AN ALL-SEASON FLASH FLOOD FORECASTING SYSTEM FOR REAL-TIME OPERATIONS

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This article describes a real-time flash flood forecasting system for small- to medium-sized upland humid catchments where rain on snow might be a factor for flooding.

Flooding is among the worst natural disasters in the United States in terms of both economic costs and loss of human life. Flash floods are particularly severe because of the short time available to warn and to respond to such events. The U.S. National Weather Service defines flash floods to be those that are produced within 6 hours of a causative event (Michaud et al. 2001), although because "flash flood" can mean different things in different regions and in different situations, they can generally be thought of as high velocity flows that occur in a short period of time (Gruntfest and Huber 1991).

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Effective prediction has been a major goal of flash flood research during the past decade (Hapuarachchi et al. 2011). Advancements in flash flood prediction require improvements in observation networks, meteorological predictions, and hydrological models because floods have a variety of causative mechanisms and involve a "synergy" between hydrological and meteorological factors (Davis 2001). That is, the nature of the flooding is modulated not only by atmospheric conditions (which affect the intensity and duration of storm precipitation) but also by the time-dependent hydrological states (e.g., soil moisture and snowpack) within a watershed. Forecasting flash flooding is further complicated because the forecast should provide information not only about the occurrence but also about the timing and magnitude of the flood flow (Doswell et al. 1996; Davis 2001).

Recent advancements in meteorological forecasts have been particularly important in flash flood situations. For example, estimates of total fallen precipitation [i.e., quantitative precipitation estimates (QPEs)] have improved because of the combination of spatially distributed radar data, with accurate point measurements from rain gauge data (e.g., Krajewski 1987; Smith and Krajewski 1991; Seo et al. 1999; Todini 2001). In addition, estimates of immediate future precipitation [i.e., quantitative precipitation forecasts (QPFs)] have improved (especially at short lead times) because of increased ability to combine numerical weather prediction (NWP) model output with patterns derived from observed radar, satellite, and gauged rainfall trends (e.g., Smith and Austin 2000). In addition, there has been increasing communication of uncertainty (e.g., Collier 2007), which is sometimes accomplished through the use of ensemble predictions.

Improvement in hydrological models' ability to utilize these new hydrometerological products is needed in order to better predict flash floods. Currently, process-based models, which have representations of the relevant physical processes, are commonly used at many operational forecast centers, because the models can be applied in a variety of environments and they do not require an extensive historical dataset to calibrate them. For example, the majority of National Weather Service (NWS) Regional Forecast Centers (RFCs) use the Sacramento Soil Moisture Accounting Model (SAC-SMA) for its flash flood guidance (FFG) system. However, such models are often lumped to increase computational efficiency and lower data requirements. These models can be improved by using distributed modeling because such models can account for the localized nature of many flash flood producing storms. Increased computing power and the increasing availability of high-resolution distributed datasets make such models attractive for flash flood forecasting (Hapuarachchi et al. 2011).

Modeling of snow distributions is an important component that is often overlooked in flash flood modeling. Although snowmelt by itself often occurs too slowly to be considered capable of producing flash flooding, snow and snowmelt can contribute to flash flooding when rain falls on top of snow, especially if the combined rainfall and snowmelt rates are high. Snowmelt can also cause antecedent conditions that make an area prone to flash flooding, as soil moisture reservoirs are filled to capacity during and after the melting of a significant snowpack (Hirschboeck et al. 2000). When rain falls on snow, a snowpack can rapidly lose its cold content because of latent heat release as rain freezes on the snowpack. In addition, turbulent transfer to the snow surface, especially in windy conditions, can cause condensation and additional snowmelt (Marks et al. 2001). During these events, rainfall intensities, freezing levels, and snowpack conditions all influence the magnitude of the resulting streamflow (McCabe et al. 2007). Furthermore, rainfall can enhance snowmelt by penetrating and mobilizing the snowpack, resulting not only in significant flooding but also in significant transport of sediment and even debris flows. Rain-on-snow events can be especially severe if ground is already saturated (e.g., due to recent snowmelt), especially since the atmosphere is often too cool for there to be significant evaporation.

