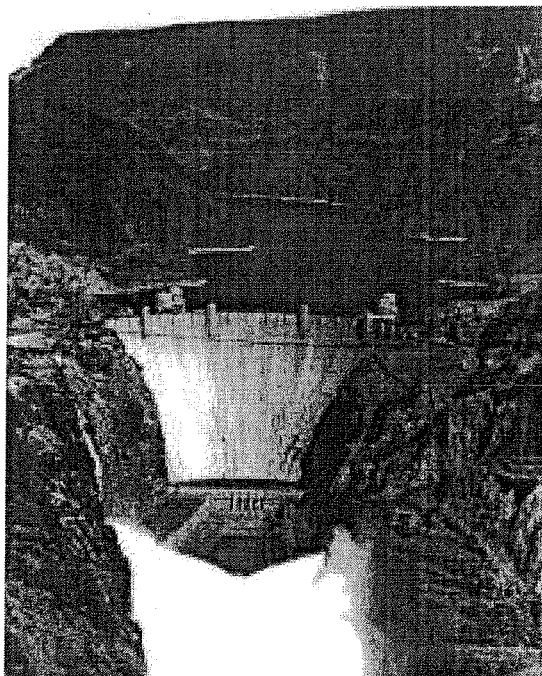# Second Federal Interagency Hydrologic Modeling Conference

July 28 – August 1, 2002

RIVIERA HOTEL, LAS VEGAS, NEVADA

"Hydrologic Modeling for the 21st Century"

AGENDA

KINEROS2 - A DISTRIBUTED KINEMATIC RUNOFF AND EROSION MODEL

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Abstract KINEROS2 (K2) is a broadly updated version of the KINEROS kinematic runoff and erosion model. This is physically-based model describing the processes of interception, infiltration, runoff generation, erosion, and sediment transport from small agricultural and urban watersheds for individual rainfall-runoff events. While KINEROS2 has evolved primarily as a research tool it is currently being used in consulting and in a more operational watershed assessment context. This has been facilitated by the incorporation of KINEROS2 into the AGWA (Automated Geospatial Watershed Assessment) tool in support of US-EPA landscape analysis activities. This paper will focus on new model features that have not been previously presented in the literature.

INTRODUCTION

The origin of the KINEROS model routed runoff from hillslopes represented by a cascade of one-dimensional overland flow planes contributing laterally to channels dates from the late 1960's (Woolhiser, et al., 1970). Rovey (1974) coupled interactive infiltration to this model and released it as KINGEN (Rovey et al., 1977). After significant validation using experimental data, KINGEN was modified to include erosion and sediment transport as well as a number of additional enhancements resulting in KINEROS (KINematic runoff and EROSion) which was released in 1990 (Woolhiser et al., 1990) and described in some detail by Smith et al. (1995a). Subsequent research with, and application of KINEROS, has lead to additional model enhancements and a more robust model structure resulting in KINEROS2 (K2). Here, instead of a lengthy written description of K2, general model structure is discussed and two summary tables are presented to provide an overview of 1) model element types for watershed characterization; and, 2) model representations of hydrological processes. Supporting references, which provide significantly more detail than afforded in this format, are also noted in the tables. Several model features illustrating new capabilities are described in further detail with a related example. The most up to date code and model description is available at http://www.tucson.ars.ag.gov/kineros/. The paper concludes with a brief description of model enhancements under development and the AGWA GIS tool developed to build K2 input files and execute the model.

PRIMARY KINEROS2 MODEL ATTRIBUTES

In K2, the watershed being modeled is characterized by a variety of spatially distributed model element types. The model elements can be configured to effectively abstract the watershed into a series of shapes (rectangular overland flow plane, simple and compound trapezoidal channels, detection ponds, etc.) which can be oriented so that 1-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. large impervious areas, abrupt changes in slope, soil type, or hydraulic roughness, etc.). Cascades of overland flow elements (abstracted to regular planar rectangular surfaces) with different widths can be formed to approximate converging or diverging contributing areas. As currently implemented, the computational order of the K2 model simulation, must proceed from upslope / upstream elements to downstream elements. This is required to ensure that upper boundary conditions for the element being processed are defined.

