

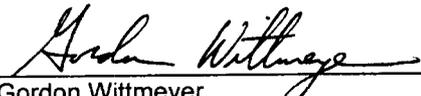
**SOFTWARE VALIDATION TEST PLAN FOR
KINEROS2 VERSION 1.12**

Roger Smith
David Woolhiser
Randall Fedors

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Center for Nuclear Waste Regulatory Analyses

Approved:



Gordon Wittmeyer
Element Manager, Hydrology

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VALIDATION TEST PLAN FOR KINEROS2 VERSION 1.12

KINEROS2 simulates surface and near-surface flow of water, erosion, and sediment transport at the watershed scale. Watersheds are modeled as cascades of plane and channel elements (Kibler and Woolhiser, 1972). Overland and channel flow is described by the kinematic wave equations with Manning's equation determining the relationship between flow concentration and flux. These partial differential equations are solved numerically by a four point implicit method. It has been shown that the kinematic wave equations are an excellent approximation to the more general De Saint Venant equations for most cases of hydrological significance (Woolhiser and Liggett, 1967, Morris and Woolhiser, 1980). The kinematic wave approximation is well-suited for water flow on the steep slopes of watersheds on Yucca Mountain. The use of other equations for steep slopes in semiarid environments is not recommended.

Hillslopes can be subdivided into plane elements and channels into line elements. The microtopography of hillslope surfaces is modeled as parallel trapezoidal channels on plane elements. The microtopography model is described in Smith (2002). Channels can be modeled as trapezoids with and without overbanks. The surface routing of water is important for Yucca Mountain to the extent that it affects the spatial distribution of net infiltration.

Infiltration is modeled by an approximation to the one-dimensional Richard's equation of vertical flow in unsaturated porous media (Smith and Parlange, 1978). Small scale spatial variability of saturated hydraulic conductivity has been shown to be an important factor (c.f. Woolhiser and Goodrich, 1988). In the KINEROS2 model, the spatial distribution of saturated hydraulic conductivity is assumed to have a lognormal distribution and the effective infiltration rate will vary as a function of the rainfall rate (Smith, et al., 1990; Smith, 2002). The unsaturated hydraulic behavior of soil is described by two relationships between three properties: the soil water content, the pressure head of the water in the soil and the relative hydraulic conductivity. Effective conductivity as used in the unsaturated version of the Darcy equation for flow is the relative conductivity scaled on the saturated hydraulic conductivity. KINEROS2 assumes that the Transitional Brooks-Corey functions describe these relations (Smith, 2002). These relationships are also used to estimate the permanent wilting point and field capacity, which affect the initial soil water profile and the potential bedrock infiltration.

1.0 SCOPE OF THE VALIDATION

The KINEROS2 program represents the physical processes of rainfall, infiltration, surface runoff, erosion and sediment transport from small watersheds. For the review of a license application for Yucca Mountain, the erosion and sediment transport components of the model will not be used.

Five tests are described in Section 6. The first test will determine if the infiltration equation is implemented as intended. The second test will compare KINEROS2 results with an analytical expression for runoff under a simple rainfall. The third test will determine if the KINEROS2 results for flow on a single plane satisfy the continuity equations and are asymptotically correct for steady nonuniform flow. The test is applied to three cases (i) a flat plane without infiltration, (ii) a flat plane with infiltration, and (iii) a rough (rilled) plane with infiltration. The fourth test will show that KINEROS2 can accurately represent features associated with saturation-induced runoff. The fifth test will compare KINEROS2 results with measurements made at the Walnut

Gulch Watershed in Arizona. In addition to these tests, it is noted that KINEROS2 has internal checks of the order of computation and the connectivity of planes and channels.

