KINEROS2/AGWA: MODEL USE, CALIBRATION, AND VALIDATION

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ABSTRACT. *KINEROS (KINematic runoff and EROSion) originated in the 1960s as a distributed event-based model that conceptualizes a watershed as a cascade of overland flow model elements that flow into trapezoidal channel model elements. KINEROS was one of the first widely available watershed models that interactively coupled a finite difference approximation of the kinematic overland flow equations to a physically based infiltration model. Development and improvement of KINEROS continued from the 1960s on a variety of projects for a range of purposes, which has resulted in a suite of KINEROS-based modeling tools. This article focuses on KINEROS2 (K2), a spatially distributed, event-based watershed rainfall-runoff and erosion model, and the companion ArcGIS-based Automated Geospatial Watershed Assessment (AGWA) tool. AGWA automates the time-consuming tasks of watershed delineation into distributed model elements and initial parameterization of these elements using commonly available, national GIS data layers. A variety of approaches have been used to calibrate and validate K2 successfully across a relatively broad range of applications (e.g., urbanization, pre- and post-fire, hillslope erosion, erosion from roads, runoff and recharge, and manure transport). The case studies presented in this article (1) compare lumped to stepwise calibration and validation of runoff and sediment at plot, hillslope, and small watershed scales; and (2) demonstrate an uncalibrated application to address relative change in watershed response to wildfire.*

Keywords. *Distributed watershed model, Erosion, Kinematic wave, KINEROS, Rainfall-runoff, Sediment.*

KINEROS2 (KINematic runoff and EROSion), or K2, originated at the USDA Agricultural Research Service (ARS) in the late 1960s as a model that routed runoff from hillslopes, represented by a cascade of overland-flow planes using the stream path analogy proposed by Onstad and Brakensiek (1968), and then laterally into channels (Woolhiser et al., 1970). Conceptualization of the watershed in this form enables solution of the flow-routing partial differential equations in one dimension. Rovey (1974) coupled interactive infiltration to this model and released it as KINGEN. After substantial validation using experimental data, KINGEN was modified to include erosion and sediment transport as well as a number of additional enhancements, resulting in KINEROS, which was released in 1990 (Woolhiser et al., 1990; Smith et al., 1995).

The spatial scales for which this model was developed can range from plot (<10 m^2) to large watersheds on the order of a thousand square kilometers. However, it has only been thoroughly validated for watersheds on the order of a hundred square kilometers where sufficient observations exist in experimental watersheds (Goodrich et al., 2004). It was originally developed as an event-based model. Simulation times can vary from tens of minutes for small plots to more than a day for larger watersheds depending on the respective runoff response time. Computational time scales are dictated by adherence to the Courant condition (Roberts, 2003). Computational time intervals are automatically adjusted in the current model implementation, and the user can select the time interval at which simulation output is reported. Subsequent research with and application of KINEROS has led to additional model enhancements and a more robust model structure, which have been incorporated into the latest version of the model: KINEROS2 (K2).

The objectives of this article are to:

- Provide a brief description of the primary K2 model processes and attributes.
- Describe prior K2 calibration and validation studies.
- Describe K2 validation and calibration procedures with ideal and with minimal observations.
- Present case studies of K2 applications with multi-scale calibration and validation and in an un-

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gauged watershed.

- Discuss calibration and validation of K2 and comparable models.
- Describe on-going and future development of K2.

K2 is open-source software that is distributed freely via the internet, along with associated model documentation and example input files (www.tucson.ars.ag.gov/kineros). The companion ArcGIS-based Automated Geospatial Watershed Assessment (AGWA) tool (Miller et al., 2007; www.tucson.ars.ag.gov/agwa) automates the time-consuming tasks of watershed delineation into distributed model elements and initial parameterization of these elements for K2. This tool uses commonly available, national GIS data layers to fully parameterize, execute, and visualize results for both the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) and K2 models. The theoretical background of the most current versions of K2 and AGWA, with example applications, is presented by Semmens et al. (2008). Like K2, AGWA is open-source software available from the AGWA website. This site also contains documentation, supporting references, tutorials, and a user forum. Support for K2 and AGWA is typically accomplished by e-mail and phone communication. In selected cases, users experiencing problems can e-mail their input files to K2 and AGWA developers to allow in-house debugging. We also welcome visitors to the USDA-ARS Southwest Watershed Research Center to work with model developers on application projects and/or model improvements. On an intermittent basis, AGWA training classes have also been conducted in a computer classroom setting.

Table 1. Selected sample of prior studies using K2.

Study	Watershed Location and Area	Application
Zevenberger and Peterson (1988)	Northwest Mississippi (1.9 ha)	Evaluation of a variety of storm event hydrologic and erosion models
Guber et al. (2010)	Eastern Maryland (3.55 ha)	Evaluate the uncertainty in model predictions of the manure-borne bacteria overland transport
Kalin and Hantush (2006)	Treynor, Iowa (13.6 ha)	Comparative assessment of KINEROS2 and GSSHA for hydrology and sediment
Zielger et al. (2004, 2007)	Northern Vietnam (9.1 and 12.3 km^2)	Effects of land cover transitions on buffering and acceleration of overland flow
Nikolova et al. (2009)	Malki Iskar River basin, Bulgaria (21.2 km^2)	Flood risk prediction under land use change
Michaud and Sorooshian (1994)	Southeast Arizona (149 km^2)	Flash flood forecasting with typical ALERT data constraints
Schaffner et al. (2010)	South-central New York and northeast Pennsylvania (six watersheds, 64.0 to 624 km^2)	Flash flood prediction using near real-time National Weather Service radar-rainfall estimates

K2 Description

K2 is a distributed model that is applicable from plot to watershed scales and has been successfully calibrated and validated on experimental watersheds with high-resolution inputs and observations up to 150 km^2 in size. K2 is an event-based model that estimates runoff, erosion, and sediment transport in overland flow (hillslope), channel, detention pond, urban, injection, and non-pressurized culvert model elements. Table 1 lists a sample of studies that employed K2 across a range of scales and locations around the U.S. and world for a variety of applications. A continuous-simulation version of the model with biogeochemistry is undergoing testing but is not discussed here. Precipitation inputs are typically in the form of rain gauge observations in either time and accumulated rainfall pairs or time-intensity pairs, or radar-rainfall intensity estimates provided on time scales of tens of minutes or less. Internal computational time steps are automatically adjusted to satisfy the Courant condition (Roberts, 2003), and output time steps are user-defined.

Watershed Conceptualization and Model Setup

In K2, the watershed being modeled is conceptualized as a collection of spatially distributed model elements. The model elements effectively abstract the watershed into a series of shapes, which can be oriented so that one-dimensional flow can be assumed. A typical subdivision, from topography to model elements, of a small watershed in the USDA-ARS Walnut Gulch Experimental is illustrated in figure 1. Further, user-defined subdivision can be made to isolate hydrologically distinct portions of the watershed if desired (e.g., for large impervious areas, for abrupt changes in slope, soil type, or hydraulic roughness, etc.). Attributes of each of the model element types are summarized in table 2.

Watershed characterization is important to estimate both the geometric characteristics of watershed modeling elements (e.g., slope, flow length, area) and the factors affecting infiltration and routing (e.g., soil hydraulic properties, hydraulic roughness, land use, and land cover). Ideally, a high-resolution topographic survey derived from lidar or a real-time kinematic (RTK) GPS survey would be available. A distributed set of tension infiltrometer or rainfall simulator measurements, coupled with soil textural and bulk density analyses sufficient to characterize the variability of the fields, commensurate with the model's geometric complexity, would be desirable if resources are not limited. In all cases, the input, state, output, and basin characterization data should be carefully screened for outliers, errors, and temporal trends and for temporal record discontinuities, such as if land use or instrumentation changes occur.

Model Processes Overview

Rainfall and Interception

Rainfall data are entered as time-accumulated depth or time-intensity pairs. A time-depth pair simply defines the total rainfall accumulated up to that time. A time-intensity pair defines the rainfall rate until the next data pair. Rainfall is modeled as spatially uniform over each element, but varies between elements if there is more than one rain gauge (Semmens et al., 2008) or multiple radar-rainfall pixels. As implemented in K2, interception is the portion of rainfall that initially collects and is retained on vegetative surfaces.

