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A distributed real-time semiarid flash-flood forecasting model utilizing radar data

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Abstract One-third of the Earth's surface can currently be classified as arid or semiarid. This fraction may increase in the future for example due to global warming effects. Many arid and semiarid regions are particularly affected by flash floods, caused mainly by convective storm systems, and often resulting in significant damages to property and even loss of life. The short duration and the small geographic extent of these events make predicting the subsequent floods extremely difficult. To improve our predictive capability, we are currently developing a semiarid specific model based on the well-established event-based rainfall–runoff model KINEROS2, capable of continuously simulating the response of a specific basin and driven by high-resolution precipitation measurements. This spatially distributed kinematic wave model represents the basin as a cascade of planes and channels. The dynamic infiltration algorithm is particularly well suited for simulation of semiarid hydrological processes. Adjustments to the original model include restructuring the code in a modular fashion, adding long-term soil moisture storage and evapotranspiration algorithms, and including optimization tools for parameter estimation. The project aims towards more accurate, reliable and probabilistic flood warnings, for semiarid flash-flood forecasting, risk assessment and decision making. This paper outlines the model and some associated data processing tools, and represents some initial results of applying the model to a small semiarid basin in the southwestern USA.

Key words decision making; flash floods; KINEROS; parameter estimation; parameter sensitivity; radar-based precipitation estimates; semiarid regions; southwest USA; Walnut Gulch

INTRODUCTION

One-third of the Earth's surface can currently be classified as semiarid/arid, with desertification negatively affecting approximately one billion humans (FAO, 1993). Many of these regions are also water-stressed and potentially unsustainable due to human factors (Watson *et al*., 1998). This fraction may increase in the future due to natural global warming effects causing a drier and more variable future climate (UNEP, 1997).

Watersheds in semiarid regions like the southwestern United States of America are prone to severe flash floods (Costa, 1987), caused mainly by summertime convective thunderstorm systems (Michaud, 1992; Roeske *et al*., 1989). Flash floods are those occurring within six hours of the causative event (NWS, 2002). In the USA alone, flash floods kill more people annually than any other natural disaster, accounting for more than 80% of all flood-related deaths (AMS, 1985), and causing an average of US$ 1 billion of economic losses annually.

Many small rivers and streams in the western USA experience significant flooding which impacts communities, but for which hydrological forecasts are not currently supported by the present River Forecast Center (RFC) environment. The RFC produces 6-hour output from the Sacramento model (Burnash, 1995) for forecast points and a number of other gauged sites, which is inadequate in many cases due to the short reaction time of these rivers. In addition, many small basins often affected by flash floods are ungauged and no data for adequate model evaluation are available. Thus, the current National Weather Service (NWS) forecasts and warnings provided to the public for these locations have to be based on the forecaster's judgment and experience and can only be general in nature. Rainfall amounts are often directly converted into flooding potential using experience-based guidelines and flash-flood warnings are almost always issued on a local or regional basis. Mention of individual streams/basins or gauging points is the exception. Specific sub-hourly hydrological forecasts for individual rivers and streams would potentially provide improved services and reduce loss of life and property.

To this end, this research project is developing a continuous semiarid specific distributed model for flash-flood forecasting utilizing high 1°, 1-km spatial and 5-min temporal resolution radar precipitation input estimates. In this paper, as an initial step, the model is run on a single watershed and the sensitivity of the model response to changes in selected parameters is investigated.

MODELLING TOOLS

Several data processing and modelling tools are combined here to create the modelling system used in this study. These tools are a rainfall–runoff model, KINEROS2, a GIS framework, AGWA, and a radar rainfall estimate extraction algorithm, AMBER (set-up shown in Fig. 1).

