REAL-TIME FLASH FLOOD FORECASTING USING WEATHER RADAR AND A DISTRIBUTED RAINFALL-RUNOFF MODEL

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Abstract: Flash floods pose a significant danger to life and property in many areas of the world. In the United States, flash floods kill more people than any other form of severe weather, and are responsible for economic losses averaging one billion dollars per year. One way to mitigate flood risk is to provide a tool that allows forecasters to better predict the timing and magnitude of peak flows in high-risk areas. The Kinematic Runoff and Erosion Model (KINEROS2) is a spatially distributed watershed model that can assimilate real-time, high resolution Doppler weather radar data. Initial estimates of watershed parameters can be derived from readily available geospatial datasets using the Automated Geospatial Watershed Assessment (AGWA) GIS tool. KINEROS2 provides a temporal and spatial resolution not currently available with other National Weather Service (NWS) flash flood forecasting models. The computational time steps in KINEROS2 follow the nominal 4 to 5 minute interval of the Digital Hybrid Reflectivity (DHR) radar product which has an average 1-degree by 1-km spatial resolution. KINEROS2 can also simulate a number of scenarios simultaneously, such as different reflectivity/rainfall relationships, to help quantify the uncertainty in the resulting forecast. KINEROS2 has undergone calibration and limited operational testing in two widely disparate climatic/landscape regimes in the United States. It was first applied in a 91 km^2 semiarid watershed in southern Arizona, which experienced a flood event in excess of the 100-yr recurrence interval during the test period. The second set of test basins are located in the Catskill Mountains of central New York State within the Delaware River Basin. They are six fast responding headwater watersheds ranging in area from 12 to 624 km^2. Based on the models' response to calibration and its operational performance, a number of improvements have been identified. These include the addition of subsurface/inter-storm model components, to improve its capability in humid regions and to provide automated estimation of pre-storm initial conditions, and a snow-energy balance component for watersheds where rain on snow and snowmelt events are important. Also to be added are the ability to assimilate local rainfall forecasts, to utilize rain gage data for removing radar bias, and to query NWS databases for data to drive the inter-storm and snow components of the model.

INTRODUCTION

Flash floods are defined as those that occur within six hours of the causative rainfall event (National Weather Service, 2002). Flash floods can be caused by extremely high rainfall intensities alone or by a combination of high intensity rainfall and steep terrain, or by rain on snow or frozen ground. Flash floods are generally associated with smaller watersheds due to the limited areal extent of convective storms (thunderstorms), which typically produce the highest rainfall rates.

The National Weather Service (NWS) supports two methods of evaluating the potential for flash flooding in fast-responding watersheds. The Flash Flood Monitoring and Prediction (FFMP) tool uses rainfall estimates from radar to compute cumulative, area-averaged rainfall over small basins for time spans ranging from 15 minutes to 24 hours. These amounts are then compared to either flash flood guidance values issued by the NWS River Forecast Centers (RFCs) or to guidelines established from local experience. The FFMP tool allows a forecaster to identify areas where flash flooding is likely, but does not provide information on the timing or potential magnitude of the flood event.

The second option available to a local Weather Forecast Office (WFO) is to use a "site-specific" rainfall-runoff model. Two models are supported by the NWS: the empirically-based Kansas City Antecedent Precipitation Index (API) Model, and the physically-based Sacramento Soil Moisture Accounting Model (SAC-SMA). Both are lumped models which run on hourly time steps and use hourly rainfall estimates from the Multi-Sensor Precipitation Estimator product (MPE). They also allow input of Quantitative Precipitation Forecast (QPF) estimates in hourly increments. Which model is used depends on the degree of support provided by the RFC and the preference of the WFO.

KINEROS2 is an event-oriented, distributed, physically-based model developed to simulate the runoff response in basins having predominantly overland flow (Woolhiser et al., 1990; Smith et al., 1995; Goodrich et al., 2002; Semmens et al., 2008; http://www.tucson.ars.ag.gov/kineros). KINEROS2 simulates both infiltration-excess and saturation-excess runoff-generating mechanisms, with flow routed downstream using a finite difference solution to the one-dimensional kinematic wave equations. A watershed is conceptualized as a collection of planes (hillslopes) and trapezoidal channels (Figure 1).

The Automated Geospatial Watershed Assessment (AGWA) tool, an ArcView/ArcGIS extension, was developed to facilitate the process of building input parameter files for KINEROS2 (Goodrich et al., 2006; Miller et al., 2007; http://www.tucson.ars.ag.gov/agwa). Using widely available spatial datasets, AGWA delineates the watershed boundary, discretizes the watershed into areas of overland flow (rectangular plane elements) and channel elements (Figure 2), then intersects the watershed elements with soil and land cover data layers to derive the requisite model parameters.