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3.0 ENVIRONMENT

3.1 Software

The KINEROS2 program was developed by scientists of the Agricultural Research Service of the U. S. Department of Agriculture (USDA) and was first thoroughly documented by Woolhiser, et al. (1990) and Smith et al. (1995). Several additions have been made by the developers since then to accommodate more complicated watershed situations and to provide more detailed output information. A description of the software may be found at <http://www.tucson.ars.ag.gov/kineros/Home.html>. Only Version 1.0 is available at this web page. The version being tested is 1.12, which may be obtained directly from D. Goodrich at the Agricultural Research Service Department of Agriculture Office in Tucson, Arizona. The USDA also uses a graphical user interface, which they have designated as Version 3.0, to run KINEROS2 Version 1.12. The version stamp on output files is KINEROS2 Version 1.12 even if the graphical user interface is used.

KINEROS2 Version 1.12 operates in a WINDOWS environment. The graphical user interface now used with KINEROS2 is started by clicking on the executable file. A control file is selected using the START menu selection. The control file includes the names of all input and output files, a descriptive header for the simulation, and time-stepping and output control statements. Input files with meteorological data and parameter values must reside in the directory specified in the input control file. OPTIONS may be checked to confirm the input instructions. The menu item RUN starts the simulation and writes the output files in the directory specified by the input control file.

3.2 Hardware

The program can be run on personal computers running the Windows operating systems, including Windows98, WindowsNT, Windows2000, and WindowsXP.

4.0 PREREQUISITES

None.

5.0 ASSUMPTIONS AND CONSTRAINTS

None.

6.0 TEST CASES

6.1 Infiltration

KINEROS2 solves the Parlange 3-parameter infiltration equation in the course of solving the runoff routing equations for infiltrability of a plane or channel. Infiltration is described by the algebraic equation

$$f_c = K_s \left[1 + \frac{\gamma}{\exp(\frac{\gamma I}{G'})} \right] \quad (1)$$

in which f_c is infiltrability [length/time], K_s is the saturated hydraulic conductivity [length/time], I is cumulative infiltrated depth [length], and input parameter G' [length] is the multiplicative combination of capillary drive, H_c , and initial soil water deficit ($\theta_s - \theta_i$). θ_s is saturated water content, and θ_i is initial soil water content. The parameter γ is a weighting function from zero to 1. For $\gamma = 1$ the expression equals the Smith-Parlange equation, and for $\gamma \rightarrow 0$ it approaches the Green-Ampt expression. A value of 0.8 is considered a good mean for most real soils.

The infiltration flux, f , is less than or equal to the infiltrability. When infiltrability exceeds the rainfall rate, infiltration flux equals the rainfall rate. When infiltrability is less than or equal to the rainfall rate, the infiltration flux equals the infiltrability. Relations for f_c as a function of time comparable to Eq. (1) are given by Smith (2002).

The validation test will produce a time sequence of values of infiltration flux as calculated by KINEROS2, which can be plotted directly against the values described by Eq. (1). The KINEROS2 f and I values can be taken from the auxiliary diagnostic printout, which is an optional output from the model. The procedure will determine if the model faithfully computes infiltration flux as described by Eq. (1).

6.1.1 Test Input

A parameter input file will be used that describes a single plane without microrelief, with a single soil layer, and designating diagnostic output option, PR = 4. A rainfall data file describing a uniform rate rainfall, $R \gg K_s$, will be used to produce the sequence of f values as a function of time in the diagnostic output file. For the test described, $R = 40$ mm/h, $K_s = 5.0$ mm/h, $G' = 12.52$ mm.

6.1.2 Test Procedure

KINEROS2 will be run using a single parameter and rainfall file. The diagnostic output values of f and I at each time step will be extracted to a separate data file and graphically compared with the solution of Eq. (1). Values used in the comparison will be limited to the time period prior to the onset of runoff, which is the period when infiltration equals infiltrability.

6.1.3 Expected Test Results

Hand calculated and KINEROS2 output values of infiltrability will be plotted as a function of cumulative infiltration for a visual comparison. The quantitative criteria for test acceptance is for hand calculated and KINEROS2 output of infiltrability to differ by less than 0.01 for values of infiltration greater than 10 mm/h during the period when no runoff occurs.

6.2 Overland Flow with Unsteady Infiltration

The finite difference technique in KINEROS2 provides a coupling between surface runoff described by the kinematic wave equations and infiltration described by the Smith-Parlange relation at each computational node for planes and channels. Giráldez and Woolhiser (1996) developed an analytical solution for the kinematic wave equations with hydraulic resistance exponent of 2 for flow on a plane under constant rainfall for the Smith-Parlange infiltration model (Smith and Parlange, 1978) without small scale spatial variability of saturated hydraulic conductivity.