The KINEROS2 rainfall–runoff model

KINEROS2 is an event-oriented, physically-based model developed to simulate the runoff response of semiarid basins (Woolhiser *et al*., 1990; Smith *et al*., 1995). In the model, the watershed is represented by a cascade of planes and channels, thereby allowing rainfall, infiltration, runoff, and erosion parameters to vary in space. As a first step, the KINEROS2 code has been restructured from subroutine-based to modular form. KINEROS2 uses one-dimensional kinematic equations to simulate flow over rectangular planes and through trapezoidal open channels, and allows for the inclusion of transmission losses, which is a required capability to model semiarid ephemeral

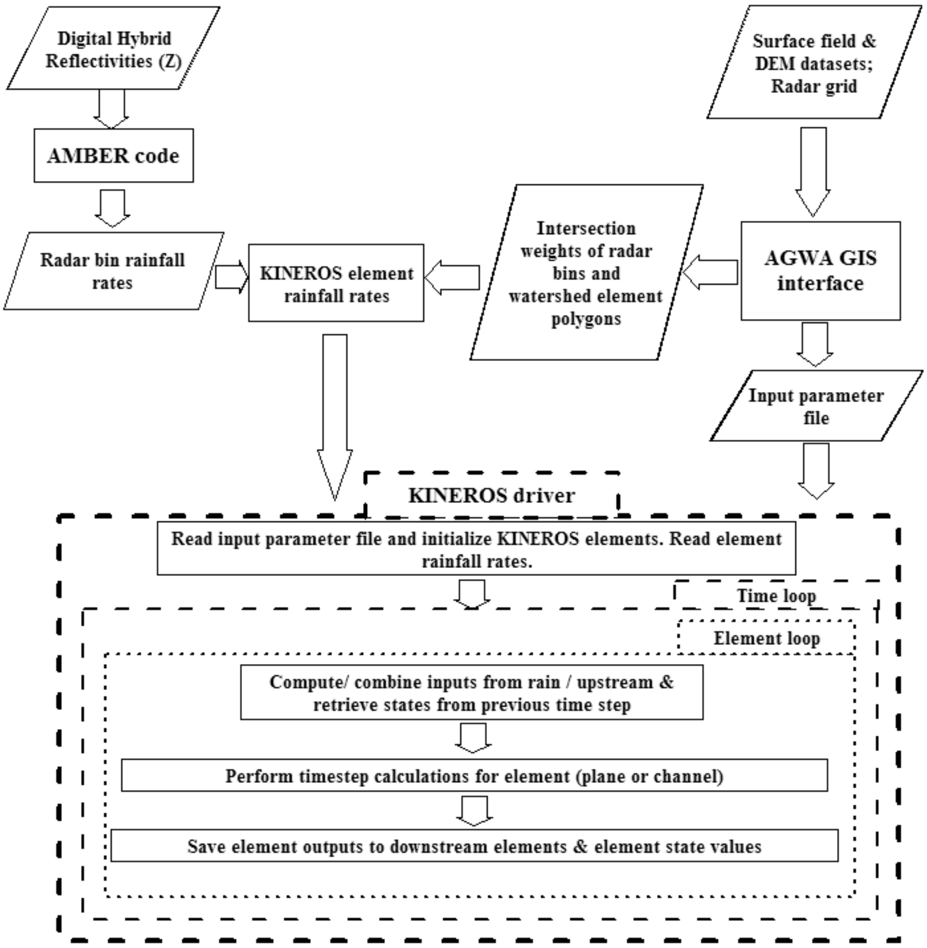

Fig. 1 KINEROS set up for an event run.

streams. The dynamic infiltration algorithm interacts with both rainfall and surface runoff in transit. The open channel algorithm has been extended to allow compound cross-sections with an overbank level where hydraulic and infiltration parameters can differ from those in the main section. Baseflow can be specified for open channels. The plane elements can be run using a one- or a two-layer soil model that redistributes rainfall during a dry period.

Current models of basin hydrology are generally not capable of reproducing the basin's response without some calibration of at least some main parameters (Wagener *et al.*, 2004). Calibration is a process of (manually or automatically) adjusting the model parameters until the model response is as similar as possible to the measured response of the real system, usually streamflow. In the case of KINEROS2, separate multipliers are applied to each model parameter type (e.g. surface roughness or soil saturated hydraulic conductivity) to preserve the basin spatial variability while constraining the dimension of the free parameter space in the study. These multipliers are listed in Table 1.

Rainfall–runoff modelling studies using KINEROS2 have mostly been in small watersheds (less than 100 square miles) in the USA (Faures *et al.*, 1995; Goodrich, 1990; Goodrich *et al.*, 1997; Houser *et al.*, 2000; Michaud, 1992; Woolhiser *et al.*, 2001).

Table 1 Model parameters and multiplier ranges used in 1-parameter sensitivity tests.