This paper describes a coupled modeling system that considers the localized nature of many flash flood–producing storms, and the importance of snowmelt, and allows high temporal and spatial resolutions required for accurate flash flood prediction. The coupled model (called KINEROS/hsB-SM) combines the Kinematic Erosion and Runoff (KINEROS) overland flow/channel routing model and the hillslope-storage Boussinesq Soil Moisture (hsB-SM) modular modeling framework. KINEROS is an event-oriented, physically based overland flow simulation model (Woolhiser et al. 1990; Goodrich et al. 2012) that was developed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center (SWRC) to model floods, primarily resulting from overland flow in semi-arid and arid regions. The hsB-SM was developed at the University of Arizona and includes physical descriptions of processes related to baseflow generation (Carrillo et al. 2011), which is more applicable in humid areas. In this application, hsB-SM also includes an energy balance snow model. The resulting combination is an operational modeling system that has the following features:

- fully distributed (KINEROS divides watersheds up into a series of channel elements and overland flow planes, and hsB-SM runs on a 0.0125° × 0.0125° grid);
- continuous (i.e., keeps track of catchment wetness and snow water equivalent);
- applicable in a variety of environments as it accounts for snow, multiple flow generation mechanisms (infiltration excess or saturation excess), evapotranspiration, canopy interception, subsurface flow, overland flow, and channel routing (see Fig. 1);
- flexible spatial and temporal resolution;
- includes a framework to easily calibrate the models using historical streamflow data and historical meteorological data as model input; and
- real-time operation, using hourly precipitation estimates of rain that has already fallen and NWS forecasts to predict streamflow up to 24 hours into the future.

We have implemented and tested KINEROS/hsB-SM for five catchments in the Catskill Mountains in southeastern New York State (Fig. 2). There are two watersheds along the main stem of the west branch

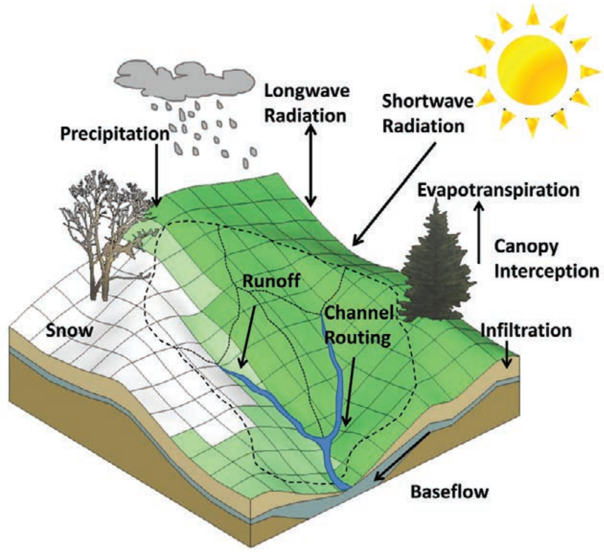

Fig. 1. Model schematic for the KINEROS/hsB-SM system that shows important modeled physical processes. Both KINEROS and hsB-SM are distributed and take into account a variety of surface and subsurface processes that are important for flash flooding.

Delaware River (defined by outlets at the towns of Walton and Delhi, New York), and three smaller, steeper watersheds (East Brook, Town Brook, and Platte Kill). These catchments range in size from 36 to 870 km^2 and have different degrees of "flashiness." The region is sparsely populated and there are no major dams or reservoirs, though there is a significant amount of farming and pasture land. The area is cool and humid, with annual precipitation totaling in excess of 1300 mm. Of this, roughly 800 mm becomes runoff, giving annual runoff coefficients of ~0.65. In general, the area receives adequate precipitation throughout the year, though streamflows are generally higher in the spring and snowmelt is a significant factor in many of the watersheds. Low flows occur during the summer because evapotranspiration is high and soils are drier. Floods most commonly occur during the winter and spring because of a combination of rain and snowmelt over wet soils, but intense summer thunderstorms and tropical storms can also cause floods and flash floods during the summer and fall. The model is currently being used at the National Weather Service Binghamton, New York, Weather Forecast Office in an experimental fashion.

MODEL DESCRIPTION. This section contains a general overview of KINEROS/hsB-SM; however, for a more detailed explanation, we refer you to the model documentation, which can be found in the electronic supplements for this article. KINEROS/hsB-SM involves a loose coupling between the KINEROS and hsB-SM models, meaning that, at this point, the components of each model run semi-autonomously from the other. The hsB-SM model's primary purpose is to keep track of distributed snow and soil moisture conditions between events. This implementation of hsB-SM is also fully distributed with a spatial resolution of 0.0125° × 0.0125° (about 1 km) and has a high temporal resolution (1 h between events and 5 min during events). This gives it appropriate capabilities to resolve impacts from precipitation events that are limited in spatial extent. This capability is especially important during the summer, when storms are more localized, and allows the model to take advantage of fine-resolution distributed rainfall datasets.