This test will use the results published by Giráldez and Woolhiser (1996), who used an earlier version of KINEROS2 called KINEROS. The relevant algorithms in KINEROS used by Giráldez and Woolhiser (1996) and KINEROS2 Version 1.12 have not changed. No new simulations will be performed for the validation test report.

Analytical solutions are not possible with the exponent $5/3$, which is a common value used for the exponent n in the Manning equation. A numerical solution along characteristic curves is possible, however, and will serve as a test of the rectangular finite difference scheme used in KINEROS and KINEROS2. Giráldez and Woolhiser (1996) modified KINEROS to use a Mannings n value of 2, and to use a different time stepping scheme than the automatic algorithm previously in the code. The use of an exponent of 2 instead of $5/3$ should not lead to different conclusions for validation of KINEROS2.

6.2.1 Test Input

Five cases were run by Giráldez and Woolhiser (1996). All were for a single plane, but the plane lengths, slopes, sorptivity, saturated hydraulic conductivity, hydraulic roughness and rainfall rates were changed. These cases represent combinations of high and low rainfall excess rates with rapidly and slowly responding runoff planes. Time and space increments were chosen by procedures recommended by Woolhiser, et al. (1990). See Giráldez and Woolhiser (1996) for additional details.

6.2.2 Test Procedure

This test case is published in the peer-reviewed literature (Giráldez and Woolhiser, 1996). Figure 3 of Giráldez and Woolhiser (1996) and associated text contain the results of this test case.

6.2.3 Expected Test Results

Graphs in Figure 3 of Giráldez and Woolhiser (1996) and associated conclusions will be reviewed. The comparisons will be done visually based upon the discharge hydrographs at the

lower boundary of the planes. Generally, the KINEROS values should visually match the analytical result, although there may be conditions where the time-stepping cannot adequately be resolved to match sharp changes in the hydrographs. The general shape of the hydrographs should not differ.

6.3 Runoff-Runon Phenomena on a Plane Element

One of the features of KINEROS2 is the ability to account for flows moving across an infiltrating surface. This feature of infiltration could be important for upland areas where a thin or less porous soil lies upslope of a deeper soil. This feature of infiltration also will be important for upstream inflows into a "dry" channel. This scenario is a difficult dynamic hydraulic case involving two interacting and highly nonlinear equations, with no general analytical solution. For this validation test, three cases will be simulated that approach steady nonuniform flow to show that the solution in KINEROS2 preserves continuity and is asymptotically correct. Also, a simple dynamic case will be simulated to compare with a published solution for kinematic shock advance over a surface with constant infiltration rate.

6.3.1 Test Input

For this test, the INJECT feature of KINEROS2 will be used to provide a steady inflow at the upper boundary of a plane surface, and a single plane will be specified in the parameter input file. The rainfall file will specify a zero rain rate. There is an option of KINEROS2 which allows steady infiltration rates. The infiltration rate may be zero, or small, such that runoff reaches the outlet at a time which can be analytically calculated. Alternatively, the specified infiltration rate may be large enough that the inflow should be infiltrated before the end of the plane is reached. The discharge and depth distributions as the flow becomes steady will be compared with analytical solutions. Three cases will be assessed.

For the first case, a steady flow will be started at the upstream edge of an impervious plane and the time of arrival of the resulting kinematic shock at the outlet will be found. This is the most difficult test of KINEROS2, since shocks are not represented well by KINEROS2, and tend to bias the volume balance of the results. In addition, somewhat realistically, the first-order finite difference scheme in KINEROS2 creates some numerical dispersion which is not unlike that seen in nature, as pure kinematic shocks are not observed in runoff.

For the second case, a simple dynamic problem will be simulated with steady infiltration rate, for which the input parameters will be similar to those used in the first test, and the infiltration rate and the input rate will be scaled such that flow reaches the outlet in the simulated time period. The diagnostic output file will be created using the print parameter PR = 4.