Element	Model parameter**	Explanation	Ranges for Walnut Gulch
Plane	d^p	Soil pore size distribution index	0.25–0.3
	i^p	Maximum interception depth	2.64–3.0 mm
	n^p	Surface hydraulic roughness	0.053–0.059
	p^p	Soil porosity	0.459–0.463
	r^p	Soil volumetric rock fraction	0.57–0.62
	CV^p	Coefficient of variation of K_s^p	0.57–0.95
	G^p	Soil capillary drive	115.0–154.6 mm
	K_s^p	Soil saturated hydraulic conductivity	3.45–7.5 mm h^{-1}
Channel	d^c	Soil pore size distribution index	0.545
	n^c	Surface hydraulic roughness	0.035
	p^c	Soil porosity	0.44
	w^c *	Woolhiser coefficient	0.15
	G^c	Soil capillary drive	101 mm
	K_s^c	Soil saturated hydraulic conductivity	210 mm h^{-1}
General	SM_I*	Initial soil moisture	0.4

* Values not AGWA-generated, but set by user.
** ^{p}, plane; ^{c}, channel.

The AGWA GIS framework

The Automated Geospatial Watershed Assessment Tool (AGWA) is a simple, direct and repeatable GIS framework within which spatially-distributed data are collected and used to prepare model input files and evaluate model results. AGWA has mainly been developed by the United States Department of Agriculture Agricultural Research Service (USDA-ARS). AGWA uses widely available standardized spatial data sets obtainable from the Internet, and develops the parameter input files for the KINEROS2 rainfall–runoff model using a digital elevation model (DEM) of the selected basin. It splits the basin into a selected number of plane and channel elements. In the present study, a customized version of AGWA that also provides the radar rainfall bin areal weights from the intersection of each sub-watershed plane element polygon with the radar bins, was used to help read the radar rainfall data into the KINEROS2 model.

The AMBER radar rainfall estimate extraction algorithm

The Areal Mean Basin Estimated Rainfall (AMBER) algorithm of the NWS provides the mean areal precipitation (R) over small-scale watersheds from the original digital hybrid reflectivity data input (Z) available from the Weather Surveillance Radar–1988 Doppler (WSR-88D) system. In this study, AMBER was customized to provide the rainfall amount over each radar bin that was then combined with weight files, derived using AGWA, to yield the fractional rainfall input to each KINEROS2 plane and channel element. AMBER typically uses a standard NWS Z–R relationship for convective rainfall of the following form (Fulton *et al*., 1998):

$$Z = 300 \cdot R^{1.4} \tag{1}$$

Morin *et al*. (2004) found that the parameters used in this relationship can result in a gross overprediction of rainfall for certain locations in Arizona and suggested that a re-calibration to local conditions might be required. This aspect is further discussed in the next section.

BASIN, DATA AND METHOD

The Walnut Gulch Experimental Watershed in southeastern Arizona, USA (31°43′N, 110°41′W) spans 150 km^2 in area and 1220–1830 m in elevation. The climate over the watershed is semiarid, with an average annual precipitation of about 300 mm mostly divided between the thunderstorms of the summer monsoon (approx. two thirds of annual precipitation) and winter frontal systems. Infiltration excess is the dominating runoff production mechanism (Pilgrim *et al.*, 1988). Vegetation is of the Sonoran desert scrub type; the lower two-thirds of the watershed are dominated by brush, and the upper one-third is dominated by grass. Soils are primarily sandy loams.

Morin *et al*. (2004) analysed 13 separate storm events over Walnut Gulch and found that the general *Z–R* relationship of the NWS (equation (1)) had to be adjusted to provide adequate rainfall estimates in this area. They derived the following relationship that was also used in this study:

$$Z = 655 \cdot R^{1.4} \qquad (2)$$

This equation yields much smaller rainfall values than the one mentioned earlier.

The model is applied to simulate a single event that occurred on 25 July 2003. The basin mean areal precipitation and the maximum rain rate values over any element of the watershed were 14.5 mm h^{-1} and 93.5 mm h^{-1}, respectively (Fig. 2), using the adjusted *Z–R* relationship of Morin *et al*. (2004). The difference between the mean and maximum intensity shows the large spatial variability of the rainfall input, even over such a relatively small basin, and explains the need for spatially distributed rainfall input if the system response should be captured successfully. The event discharge observation values collected at 1-min time intervals were averaged to the 5-min radar time resolution.