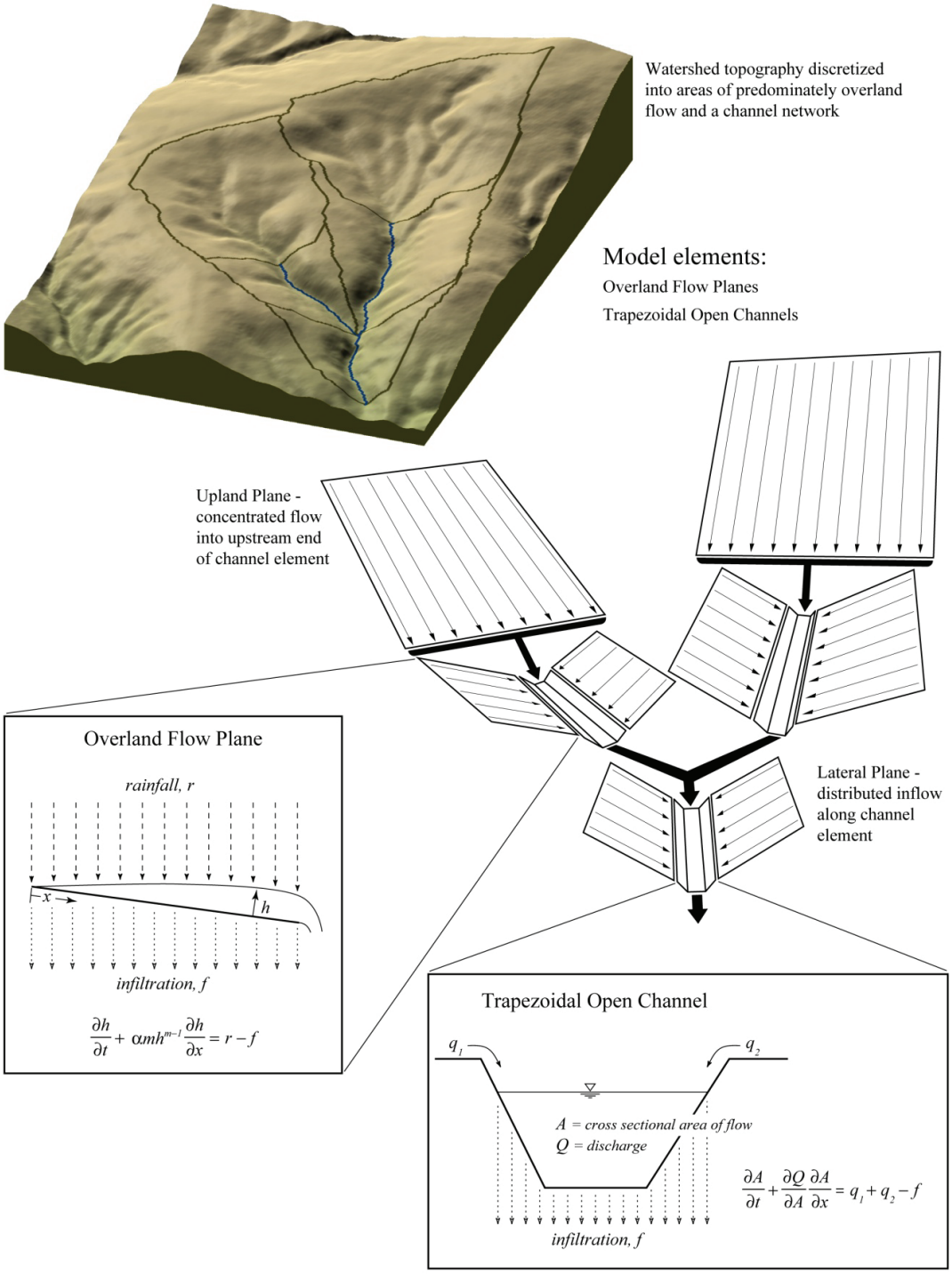

Figure 1. Schematic of the process by which topographic data and channel network topology are abstracted into the simplified geometry of KINEROS2 model elements. Note that overland flow planes (or curvilinear surfaces) are dimensioned to preserve average flow length; therefore, planes contributing laterally to channels generally do not have widths that match the channel length (from Goodrich et al., 2010).

Table 2. KINEROS2 model-element types and attributes.

Model Element Type	Attributes
Overland flow	Cascade of planes or curvilinear surfaces; varied lengths, widths, and slopes; and microtopography
Urban overland	Mixed infiltration and impervious areas with runoff-runon
Channels	Simple and compound trapezoidal; differential infiltration of main and overbank channel areas
Detention structures	Arbitrary shape, controlled outlet; discharge *f*(stage)
Culverts	Circular with free surface flow using Darcy-Weisbach formula
Injection	Hydrographs and sedigraphs injected from outside the modeled system or from a point discharge (e.g., pipe or drain)

The effect of interception is controlled by two parameters: an interception depth associated with the type of vegetation present, and the fraction of the surface covered by this vegetation. Interception can be specified on each model element.

Infiltration

The conceptual model of soil hydrology in K2 represents a soil of either one or two layers, with the upper layer of arbitrary depth, exhibiting lognormally distributed values of saturated hydraulic conductivity (K_s) (Smith and Goodrich, 2000). The surface of the soil exhibits microtopographic variations that are characterized by a mean micro-rill spacing and height. This latter feature is significant in the model, since one of the important aspects of K2 hydrology is an explicit interaction of surface flow and infiltration. Infiltration may occur from either rainfall directly on the soil or from ponded surface water created from upslope rainfall excess. Also involved in this interaction is the small-scale random variation of K_s. K2 uses the Parlange three-parameter model for this process (Parlange et al., 1982), in which the models of Green and Ampt (1911) and Smith and Parlange (1978) are included as the two limiting cases. Smith et al. (2002) provide further details about infiltration techniques used by the K2 model.

Overland Flow

Hydrology in KINEROS2 is described by the 1-D kinematic wave equation (Woolhiser et al., 1990). The numerical solution provides discharge at any point in time and at any distance along a flow path. Rainfall can produce ponding by both infiltration excess and saturation excess mechanisms. For the infiltration excess case, the rate of rainfall exceeds the infiltrability of the soil at the surface. In the saturation excess case, a soil layer deeper in the soil restricts downward flow, and the surface layer fills its available porosity. Routing of overland flow is accomplished within K2 by solving the kinematic-wave equations using a four-point implicit finite difference method using either the Manning or Chezy hydraulic resistance law (Woolhiser, 1975; Engman, 1986).

Channel Flow

Unsteady, free-surface flow in channels is also represented by the kinematic approximation to the unsteady, gradually varied flow equations. A simple or compound trapezoidal channel cross-section (to accommodate overbank flow) can be represented in K2. The main channel and overbank portions of the channel can have different roughness and infiltration characteristics. Channel segments may receive uniformly distributed but time-varying lateral inflow from overland flow elements on either or both sides of the channel, from one or two channels at the upstream boundary, from an upland area, and/or from an injection element. The dimensions of overland flow elements are chosen to completely cover the watershed, so rainfall on the channel is not considered directly. As in the overland flow case, channel routing is computed dynamically with infiltration (and erosion and sediment transport if that option is selected) for a more realistic treatment of advancing flow fronts on highly permeable soils in the overland flow case or to treat channel transmission losses in ephemeral channels.

Erosion and Sedimentation

Erosion is computed for upland, channel, and pond elements. In the release version of K2, erosion caused by raindrop energy (splash erosion) and erosion (or deposition) caused by flowing water (hydraulic erosion) are accounted for separately, and multiple particle sizes can be treated (Semmens et al., 2008). For the case study presented later in this article, a dynamic version of WEPP (Water Erosion Prediction Project; Bulygina et al., 2007), termed DWEPP, is used. This is another erosion option that can be selected in K2 in which the WEPP source term equations for erosion are coded within the finite difference solution of the kinematic wave routing equations. In this approach, sediment sources are conceptualized to arise from interrill and rill erosion processes. Interrill erosion treats soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rills, while rill erosion is a function of the flow's ability to detach sediment, the sediment transport capacity, and the existing sediment load in the flow. The DWEPP erosion formulation in K2 also treats up to five particle class sizes.

K2 Calibration and Validation

Calibration and validation of K2 has been conducted in a variety of settings with a variety of methods, ranging from artificial laboratory watersheds (Wu et al., 1982), to adjacent watersheds over a range of scales (Goodrich, 1990; Goodrich et al., 1997), to watersheds with drainage areas in excess of 500 km^2 (Al-Qurashi et al., 2008) for runoff, as well as rainfall simulator plots (Bulygina et al., 2007) and small watersheds for erosion and sediment (Canfield and Goodrich, 2006). Methods for calibration and validation have ranged from simple manual approaches for a small number of events in which a few of the most sensitive parameters (typically soil saturated hydraulic conductivity and hydraulic roughness) are varied, to complex methods employing variance-based global sensitivity analysis and the Generalized Likelihood Uncertainty Estimation framework (GLUE; Beven and Freer, 2001), as used by Yatheendradas et al. (2008).

Validation results on independent event sets range from excellent (Nash-Sutcliffe statistics for peak runoff rate and runoff volume equal to 0.96 and 0.99, respectively, n = 10 for calibration and n = 20 for validation events; Goodrich et al., 1997) for a small catchment (<5 ha) with high-quality rainfall-runoff data and detailed catchment characteristics, to very poor where a "parameter set which gave best calibration performance over any combination of 26 events did not generally produce acceptable performance (defined as within 30% of observed) when used to predict the 27th event" (Al-Qurashi et al., 2008, p. 104). The latter study was in a 734 km^2 watershed with seven rain gauges and one runoff measuring site. In this and similar situations, the authors noted that "data sets typically used for distributed (or semi-distributed) rainfall-runoff modeling in arid regions cannot provide an accuracy which justifies the effort and

expense of this modeling approach. The limitations imposed by relatively sparse observations of rainfall are of particular concern" (Al-Qurashi et al., 2008, p. 104). Watershed modeling to predict runoff in any arid or semi-arid watershed is inherently more difficult than in humid regions, as runoff to rainfall ratios are very small (e.g., a low signal-to-input ratio and a high noise-to-signal ratio due to input rainfall (Sevruk, 1989) and parameter uncertainties).

