ 0.50</td>
<td>2,579 (45.2%)</td>
<td>2,054 (45.1%)</td>
<td>525 (45.9%)</td>
</tr>
<tr>
<td>PBias ≤ [25%]</td>
<td>1,462 (25.6%)</td>
<td>1,165 (25.6%)</td>
<td>297 (26.0%)</td>
</tr>
<tr>
<td>NSE ≥ 0.25</td>
<td>602 (10.6%)</td>
<td>479 (10.5%)</td>
<td>123 (10.7%)</td>
</tr>
<tr>
<td>PBias ≤ [25%] and NSE ≥ 0.25</td>
<td>341 (6.0%)</td>
<td>266 (5.8%)</td>
<td>75 (6.6%)</td>
</tr>
</tbody>
</table>

Within the Texas Gulf Coast basin, depicted in Figure 10, one can see that when reservoirs are included, model results improve. Figures 10a and 10b show PBias and NSE, respectively, when reservoirs are not accounted for in the simulation. Figure 10a shows the locations where PBias ≤ [25%] while Figure 10b shows the locations where NSE ≥ 0. It is evident in Figure 10a that most gages have a bias greater than ≥25%, indicating poor overall performance; 341 of the 367 gages fall into this category. If

![Figure 10](image-url)
one looks solely at NSE, the results appear more positive with 89 gages showing NSE ≥ 0.25. However, NSE scores can be strongly influenced by bias and so of the 89 gages, only 42 demonstrate an NSE ≥ 0.5. Figures 10c and 10d demonstrate improvement in both these metrics as the figures depict model results that account for the 72 modeled reservoirs. While Figure 10a only shows 26 gages with PBias ≤ [25%], Figure 10c shows 63. A similar improvement can be seen in Figure 10d where 140 gages demonstrate an NSE ≥ 0.25, compared to 89 in Figure 10b. Of these 140 gages, 91 have NSE scores ≥0.5.

Figures 11a and 11b show the locations where simulations meet the relaxed Moriasi et al. (2011) criteria. Of the 367 reporting gages, only 13 meet both criteria when reservoirs are not accounted for in the simulation, as seen in Figure 11a. When reservoirs are accounted for, however, 52 gages meet both; see Figure 11b. These results are summarized in Table 4 and are compared against subsets of the 367 gages used in this study: gages downstream of modeled reservoirs (n = 112) and reference gages (n = 60). All metrics show an improvement when reservoirs are accounted for in the simulation but many gages still demonstrate poor performance with PBias ≥ [25%] and NSE scores less than 0.25. One will also notice in these figures that most of the better performing gages reside in the eastern half of Texas where the climate is more humid and groundwater influence is minimal.

Finally, Table 5 depicts gages that demonstrate PBias ≤ [25%] and NSE ≥ 0.25 as a function of drainage area for all 5,701 reporting gages across the contiguous U.S.; these statistics represent NFIE-Hydro simulations when reservoirs are not accounted for. One can see that less than 11% of the gages, in each category, meet both of these metrics. Of the gages that do, one can see in Figure 12 (on the far left) the distribution of NSE for each range of drainage area through a set of box plots. It is evident in Figure 12 that a fairly consistent range of NSE exists across all sized drainage areas. Included in Figure 12 (to the right) is NSE in Texas when reservoirs are accounted for and when they are not. The plot on the far right

![Figure 11](image_url)

**FIGURE 11.** Gage Locations where PBias ≤ [25%] and NSE ≥ 0.25. Part (a) depicts results that do not account for reservoirs while (b) depicts results that do (72 reservoirs were modeled in case study).

**TABLE 4.** Relaxed Moriasi et al. (2007) Criteria for 367 Gages within Texas Gulf Coast Basin.

<table>
<thead>
<tr>
<th></th>
<th>All Gages (n = 367)</th>
<th>Gages Downstream of Modeled Reservoirs (n = 112)</th>
<th>Reference Gages (n = 60)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/out reservoir</td>
<td>w/reservoir</td>
<td>w/out reservoir</td>
</tr>
<tr>
<td>PBias ≤ [25%]</td>
<td>45 (12%)</td>
<td>82 (22%)</td>
<td>10 (8.5%)</td>
</tr>
<tr>
<td>NSE ≥ 0.25</td>
<td>89 (24%)</td>
<td>140 (38%)</td>
<td>12 (11%)</td>
</tr>
<tr>
<td>PBias ≤ [25%] and NSE ≥ 0.25</td>
<td>13 (3.5%)</td>
<td>52 (14%)</td>
<td>2 (1.8%)</td>
</tr>
</tbody>
</table>

Note: Statistics demonstrate improved model skill when reservoirs are accounted for in the simulation. Gages downstream of modeled reservoirs and reference gages are included as subsets.
TABLE 5. PBias and NSE Metrics, as a Function of Drainage Area, for the 5,701 Reporting Gages Spread across the Contiguous U.S.