The upslope source area (CSA), which is a function of the total watershed area and applied to define stream networks, is used here to discretize the Walnut Gulch watershed utilized in KINEROS2. A CSA value of 2.5% results in 53 plane and 21 channel elements.

Uniform sampling runs were performed to gain some initial understanding of the model’s behaviour. This was combined with manual parameter adjustment to yield reasonable starting values for a more detailed sensitivity analysis. A one-parameter-at-a-time sensitivity analysis was then performed to identify those parameters that dominate the model response. In this analysis, individual parameters are perturbed while the remaining parameters are kept at a specific value. A total of 15 (multiplier) parameters, listed in Table 1, were analysed in this manner. They were all varied in fractions of 0.25 between 0.25 and 1.75, with 1 being the original value. This approach requires reasonable initial estimates and, due to the use of multipliers, insignificant nonlinear behaviour by the true distributed parameter values, thus preserving the

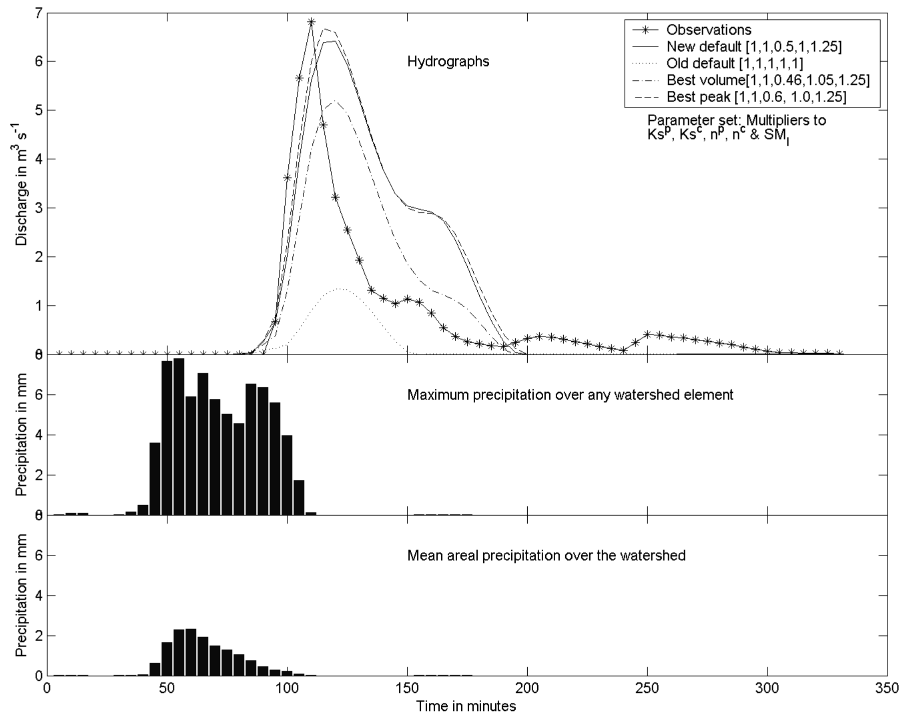

Fig. 2 Comparison of hydrographs.

spatial variation assumed for each parameter type. In this study, the channel coefficient of variations of hydraulic conductivities, channel soil volumetric rock fractions, and rill depth, and rill spacing used to simulate the micro-topography, were not perturbed from the default zero values (hence, multipliers were redundant; they might be considered, however, in an optimization process). Also, element geometry, and discretization complexities (spatial and temporal) were not adjusted in this case study.

RESULTS AND DISCUSSION

The initial uniform random sampling provided only limited information except for detecting some sensitivity of the model response to changes in the plane soil porosity parameter (n^P). It also revealed that the root mean squared error (RMSE) criterion used initially, did not provide indications of important differences in model performance as parameters are varied. A major reason for this is the existence of some timing mismatch, where the simulated hydrograph peak often trailed the observed one, resulting in large *RMSE* values. Additional criteria to describe the model performance were introduced to solve this problem. These were the Absolute Difference in Peak (*ADP*), the Absolute Difference in Time to Peak (*ADTP*), and the Absolute Difference in discharge Volume (*ADV*).