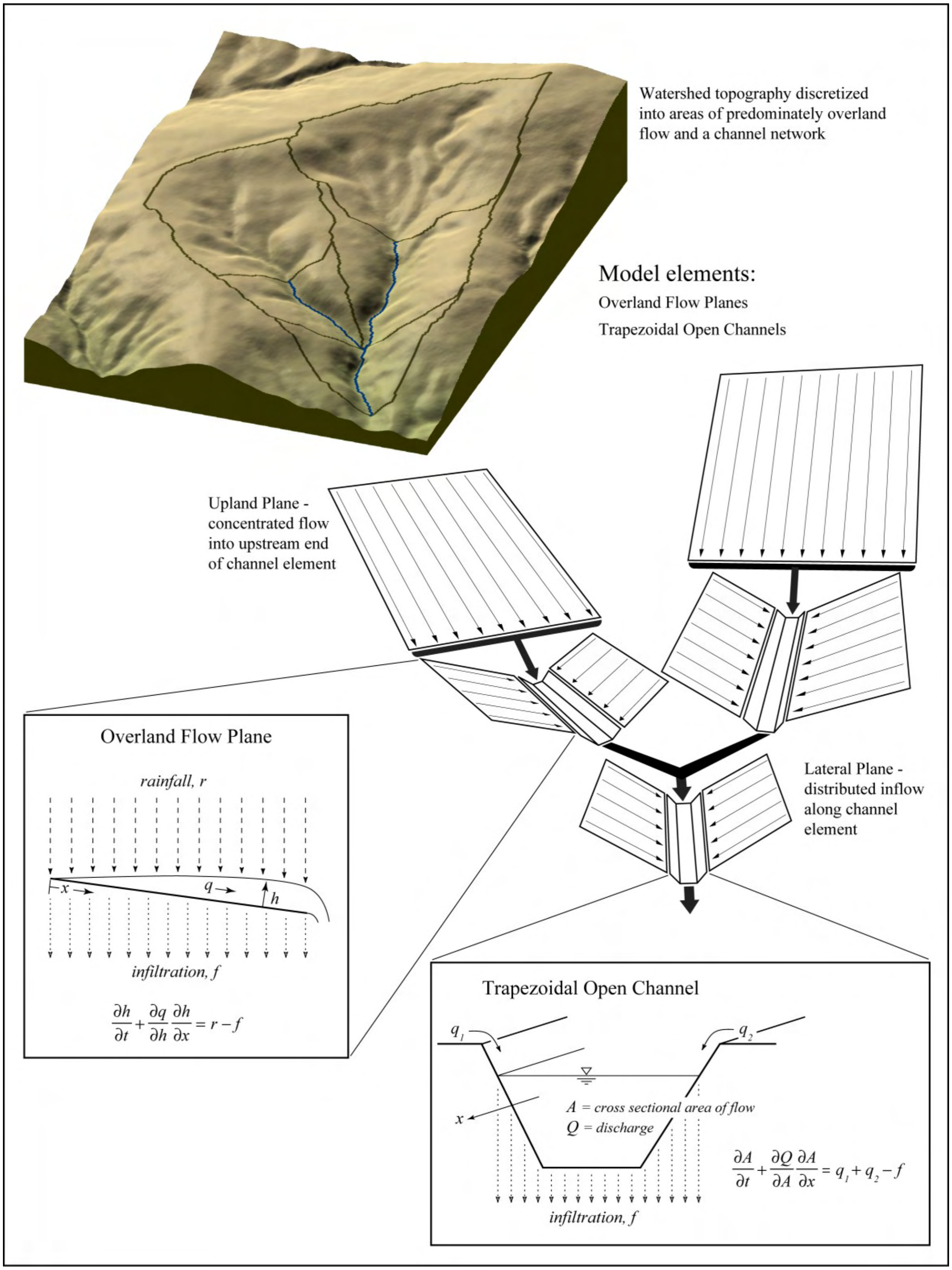

Figure 1. The KINEROS2 rainfall-runoff model.