<table>
<thead>
<tr>
<th>Drainage Area (km²)</th>
<th>0-100 (n = 1,921)</th>
<th>100-500 (n = 1,812)</th>
<th>500-5,000 (n = 1,607)</th>
<th>5,000 &lt; (n = 361)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBias ≤ [25%]</td>
<td>478 (25%)</td>
<td>492 (27%)</td>
<td>412 (26%)</td>
<td>80 (22%)</td>
</tr>
<tr>
<td>NSE ≥ 0</td>
<td>284 (15%)</td>
<td>339 (19%)</td>
<td>311 (19%)</td>
<td>58 (16%)</td>
</tr>
<tr>
<td>PBias ≤ [25%] and NSE ≥ 0</td>
<td>119 (6.2%)</td>
<td>165 (9.1%)</td>
<td>162 (10%)</td>
<td>30 (8.3%)</td>
</tr>
</tbody>
</table>

FIGURE 12. Box Plots as a Function of Drainage Area Depicting Gages that Demonstrate PBias ≤ [25%] and NSE ≥ 0. Box plot on the far left shows results at the continental scale (reservoirs not accounted for) and box plot on the far right shows results for the case study in Texas when reservoirs are accounted for. The box plot in the center shows results for the case study in Texas when reservoirs are not accounted for. The mean of each distribution is represented by the red X.

depicts model results when reservoirs are accounted for and demonstrates improved model skill across all sized drainage areas. One can see that the sample size in large drainage areas increases substantially when reservoirs are included and this is most likely a result of modeled reservoirs residing along rivers with higher stream orders; gages with smaller drainage areas are not as likely to be impacted by major reservoirs.

DISCUSSION

Although this preliminary analysis (based on an uncalibrated model) shows poor performance over large areas and substantial variability across space with respect to PBias, NSE, and correlation, one can also see significant skill for both small and large drainage areas in the model’s ability to reproduce dynamic elements of the hydrologic cycle. Based on other studies using the WRF-Hydro system and Noah-MP (Cai et al., 2014; Mendoza et al., 2015; Yucel et al., 2015; Silver et al., 2017), we expect model calibration, particularly soil parameter calibration, as is commonly done in hydrologic models, to improve performance in some areas. As indicated in previous sections, the WRF-Hydro model configuration implemented for NFIE only included the 1-D LSM and did not route surface and subsurface runoff over the terrain or laterally through the soil column or deeper groundwater system. Moreover, the implemented RAPID model was not spun up prior to the simulation period, did not take into account the routing of flow through lakes or reservoirs, and did not account for backwater effects or storage of flow within the floodplain. Although the implemented models contain other simplifications and assumptions (with respect to frozen soil water, flow recession, etc.), the aforementioned components are arguably the most prominent within the context of streamflow simulation especially when looking at warm-season high flows.

As one can see in Figure 9, several areas of the country demonstrate poor model performance although correlation coefficients are >0.5. This indicates the model is responding to the observed forcing and is in sync with the timing of the response, however, Figures 9c and 9d illustrate the volume estimates aren’t consistent. If one looks at PBias at the reference gages, as depicted in Figure 13, one will see negative bias in the Northwest and Rocky Mountains, and positive bias across the Southwest, Central Plains and Southeast. It is possible that the negative bias observed in the Northwest and Rockies is a
result of poor modeling of snowpack dynamics which in these areas can be a dominant driver of streamflow, especially in the late spring and early summer seasons. In particular, we suspect our 2015 model spinup suffered from early snowpack meltout in the Western U.S., resulting in negative summer streamflow biases. This error could be reduced through winter precipitation bias correction, better parameter estimation in Noah-MP, or snow data assimilation. On the other hand, the positive bias across the South (including Texas) suggests that, in these areas, surface and subsurface routing dynamics are critical to the modeling of streamflow. As described in previous sections, the implementation of NFIE-Hydro assumes that excess runoff in LSM grid cells immediately drains to the channel, which is not the case since lateral redistribution likely attenuates flow. This lack of redistribution causes the rivers to respond too quickly as is illustrated in Figures 14a and 14c. Furthermore, the influence of groundwater dynamics across the South and in North and South Dakota further supports the positive bias observations, since lateral subsurface and deep groundwater flow was not accounted for within NFIE-Hydro. Although deep groundwater systems are not prevalent in the Southeast, we suspect that the positive bias is a result of the soil column draining too quickly, especially in Florida where sandy soils are present and near surface dynamics (both surface and subsurface) dominate the hydrologic response. Finally, because NFIE-Hydro relies primarily on the precipitation provided by MRMS, a further investigation into precipitation bias is required to fully understand the behavior of the system. For example, it is possible across the Central Plains that convective storms were overestimated (or not well-captured by the 3 km resolution) throughout the summer season. As those storms moved east, however, they stabilized and resulted in more accurate precipitation and streamflow estimates.