Perhaps the most novel feature of this flash flood modeling system is the inclusion of a distributed energy balance snow model [which is broadly similar to the Utah Energy Balance Snow Model developed by Tarboton and Luce 1996)]. The snow model, which was developed to make snow predictions with high spatial and temporal resolutions, has been included to better predict floods that result from a combination of rainfall and snowmelt. It includes representations

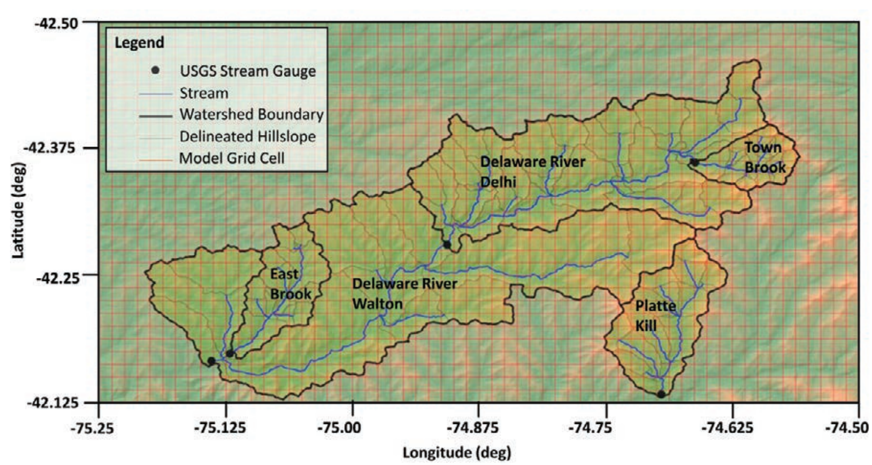

Fig. 2. Site map showing the modeled upper Delaware basin watersheds. Shown are the locations of streams and stream gauges, watershed boundaries, delineated hillslopes used for KINEROS, and ~1-km grid boxes on which the snow and subsurface models run.

of turbulent (latent and sensible) fluxes at the snow surface, heat that is advected by precipitation, canopy interception, and vegetation effects on incoming radiation using Beer's law, and it takes into account local topographic effects on solar forcing (Whiteman and Allwine 1986).

The hsB-SM model also includes modules that describe canopy interception of rainfall (Deardorff 1978), infiltration [which is computed as a modified time-compression approximation of Philip's equation (Philip 1957), a solution to the Richards equation under a simplified set of initial and boundary conditions, as in Milly (1986), Famiglietti et al. (1992), and Troch et al. (1994)], estimates of evapotranspiration (Teuling and Troch 2005), and vertical water transport in the upper soil layer, and it has a shallow and a deep aquifer. Baseflow from the deeper aquifer is modeled as a simple nonlinear reservoir model, but baseflow from the shallow, unconfined aquifer, where the water table interacts directly with the unsaturated zone, is modeled based on the hillslope-storage Boussinesq equation (Troch et al. 2003).

In KINEROS/hsB-SM, to preserve the regionalization impacts of localized rainfall events, as well as to better diagnose areas of partial saturation, the hsB model is applied for kilometer grid boxes and the rates of outflow are used to predict water transport between adjacent grid cells. This distributed modeling drastically increases the computational demand of the model, which must remain relatively fast for operational purposes (as well as for calibration, which requires repeated multiyear simulations). Therefore, we have chosen to emulate the model as nonlinear reservoirs $q = aX^b$ and aquifer height models of the form $h(x) = kXh_0(x)$, where q is discharge, X is grid cell aquifer storage, and h_0 is a characteristic distribution of aquifer heights, (a, b, and k are fitting parameters such that the simpler models are able to reproduce the behavior of the hsB model). The parameters of each of these reservoirs are informed by the behavior of hsB for a particular watershed. Figure 3 illustrates how this model emulation characterizes hsB's behavior in terms of both streamflow and aquifer heights. This emulation step results in dramatic speed increases for the subsurface portion of the model and allows the simulation of regionally varying impacts on the groundwater system due to the location of precipitation.