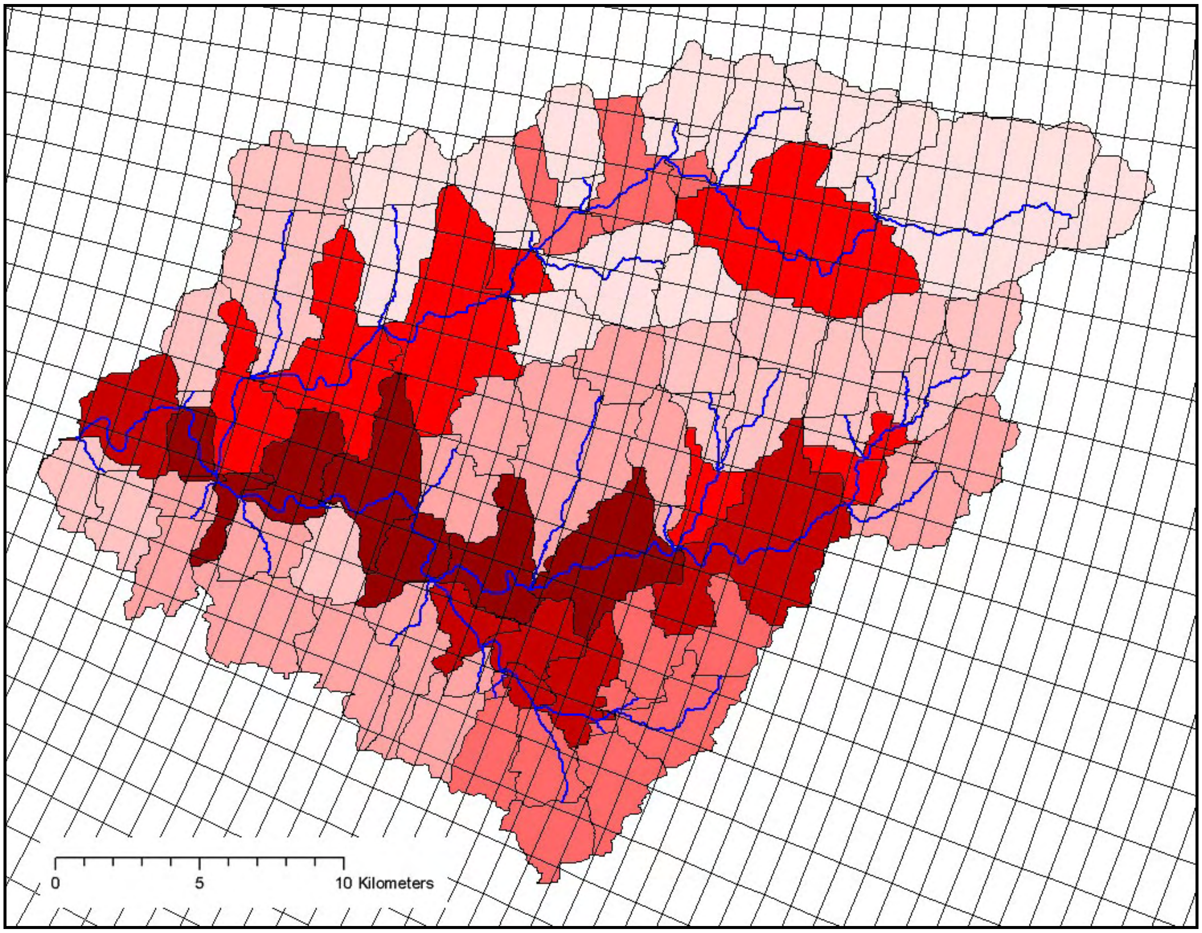

Figure 2. Example of AGWA watershed discretization and radar grid.

ADAPTING KINEROS2 TO REAL-TIME FLASH FLOOD FORECASTING

The obvious prerequisite for running a rainfall-runoff model in real time is access to real-time rainfall data. The Digital Hybrid Reflectivity Scan (DHR) product from the NWS WSR-88D (Weather Surveillance Radar 88 Doppler) radar was selected since it provides the highest temporal and spatial resolution and lowest beam angle (for a given grid cell) of any WSR-88D precipitation product. The low beam angle minimizes measurement of rainfall that subsequently evaporates or accretes before reaching the surface. The DHR product provides reflectivity and radar-derived estimated rainfall values approximately every 4 minutes on a polarimetric grid of 1° by 1 km, and because of the high spatial resolution, has historically been the default precipitation input for the FFMP program. Rainfall rate R is estimated from reflectivity Z by inverting the relationship (NOAA, 2005):

$$Z = AR^b$$

where the coefficients A and b have been standardized based on storm type.

The estimation of rainfall by radar can be compromised by a number of factors. Reflectivity may be biased by incorrect hardware calibration, ground clutter, anomalous propagation, range-dependent effects, and wet radome attenuation. An empirical Z-R relationship that is based on average conditions will likely not be optimal for a given storm, or even for different clusters within a mesoscale system. Processes that occur below the radar beam, such as the evaporation, growth, or horizontal motion of descending precipitation, are not detected. Collectively, these factors can result in large and variable errors in rainfall estimates. Errors of up to 200% are not uncommon, and can be as high as 500% (NOAA, 2005).