Walnut Gulch Subwatershed No. 11 showing the watershed boundary and primary channel network (the pond catchment is a noncontributing area).

The minimum representation required to support the channel network

Model system consisting of rectangular overland flow planes contributing to a network of trapezoidal open channel segments

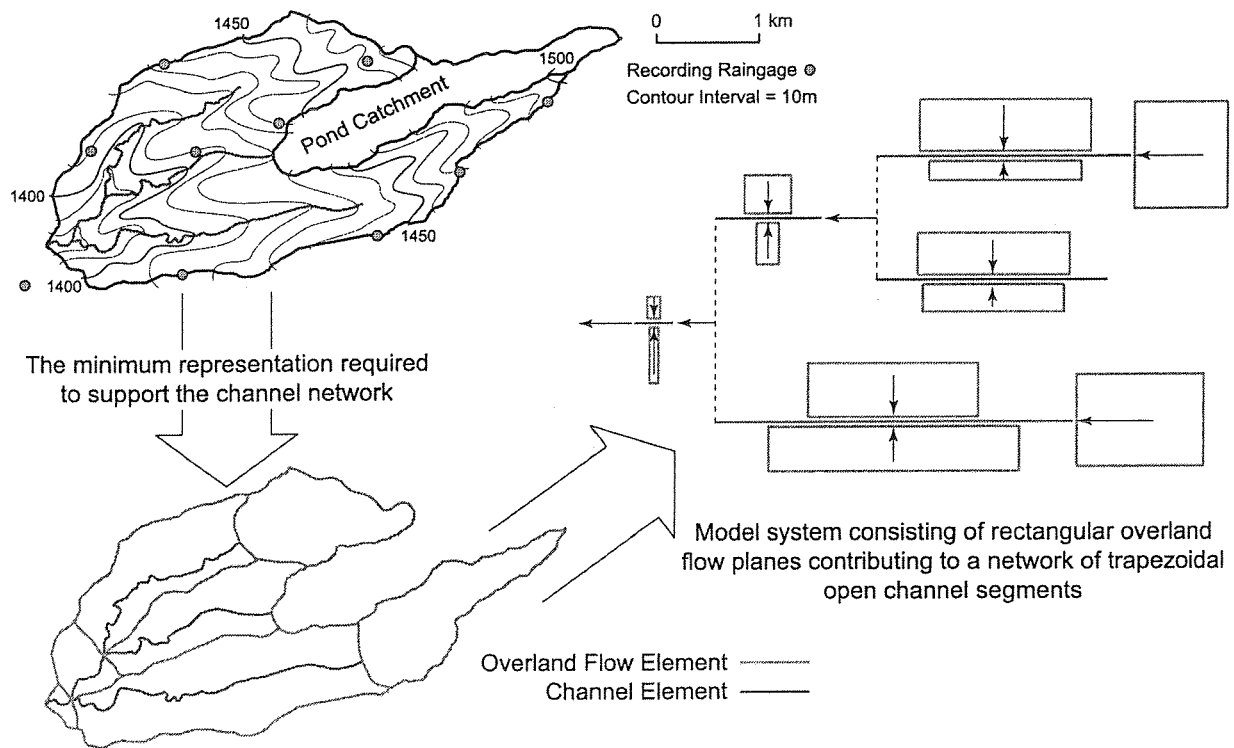Overland Flow Element ----------
Channel Element ————

Figure 1. Process by which topographic data and channel network topology are abstracted into the simplified geometry defined by KINEROS2 elements. Note that overland flow planes are dimensioned to preserve average flow length, and therefore planes contributing laterally to channels generally do not have widths that match the channel length.

Attributes for each of the model elements are summarized in Table 1. The hydrological processes represented in K2, which are pertinent to event-based simulations with intermittent rainfall, are summarized in Table 2.