In KINEROS/hsB-SM, runoff generation can occur either as infiltration excess overland flow (when the rainfall rate overcomes the infiltration capacity of soils), leading to Horton overland flow, or from saturation excess, which usually occurs next to streams and can arise when the water table rises to the surface because of rapid infiltration in place and/or rapid movement of

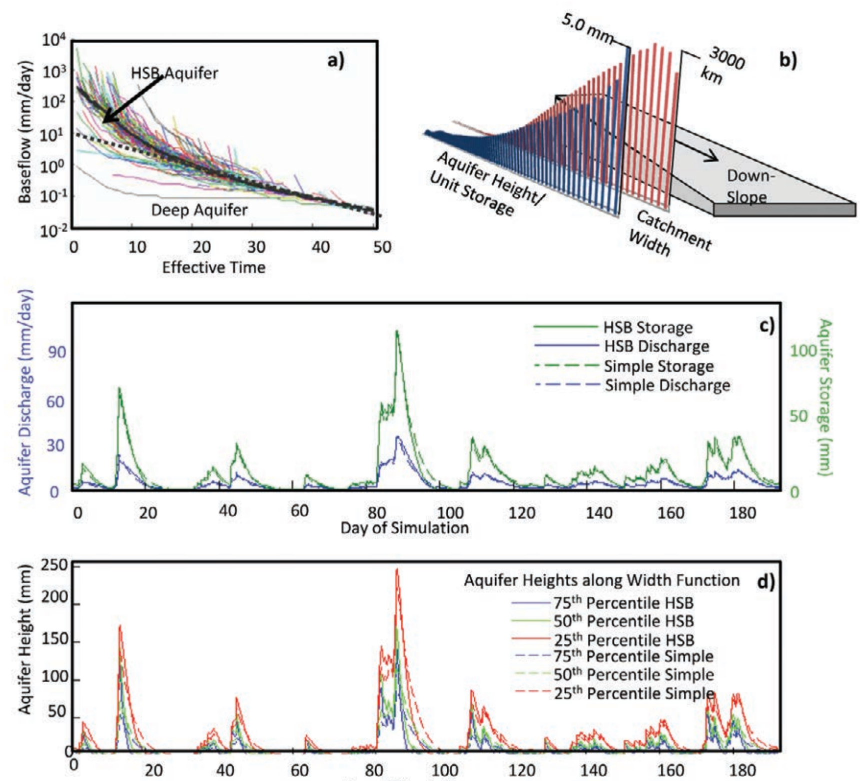

Fig. 3. Charts illustrating the aquifer calibration of hsB-SM: (a) master as well as individual baseflow recession curves for the Delaware River (Walton) using a long (~60 years) streamflow time series (in the model, the upper portion of the baseflow recession corresponds to the discharge time scale of the hsB aquifer, and the lower portion of the recession corresponds to the deep aquifer time scale); (b) model schematic illustrating the catchment width function used in the hsB model, as well as a typical distribution of aquifer heights predicted by the model; (c) storages and discharges predicted by the hsB model, as well as the simpler storage–discharge model used to emulate it; and (d) as in (c), but in terms of the distribution of aquifer heights predicted by the two models.

water downhill from upslope areas. Of the two flow generation mechanisms, saturation excess overland flow is less fully understood, as it is not definitively known how old water in the soil profile gets displaced by new water (e.g., Pearce et al. 1986; Sklash et al. 1986; McDonnell 1990) or the relative importance of this displacement mechanism in relation to the rapid movement of subsurface storm flow through macropores (large soil pores in which water is not held by capillary forces). Infiltration excess overland flow results from high intensity rainfall events, and is very important for flash flooding in the western United States, while saturation excess overland flow is, to a greater degree, influenced by overall precipitation amounts and antecedent hydrological conditions and is important in wetter catchments. It is important to represent both of these processes in an area like New York's Delaware basin, which has flooding resulting from lower intensity storms during the winter, often in combination with snowmelt, as well as intense convective storms during the summer.