Since rainfall is modeled as spatially uniform within a rectangular overland flow plane, rainfall must be mapped from the radar grid cells to a single representative value for each overland flow area. To provide this mapping, an ArcView GIS extension intersects the radar grid with the polygons created by AGWA (Figure 2). A file is written giving the fractional area weight of each radar grid intersecting a given polygon, so that a single area-weighted mean value of rainfall for each plane element can be computed.

In order to create a practical and useful tool for an operational environment, the KINEROS2 Fortran code was restructured and compiled into a dynamic link library, and a graphical user interface (GUI) was built using Delphi®. The revised Fortran code is modular, with each module implementing a single hydrologic process model at an appropriate scale, such as overland flow on a plane element, infiltration between a pair of finite difference nodes, etc. A second tier of modules provides an interface designed to simplify use of the library by non-Fortran applications. The original code required that all time steps be computed for an upstream element before moving on to the downstream element. This requirement was unsuitable for real time operation, thus the new code can accommodate both time/space and space/time loop nesting.

A key enhancement was added to extend the model's predictive capability, where, after simulating the latest real-time interval, the simulation continues into the future using forecast rainfall conditions. In order to efficiently implement this feature, the new modules are able to save their internal states at a point in time and return to that state at a later time. After the forecast interval, the modules can ‘rewind’ back to the end of the last interval of radar data, and the program does not have to start over from the very beginning of the simulation in order to arrive at that point. Figure 3 shows the flow of data processing and modeling within the real time flash flood forecasting system. Radar data undergoes several processing steps as it is moved to a networked storage device in the WFO. The KINEROS2/NWS program, running on a personal computer in the WFO, watches for the arrival of a new DHR file. When a new file arrives, the program computes a rainfall rate for each of the overland flow planes, and the new rainfall input is routed through the model system. The program saves its internal state and continues into the future for a given period of time, using the forecast rainfall condition. Then all model elements are reset back to their saved state, and the program waits again for the arrival of a new DHR file.

The GUI was developed specifically for use at the WFO, and displays graphs of both radar-derived rainfall and predicted runoff. The rainfall graph shows both accumulation and intensity, while the runoff graph shows stage and equivalent discharge rate hydrographs (Figure 4). An audible alarm capability is included to alert the forecaster when the maximum predicted stage level exceeds the critical stage or stages selected by the forecaster. The taskbar button will also flash to identify which watershed is in alarm mode when multiple watersheds are running on the same PC. A snapshot of the GUI at a given instant can be printed directly or saved as a JPEG image, or JPEG images can be automatically saved at regular intervals (e.g. for real-time internet publishing).