For an ideal calibration and validation of K2, ten or more rainfall-runoff (and sediment if modeling erosion) events, with high-quality observations, ranging from small to large and from dry to wet initial soil moisture conditions, would be available. Soil moisture measurements co-located at the rain gauges with recording intervals no longer than 1 h to define pre-storm soil moisture levels for the event-based K2 model would also be preferred. Ideally, runoff would be measured in a flume or weir to reduce uncertainties in runoff observations. Accurate precipitation driving data in time (1 min intervals for small watersheds <10 km^2) and space (a minimum of three recording rain gauges in any catchment greater than plot scale) are the most critical observations to obtain.

A user performing K2 calibration can also draw upon prior univariate (Goodrich, 1990; Michuad and Sorooshian, 1994) and global sensitivity analyses (Yatheendradas et al., 2008) to identify the key parameters to vary in calibration (see the Calibration Parameters section below). Estimating infiltration and hydraulic parameters for each modeling element is typically not feasible unless observations are available for every element. Even in an ideal setting, the ability to make great numbers of distributed measurements to estimate these parameters is not feasible, as the disturbance involved in making this level of measurements will likely alter the watershed and its response. To reduce the parameter space to a reasonable dimension, we recommend that multipliers for calibration parameters be used (e.g., a global multiplier on the saturated hydraulic conductivity (K_s) that is applied to the initially estimated K_s parameters across all modeling elements). Initial K_s parameter estimates can be derived from distributed infiltrometer measurements. Adjusting the global multipliers scales the model element input parameters while maintaining the relative differences based on *a priori* field observations (Goodrich et al., 1997) and can reduce parameter identifiability problems, as noted by Beven (1989).

If sufficient, high-quality observations and initial parameter estimates are available, we recommend using automated calibration algorithms such as PEST (Doherty, 2004), GLUE (Beven and Freer, 2001), or the Shuffled Complex Evolution Metropolis (SCEM; Vrugt et al., 2003). These algorithms can also provide users with an estimate of predictive uncertainty. K2 applications using these three approaches include Burns (2010; see case study below for PEST), Yatheendradas et al. (2008) for GLUE, and Kennedy (2007) for SCEM. A variety of objective functions were used in the above examples, but we recommend that they be selected based on the problem being addressed by the model application. For example, if the purpose of the model application is sizing a culvert or bridge opening, then the calibration and validation should focus on peak runoff rates. If sizing a detention structure is the goal, then the objective function should focus on runoff volume. A commonly used objective function is the efficiency statistic proposed by Nash and Sutcliffe (1970), although, like virtually any objective function, this statistic has advantages and disadvantages. Krause et al. (2005) compares relative strengths and weaknesses of several efficiency criteria for a variety of hydrologic models. Given the uncertainty in observations, parameters, and model structure, a unique global optimum parameter set will almost certainly not be identified. Thus, multiple parameter combinations will provide acceptable model responses (Pareto optimum). Using this set of acceptable simulations, the user can derive a range of simulated hydrographs (or sedigraphs). With the GLUE procedure, a confidence interval can be developed. In both cases, these ranges of acceptable simulations can be compared to the observed hydrograph/sedigraph. The narrower the range of acceptable simulations, the lower the uncertainty associated with the model simulations. An example is illustrated in figure 2 for six selected hydrographs showing runoff using an SCEM posterior distribution high probability density region (shaded), a single mode parameter set for all runoff events (solid line), and measured runoff (crosses) (Kennedy, 2007). Note that the grassland watershed hydrographs, shown on the right side of figure 2, have greater uncertainty in simulation than the urban watershed. A key reason for such disparate uncertainty bounds between the two land uses is attributed to the low runoff-to-rainfall ratio in the grassland watershed (cumulative runoff-to-rainfall ratios were 0.26 (urban) and 0.01 (grass), respectively, over 57 observed runoff events). It is also recommended that, for one or more acceptable calibrated parameter sets, a set of simple observed versus simulated plots (e.g., peak runoff, runoff volume, sediment yield) with a 1:1 line be examined for outliers, bias, or trends. Ideally, if good observations exist from a nearby watershed, or within a nested calibration/validation watershed, the selected set of "best" model parameters should be used to evaluate model performance at the nearby or nested watershed.

In a less than ideal case of data availability (e.g., scarce or low-resolution data), we recommend that the watershed discretization and initial parameterization be done with the Automated Geospatial Watershed Assessment tool (AGWA; Miller et al., 2007). AGWA is a GIS interface for data organization, parameterization, integration, execution, change-detection, and visualization for the K2 and SWAT models to support watershed management and assessments. AGWA uses nationally available digital data sets of topography, soils, and land use/land cover to parameterize K2 via look-up tables developed from experimental and published parameter estimates from a range of studies. The procedures noted above for the ideal calibration and validation could then be undertaken with sufficient input, state, and output observations. AGWA has been used in a number of applications, without calibration, for relative assessment where sufficient observations are lacking (Kepner et al., 2004, 2008; Semmens and Goodrich, 2005; also see the second case study below).

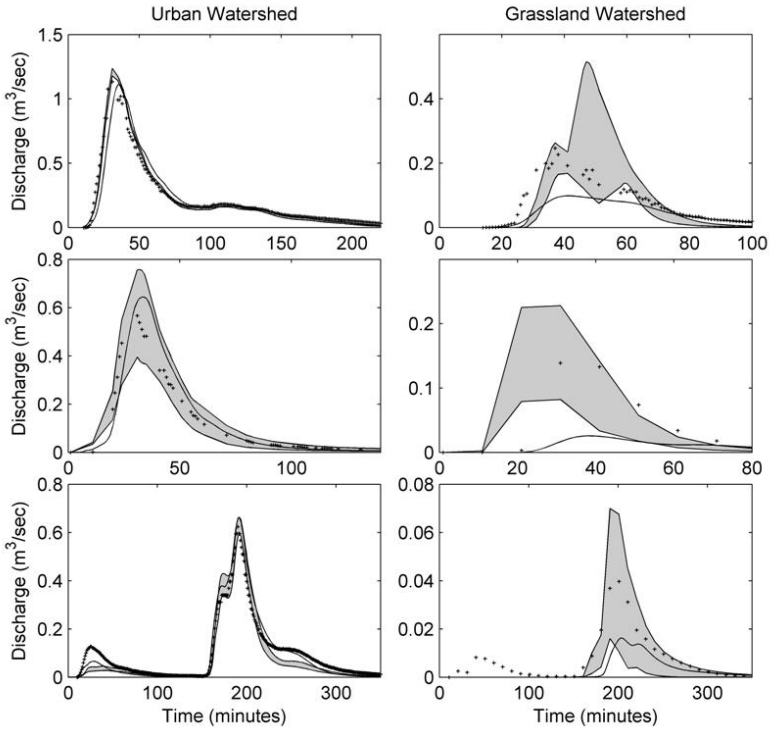

Figure 2. Selected hydrographs from urban and grassland watersheds showing runoff using SCEM posterior distribution high probability density regions (shaded), single mode parameter set runoff (solid line), and measured runoff (crosses). Plots on each row are from the same event (from Kennedy, 2007)

When rainfall and runoff observations are limited (less than roughly ten events), we recommend calibration using the entire set of events and subsequently, for each of the events, calibration on each of them individually. The variation in parameter values resulting from individual-event calibrations will provide some indication of parameter stability and uncertainty. For a simple approach to calibration with limited event observations, we recommend using the Nash-Sutcliffe (N-S) efficiency statistic as an objective function on peak runoff rate, total event runoff volume, and event sediment yield, if available. We recommend using watershed-wide parameter multipliers (M) on the saturated hydraulic conductivity (K_s) infiltration suction term (G), and hydraulic roughness (n) for calibrating the hydrology of K2. A lower and upper limit on these multipliers should be selected such that the resulting values of K_s, G, and n for individual model elements are physically realistic. The N-S statistic should then be calculated for parameter multiplier sets selected by subdividing the lower to upper limit range using a simple gridded search. First vary MK_s (multiplier on K_s) and MG (multiplier on G) to optimize the N-S efficiency with an objective function for event runoff volumes (V). Next, vary Mn (multiplier on roughness "n") using the N-S efficiency with an objective function of event peak runoff rates (Q_p). A similar procedure should be employed for calibrating and validating erosion parameters (see the first case study below). Simple plots of the objective function response surface as a function of the various combinations of multipliers can then be made to assess the nature of the response surface and parameter interactions. It is recommended that graphical assessments of model performance also be made (hydrographs, sedigraphs, modeled versus observed Q_p and event volume, etc.). If N-S values are less than or equal to zero, then the average of the observed values are considered a better predictor than the model itself. In deciding whether a calibration/validation is acceptable, professional judgment must be exercised based on the purpose of the model application and an examination of both the quantitative and qualitative methods discussed above. If time and resources permit, multiple efficiency criteria should be considered. Krause et al. (2005) concluded that, for scientifically "sound model calibration and validation, a combination of different efficiency criteria complemented by the assessment of the absolute or relative volume error is recommended" (p. 97). Figure 3 summarizes the K2 calibration and validation procedures in the form of a flowchart. If calibration/validation is considered unacceptable, and time and resources permit, consideration should given to collection of additional watershed observations (the second and third boxes in fig. 3).

Calibration Parameters

As noted above, for calibration of the hydrology, we recommend using watershed-wide multipliers of the following parameters: saturated hydraulic conductivity (MK_s), infiltration suction term (MG), and hydraulic roughness (Mn). When modeling erosion and sediment-transport in K2 with the DWEPP erosion formulation, use multipliers on rill erodibility, interrill erodibility, and critical shear stress. For the original K2 erosion formulation, use multipliers on the rainsplash parameter, transport capacity, and soil cohesion coefficient.