Table 1: KINEROS2 Model Elements for Representing a Watershed

Model Element Type	Attributes	References
Overland flow	Planes; cascade allowed with varied lengths, widths, and slopes; microtopography	32, 25, 6, 7
Urban overland	Mixed infiltrating/impervious with runoff-runon	25
Channels	Simple and compound trapezoidal	32, 25, 3
Detention Structures	Arbitrary shape, controlled outlet - discharge f(stage)	32, 25, 6, 7
Culverts	Circular with free surface flow	32, 25
Injection	Hydrographs and sedigraphs injected from outside the modeled system	

Table 2: KINEROS2 Hydrological Process Representation

Process Representation	Attributes	References
Rainfall	Breakpoint, multiple rain gauges, space-time rainfall intensity interpolation to centroid of model elements	32, 25, 5, 8, 9, 14
Interception	Reduces rainfall intensities to simulate partial areal vegetation coverage	32, 25
Soil Moisture	Externally required initial condition; physically-based approximation for the redistribution of soil water during a rainfall hiatus	32, 25, 9, 14, 23
Infiltration during rainfall	Smith-Parlange/Green-Ampt; lognormal distribution of small scale variability of hydraulic conductivity is represented; single or two layer systems to simulate infiltration or saturation excess runoff generation	32, 25, 2, 21, 22, 28, 29, 31, 33
Infiltration during rainfall hiatus and on recession	Microtopographic reduction in wetted area; recovery of infiltration capacity during a hiatus; and modified infiltration rates following a hiatus.	23
Routing	Kinematic wave; interactive with infiltration/erosion; treats channel transmission losses with same infiltration approximation as in overland elements; Manning's and Chezy roughness	32, 25, 20, 30, 10
Erosion and sediment transport	Rain splash and Hydraulic; multiple particle class sizes (up to 5 classes); transport by modified Engelund and Hansen (1967)	32, 25, 4, 11, 26, 27
Base flow	User specified in channel elements	

KINEROS2 Computation Features: A four-point finite difference solution is utilized to the solve routing and erosion partial differential equations in K2 (Woolhiser et al., 1990; Smith et at., 1995b). For each model element a total volume balance is computed as a check for excessive numerical error. A global or watershed volume balance is also computed at the conclusion of the simulation. The time step used for simulation is user-defined but may be reduced internally to accommodate rainfall breakpoints, and optionally to satisfy the Courant condition. The spatial step for the finite-difference approximation is based on a user defined characteristic length. K2 differs from KINEROS in that there is no limit to the number of model elements that can be used to describe a watershed. The linkage between and computational order of elements must be defined by the user, or alternatively the AGWA (Automated Geospatial Watershed Assessment) tool can automatically perform this task using a Geographic Information System (GIS) (Miller et al., 2002). In either case the program will report unconnected elements resulting from errors in the linkage or computational order.

Soil Infiltration: Several major changes in the soil infiltration treatment within K2 have been implemented since the last significant description of the model (Smith et al., 1995a). These include extension from one to two soil layers, microtopography and lognormally distributed saturated hydraulic conductivity. Because these interact with both runoff and erosion dynamics a brief description of infiltration treatment and its interactions are presented.

Conceptually, K2 represents a soil as either one or two layers, with a user-defined upper layer depth, exhibiting lognormally distributed values of saturated hydraulic conductivity, K_S. The surface of the soil exhibits microtopographic variations which are characterized by a mean micro-rill spacing and height which is similar in implementation to that of the EUROSEM model (Smith et al., 1995b). This feature is significant in the model, since there is an explicit interaction between surface flow and infiltration. Infiltration may occur from either rainfall directly on the soil or from ponded surface water created from previous rainfall excess. Also involved in this interaction, as discussed below, is the small scale random variation of K_S.

Basic Infiltrability: Infiltrability, f_c, is the rate at which soil will absorb water (vertically) when there is an unlimited supply at the surface. Infiltration rate, f, is equal to rainfall, $r(t)$, until this limit is reached. K2 uses the Parlange 3-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. A scaling parameter, γ, is the third parameter in addition to the two basic parameters; saturated hydraulic conductivity, K_S, and the capillary length scale, G. Most soils exhibit infiltrability behavior intermediate to these two models, and K2 uses a γ value of 0.85. The state variable for infiltrability is the initial water content, in the form of the soil saturation deficit, $\Delta\theta_i$, defined as the saturated water content minus the initial water content. In terms of these variables, the basic model is:

$$f_c = K_s \left[1 + \frac{\gamma}{\exp\left(\dfrac{\gamma \, I}{G \varDelta \theta_i}\right) - 1} \right] \qquad (1)$$

The K2 infiltration model employs the *infiltrability depth approximation* (IDA) from (Smith, 2002) in which f_c is described as a function of infiltrated depth I. This approach derives from the "time compression" approximation earlier suggested by Reeves and Miller (1975): time is not compressed but I is a surrogate for time as independent variable. This form of infiltrability model eliminates the separate description of ponding time and the decay of f after ponding.