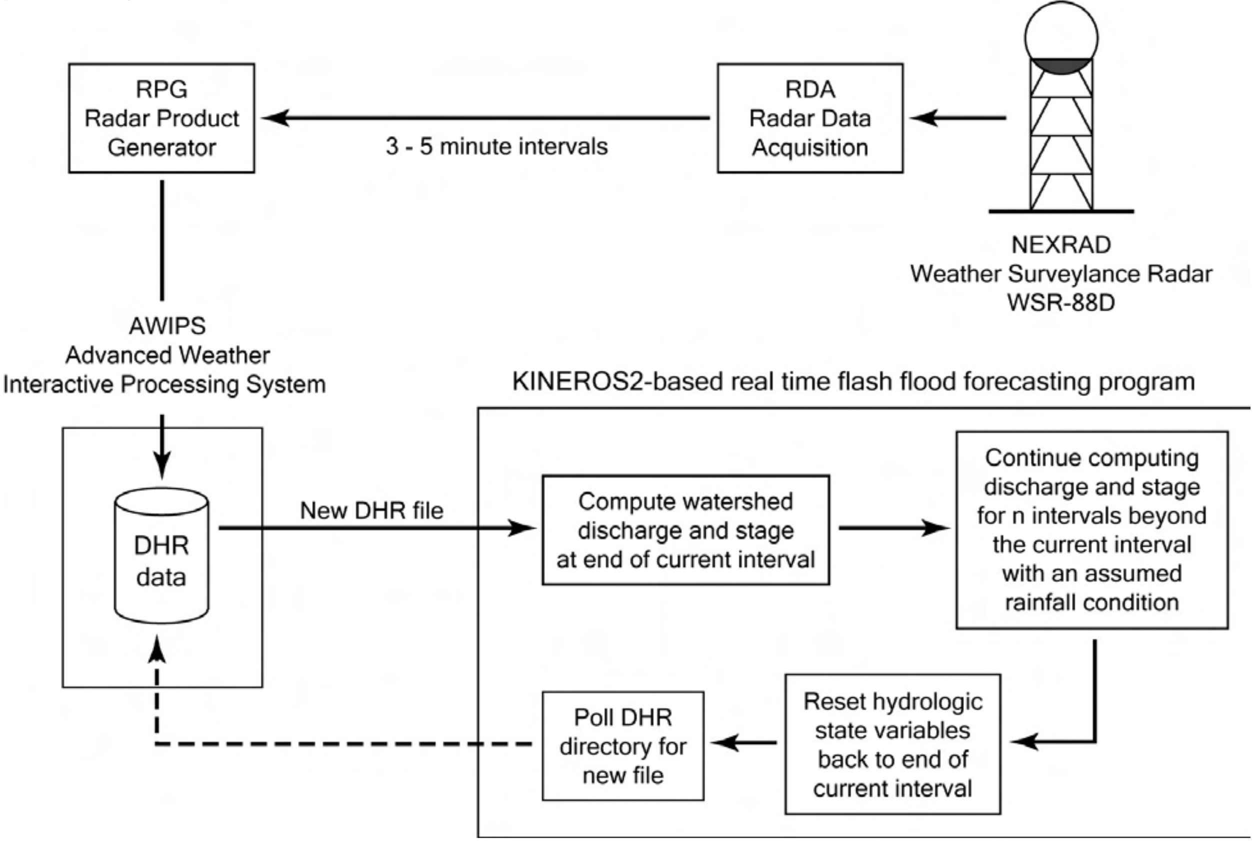

Figure 3. Real time flash flood forecasting system.

Before the program is started, there are a number of options and initializations which must be addressed. As KINEROS2 is an event-based model and does not simulate continuously, the overall soil moisture condition and base flow rate at the watershed outlet must be initialized. The base flow rate is assumed to decrease linearly as one moves upstream through the channel network, becoming zero at the top of each headwater channel. There is a choice of seven standard Z-R relationships, plus a custom option. If there is uncertainty in the choice of Z-R relationship, more than one can be run concurrently by the program, providing an ensemble of simulated hydrographs. Likewise, up to three rainfall forecasts can be specified, i.e. up to three concurrent simulations for each Z-R relationship. The rainfall forecasts can be updated (changed, added or deleted) while the program is running. The development of a program capable of parallel simulations was motivated by the premise that rainfall input into KINEROS2 is likely the single largest source of uncertainty (Yatheendradas et al. 2008). The program can operate in a non-forecast mode, using DHR files archived locally from AWIPS or files archived at the NOAA National Climatic Data Center in RPG Class 1 format.