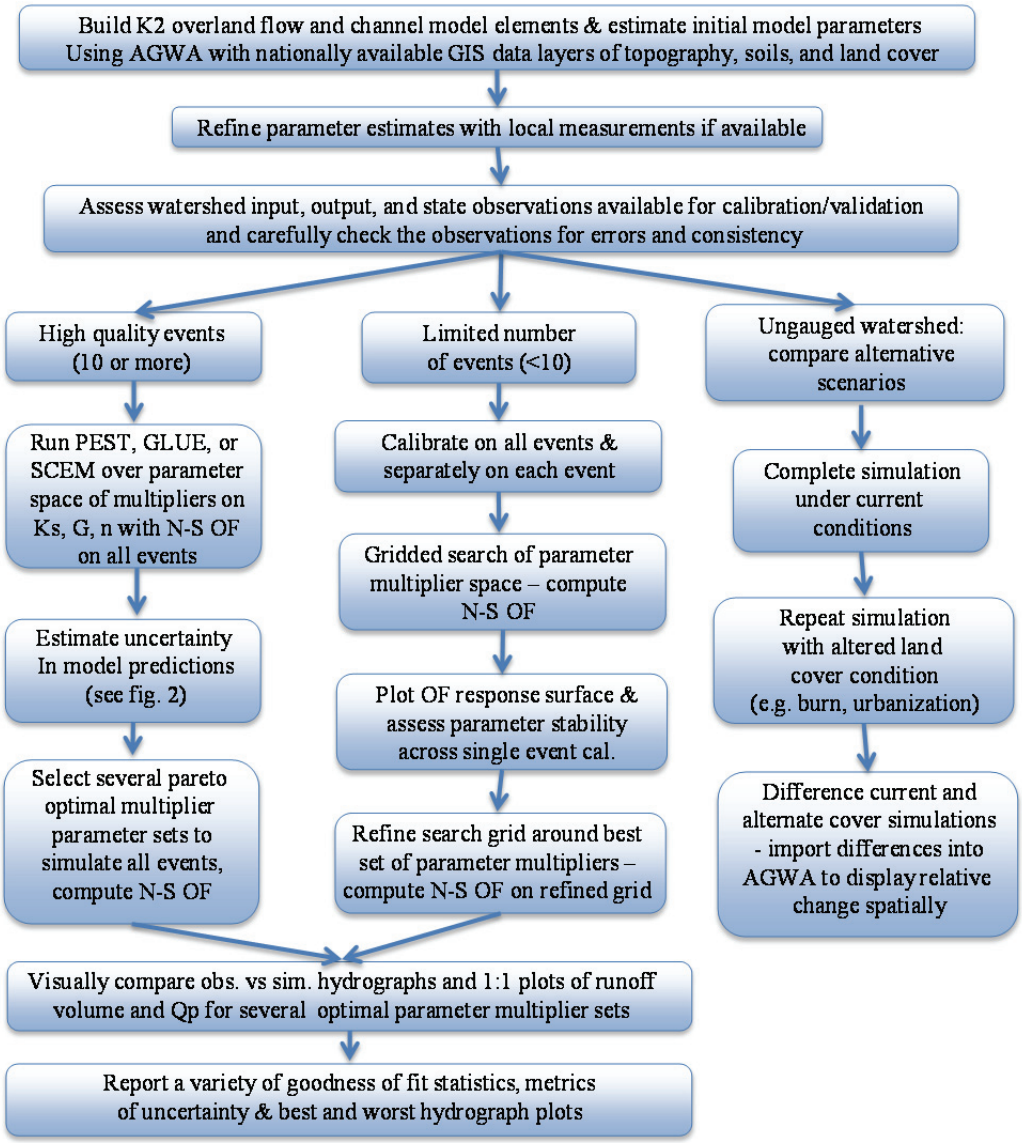

Figure 3. Flowchart of suggested calibration and validation procedures for K2 (N-S = Nash-Sutcliffe; OF = objective function). Note that other objective functions should be considered if it is believed that they will adjust the parameters so the model better represents critical aspects of the watershed response for the problem being addressed (e.g., time to peak runoff rate, recession, total runoff volume, etc.).

The original K2 manual (Woolhiser et al., 1990) and the documentation on the K2 website contain tables with supporting references to provide initial parameter estimates for virtually all of the K2 parameters based on topography, soils, and land cover. In addition, AGWA is designed to provide default K2 parameter estimates based on these tables and the properties of topography, soils, and land use/land cover represented in the nationally available GIS data layers describing the watershed. If the user chooses the DWEPP erosion option, initial parameter selection guidance is available from NSERL (1995). Selection of K2 erosion options should be guided by the information available for initial erosion parameter estimation (e.g., soils, management, and cover). In the first case study below, hydrology and erosion parameters are calibrated in a multiscale stepwise approach. In the second case study, an application is presented in which no calibration or validation was performed for an ungauged watershed.

Case Studies

Case Study 1

In the first case study, Burns (2010) compares a stepwise, multiscale calibration of K2 with the DWEPP erosion and sediment transport formulation to a more traditional calibration performed at a single scale. DWEPP is used in an attempt to improve sediment transport and erosion processes compared to K2, where representation of these processes is poor (Canfield and Goodrich, 2006). The stepwise, multiscale calibration attempts to improve upon a traditional "lumped" calibration in which uncertainty and poor performance are common when moving across spatial scales.

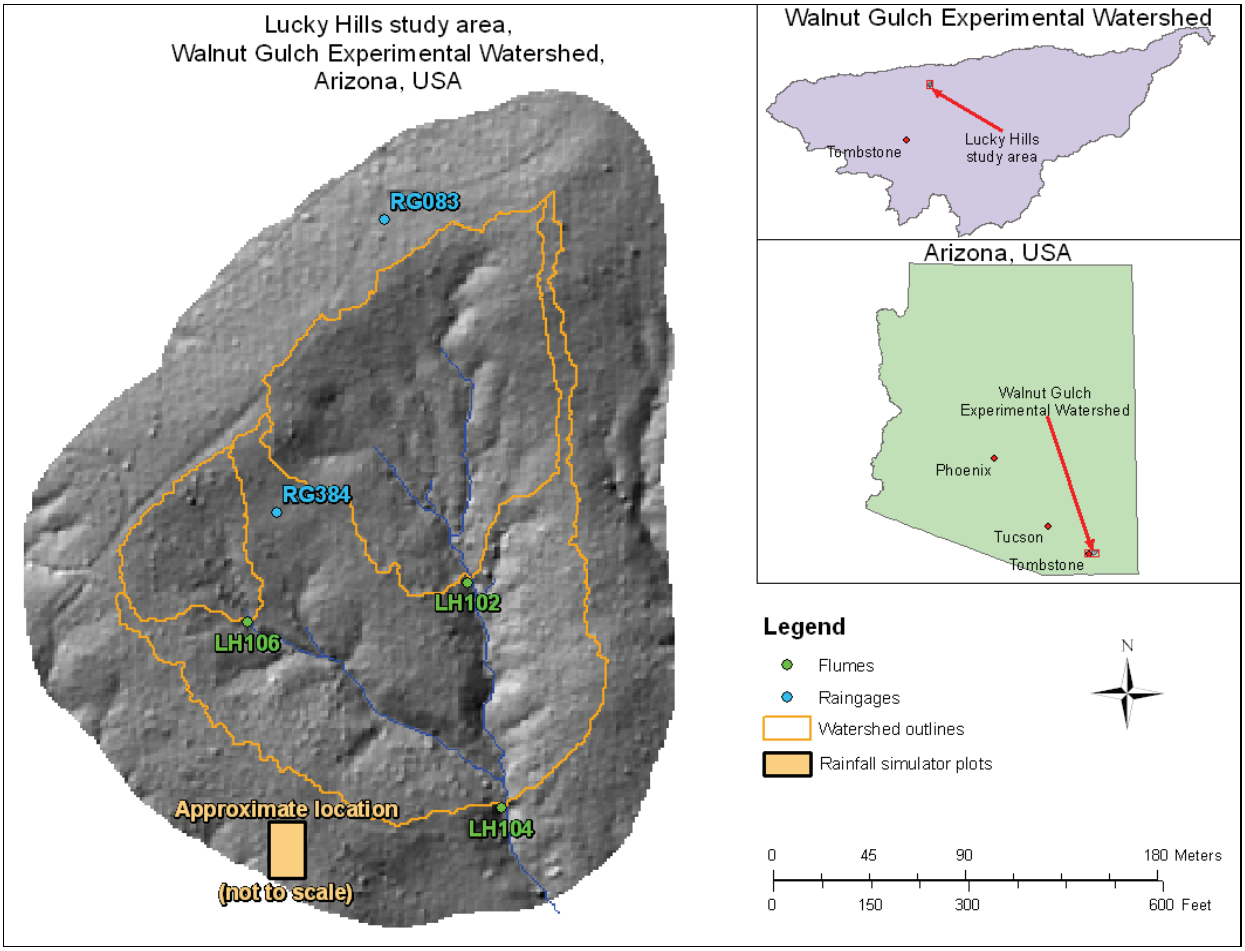

Figure 4. Lucky Hills Study area located in the Walnut Gulch Experimental Watershed, Arizona. The LH104, LH102, and LH106 watershed outlines, flume locations, rainfall simulator plot, and rain gauges are also shown overlain on a 1 m lidar hillshade.