Small-scale Spatial Variability: The infiltrability model of K2 incorporates the coefficient of variation of K_S, CV_K, as described by Smith and Goodrich (2000). Assuming that K_S is distributed log-normally, there will for all normal values of rain intensity r be some portion of the surface for which $r < K_S$. Thus for that area there will be no potential runoff. Smith and Goodrich (2000) simulated ensembles of distributed point infiltration and arrived at a function for infiltrability which closely describes this ensemble infiltration behavior:

$$f_{e*} = 1 + (r_{e*} - 1)\left\{1 + \left[\frac{(r_{e*} - 1)}{\gamma}\left(e^{\gamma I_{e*}} - 1\right)\right]^c\right\}^{-1/c} \quad , \quad r_{e*} > 1 \qquad (2)$$

in which f_{e*} and r_{e*} are infiltrability and rain rate scaled on the ensemble effective asymptotic K_S value. This effective ensemble K_e is the appropriate K_S parameter to use in the infiltrability function for an ensemble, and is a function of CV_K and r_{e*}; the ratio of r to ensemble mean of K_S defined as $\xi(K)$. Smith and Goodrich (2000) describe how effective K_e drops significantly below $\xi(K)$ for low relative rain rates and high relative values of CV_K.

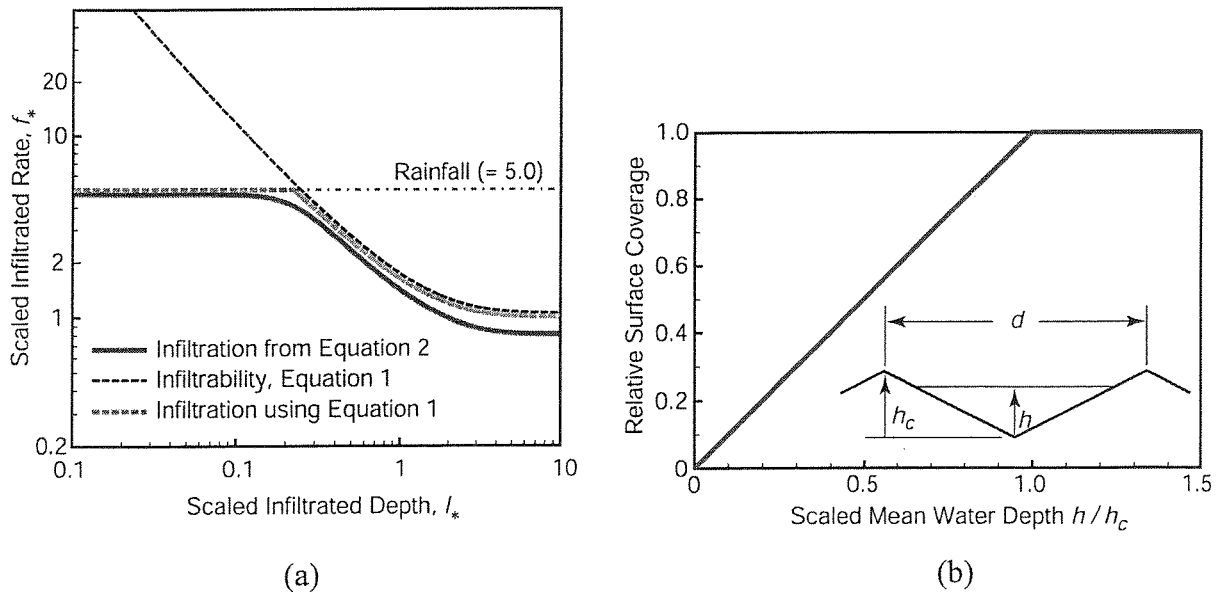(a)   (b)

Figure 2. a) Comparison of infiltrability function with and without consideration of randomly varying K_s, b) Assumed relation of covered surface area to scaled mean water depth. Parameter h_c is the microtopographic relief height and d is the mean microtopographic spacing.