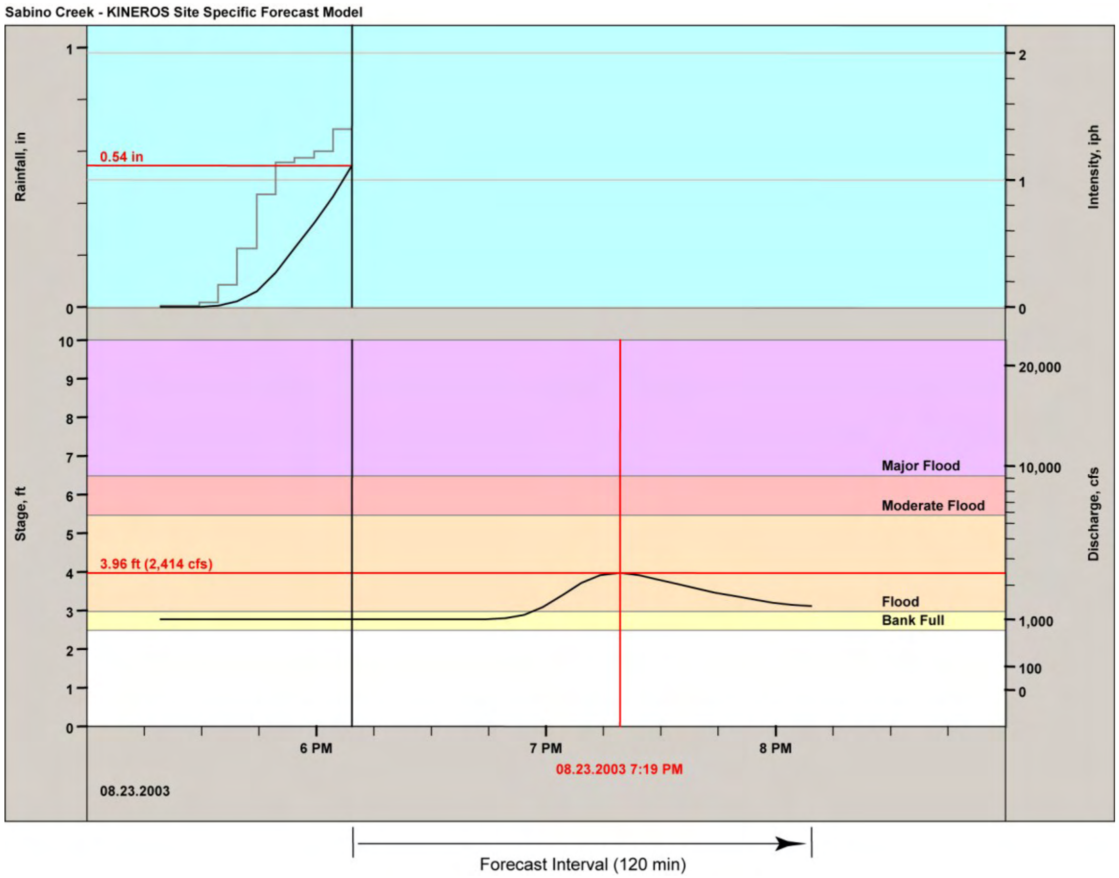

Figure 4. KINEROS2/NWS graphical user interface. The top third of the display is the basin average rainfall (black line), intensity (gray line), and accumulated rainfall (red horizontal line). The bottom two thirds of the display shows the forecast hydrograph. The vertical black line is the current time and the vertical red line is the projected time of peak flow.

CALIBRATION AND OPERATIONAL TESTING

Tucson WFO: Calibration and limited operational testing of the KINEROS2/NWS model was initially conducted at the Tucson, Arizona WFO for the 91 km^2 Sabino Creek watershed (Figure 5). The watershed is characterized by near-vertical bedrock outcrops and steep talus slopes covered by a thin (~0.5m) layer of colluvium. There is a streamflow gauging station operated by the US Geological Survey, six rain gauges operated by the Pima County Regional Flood Control District, and 13 rain gauges operated by researchers at the University of Arizona (Lyon et al., 2008). After calibrating the model's response to several modest runoff events from 2004 and 2005, heavy rainfall over a five-day period led to a record flood accompanied by debris flows on July 31, 2006. Initial efforts to calibrate the model using archived DHR data gave poor results (Figure 6, left graph). However, the rain gauge data gave very good results (Figure 6, right graph) after making only minor adjustments to a single parameter (soil depth) and the initial soil moisture. The model showed that the relatively thin soil layer became completely saturated during the first thunderstorm of the day, setting the stage for the debris flows that followed.