The calibrations use rainfall, runoff, and sediment data collected from a rainfall simulator at the plot scale (Paige et al., 2003) and from a network of rain gauges and flumes at the hillslope and watershed scales (Renard et al., 1993, 2008) in the Lucky Hills subwatersheds within the USDA-ARS Southwest Watershed Research Center's Walnut Gulch Experimental Watershed (WGEW; fig. 4). Stepwise calibrations start at the rainfall simulator plot scale (12.2 m^2), where several key parameters for plot-scale runoff and erosion processes are calibrated and fixed. In the first step, saturated hydraulic conductivity (K_s) and pre-storm soil moisture (*SAT*) were calibrated against the hydrographs from four wet rainfall simulator plots where the objective function focused on runoff volume (sum of squared differences between observed and simulated runoff volumes). With these parameters fixed, Manning's roughness (n) was calibrated with an objective function focused on peak runoff rate (Q_p). With these parameters fixed, the Manning's rill roughness (*R*n), and rill and interill erodibility (*KR* and *KI*) were calibrated against sediment yields from the same four rainfall simulator events. At the hillslope scale, plot-scale parameters remain fixed from the previous calibration, and erosion/sediment transport parameters associated with concentrated flow processes are then calibrated. These parameters include sediment transport capacity (*TC*), interrill cover fraction (*IC*), and the shear stress partitioning ratio/factor (*TA*; Foster, 1982). K_s was also re-calibrated at this scale to assess its stability across spatial scales. Calibrations were performed against hydrographs from 17 events observed on LH106 (0.37 ha), 18 events on LH102 (1.65 ha), and 18 events on LH104 (4.41 ha, fig. 4), where each was modeled separately as representative single hillslopes to help determine the optimal hillslope size to calibrate against.

To complete the stepwise calibration, channels were added to the model representations of the LH104 (4.41 ha) watershed to drain the hillslope elements. Plot- and hillslope-scale parameters remained fixed from the prior calibrations, and channel parameters were then calibrated in a stepwise fashion: K_s and the coefficient of variation of K_s (CVK_s) using runoff volume, then Manning's roughness of the channel using Q_p, and finally the rainsplash erosion coefficient (SPLASH) and soil cohesion coefficient (COH) of the channel elements against the sediment yields from the same events. A traditional watershed-wide calibration of all the parameters (non-stepwise) was also performed at the small watershed scale for comparison to the stepwise calibration. Model calibrations for both the stepwise and traditional calibrations were performed using PEST (Doherty, 2004).

Calibration performance was evaluated by combining rankings of runoff volume, sediment yield, and peak flow

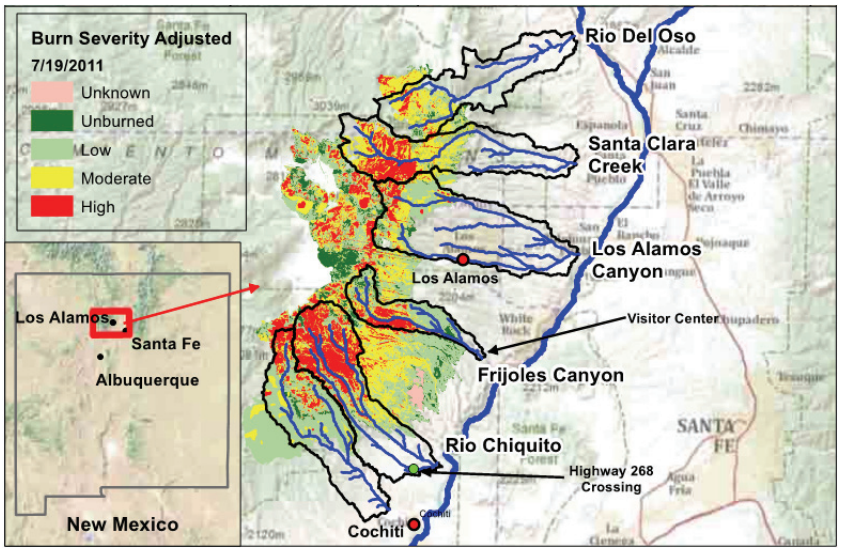

Figure 5. Burn-severity map for the Las Conchas fire, July 2011.

based on (1) predicted divided by observed, (2) slope of the 1:1 plots for predicted versus observed, and (3) the coefficient of determination of the 1:1 plots for predicted versus observed. Results indicate that the stepwise, multiscale calibrations are able to outperform the lumped calibrations for both hydrology and sediment at both the hillslope and watershed scales. At the hillslope scale, a single hillslope model element was used to compare the performance of the traditional calibration's hillslope parameters to the stepwise calibration's hillslope parameters. It is at this scale that the stepwise calibration shows its strength; the hillslope element comparison clearly shows that the traditional calibration did not represent hillslope processes well and relied solely on channel processes to increase calibration performance.

Because the stepwise calibrations clearly outperformed the traditional lumped calibrations at the hillslope scale, the results support the case for collecting data at multiple scales. In this study, K_s could not be scaled from rainfall simulator plots to the hillslope or watershed scale due to the difference in rainfall intensities and the relationship between rainfall intensity and infiltration rate (Hawkins and Cundy, 1987; Paige and Stone, 2003; Paige et al., 2002; Stone and Paige, 2003); however, the other parameters could be scaled from the plot to the hillslope and from the hillslope to the watershed effectively. By constraining the parameter space through the stepwise, multiscale calibration, parameter uncertainty is reduced when using these parameters at other scales. In essence, the additional information from the smaller area is useful in improving the calibration at a larger area, in contrast to a more traditional calibration which occurs only at a single (watershed) scale.

Case Study 2

In the second case study, AGWA and K2 are applied to pre- and post-fire conditions for the largest recorded fire in New Mexico: the 2011 Las Conchas fire. This fire began on 26 June 2011, and over the following month it burned nearly 63,373 ha (156,600 acres), destroyed 63 residences, forced the evacuation of 12,000 residents of Los Alamos, and burned over 1100 archeological sites and more than 60% of Bandelier National Monument. To mitigate the impacts of wildfires, interagency Burn Area Emergency Response (BAER) teams are dispatched to the fires to identify both natural and developed areas at risk and develop recommendations for mitigating these risks. This can include immediate measures such as applying hay or straw mulch to protect the soil from rapid erosion to longer-term measures such as replanting. Erosion, downstream flooding, and large quantities of sediment and ash transported downstream that might impact water supplies, roads, and structures are a major concern of the BAER teams.

When a wildfire is in the stages of suppression, a burn-severity map (fig. 5) is produced. Prior research by Canfield et al. (2005) and Goodrich et al. (2005) derived changes in K2 (and SWAT) parameters as a function of burn severity and pre-fire land cover type. Using nationally available digital datasets of topography, soils, and land cover, AGWA can be used to rapidly set up, parameterize, and simulate pre-fire watershed response while driving the model with nationally available National Oceanic and Atmospheric Administration (NOAA) design storms. Pre-fire K2 simulation outputs from all the overland and channel model elements are automatically saved by AGWA (e.g., runoff volume, Q_p, sediment yield, etc.). The burn-severity map (fig. 5) is then imported into AGWA to derive post-fire K2 parameter estimates, and a simulation with the same design storm(s) is conducted. AGWA has a differencing function with which the stored results from two simulations can be subtracted over all the spatially distributed model elements. These differences, in absolute or percentage change terms, can then be mapped back into the GIS display to provide a quick visual indication of watershed "hot-spots" where large changes between the two simulations have taken place. All the watersheds named in figure 5 were simulated with the above procedure using the 6-hour, 25-year design storm. The estimated relative change in pre- and post-fire peak runoff rate (Q_p) and sediment yield for the Frijoles watershed at the outlet adjacent to the Bandelier National Monument Visitor Center is approxi-

Table 3. Simulated change in Frijoles watershed response from before and after the Las Conchas fire for a spatially uniform 6-hour, 25-year design storm of 58 mm (2.28 in.) at the outlet adjacent to the Bandelier National Monument Visitor Center.

Simulated Variable at Watershed Outlet	Pre-fire	Post-fire	Percent Change (nearest 10%)
Peak flow (cfs)	2490	8930	260
Peak sediment (tons s^{-1})	14	120	760
Sediment yield (tons $acre^{-1}$)	5.1	21	310
Total sediment yield (tons)	59400	244800	310

mately +260% and +310%, respectively (table 3).

The pre- to post-fire relative changes in Q_p are illustrated spatially in figure 6, and the pre- and post-fire hydrograph is shown in figure 7. These modeling results proved to be valuable tools for the Las Conchas BAER team to focus where mitigation was undertaken and provide warnings and recommendations to downstream residents and resources managers. In a post-fire workshop, a local county official noted that it is difficult to defend a single flood peak numerical estimate in an ungauged watershed and that relative change estimates would be easier to explain to the public to draw attention to areas at risk. BAER team leaders concurred with this observation. When K2 and AGWA are employed in this type of relative change analysis, where the lack of data does not allow calibration and validation, it must be made clear that the model results should only be used as an indicator of areas of the watershed that might experience substantial changes in watershed response. If more quantitative change estimates are required, the relative change analysis described above can be employed to target where a more thorough data collection and modeling effort might be undertaken.