Equation 2 also scales I by the parameter pair $G\Delta\theta_i$. The additional parameter c is a function only of CV_K and the value of r. There is evidence in watershed runoff measurements (Smith and Goodrich, 2000) that this function is more appropriate for watershed areas than the basic (uniform K_s) relation of Equation 1. Figure 2a compares Equation 2 for $CV_K = 0.8$ to Equation 1, in which CV_K is implicitly zero. Note that equation 2 does not have a unique ponding point, but rather exhibits a gradual evolution of runoff as more of the area contributes excess infiltration, and thus Equation 2 describes infiltration rate rather than infiltrability.

Infiltration with Two-layer Soil Profiles: For a soil with two layers, either layer can be flow limiting and thus can be the infiltration control layer, depending on the soil properties, thickness of the surface layer, and the rainfall rate. There are several possibilities, most of which have been discussed by Corradini, et al. (2000) and Smith et al. (1993). KINEROS2 attempts to model all cases in a realistic manner, including the redistribution of soil water during periods when r is less than K_s and thus runoff is not generated from rainfall.

Upper Soil Control: For surface soil layers that are sufficiently deep, the case where $r > K_{S1}$ resembles a single soil profile. However, when the wetting front reaches the layer interface, the capillary drive parameter and the effective value of K_S for equation 1 must be modified. The effective parameters for this case have been discussed by Smith (1990). The effective K_S parameter, K_∞, is found by solving the steady unsaturated flow equation with matching values of soil capillary potential at the interface. This effective conductivity (K_∞) is independent of the effective ensemble conductivity (K_e) defined above. If user-defined spatial variability of K_S is used ($CV_K > 0$), K_∞ may be modified to reflect the spatial variability.

Lower Soil Control: When the condition $K_{S1} > r > K_{S2}$ occurs, the common runoff mechanism called saturation runoff may occur. K2 treats the limitation of flow through the lower soil by application of Equation 1 or 2 to flow through the layer interface, and when that water which cannot enter the lower layer has filled the available pore space in the upper soil, runoff is considered to begin. The available pore space in the upper soil is the initial deficit $\Delta\theta_{1i}$ less rain water in transit through the upper soil layer. For reasonably deep surface soil layers, it is possible for control to shift from the lower to the upper if the rainfall rate increases to sufficiently exceed K_{S1} before the surface layer is filled from flow limitations into the lower layer.

An example of runoff generation from a single and two-layer soil profile is illustrated in Figure 3. Both the single layer profile and the upper soil layer in the two-layer profile have identical porosity and saturated hydraulic conductivity. The shallow top layer in the two-layer case has significantly more available pore space to store and transmit infiltrated water than the lower, less permeable layer. Note that the burst of rainfall occurring at roughly 850 minutes into the event produces identical Hortonian runoff from both profiles for approximately 40 minutes. The wetting front has not yet reached the lower layer in the two-layer profile, and runoff is produced by rainfall excess. The long, low-intensity period of rainfall between 950 and 1850 minutes is fully absorbed by both soil profiles but is effectively filling the available pore space in the shallow upper layer of the two-layer profile. When the rainfall intensity increases at

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approximately 1850 minutes to around 5 mm/hr (r < Ks of the upper soil layer), runoff is generated via saturation excess from the upper layer in the two-layer system because the lower layer is limiting infiltration. The single layer profile again generates runoff via rainfall excess when the rainfall intensity increases (at ~2010 min.) above the infiltrability of the soil. It should be noted that, at this time, K2 does not treat lateral flow along the interface of the two soil layers.