Finally, runoff is routed to the channel outlet. KINEROS (Woolhiser et al. 1990; Goodrich et al. 2012) is used as the runoff model. In KINEROS, overland flow and channel routing are simulated using a kinematic wave approach over a network of hillslope (plane or curvilinear) and channel model elements, and it is used to simulate overland flow and channel routing of runoff from hsB-SM (for more detailed information, see www.tucson.ars.ag.gov/kineros). The overland flow and channel model elements are derived from the morphology of the landscape using the Automated Geospatial Watershed Assessment Tool (AGWA; Semmens et al. 2008; www.tucson.ars.ag.gov/agwa) and therefore do not follow the 1-km grid of the other model components. To map between the 1-km grid and the KINEROS hillslopes, a weighting scheme is developed that indicates the relative contributions of each grid cell to each KINEROS model element. Because of computational constraints, we also use a simple routing model that is that is based on catchment geometry and the Saint Venant equations for shallow-water transport (Mesa and Mifflin 1986; Troch et al. 1994) during continuous past simulations (those involving many years of simulation at one time) used to calibrate parameters related to infiltration and evapotranspiration.

IMPLEMENTATION AND CALIBRATION.

KINEROS/HsB-SM is designed to be easy to learn to use and to implement. Model components are coded in Fortran (KINEROS) and the Mathworks Matlab (HsB-SM), while most of the interface is written in Matlab, making it relatively simple to modify model components and to visualize model results. Although Matlab is proprietary software, the model can be compiled with the built-in Matlab Compiler and distributed with runtime libraries for free (though end users will not be able to modify the code directly without Matlab). KINEROS/hsB-SM also relies on widely available national spatial and hydrometeorological forcing datasets, giving it the capacity for broad implementation. Spatial data include digital elevation data, vegetation data, and soils data, which can be obtained from the U.S. Geological Survey (USGS) and the National Resource Conservation Service (NRCS). In addition, the model uses the capabilities of the USDA's AGWA, which allows for watershed and hillslope delineation, as well as intersection with spatial datasets (Semmens et al. 2004; Miller et al. 2007).

Forcing data comes from a variety of sources. For past simulation, the North American Land Data Assimilation System (NLDAS) forcing product is used to provide estimates of humidity, wind, and incoming shortwave and longwave radiation, and it is combined with the PRISM climate dataset to provide elevation-dependent estimates of air temperature and pressure. NLDAS is a 1/8° product that is developed using North American Regional Reanalysis (NARR) output but is further enhanced by using bias corrected radiation estimates. NLDAS precipitation data are replaced with higher-resolution NWS radar rainfall estimates using the NWS Multisensor Precipitation Estimator (MPE) product. MPE, which is generated on a 4 km × 4 km grid, combines gauge precipitation measurements with radar-estimated spatial rainfall fields. During the flood events, however, the model uses high-resolution (1 km × 1°) radar data from the Binghamton Next Generation Weather Radar (NEXRAD) radar site with the NWS's standard Z–R relationship ($300 \times R^{1.4}$) to provide radar estimates of rainfall at a 5-min temporal resolution. Radar rainfall estimates are then subject to a bias field, such that the precipitation amounts in each MPE grid box match the MPE (which already incorporates information from rain gauges) amounts. This provides a result that the precipitation fields are nearly identical in terms of their averages with the spatial pattern derived from the high-resolution radar data. In addition to the forcing data that are used to drive the model, snow water equivalent (SWE) estimates from the Snow Data Assimilation System (SNODAS) are used to verify snow model results. For real-time simulation, the same data are used with the exception of NLDAS product, which is not available for real-time operation. Instead, forecast values of the necessary quantities are obtained from the National Digital Forecast Database (NDFD).

KINEROS/hsB-SM also requires model calibration. The calibration process for KINEROS/hsB-SM seeks to provide a calibration that is physically consistent with the hydrological processes that are simulated in the model. During the calibration process, parameters that are associated with individual processes are calibrated separately and iteratively, similar to the process described in Carrillo et al. (2011). KINEROS/hsB-SM also includes subroutines to easily automate any portion of this calibration process. It is also easy to perform some calibration steps manually, which may lead to greater insight into how model parameters relate to a certain process, while at the same time automating others, so that the model is still manageable to set up and to calibrate.