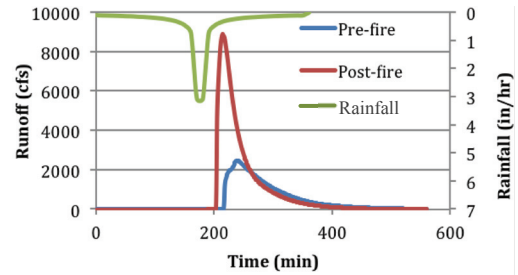

Figure 7. Simulated pre- and post-fire hydrographs at the Frijoles watershed outlet adjacent to the Bandelier National Monument Visitor Center for the 6-hour, 25-year design storm of 58 mm (2.28 in.).

Discussion

K2, like virtually all physically based, distributed watershed models, held great promise to improve the predictability of watershed response when initially conceptualized, developed, and introduced in the 1950s to 1970s. However, these models have fallen short of initial expectation for a variety of reasons. Grayson et al. (1992a, 1992b) critiqued physically based hydrology models, noting that simpler conceptual models may be just as good or superior. What most researchers fail to cite is the response by Smith et al. (1994), who noted that the physical processes of conservation of mass and energy are quite valid at small temporal and spatial scales. The real challenge is how to characterize and/or parameterize the variability of the abiotic and biotic media over and through which the processes are occurring at larger scales. In a careful examination of selected papers, Woolhiser (1996) assessed whether simpler models are superior to more complex physically based models. He found that, at relatively small scales, physically based models are in most cases better than simpler models. When they are not, it is often due to hydrologic measurement, variability, and interpretation problems. However, Woolhiser (1996) notes that "there are great difficulties involved in scaling up to larger watersheds" (p. 122). This was reiterated by Bulygina and Gupta (2009), who noted that application of physically based models at watershed scales (macroscales) carries an implicit premise of the ability to scale up from small-scale studies and observations. A critical observational weakness that still persists is adequate representation of the precipitation inputs driving watershed models. The profound role of precipitation uncertainty and its impact,

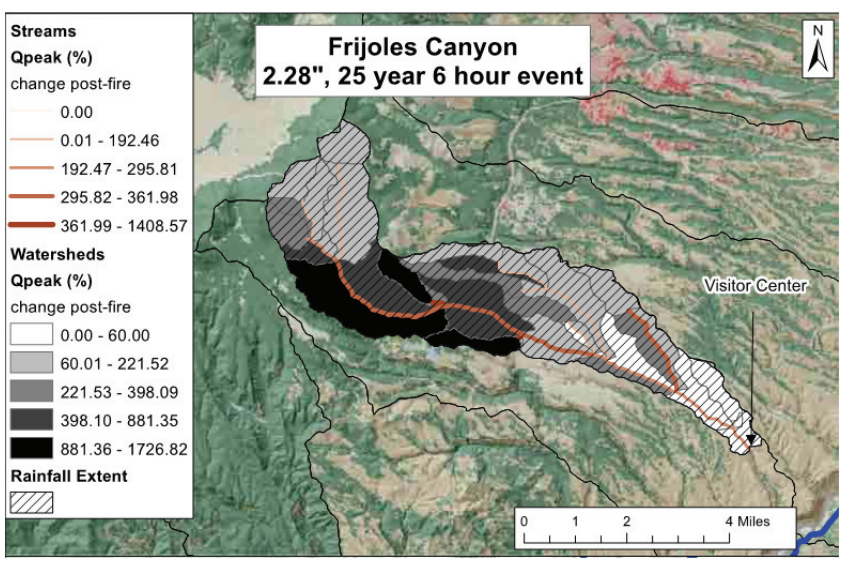

Figure 6. Percent change in pre- and post-fire peak runoff rates (streams and adjacent contributing areas) for the 6-hour, 25-year design storm as simulated by AGWA/K2. The diagonal shading indicates spatially uniform application of rainfall over the entire watershed.

even at small scales, on model performance has been documented in numerous studies (for K2, see Faurès et al., 1995; Goodrich and Woolhiser, 1994; Goodrich et al., 1994, 1995; and Yatheendradas et al., 2008). Our models will never be able to overcome the deficiencies of poorly characterized precipitation inputs.

Even with these shortcomings, it is important that we recognize the value of physically based models for watershed assessments and evaluation of alternative scenarios (Kepner et al., 2008) in ungauged basins where precipitation and runoff observations are not available (e.g., the second case study above). Simple conceptual or parametric models cannot be readily used to predict how watersheds might respond to different development scenarios and different spatial placement of conservation or land management practices. It is our contention that uncalibrated physically based models can be used with some confidence in identifying the trends and directions of changes in watershed response due to changes in watershed conditions, characteristics, or climatic inputs. We term this application "relative" watershed assessment, where a comparative change in watershed response from a current condition to an alternative condition can be predicted. This information can provide a valuable aid to watershed and natural resource managers in identifying portions of the watershed where conservation and mitigation efforts might be focused to offset the impacts of altered watershed characteristics due to common changes in land cover and land use (e.g., urbanization, wildfire, etc.). The typical "absolute" assessment is the case where adequate input-output observations are available to perform model calibration and validation to obtain predictions with some measure of model uncertainty. If model calibration and validation are acceptable, we believe more quantitative watershed assessments can be conducted.

In either a relative or absolute assessment, setup, parameterization, and execution of physically based watershed models and visualization of model results can be a time-consuming task. The AGWA tool expedites watershed assessments with distributed, physically based hydrologic models using nationally available digital datasets. K2 has a number of limitations. It is event-based, and it does not treat snowmelt, lateral subsurface flow, or biogeochemistry. Efforts to address many of these limitations are under way (see next section). A distinct advantage of K2 and AGWA is the explicit placement of development and conservation practices (e.g., buffer strips, vegetation change) and other modifications in the correct position to receive upslope flow. The new condition (e.g., buffer strip) can be represented as a "new" model element with distinct infiltration, hydraulic, and erosion parameters. Due to the runoff-runon routing coupled with dynamic infiltration in K2, the downstream effects of land cover changes can be readily simulated.

The USDA-ARS Southwest Watershed Research Center has a long-term commitment to support and further develop K2 and AGWA. Available resources may not allow an immediate response to user requests and questions, but we will attempt to respond in a timely manner.

Future Developments

A number of developments have been undertaken to broaden the application ability of K2. To conduct continuous modeling with management and biogeochemistry, the K2-O2 (KINEROS2-Opus2) prototype has been developed and initial small-scale testing has been completed (Massart et al., 2010). Opus2 (Müller et al., 2003) treats changes in plant cover, soil-water conditions, and the soil and plant characteristics of a catchment or portion thereof by management changes such as harvesting, planting, fertilizing, or tillage. The development of K2-O2 includes adding the soil and plant processes of Opus2 to K2, including treatment of evapotranspiration and snow accumulation and melt. These improvements enable K2 to operate in a continuous mode and effectively track the cycling of carbon, nitrogen, phosphorus, and several pesticides.

K2-NWS (National Weather Service) is an operational real-time flash flood forecasting model that provides temporal and spatial resolution not currently available with other NWS flash flood forecasting models. This is particularly important for smaller, fast-responding headwater basins. The computational structure of K2-NWS allows for compatibility with the nominal 4 to 5 min interval of the NWS Digital Hybrid Reflectivity (DHR) radar product to ingest this product as input for each radar scan in near real-time. To enable real-time forecasting, K2 was re-coded and a graphical user interface (GUI) was developed specifically for use at NWS Weather Forecast Offices. The GUI displays graphs of both radar-derived rainfall and predicted runoff. K2-NWS can also simulate a number of scenarios simultaneously, such as different Z-R (radar-rainfall) relationships, to help quantify the uncertainty in the resulting forecasts. K2-NWS has undergone calibration and limited operational testing in two disparate climatic/landscape regimes in the U.S. Unkrich et al. (2010) describe the forecast version of K2 and its application. K2-NWS is also in the process of being updated to improve flood forecasting where melting snow or rain-on-snow can cause flooding.

K2-SM-hsB couples KINEROS2 with a detailed snow model and lateral saturated subsurface transport algorithms. Like K2-O2, this will provide automated estimation of pre-storm initial conditions; however, it will not treat nutrient and carbon cycling. The first module consists of a distributed water and energy balance model of the vegetation canopy and the land surface. The second module is the soil-water balance model (Teuling and Troch, 2005), and the third module is based on the hillslope storage Boussinesq (hsB) equation (Troch et al., 2003). These modules operate at the hillslope scale, treating lateral saturated subsurface transport of soil water for complex hillslopes. Lateral saturated subsurface transport is parameterized using a new algorithm developed by Bogaart et al. (2008). The last component is a deep groundwater module (linear or non-linear reservoir receiving deep percolation from a leaky hsB module). Initial application and testing of the K2-SM-hsB model on several small watersheds in the northeastern U.S. was recently presented by Broxton et al. (2011).

K2-RHEM is a new rangeland erosion model. RHEM (Wei et al., 2007) is a newly conceptualized model de-

signed to treat rangeland conditions. It incorporates a new equation for splash and sheet erosion, which are typically the dominant erosion processes on rangeland sites in good condition with adequate cover. The model also represents the process of concentrated flow erosion, which may be important if a site is disturbed or if the cover consists of shrubs with large interplant distances and bare ground. RHEM incorporates the interaction between hydrology, erosion processes, and plant forms by parameterizing the hydraulic conductivity and erodibility parameters based on the classification of plant growth forms and cover conditions. Importantly, the new RHEM formulation has also been incorporated into the K2 model to represent rangeland hillslope elements. This will allow parameterization algorithms to be developed that can support both models.