Redistribution and Initial Wetting: Rainfall patterns of all types and rainfall rates of any value should be accommodated realistically in a robust infiltration model. This includes the effect on runoff potential of an initial storm period of very low rainfall rates, and the reaction of the soil infiltrability to periods within the storm of low or zero rainfall rates. K2 simulates the wetting zone changes due to these conditions with an approximation described by Smith et al. (1993) and Corradini et al. (2000). Briefly, the wetting profile of the soil is described by a water balance equation in which the additions from rainfall are balanced by the increase in the wetted zone value of θ and the extension of the wetted zone depth due to the capillary drive of the wetting front. The soil wetted shape is treated as a similar shape of depth Z with volume $\beta Z(\theta_o - \theta_i)$ where β is a constant scale factor defined in Smith et al. (1993). Space does not permit detailed description here, but the method is applicable to prewetting of the soil as well as the decrease in θ_o during a storm hiatus. It is also applicable, with modification, to soils with two layers.
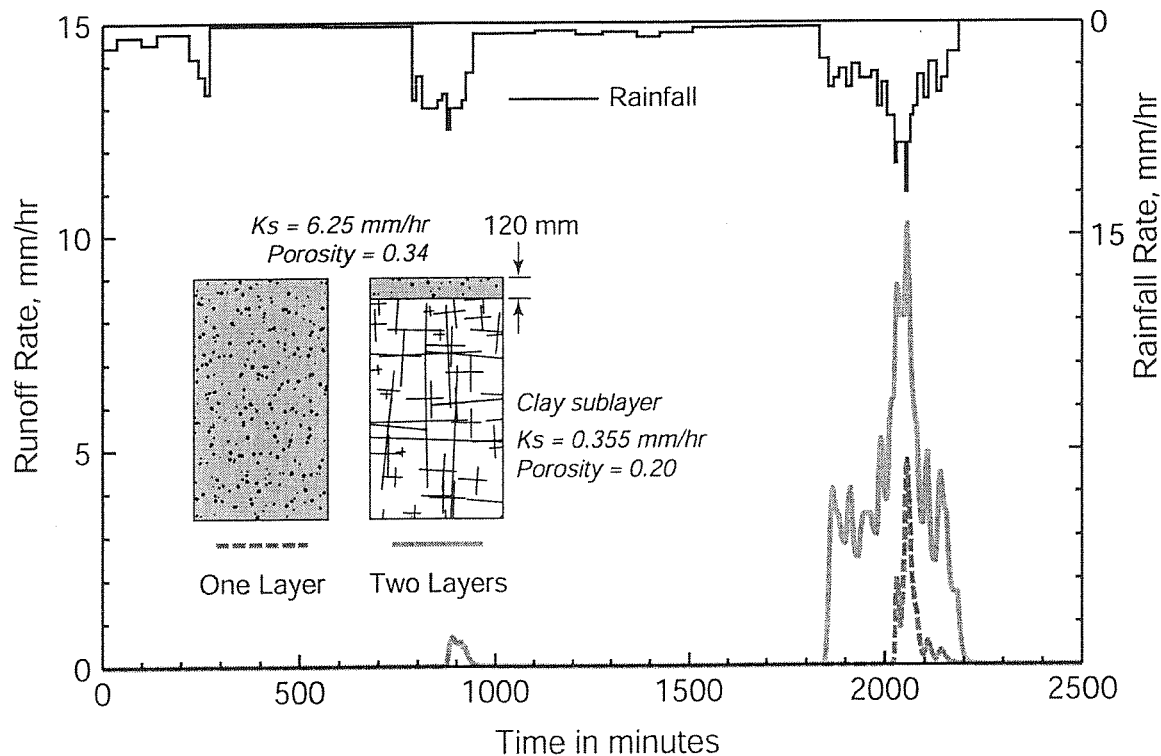

Figure 3: Example simulation for a single and two-layer soil exhibiting infiltration and saturation excess runoff generation.

Interactions of Surface Water Flow and Erosion: Figure 2b presents the conceptual relation used in KINEROS2 to describe the relation of relative area covered by surface water to effective mean hydraulic depth, h_m. This effective depth is the cross sectional area of flow divided by the width of the element. The relation here is scaled, and the maximum topographic relief, h_c, is a parameter that can be user-defined. Infiltration from the portion of the surface covered by water proceeds at the infiltrability rate, and the remaining area will have a value of f determined by the rainfall rate. Thus infiltration proceeds during recession flows depending on the micro-topography. The infiltration model may also be applied to dry channels subject to inflow regardless of the relation of channel K_S to rainfall rate. By default, channels are treated as linear features without area, but rainfall on channels can be modeled if it is considered significant. The user should be aware that the channel areas will then contribute to the total watershed area, so adjacent overland flow elements may have to be reduced by the area of the channel to maintain the same overall watershed area. Moreover, when small scale variation of K_S is described by a value of CV_K, the portion of the surface covered with water is simply the ensemble mean of K_S [$\xi(K)$] (independent of r) and the remainder is subject to an effective value determined by CV_K and relative r.