The first calibration step involves the determination of the perched aquifer properties such that modeled aquifer discharge matches observed winter baseflow recessions. That is, the modeled aquifer discharge is determined from periods when the catchment is relaxing from prior rainfall/snowmelt inputs. To find the baseflow recessions, we first apply a low-pass filter to the streamflow hydrograph to separate baseflow from quicker stormflow (Lyne and Hollick 1979). Once we separate out the baseflow time series, we connect each individual baseflow recession to the master recession curve according to the low streamflows in the tails of the recessions. We only consider winter baseflow recessions to minimize effects from growing vegetation and evapotranspiration losses, so that the baseflow recessions are mainly controlled by aquifer properties. Once the master recession curve is built, we infer that different portions of the baseflow recession curve are representative of contributions from different aquifers. The upper portion of the baseflow recession curve is steeper, and represents a quicker release of water than the lower portion. We consider the upper portion to be indicative of the

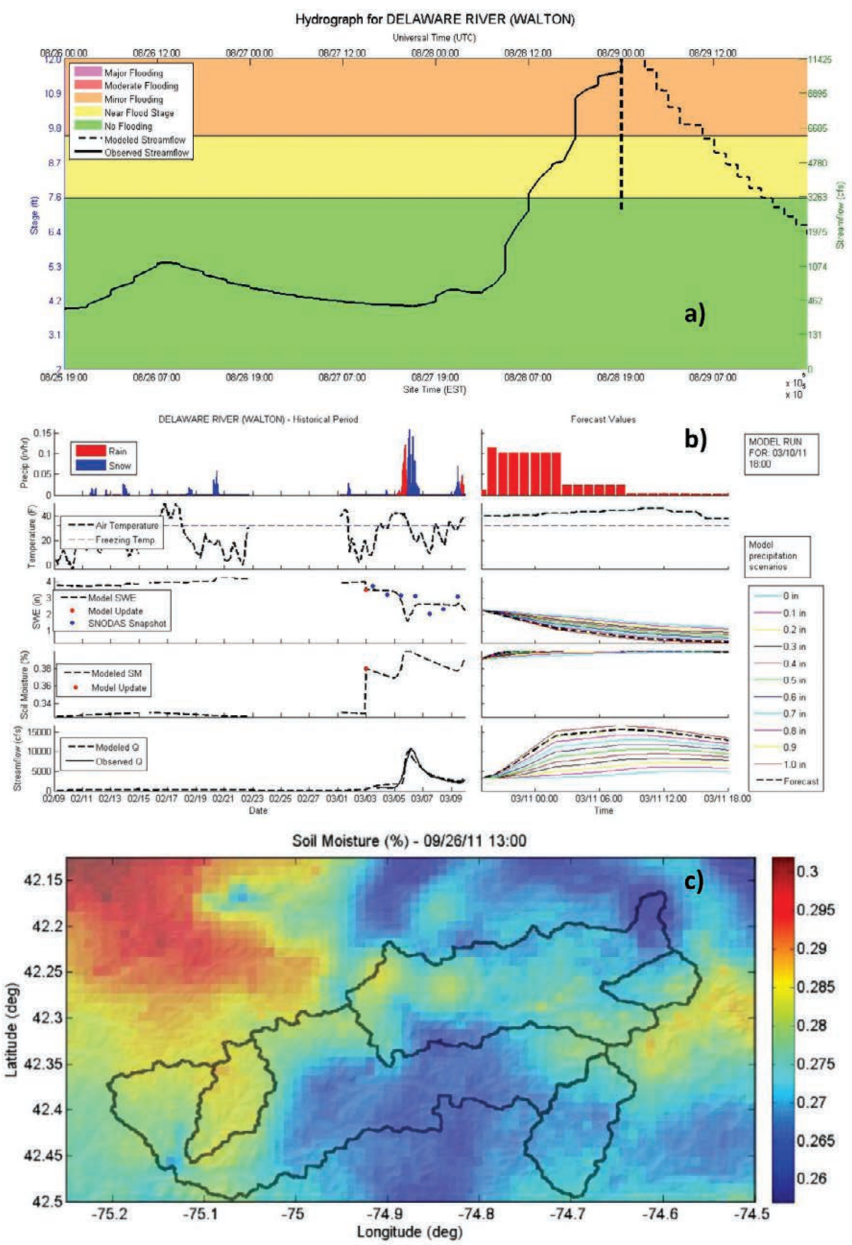

Fig. 4. Screenshots of real-time model output from KINEROS/hsB-SM: (a) time series of recent and predicted discharge values; (b) historical and predicted model values (including precipitation, temperature, snow water equivalent, soil moisture, and streamflow); and, (c) example spatial output from the model. Note that that all units on the model output are English units to match the conventions of other operational products in the United States.

release from the shallow hsB aquifer, while the lower portion is indicative of the deeper bedrock aquifer and the corresponding model is parameterized appropriately to match the baseflow recession characteristics.