K2-STWIR couples K2 with a module to simulate the overland transport of manure-borne pathogen and indicator organisms. Concerns over the microbial safety of receiving waters has resulted in the need for models to estimate the concentrations and total numbers of pathogen and indicator organisms leaving manured fields in overland flow, and the ability of vegetated filter strips to reduce the transport of pathogens and indicators from the edge of fields to surface water sources. In an attempt to address this need, the add-on STWIR (Solute Transport with Infiltration and Runoff) module has been developed and successfully tested with data from simulated rainfall experiments on vegetated and bare 2×6 m plots and with data from a 3 ha field obtained after manure applications. The STWIR module includes estimation of bacteria release from manure as affected by rainfall intensity and vegetation. Additional details on K2-STWIR can be found in Guber et al. (2011).

Upon testing and validation, the various K2 improvements described above will be compiled into a comprehensive version in which K2 model types can be user selected. We welcome outside developers and users to offer improvements to K2 and AGWA, and we will assist these efforts as time and resources allow. Please contact any of the co-authors if you would like to explore collaboration to improve K2 and/or AGWA.

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References

Al-Qurashi, A., N. McIntyre, H. Wheater, and C. L. Unkrich. 2008. Application of the Kineros2 rainfall-runoff model to an arid catchment in Oman. *J. Hydrol.* 355(1-4): 91-105.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resources Assoc.* 34(1): 73-89.

Beven, K. J. 1989. Changing ideas in hydrology: The case of physically based models. *J. Hydrol.* 105(1-2): 157-172.

Beven, K. J., and J. Freer. 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modeling of complex environmental systems using the GLUE methodology. *J. Hydrol.* 249(1-4): 11-29.

Bogaart, P. W., A. J. Teuling, and P. A. Troch. 2008. A state-dependent parameterization of saturated-unsaturated zone interaction. *Water Resources Res.* 44: W11423, doi: 10.1029/2007WR006487.

Broxton, P., P. A. Troch, M. Schaffner, C. Unkrich, and D. Goodrich. 2011. Improving flash flood predictions in moderate-sized watersheds by adding snowmelt and baseflow to KINEROS2. In *Proc. AGU Fall Meeting* (abstract and poster presentation). Washington, D.C.: American Geophysical Union.

Bulygina, N., and H. Gupta. 2009. Estimating the uncertain mathematical structure of a water balance model via Bayesian data assimilation. *Water Resources Res.* 45: W00B13, doi: 10.1029/2007WR006749.

Bulygina, N. S., M. A. Nearing, J. J. Stone, and M. H. Nichols. 2007. DWEPP: A dynamic soil erosion model based on WEPP source terms. *Earth Surface Proc. and Landforms* 32(7): 998-1012.

Burns, I. S. C. 2010. Reducing uncertainty in hydrological modeling: A step-wise multi-scale calibration approach. MS thesis. Tucson, Ariz.: University of Arizona, School of Natural Resources.

Canfield, H. E., and D. C. Goodrich. 2006. Differentiating the impact of parameter lumping from the impact of geometric simplification in modeling runoff and erosion. *Hydrol. Proc.* 20(1): 17-35.

Canfield, H. E., D. C. Goodrich, and I. S. Burns. 2005. Selection of parameter values to model post-fire runoff and sediment transport at the watershed scale in southwestern forests. In *Proc. 2005 Watershed Management Conf.* Reston, Va.: ASCE.

Doherty, J. 2004. *PEST: Model-Independent Parameter Estimation User's Manual*. 5th ed. Brisbane, Australia: Watermark Numerical Computing.

Engman, E. T. 1986. Roughness coefficients for routing surface runoff. *J. Irrig. and Drain. Eng.* 112(1): 39-53.

Faurès, J. M., D. C. Goodrich, D. A. Woolhiser, and S. Sorooshian. 1995. Impact of small-scale spatial rainfall variability on runoff simulation. *J. Hydrol.* 173(1-4): 309-326.

Foster, G. R. 1982. Modeling the erosion process. In *Hydrologic Modeling of Small Watersheds*, 297-360. ASAE Monograph 5. C. T. Haan, ed. St. Joseph, Mich.: ASAE.

Goodrich, D. C. 1990. Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. PhD diss. Tucson, Ariz.: University of Arizona.

Goodrich, D. C., and D. A. Woolhiser. 1994. Comment on "Physically based hydrologic modeling: 1. A terrain-based model for investigative purposes" by R. B. Grayson, I. D. Moore, and T. A. McMahon. *Water Resources Res.* 30(3): 845-847.

Goodrich, D. C., T. J. Schmugge, T. J. Jackson, C. L. Unkrich, T. O. Keefer, R. Parry, L. B. Bach, and S. A. Amer. 1994. Runoff simulation sensitivity to remotely sensed initial soil water

content. *Water Resources Res.* 30(5): 1393-1405.
Goodrich, D. C., J. M. Faures, D. A. Woolhiser, L. J. Lane, and S. Sorooshian. 1995. Measurement and analysis of small-scale convective storm rainfall variability. *J. Hydrol.* 173(1-4): 283-308.
Goodrich, D. C., L. J. Lane, R. M. Shillito, S. N. Miller, K. H. Syed, and D. A. Woolhiser. 1997. Linearity of basin response as a function of scale in a semiarid watershed. *Water Resources Res.* 33(12): 2951-2965.
Goodrich, D. C., D. G. Williams, C. L. Unkrich, J. F. Hogan, R. L. Scott, K. R. Hultine, D. Pool, A. L. Coes, and S. N. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River basin, Arizona. In *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, 77-99. F. M. Phillips, J. F. Hogan, and B. Scanlon, eds. Water Science and Application, vol. 9. Washington, D.C.: American Geophysical Union.
Goodrich, D. C., H. E. Canfield, I. S. Burns, D. J. Semmens, M. Hernandez, L. R. Levick, D. P. Guertin, and W. Kepner. 2005. Rapid post-fire hydrologic watershed assessment using the AGWA GIS-based hydrologic modeling tool. In *Proc. 2005 Watershed Management Conf.* Reston, Va.: ASCE.
Goodrich, D. C., C. L. Unkrich, R. E. Smith, D. P. Guertin, M. Hernandez, I. S. Burns, J. E. Massart, L. R. Levick, S. N. Miller, D. J. Semmens, and W. G. Kepner. 2010. The AGWA-KINEROS2 suite of modeling tools. In *Proc. 2010 Watershed Management Conf.*, 1294-1305. Reston, Va.: ASCE
Grayson, R. B, I. D. Moore, and T. A. McMahon. 1992a. Physically based hydrologic modeling: I. A terrain-based model for investigative purposes. *Water Resources Res.* 28(10): 2639-2658.
Grayson, R. B., I. D. Moore, and T. A. McMahon. 1992b. Physically based hydrologic modeling: 2. Is the concept realistic? *Water Resources Res.* 28(10): 2659-2666.
Green, W. H., and G. Ampt. 1911. Studies of soil physics: Part I. The flow of air and water through soils. *J. Agric. Sci.* 4: 1-24.
Guber, A. K., Y. A. Pachepsky, A. M. Yakirevich, D. R. Shelton, A. M. Sadeghi, D. C. Goodrich, and C. L. Unkrich. 2011. Uncertainty in modelling of faecal coliform overland transport associated with manure application in Maryland. *Hydrol. Proc.* 25(15): 2393-2404.
Hawkins, R. H., and T. W. Cundy. 1987. Steady-state analysis of infiltration and overland flow for spatially varied hillslopes. *Water Resources Bulletin* 23(2): 251-256.
Kalin, L., and M. H. Hantush. 2006. Comparative assessment of two distributed watershed models with application to a small watershed. *Hydrol. Proc.* 20(11): 2285-2307.
Kennedy, J. R. 2007. Changes in storm runoff with urbanization: The role of pervious areas in a semi-arid environment. MS thesis. Tucson, Ariz.: University of Arizona.
Kepner, W. G., D. J. Semmens, S. Bassett, D. A. Mouat, and D. C. Goodrich. 2004. Scenario analysis for the San Pedro River, analyzing hydrological consequences of a future environment. *J. Environ. Monitoring and Assessment* 94(1-3): 115-127.
Kepner, W. G., M. Hernandez, D. Semmens, and D. C. Goodrich. 2008. The use of scenario analysis to assess future landscape change on watershed condition in the Pacific Northwest (USA). In *Use of Landscape Sciences for Environmental Security*, 237-261. Dordrecht, The Netherlands: Springer.
Krause, P., D. P. Boyle, and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosci.* 5: 89-97.
Massart, J., D. P. Guertin, R. E. Smith, D. C. Goodrich, C. L. Unkrich, and L. R. Levick. 2010. K2-O2 (KINEROS-Opus) spatially based watershed hydrologic and biogeochemical model. In *Proc. Joint Federal Interagency Conf. on Sedimentation and Hydrologic Modeling*. Washington, D.C.: Advisory Committee on Water Information. Available at: http://acwi.gov/sos/pubs/2ndJFIC/index.html.
Michaud, J., and S. Sorooshian. 1994. Effects of rainfall sampling errors on simulation of desert flash floods. *Water Resources Res.* 30: 2765-2775, doi: 10.1029/94WR01273.
Miller, S. N., D. J. Semmens, D. C. Goodrich, M. Hernandez, R. C. Miller, W. G. Kepner, and D. P. Guertin. 2007. The automated geospatial watershed assessment tool. *J. Environ. Modeling and Software* 22(3): 365-377.
Müller, K., R. E. Smith, T. K. James, P. T. Holland, and A. Rahman. 2003. Prediction of field atrazine persistence in an allophanic soil with Opus2. *Pest Mgmt. Sci.* 60(5): 447-458.
Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: I. A discussion of principles. *J. Hydrol.* 10(3): 228-290.
Nikolova, M., N. Stoyan, V. Nikolov, I. Zuzdrov, M. Genev, T. Kotsev, R. Vatseva, and Y. Krumova. 2009. Implementation of the "KINEROS" model for estimation of the flood prone territories in the Malki Iskar River basin. *Info. and Security* 24: 76-88.
NSERL. 1995. WEPP user summary. NSERL Report No. 11. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory. Available at: www.ars.usda.gov/SP2UserFiles/ad_hoc/36021500WEPP/usersum.pdf.
Onstad, C. A., and D. L. Brakensiek. 1968. Watershed simulation by stream path analogy. *Water Resources Res.* 4(5): 965-971. doi: 10.1029/WR004i005p00965.
Paige, G. B., and J. J. Stone. 2003. Infiltration and runoff: Point and plot scale. In *Proc. 1st Interagency Conf. on Research in the Watersheds*, 186-191. Washington, D.C.: USDA-ARS.
Paige, G. B., J. J. Stone, D. P. Guertin, and L. J. Lane. 2002. A strip model approach to parameterize a coupled Green-Ampt kinematic wave model. *J. American Water Resources Assoc.* 38(5): 1363-1377.
Paige, G. B., J. J. Stone, J. Smith, and J. R. Kennedy. 2003. The Walnut Gulch rainfall simulator: A computer-controlled variable-intensity rainfall simulator. *Applied Eng. in Agric*. 20(1): 25-31.
Parlange, J.-Y., I. Lisle, R. D. Braddock, and R. E. Smith. 1982. The three-parameter infiltration equation. *Soil Sci.* 133(6): 337-341.
Renard, K. G., L. J. Lane, J. R. Simanton, W. E. Emmerich, J. J. Stone, M. A. Weltz, D. C. Goodrich, and D. S. Yakowitz. 1993. Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrol. Sci. and Tech*. 9(1-4): 149-159.
Renard, K. G., M. H. Nichols, D. A. Woolhiser, and H. B. Osborn. 2008. A brief background on the U.S. Department of Agriculture Agricultural Research Service Walnut Gulch Experimental Watershed. *Water Resources Res.* 44: W05S02, doi: 10.1029/2006WR005691.
Roberts, A. J. 2003. A holistic finite difference approach models linear dynamics consistently. *Math. of Computation* 72(241): 247-262.
Rovey, E. W. 1974. A kinematic model for upland watersheds. MS thesis. Fort Collins, Colo.: Colorado State University.
Schaffner, M., C. L. Unkrich, and D. C. Goodrich. 2010. Application of the KINEROS2 site-specific model to south-central NY and northeast PA: Forecasting gages and ungaged fast-responding watersheds. Tech. Attachment No. 2010-01. Bohemia, N.Y.: National Weather Service, Eastern Region.
Semmens, D. J., and D. C. Goodrich. 2005. Planning change: Case studies illustrating the benefits of GIS and land-use data in environmental planning. *Proc. Intl. Conf. on Hydrological Perspectives for Sustainable Development*, 346-354. Roorkee, India: Indian Institute of Technology.