The treatment of infiltration and microtopography also interacts with erosion as the effective mean hydraulic depth and related velocity drive the hydraulic erosion component. Note that the K2 concept of microtopography does not directly define rill and interrill regions. The local erosion/deposition rate is determined by two independent erosion processes: rainsplash erosion, which is dependent on the rain rate and water depth, and net hydraulic erosion, the removal or deposition of material by flowing water. Because rills and interrills are often defined in differing ways, KINEROS2 does not explicitly separate "rill" and "interrill" processes (Smith et al., 1995b). Both processes can occur simultaneously in shallow flow as splash erosion can occur on the sides of rills and in rills when flow is sufficiently shallow so that raindrop momentum is transmitted to the soil surface.

Urban Element: The urban element represents a composite of up to six overland flow areas (Figure 4), including various combinations of pervious and impervious surfaces, contributing laterally to a paved, crowned street. This type of model element was conceived to provide an aggregate representation of a typical residential or urban block. This aggregate model representation is offered as an alternative to describing each roof, driveway, lawn, sidewalk, etc., as individual model elements. The urban element can receive upstream inflow (into the street) but not lateral inflow from adjacent urban or overland flow elements. The relative proportions of the six overland flow areas are specified as fractions of the total element area.
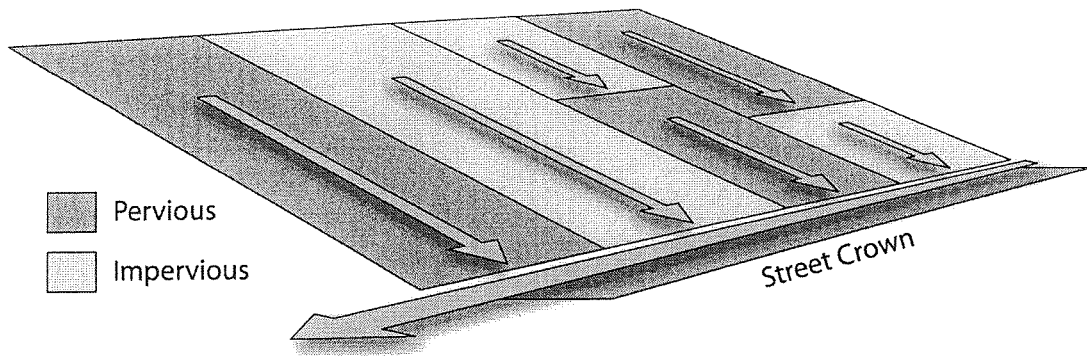
Figure 4. Layout of urban element showing all six possible contributing areas.

For example, aerial photography of a typical residential block might be used to estimate the following percentage areas of infiltrating and impervious surfaces. Infiltrating area flowing directly into the street (left most strip in Figure 4); impervious area flowing directly into the street (second strip from left in Figure 4); or impervious area flowing into an infiltrating area before entering the street (third strip from left in Figure 4) and so on. It is not required to have all six types, but intervening connecting areas must be present if the corresponding indirectly connected area is specified. The element is modeled as rectangular.