Figure 2 shows the observed hydrograph and some simulations performed in this case study. All the multipliers were initially set to 1, the so-called "old default" case (Fig. 2). The resulting hydrograph strongly underpredicts the watershed response. Using the new criteria mentioned above, in conjunction with the uniform random

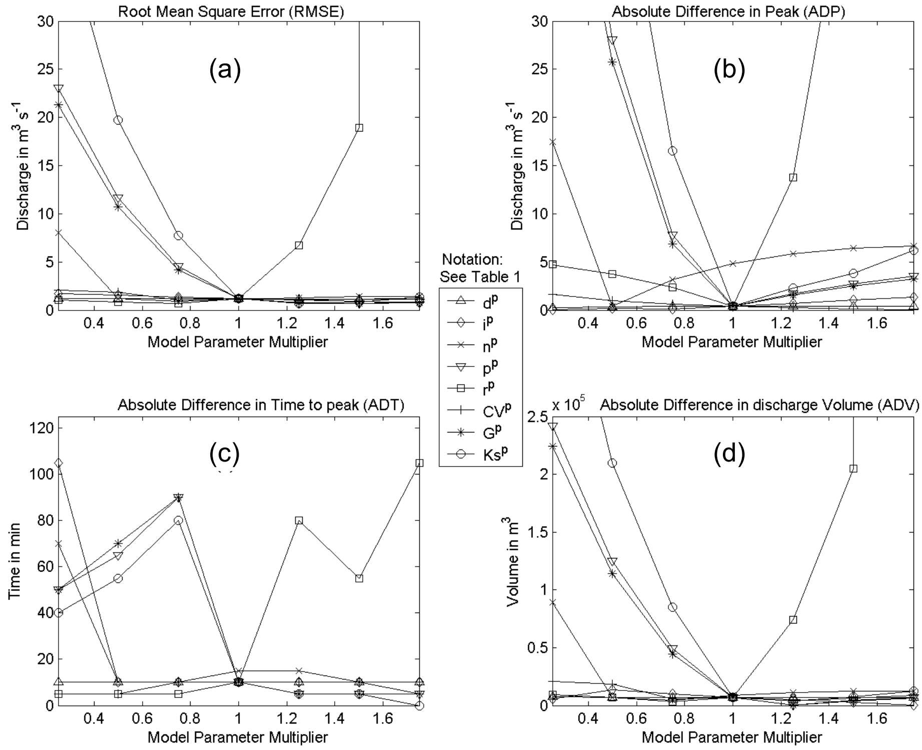

Fig. 3 Single-parameter model sensitivity tests using plane parameter multipliers.

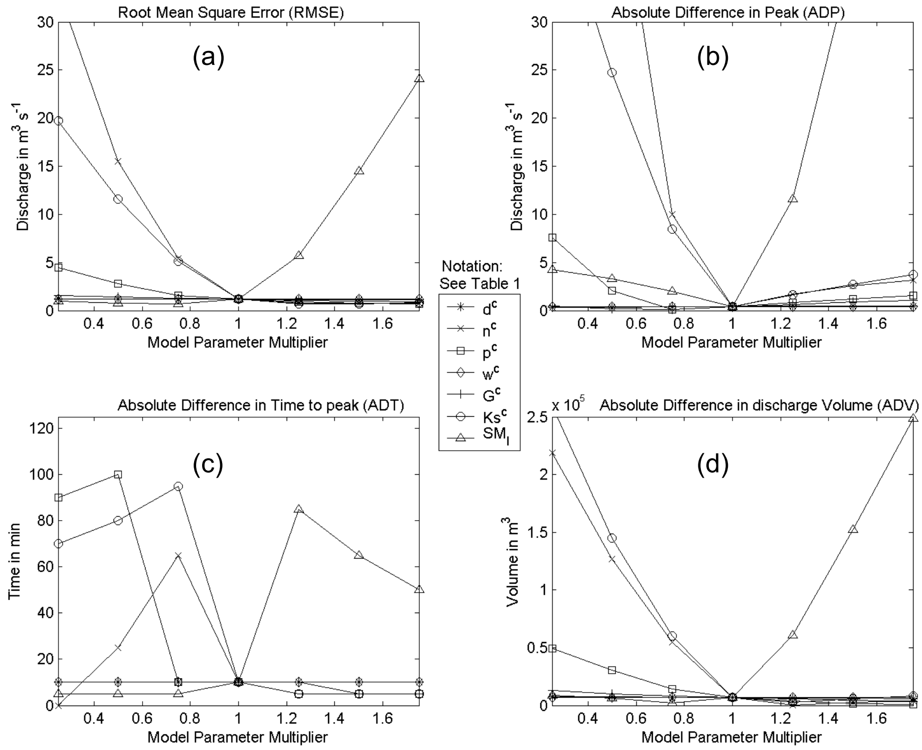

Fig. 4 Single-parameter model sensitivity tests using multipliers to channel parameter/ initial soil moisture.