Semmens, D. J., D. C. Goodrich, C. L. Unkrich, R. E. Smith, D. A. Woolhiser, and S. N. Miller. 2008. Chapter 5: KINEROS2 and the AGWA modeling framework. In *Hydrological Modelling in Arid and Semi-Arid Areas*, 49-69. H. Wheater, S. Sorooshian, and K. D. Sharma, eds. Cambridge, U.K.: Cambridge University Press.

Sevruk, B. 1989. Wind-induced measurement error for high-intensity rains. In *Proc. WMO/IAHS/ETH Workshop*, 199-204. B. Sevruk, ed. Zurich, Switzerland: Swiss Federal Institute of Technology.

Smith, R. E., and D. C. Goodrich. 2000. Model for rainfall excess patterns on randomly heterogeneous areas. *J. Hydrol. Eng.* 5(4): 355-362.

Smith, R. E., and J.-Y. Parlange. 1978. A parameter-efficient hydrologic infiltration model. *Water Resources Res.* 14(3): 533-538.

Smith, R. E., D. C. Goodrich, D. A. Woolhiser and J. R. Simanton. 1994. Comment on "Physically based hydrologic modeling 2: Is the concept realistic?" by R. B. Grayson, I. D. Moore, and T. A. McMahon. *Water Resources Res.* 30(3): 851-854.

Smith, R. E., D. C. Goodrich, D. A. Woolhiser, and C. L. Unkrich. 1995. Chapter 20: KINEROS: A kinematic runoff and erosion model. In *Computer Models of Watershed Hydrology*, 697-732. V. J. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Smith, R. E., K. R. J. Smettem, P. Broadbridge, and D. A. Woolhiser. 2002. Infiltration theory for hydrologic applications. In *Infiltration Theory for Hydrologic Applications.* Water Resources Monograph Series, vol. 15. Washington, D.C.: American Geophysical Union

Stone, J. J., and G. B. Paige. 2003. Variable rainfall intensity rainfall simulator experiments on semi-arid rangelands. In *Proc. 1st Interagency Conf. on Research in the Watersheds*, 83-88. Washington, D.C.: USDA-ARS.

Teuling, A., and P. A. Troch. 2005. Improved understanding of soil moisture variability dynamics. *Geophys. Res. Letters* 32: L05404, doi: 10.1029/2004GL021935.

Troch P. A., C. Paniconi, and E. E. van Loon. 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. *Water Resources Res.* 39(11): 1316, doi: 10.1029/2002WR001728.

Unkrich, C. L., M. Schaffner, C. Kahler, D. C. Goodrich, P. Troch, H. Gupta, T. Wagener, and S. Yatheendradas. 2010. Real-time flash flood forecasting using weather radar and a distributed rainfall-runoff model. In *Proc. Joint Federal Interagency Conf. on Sedimentation and Hydrologic Modeling*. Washington, D.C.: Advisory Committee on Water Information. Available at: http://acwi.gov/sos/pubs/2ndJFIC/index.html.

Vrugt, J. A., W. Bouten, H. V. Gupta, and J. W. Hopmans. 2003. Toward improved identifiability of soil hydraulic parameters: On the selection of a suitable parametric model. *Vadose Zone J.* 2(1): 98-113.

Wei, H., M. A. Nearing, and J. J. Stone. 2007. A new sensitivity analysis framework for model evaluation and improvement using a case study of the Rangeland Hydrology and Erosion Model. *Trans. ASABE* 50(3): 945-953.

Woolhiser, D. A. 1975. Simulation of unsteady overland flow. In *Unsteady Flow in Open Channels*, vol. II: 502. K. Mahmood and V. Yevjevich, eds. Fort Collins, Colo.: Water Resources Publications.

Woolhiser, D. A. 1996. Search for physically based runoff model: A hydrologic El Dorado? *J. Hydraulic Eng.* 122(3): 122-129.

Woolhiser, D. A., C. L. Hanson, and A. R. Kuhlman. 1970. Overland flow on rangeland watersheds. *J. Hydrol. (New Zealand)* 9(2): 336-356.

Woolhiser, D. A., R. E. Smith, and D. C. Goodrich. 1990. *KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual*. ARS-77. Tucson, Ariz.: USDA-ARS Southwest Watershed Research Center. Available at: www.tucson.ars.ag.gov/kineros.

Wu, Y.-H., D. A. Woolhiser, and V. Yevjevich. 1982. Effects of spatial variability of hydraulic resistance on runoff hydrographs. *J. Hydrol.* 59(3-4): 231-248.

Yatheendradas, S., T. Wagener, H. Gupta, C. L. Unkrich, D. C. Goodrich, M. Schaffner, and A. Stewart. 2008. Understanding uncertainty in distributed flash flood forecasting for semiarid regions. *Water Resources Res.* 44: W05S19, doi: 10.1029/2007WR005940.

Zevenberger, L. W., and M. R. Peterson. 1998. Evaluation and testing of storm-event hydrologic models. In *Proc. ASCE Natl. Conf. Hydraulic Eng.*, 467-472. Reston, Va.: ASCE.

Ziegler, A. D., T. W. Giambelluca, L. T. Tran, T. T. Vana, M. A. Nullet, J. Fox, T. D. Vien, J. Pinthong, J. F. Maxwell, and S. Evett. 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Evidence of accelerated overland flow generation. *J. Hydrol.* 287(1-4): 124-146.

Ziegler, A. D., T. W. Giambelluca, D. Plondke, S. Leisz, L. T. Tran, J. Fox, M. A. Nullet, J. B. Vogler, D. M. Troung, and T. D. Vien. 2007. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Buffering of Hortonian overland flow. *J. Hydrol.* 337(1-2): 52-67.