The remaining portions of the model are calibrated using multiple year simulations. Parameters are only varied a few at a time (e.g., parameters that relate to a specific process are calibrated separately), but in most cases the model is optimized to be able to reproduce multiple years of observed streamflow using a standard optimization routine (Nelder and Mead 1965). The only exception is the calibration of parameters that are associated with snow. In this case the model is optimized to match multiyear observations of snow (or systems such as the Snow Data Assimilation System, which involve a model but also assimilate snow observations). The snow parameters are, by and large, meant to be applicable everywhere. After the calibration of the snow model, parameters describing evapotranspiration, infiltration, and overland flow/channel routing are calibrated iteratively to get the best possible representation of streamflow. In addition, KINEROS is also tested and, if necessary, calibrated during simulation of individual flood events or the long time series simulation. The second electronic supplement gives results of this continuous calibration, as well as case studies illustrating the performance of KINEROS/hsB-SM during flood events.

REAL-TIME OPERATION. Once calibrated, KINEROS/hsB-SM is designed to be run in real time with NWS forcing data. It is forced with radar-derived rainfall products (MPE or ~1-km radar products), and pulls forecasts for all other required hydrometeorological variables from the NDFD. Like past simulations, real-time model runs are continuous and update automatically every hour. In addition, the model can be run more frequently during events, as the model time step is set to be 5 min during real-time operation. There is also some assimilation of observations during real-time operation of KINEROS/hsB-SM. For example, daily snow estimates from SNODAS (which is a snow modeling system that is corrected with observed data) are downloaded and displayed for comparison with KINEROS/hsB-SM's snow model and can be used to update the model snow water equivalent as the model runs. Also, USGS streamflow observations are downloaded continuously and used to make sure that modeled streamflows match observations for the historical period. In addition to using the forecasted values of precipitation, the model can also be run with different precipitation scenarios, so that multiple streamflow scenarios can be viewed simultaneously.

There are three main methods to display the model results. First, the model outputs a graph similar to what is found on the NWS's Advanced Hydrologic Prediction Service web page, where recent streamflows (for the past 48 hour) are shown alongside streamflow forecasts with information about flood stage for the next 24 hours (Fig. 4a). The user can also view time series charts for more modeled and observed quantities (precipitation, temperature, SWE, soil moisture, and streamflow) for the past 30 days (Fig. 4b), as well as spatial maps showing where in each catchment there are potentially areas of high soil moisture or a lot of snow (Fig. 4c), which might exacerbate flooding problems. All of this is intended to give forecasters a fairly complete picture about potential flash flood threats.

CONCLUSIONS. While KINEROS/hsB-SM takes into account many aspects of flash flood prediction in small to medium sized nonurban watersheds, it is just a step toward flash flood forecasting, and there is much room for improvement. For example, flash flood producing storms are often associated with other natural hazards such as landslides, which also present potentially serious hazards to life and property. Using such a model in conjunction with a landslide model (e.g., Ren et al. 2010) would make sense in some cases. We are also optimistic about the use of such flash flood models in the future given fewer computational constraints and greater data availability, especially of high-resolution precipitation data that can be used consistently throughout the modeling periods (e.g., the National Weather Service's Q2 precipitation product). For this study, while we have sought to be as consistent as possible with our forcing data, the differences between the forecast period and the observed period, in terms of the temporal and spatial resolutions of the available forcing products, currently presents some challenges (see subsection "Evaluation of the temporal characteristics of precipitation during a spring flood and a fall flood" in online supplement). Nevertheless, we believe that KINEROS/hsB-SM offers improvements over existing flash flood forecasting systems, including the use of a snow model to help improve flash flood predictions for rain-on-snow events. It also has many other essential features of successful flash flood prediction, including the use of quantitative precipitation estimates and forecasts; a continuous distributed hydrological model that operates at the same spatial scale as convective storms, which can be a major cause of flash flooding; a programmatically assisted method of calibration/validation; and real-time operation. The model is also designed to provide a balance between model parsimony, which allows for the successful and flexible model implementation, and enough complexity to be able to represent a range of important processes for flooding. These aspects are among the many potential improvements over traditional methods used for operational flash flood forecasting.

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