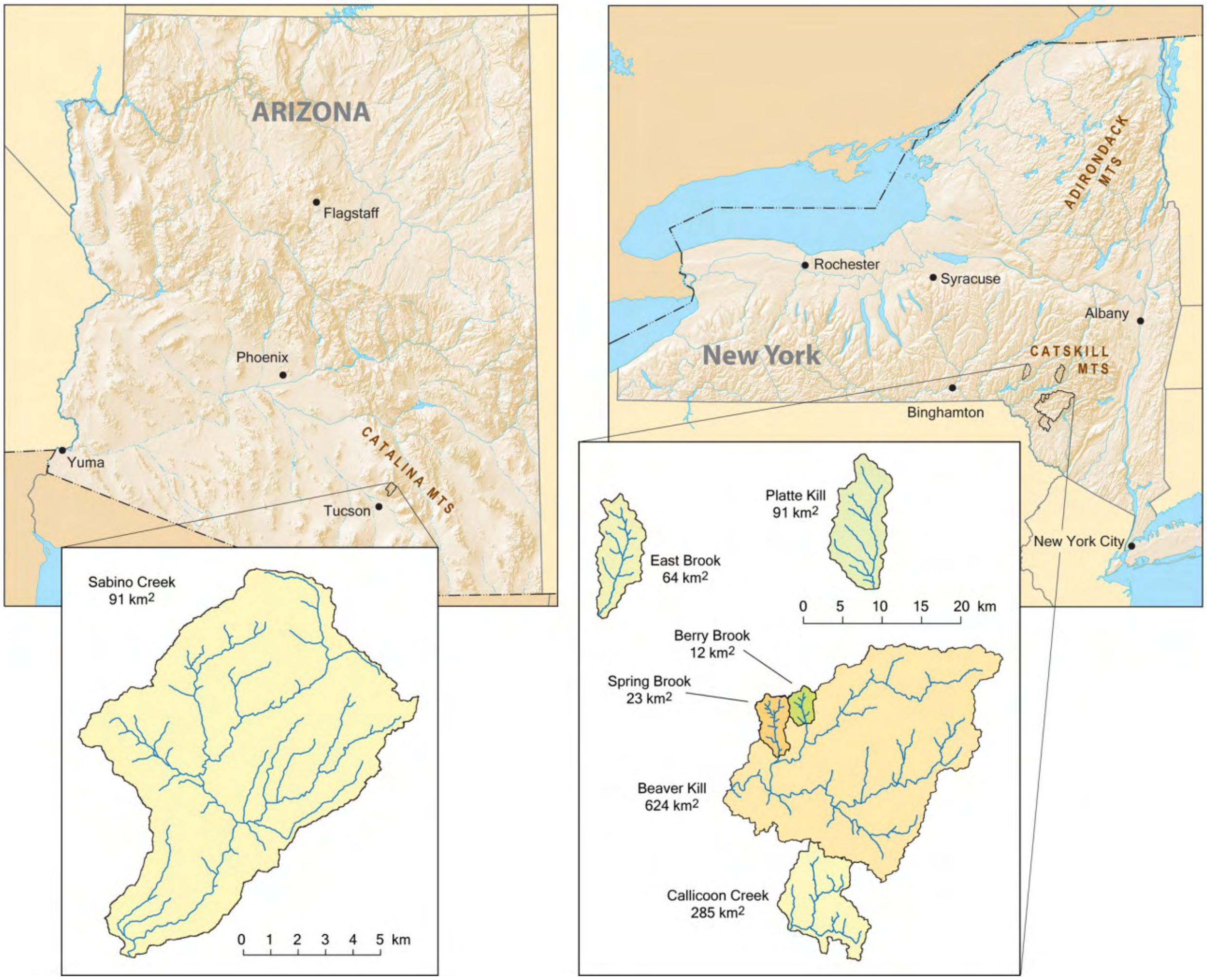

Figure 5. Watersheds calibrated for the KINEROS2/NWS model (state base maps from the National Atlas of the United States, http://nationalatlas.gov).

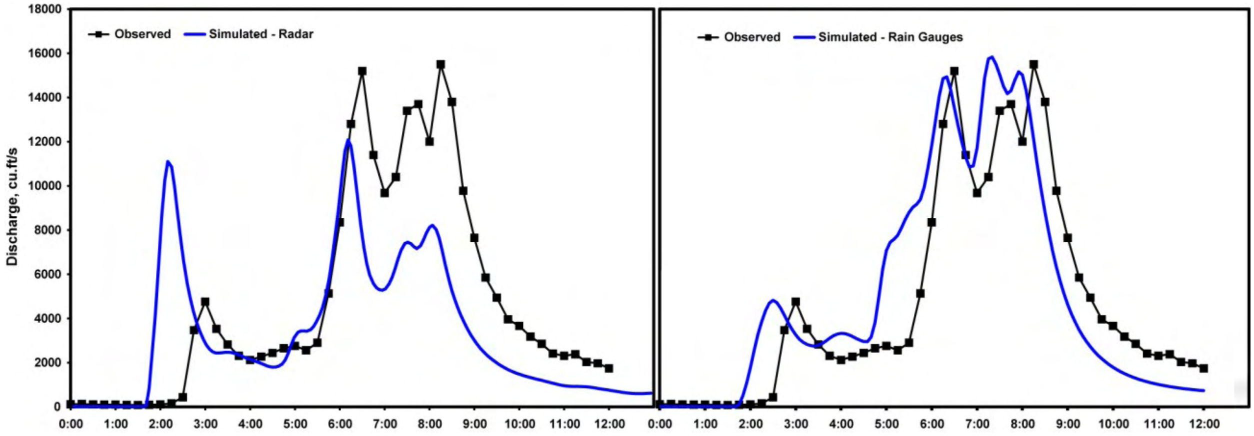

Figure 6. Simulated and observed runoff from the Sabino Creek watershed, July 31, 2006.

Binghamton WFO: The County Warning Area (CWA) for WFO Binghamton encompasses south-central New York State and north-east Pennsylvania. The CWA contains many watersheds with moderate to high flash flood potential. Figure 5 shows the locations of the six watersheds within the CWA for which the model was calibrated. The number of rainfall-runoff events used to calibrate each watershed ranged from 2 to 14, with an average of 7. The model was calibrated separately for each event to match the observed timing and magnitude of the peak flow. Only two parameters were adjusted, the channel length and plane saturated hydraulic conductivity (K_s). A third parameter, the soil capillary potential, was automatically updated within the program based on the adjusted K_s using a linear regression between the two parameters (Goodrich, 1990). The calibration process was streamlined by the use of global parameter multipliers, which adjust the parameter values for all elements by a percentage of their original values. Channel lengths were increased to retard the timing of the peak flow, which was invariably early (deriving channels from a digital elevation model often underestimates their sinuosity). K_s was adjusted to obtain a best fit for the magnitude of the peak flow.