Compound Channel: A compound trapezoidal channel is obtained from two independent kinematic equations describing a parallel pair of channels, each with its own hydraulic and infiltrative characteristics. For each channel, the geometric relations for cross-sectional area of flow A and wetted perimeter P are expressed in terms of the same depth, h, whose zero value corresponds to the level of the lower-most channel segment (Figure 5). Note that the wetted perimeters do not include the interface where the two sections join, i.e., this constitutes a frictionless boundary (dotted vertical line). There is no need to explicitly account for mass transfer between the two channels, as it is implicit in the common depth (level water surface) requirement. However, for exchange of suspended sediment, a net transfer rate q_t is recovered via a mass balance after computation of h at the advanced time step.
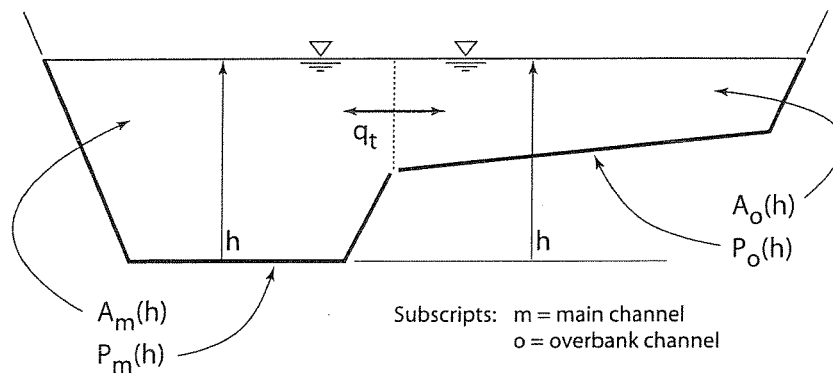

Figure 5. Basic compound channel cross section geometry.

ONGOING DEVELOPMENTS AND CONCLUSIONS

Ongoing Developments: The Fortran 77 code is currently being modified to take advantage of Fortran 90/95 features and will also be restructured so that the user interface is completely uncoupled from the model itself. K2 will communicate with the user interface through a collection of functions and subroutines. This will simplify the maintenance and continued development of the computational core, as well as the use of more powerful, non-Fortran development tools when building a graphical user interface. It will also provide the option of supporting one or more of the standardized object interface specifications, such as COM, CORBA or SOAP. An additional requirement is that the new version be backward-compatible in the sense that it will run with preexisting input files.

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The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Office of Research and Development, Landscape Ecology Branch, has developed the AGWA (Automated Geospatial Watershed Assessment) GIS tool to automate input parameter file creation for KINEROS2 and SWAT (Arnold et al., 1994), execute the models, and spatially display model results. AGWA is packaged as an ArcView 3.x extension and uses widely available standardized spatial datasets that can be obtained via the internet. A separate paper describing AGWA in more detail is also a part of the 2002 Federal Interagency Hydrologic Modeling Conference proceedings (Miller et al., 2002). In addition, the AGWA web site can be accessed at: http://www.tucson.ars.ag.gov/agwa/ and an example of its successful application is presented in Hernandez et al. (2000).

With K2 – GIS coupling completed via AGWA, the next major objective is to couple the event-based K2 storm model to an interstorm model to effectively make K2 a continuous hydrologic simulation model. An interstorm model being considered is presented by Nouvellon et al. (2001). The model is capable of tracking soil moisture evolution (an initial condition required by the current K2 model prior to a rain storm), of assimilating remotely sensed data, and simulating desert grassland plant growth. A final modification is the incorporation of a more complex channel routing algorithm is being explored to handle diffusion waves and channel morphology changes due to erosion and sediment deposition.

Conclusions: The KINEROS2 model has evolved over several decades with a user base in excess of 500 individuals and projects worldwide. The model has been more widely applied in semiarid watersheds where infiltration excess runoff generation dominates. Wider applicability to more humid regions is anticipated with the addition of two-layer soil systems. The new feature has been tested extensively in an intensively characterized field study. The model has demonstrated its ability to simulate both observed watershed hydrologic and erosion/sediment response in a variety of circumstances (Rovey et al., 1977; Zevenberger and Peterson, 1988; Goodrich, 1990; Smith et al., 1995a and 1995b; Smith et al., 1999; and Houser et al., 2000, among others). It is also anticipated that K2 model use will be made substantially easier with the coupling of K2 within the AGWA geospatial watershed assessment tool. However, it is still worth reiterating that, ease of model application, and additional model complexity do not necessarily imply better and more accurate models. As Smith et al. (1994) noted, our ability to develop accurate physically based models is very good for very limited scales (1-10 m^2) but our ability to accurately measure and model spatial heterogeneity at larger scale remains the Achilles heel of watershed modeling. Our computational modeling capabilities have far outstripped our ability to measure and estimate spatially distributed hydrologic parameters over large areas. Without a greater emphasis on collection and analysis of field data we feel that hydrologic modeling advances will be marginal at best.

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