The third case will use a rilled plane surface, and the steady infiltration will be scaled such that the flow reaches a steady state at some length along the surface where the infiltration rate times the wetted area equals the upstream input rate.

6.3.2 Test Procedure

Shock Advance Approximation Without Infiltration

The advance of the front, assuming a kinematic shock (square wave) front, can be calculated by volume balance given the normal depth of flow. An initial boundary condition flux of $q_0 = 0.0005 \text{ m}^3/\text{m}\cdot\text{s}$ is applied at the downslope distance $x = 0$ (top of plane) on an impervious plane with 5-percent slope with a Manning roughness n value of 0.151. The normal depth then is 0.00207 m, and the shock front should reach the 50-m point in about 34.4 minutes.

Shock Advance on a Flat Surface With Steady Infiltration

The same parameter file describing runoff will be used for this simulation, except that a steady value of infiltration, f , is used. Again the diagnostic output file for KINEROS2 provides the necessary output, and the output data will be compared with the simple analytic solution for runoff with steady infiltration

$$\frac{dq}{dx} = -f \quad (2)$$

where q is discharge per unit width. This equation is solved to simply state that $q(x) = q_0 - f \cdot x$. A parameter file for "irrigation advance" is prepared to follow the example published by Cunge and Woolhiser (1975). The value of q_0 must be greater than $f \times L$, where L is the plane length. The rate of front advance and the time the advancing front reaches the end of the plane will be compared with the published dimensionless solution of Cunge and Woolhiser (1975)

$$t^* = m \left[1 - (1 - x^*)^{\frac{1}{m}} \right] \quad (3)$$

in which m is 5/3 for the Manning equation and x and t are normalized to account for q_0 , f , plane roughness, and length. Although KINEROS2 will not accurately simulate an advancing shock, the numerical advance rate can be usefully compared with this equation using output information in the diagnostic output file. The front location will be estimated by finding the interpolated distance at which a given depth is found, such as $h^* = 0.2$, where h^* is depth scaled on upstream depth, H_0 .

When the steady infiltration rate multiplied by the wetted distance equals the upstream input rate, the advance stops and a steady profile is developed. The depth profile will be obtained from the solution to Eq. (2) above, by substituting the normal flow relation of q to h

$$q = \alpha h^m \quad (4)$$

to obtain the profile relation

$$h(x) = \left(\frac{q_0 - fxw}{\alpha w} \right)^{1/m} \quad (5)$$

in which α is the roughness coefficient that includes slope and hydraulic roughness and w is width.

The criteria for evaluating this test case considers the simulated flow depth and discharge along the plane element at steady state compared with analytical results. The difference should not be more than 1 percent at most locations along the plane. For locations near the toe of the front (i.e., the last 5 percent of the profile), the depth and discharge may be overestimated because of dispersion and smoothing of the sharp front.

Shock Advance on a Rilled Surface with Steady Infiltration

The KINEROS2 model has a provision whereby the "plane" element surface is represented by parallel vee-shaped channels, which are called rills in the KINEROS2 vernacular. Rills are a simple analogy for the natural irregular microchannels that result in infiltration on only part of the area when runoff is occurring and the rainfall rate is less than the plane infiltrability. This option was used for all simulations of the Upper Split Wash watershed. This runoff case is more complicated than that for a flat plane because wetted perimeter varies with depth, and thus infiltration rate is steady but losses vary both in space and time as the wetted widths change.

A schematic of a cross-section of a rilled surface and definitions for the geometric features are shown in Figure 1. Infiltration occurs over a width, $w(x)$. The side-slopes are symmetrical with slope:

$$Z = 2 \frac{RE}{(SPA - BW)} \tag{6}$$

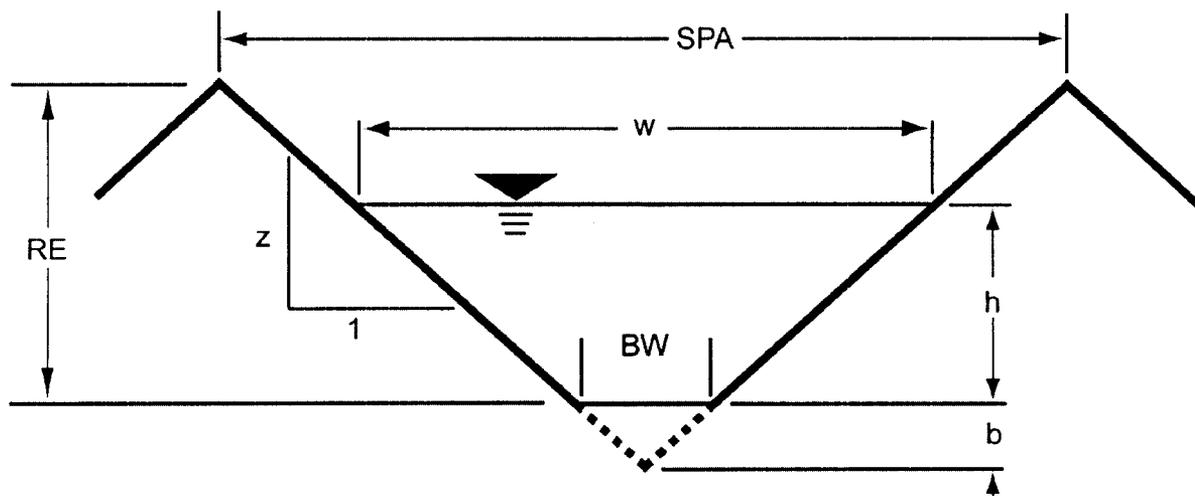


Figure 1. Definition Diagram for the Geometry of the Abstracted Rills Used in KINEROS2

Consider a case with a steady volumetric input rate of Q (m^3/s) at the upper boundary of the element. Suppose there is no rainfall on the element and that infiltration occurs at a rate of K_s (m/s) over the width, w . The steady state differential equation is

$$\frac{dQ}{dx} = -K_s w(Q) \quad (7)$$

where x is the distance downstream and w is a function of the discharge Q . Following the Manning uniform flow equation, Q can be written as a function of the cross sectional area, A , with hydraulic radius $R(A)$

$$Q = \frac{1}{n} S^{1/2} R^{2/3} A \quad (8)$$

where n is the Manning hydraulic roughness, and S is slope. Using the geometric terminology defined in Figure 1, it can be shown that the following expression is valid for the function $Q(w)$

$$Q(w) = \frac{1}{n} S^{1/2} [(w - BW) \{b + (w - BW)z / 4\}]^{5/3} \left[\frac{2b}{z} + z(w - BW) \sqrt{1 + \frac{1}{z^2}} \right]^{-2/3} \quad (9)$$

Equation (9) can be simplified using $b = z \cdot BW/2$ to

$$Q(w) = \frac{1}{n} S^{1/2} [(w - BW) (w + BW)z / 4]^{5/3} [BW + (w - BW) \sqrt{1 + z^2}]^{-2/3} \quad (10)$$

A Newton-Raphson technique is used to solve Equation (10) for $w(Q)$ at the top of the plane. The differential equation in Equation (7) is rearranged to

$$\frac{dx}{dQ} = \frac{-1}{K_s w(Q)} \quad (11)$$

to solve for the downslope position x for decreasing increments of Q . Eq. (11) cannot be solved analytically, but can be solved by a 4th order Runge-Kutta technique. Within the Runge-Kutta algorithm, Newton-Raphson iterations are utilized to solve Eq. (10) to obtain values of $w(Q)$ at each location.

6.3.3 Expected Test Results

The expected results for each of the three parts of this test case are described next.

Shock Advance Approximation Without Infiltration

The criteria for evaluating this test case considers the simulated time of arrival of the sharp front compared with the analytical result. The time of the 50-percent breakthrough should not differ from the analytical result by more than 10 percent. There should also be less than 5-percent mass balance error in the simulated result.