In most cases, there was a significant amount of variation in both parameter multipliers between events, meaning no single parameter set would produce acceptable results for all events, or could be used to run the model operationally. However, further investigation revealed trends between the multipliers and two measures of storm characteristics: the total basin average rainfall amount and/or the maximum basin average rainfall intensity. The trends were especially consistent between K_s and the maximum basin average rainfall intensity (Figure 7). The cause of these trends has not yet been determined, possible explanations range from micro-topographic effects to errors in rainfall estimation by the radar. Regardless of the cause, we can use K_s adjustments based on storm metric to increase the accuracy of the simulation. To that end, in an operational setting KINEROS2/NWS monitors the appropriate storm metric and updates the parameter multipliers when pre-determined thresholds are crossed. After revising the multipliers, the program re-computes the entire hydrograph, from the beginning of the storm, using the new multipliers

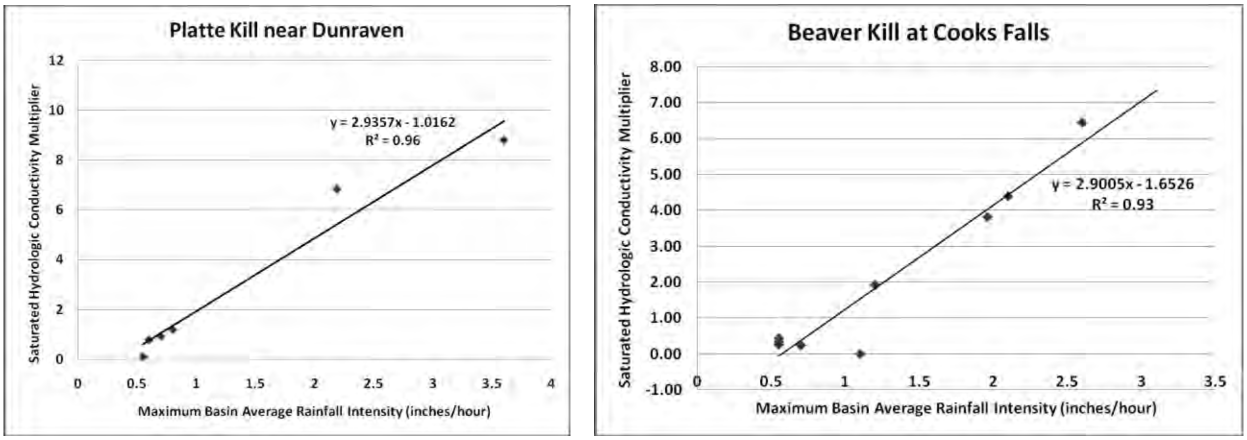

Figure 7. Maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier. Platte Kill is 91 km^2 and Beaver Kill is 624 km^2.

FUTURE WORK

Work has begun on a project to integrate components of the Soil Moisture - hillslope storage Boussinesq (SM-hsB) modeling framework (Troch et al., 2003; Bogaart et al., 2008) into the KINEROS2/NWS model. These components include a distributed water and energy balance model of the vegetation canopy and the land surface, a soil water balance model, a lateral saturated subsurface flow model, and a snow accumulation/melt model. The energy/water/snow balance additions would allow the KINEROS2/NWS model to function as a continuous, four-season model and not be restricted to summer rainfall events. Adding the lateral subsurface flow component would extend the model's applicability, particularly in humid regions.

For real-time continuous operation, climate forcing data will have to be ingested from live sources, such as the National Digital Forecast Database (NDFD), which provides forecast temperature, dew point, wind, and precipitation data, or the National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS), which provides snow, temperature, and soil moisture data. When forecasts are needed, the snow model can utilize NDFD data, otherwise the model can be updated daily using SNODAS.

As discussed previously, rainfall rates estimated from radar can have large errors. The Multiple Precipitation Estimator (MPE) product combines radar and rain gauge data to synthesize a rainfall estimate more representative of ground truth. MPE is only produced on the hour and on a 4 km square grid, much coarser than DHR which is produced every volume scan of the radar (~4 minutes) and on a 1 km by 1o grid. To use MPE in the KINEROS2/NWS model, every hour the radar bias for each 1 km by 1^o DHR cell is computed based on the 4 km MPE grid for the prior hour, then the model is rewound by one hour and run forward again using the MPE-corrected DHR. The MPE for the prior hour can also be used to compute a new Z-R relationship which could then be applied proactively to the DHR over the next hour.

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