Although part of this study was motivated by the capacity to model streamflow at the continental scale, the case study in Texas was performed to augment the analysis and study the impact of reservoirs. As can be seen in Figure 11 and Table 4, model performance improved significantly along rivers impacted by the 72 modeled reservoirs. This is also further illustrated in Figures 14b and 14d where hydrographs are plotted when reservoirs are accounted for and when they are not. Figure 14b depicts an area in East Texas where the floodplain is large. In this case, even though reservoirs are accounted for in the simulation, the lack of floodplain storage in the Muskingum routing scheme is noticeable in early June (high flow caused by the 2015 Memorial Day flood event). Although the literature provides several advancements in the area of reservoir modeling (Labadie, 2004), it is clear that managed reservoirs have complex rules and would be difficult to implement in real-time or forecast mode at the continental scale. As such, the approach used here assumes that reservoir releases are provided by the reservoir operator or a third party (in this case the NWS) and uses that information to interrupt the channel routing process within RAPID. Due to recent advancements in cyber infrastructure and Web services, it is reasonable to assume that such data will exist in the future and will be available as input to a data assimilation scheme. Finally, because NFIE-Hydro operates on the NFIE-Geo river network (based on NHDPPlus river reaches), it is possible to confine many anthropogenic processes in space (not only reservoirs); this includes locations of diversions, canals, pipelines, and more.

In 2016, the NOAA/NWS NWC in conjunction with the National Center for Atmospheric Research began evaluating an evolved implementation of the NFIE-Hydro system, the National Water Model (NWM). Similar to NFIE-Hydro, the NWM leverages the WRF-Hydro modeling architecture. In contrast, however, the NWM runs the Noah-MP LSM on a 1-km grid and couples with (1) an overland and subsurface flow routing scheme on a 250-m grid and (2) a conceptual groundwater bucket model. Furthermore, a Muskingum-Cunge-based channel routing scheme, operating on the NHDPPlus dataset, is executed within WRF-Hydro and takes into account lakes and reservoirs using a simplified level pool routing scheme. Based on the preliminary analysis from NFIE, it would be reasonable to conjecture that the
inclusion of these additional processes will substantially improve the agreement between simulated and observed streamflow in particular regions of the country. One specific example is demonstrated in Texas where the simulation produces flashy behavior that is not observed (see Figures 14a and 14c). The inclusion of a terrain routing process would certainly dampen the flashiness of the simulation.

There will, however, remain challenges with respect to implementing an operational and nationally consistent hydrologic model at the reach scale (that includes Alaska and Hawaii). One substantial challenge will be the inclusion of a fully coupled and dynamic groundwater model. Another challenge will revolve around the coupling of overland flow routing processes with reach scale channel routing processes (i.e., coupled floodplain inundation and channel dynamics) as there are complications that arise when mapping gridded lateral flow to reach features (David et al., 2009). The implementation of higher resolution models will also need to be evaluated especially within urban and peri-urban areas susceptible to flooding. Finally, the inclusion of real-time reservoir operations remains a challenge but is essential to modeling flow accurately as many of the nation’s channels are significantly impacted by managed reservoirs as demonstrated in the previous section.

CONCLUSION

In Maidment (2016), a conceptual framework for NFIE is presented as a road map for evolving the nation’s capacity to respond to impending flood events. In companion, this paper describes the components within NFIE-Hydro which produce continuous streamflow forecasts at the scale of 2.7 million NHDPlus river reaches across the contiguous U.S. This is made possible through (1) the implementation of a 3 km Noah-MP LSM, within the WRF-Hydro framework, (2) the RAPID river routing model, (3) the processing of real-time HRRR model outputs and MRMS precipitation, and (4) the leveraging of the NHDPlus and several geospatial datasets available.
through the IWRSS consortium. As such, in this study, we lay out the geospatial framework, NFIE-Geo, utilized within NFIE to connect these disparate models and establish a baseline for future modeling efforts. It is demonstrated through a retrospective analysis (i.e., a nowcast) that the implementation of NFIE-Hydro is capable of producing reasonable flow simulations in certain regions of the country even though several hydrologic processes were neglected. In areas where poor model results are observed, one can argue that the strategic model enhancements outlined in the discussion section will significantly improve agreement with observations. Finally, the impact of managed reservoirs was presented through a case study within the Texas Gulf Coast basin and demonstrates the importance of communicating operations data when simulating streamflow. As there now exists the potential to model flow at the continental scale, it will be critical to develop scalable terrain processes that enable real-time inundation mapping so that the communication of risk to infrastructure becomes standard practice.

ACKNOWLEDGMENTS

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LITERATURE CITED


Towards Real-Time Continental Scale Streamflow Simulation in Continuous and Discrete Space