Shock Advance on a Flat Surface With Steady Infiltration

The criteria for evaluating this test case considers the simulated flow depth and discharge along the plane element at steady state compared with analytical results. The difference should not be more than 1 percent at most locations along the plane. For locations near the toe of the front (i.e., the last 5 percent of the profile), the depth and discharge may be overestimated because of dispersion and smoothing of the sharp front.

Shock Advance on a Rilled Surface with Steady Infiltration

The criteria for evaluating this test case considers simulated flow depth and discharge along the rilled plane element at steady state compared to analytical results. The difference should not vary by more than 1 percent at most locations along the plane. For locations near the toe of the front (i.e., the last 5 percent of the profile), the depth and discharge may be overestimated because of dispersion and smoothing of the sharp front.

6.4 Saturation Induced Runoff for a Layered Soil Profile

KINEROS2 has the ability to simulated saturation-induced runoff, where surface runoff is caused by the saturation of an upper layer of soil due to limited infiltrability of a lower restrictive layer. Saturation-induced runoff occurs in the modeling of the Upper Split Wash watershed using KINEROS2. A simplified example will verify the model's ability to treat this case accurately.

6.4.1 Test Input

A steady rainfall of 20 mm/h is applied to a simple rectangular plot for which the soil is composed of a relatively porous upper layer of 200 mm, underlain by a material with a fixed infiltrability of 0.5 mm/h (i.e., saturated permeability of lower layer, $K_{s2} = 0.5$ mm/hr). A single plane element will be used in the parameter input file. The initial water content (0.134) and porosity (0.323) of the upper soil, also specified in the parameter input file, are factors that determine when the upper layer will fill and runoff will begin. After saturating the upper layer, the K_{s2} value should then control the asymptotic rate of runoff rate of 19.5 mm/h in this case, which will be achieved as soon as the entire area is contributing runoff.

6.4.2 Test Procedure

The input file will be created and simulated runoff results will be plotted along with the precipitation rate.

6.4.3 Expected Test Results

The onset of runoff should not differ from a value of 115 minutes by more than 2 percent and the runoff rate should evolve to within 2 percent of the predicted asymptotic rate of 19.5 mm/h.

6.5 Measurements in the Walnut Gulch Watershed

The KINEROS model, an earlier version of KINEROS2 has been thoroughly tested over a range of catchment sizes in a semiarid environment where only Hortonian runoff occurred (Goodrich,

1990). KINEROS2 Version 1.12 will be used to simulate runoff from the Walnut Gulch Watershed. Goodrich (1990) used split sample tests with half of the rainfall-runoff data used to identify parameters. The validation test for KINEROS2 will simulate the events not used for the calibration. The goodness of fit of computed and measured hydrographs will provide information on how well model results compare with measured data.

6.5.1 Test Input

Measured rainfall, measured runoff, and parameter files for a small subwatershed of the Walnut Gulch Experimental Watershed have been obtained from D.C. Goodrich of the Agricultural Research Service, USDA, Tucson, Arizona. These are the same files used in Goodrich (1990).

6.5.2 Test Procedure

Using the same input files as used by Goodrich (1990), simulation results from KINEROS2 Version 1.12 will be used to plot precipitation profile and simulated runoff hydrograph for comparison with the measured runoff hydrograph. The input files from Goodrich are not calibrated to the events used in this test case.

6.5.3 Expected Test Results

Measured and computed hydrographs will be compared visually, primarily for the number of peaks, relative magnitude of peaks, and shapes of the pulses. Because these models will not be calibrated specifically to these events, quantitative comparisons are not useful. Differences in initial conditions would significantly affect the magnitude and timing of early runoff. In addition, timing errors with the old spring-driven clocks on the rain and runoff gages are known to occur. Given these constraints, a qualitative comparison of the KINEROS2 Version 1.12 results with those of KINEROS (Goodrich, 1990) will be sufficient.

7.0 INDUSTRY EXPERIENCE

Whereas KINEROS2 was designed by the USDA for use in arid and semi-arid climates, it has been used nationally and internationally for arid and humid climates by government agencies, academic institutions, and private industry. The code has evolved over the past 25 years because of continued use, testing, and comparison with measured data, and thus, should be considered to be a mature code.

8.0 NOTES

None.