sampling results, a new set of initial multiplier values was derived using a manual adjustment strategy ("new default"). An experiment in which the two parameter multipliers n^p and n^c were varied over a grid, to compute the distribution of all four objective functions (*RMSE*, *ADP*, *ADTP*, and *ADV*), led to a new "best" multiplier set with 0.5 for the surface hydraulic roughness n^p (also a small change was made to the initial soil moisture, i.e. $SM_I = 0.5$). The n^p reduction corresponds to a similar case (0.05 to 0.02) reported by Michaud (1992) while implementing the model to the same basin, effectively reducing the time to peak (Goodrich, 1990). The new multiplier set gives a hydrograph shape that is much closer to the observations, and was therefore selected as the new default from which the parameters were perturbed one-at-a-time in the single-parameter sensitivity tests. Figure 2 shows the event hydrographs for the original and the new multiplier sets, along manually selected multiplier sets that provide improved matches to the observed peak magnitude, timing or discharge volume. While these multiplier sets provide a significant improvement over the original set, there is a visible damping effect, where the simulated hydrograph recession is too slow, with the hydrograph reaching its highest value too late. The observed peak timing discrepancy of only 10–15 minutes is, however, considered not very important in the operational flood warning context, where the exceedence of the peak above a selected threshold is more important.

The one-parameter-at-a-time perturbation results are shown in Figs 3 (plane parameters) and 4 (channel parameters and initial conditions). Parameters like plane porosity (p^p) and plane soil capillary drive (G^p) were seen to affect the model output more than the plane surface roughness (n^p). The plane soil hydraulic conductivity (K_s^p) is physically related to p^p, and G^p is observed to be correlated with K_s^p (Goodrich, 1990), thus compounding the sensitivity of the model output to these parameters. The analysis also indicates the potential importance of the vadose/subsurface control on flood events. The plane volumetric rock fraction (r^p) mirrors the sensitivity pattern of K_s^p, essentially because increasing r^p decreases the effective K_s^p, and *vice versa*. The parameter n^p is seen to provide information about the hydrograph peak, i.e. it is sensitive to the *ADP* criterion (Fig. 3(b)). The channel parameters give the same patterns except for the channel soil capillary drive (G^c) to which the model response seems to be relatively insensitive. The model behaviour was also insensitive to the Woolhiser coefficient (w^c, affecting channel infiltration) for this event: the effective channel cross-sectional wetted perimeter adjustment for infiltration would be expectedly ineffective for this small event, unlike large events where the channel infiltration change can be significant.

CONCLUSIONS AND FUTURE RESEARCH

The prediction of flash floods in arid and semiarid regions of the world requires high resolution precipitation measurements, in space and time, and spatially distributed hydrological models that realistically represent the physics of these areas and translate the precipitation input into runoff (or runoff potential). This paper describes a new version of an established model, KINEROS2, for this purpose and shows some initial results of a sensitivity analysis using a runoff event in a small watershed in the southwestern USA. This initial analysis was unable to capture the variations in behaviour of the model using the simple *RMSE* criterion, leading to implementation of some alternative criteria, the absolute difference in peak, the absolute difference in the time to peak, and the absolute difference in discharge volume between the simulations and observations. These criteria reflect factors considered important in traditional manual calibration where a similar focus is put on obtaining parameters that improve the hydrograph peak/timing/volume. The key factor for decision making and early flood warning is, of course, the rate and timing of the rising limb of the hydrograph. Other calibration criteria and improvements in the description of the physical system might be needed to enhance reproduction of the hydrograph recession. Correct initial soil moisture conditions were also crucial in obtaining good model predictions. Ongoing work over a range of basin sizes, more detailed multi-parameter sensitivity analysis and optimization, and potential improvement of the subsurface control is underway to improve the utility of this tool for flash-flood forecasting in semiarid basins.

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