SOFTWARE VALIDATION TEST RESULTS FOR KINEROS2 VERSIONS 1.9, 1.12, AND 1.13

Roger Smith
Randall Fedors
David Woolhiser

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Center for Nuclear Waste Regulatory Analyses
and
U.S. Nuclear Regulatory Commission

Approved:

Robert Lenhard
Group Manager, Hydrology

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This report documents the results of performing software validation tests for KINEROS2 following the software validation test plan developed by Smith, et al. (2005). First, an introduction to KINEROS2 and background on the validation efforts are provided. Second, the scope of the validation, references, software and hardware requirements, prerequisites, and assumptions are listed or described. Third, and covering a majority of this report, the tests are described and results of the validation are provided.

Introduction

KINEROS2 simulates surface and near-surface flow of water, erosion, and sediment transport at the watershed scale. Watersheds are represented in KINEROS2 as cascades of plane and channel elements (Kibler and Woolhiser, 1972). Overland and channel flow are 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 controlling net infiltration (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.

Background on Software Validation

A software validation plan (Smith, et al., 2005) was completed in preparation for performing tests on various aspects of the coded algorithms in KINEROS2 Version 1.12. When performing the software validation tests, errors were found in version 1.12 related to the flow algorithm for channels, and in the output of precipitation at each time step of a simulation. These errors were corrected by the code author (D. Goodrich, Agricultural Research Service, Department of Agriculture, Tucson, Arizona), and version 1.13 was established. Version 1.13 also contains other changes deemed important by the code author. These errors do not preclude Version 1.12 from being considered validated for use at Yucca Mountain. It was established in David Woolhiser's scientific notebook (#444) that versions 1.12 and 1.13 produced similar results for the Upper Split Wash watershed at Yucca Mountain.

A third version of KINEROS2 is used in this software validation exercise. Because the output in Version 1.9 was modified for the third test case of this validation, and Versions 1.12 and 1.13 were not similarly modified, results for Version 1.9 are included in this validation exercise. For completeness, Version 1.9 was included in all test cases so that it could also become a software validated version KINEROS2.

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 determine if 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 versions being tested are 1.9, 1.12, and 1.13, which may be obtained directly from D. Goodrich at the Agricultural Research Service Department of Agriculture Office in Tucson, Arizona. In 2005, the USDA used a graphical user interface, which they had designated as Version 3.0, to run the current KINEROS2 Version. Previously, staff used the KINEROS Version 03_2 numbering scheme, in apparent reference to the year (2003) of the version release of the software, or in reference to the version of the graphical user interface. Because KINEROS2 Versions 1.9, 1.12, and 1.13 all run under the Version 3.0 graphical user interface, potential confusion could arise. Note that the graphical user interface is compiled with the KINEROS2 code in an integrated fashion. Thus, usage of the Version 03_2 numbering scheme was dropped. The version stamp on output files would be KINEROS2 Version 1.13, for example, regardless of the use of the graphical user interface version or the DOS-executable version.

KINEROS2 Versions 1.9, 1.12, and 1.13 operate 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. Alternatively, the input and output files and simulation control parameters may be specified within the graphical user interface using the pop-down menus. Input files with meteorological data and parameter values must reside in the directory specified in the input control file. The OPTIONS menu item should be checked to confirm the input instructions. The PR input parameter in the input parameter file should be set to PR=4 to obtain intermediate output in a file named diagno.out. Version 1.9 used for the software validation tests has been modified to output additional intermediate results to aid in recording and plotting of needed data for the third test case. 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

No assumptions or contraints.

Conversion factors for metric and non-metric units used in this report are included below:

1 mm = 0.0254 inches
1 m = 3.28 feet
1 mm/hr = 0.0254 in/hr
1 m/s = 3.28 ft/s
1 m^3/s = 35.3 ft^3/s
1 in/hr = 2.54 cm/hr

6.0 TEST CASES

6.1 Infiltration

KINEROS2 solves the Parlange 3-parameter infiltration equation (Smith, 2002) in the course of solving the runoff routing equations for infiltrability of a plane or channel. Infiltrability has also been referred to as infiltration capacity in the general literature. Infiltrability is used here because capacity is not a dynamic term. Infiltrability [length/time] is described by the algebraic equation

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

in which K_s is the saturated hydraulic conductivity [length/time] and I is cumulative infiltrated depth [length]. The input parameter G' [length] is the multiplicative combination of capillary drive plus surface water height and the initial soil water deficit (θ_s-θ_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 used in KINEROS2, which is a good mean value for most real soils.

This test will compare the results from Equation (1) to intermediate output from KINEROS2 for times when the rainfall rate is greater than the infiltrability. The infiltration flux, f, is always 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 Equation (1) are given by Smith (2002).

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, where $R >> K_s$, 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/hr and K_s = 5.0 mm/hr will be sent in the appropriate input files. Porosity, initial water content, and capillary drive input parameters will be set so that $G' \cong 12.525$ mm when there is no ponded water.

6.1.2 Test Procedure

KINEROS2 will be run using a single plane and a constant rainfall that is much larger than the saturated hydraulic conductivity. The diagnostic file contains output values of f and I at each time step that will be extracted to a separate data file and graphically compared with the solution of Equation (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. The procedure will determine if the model computes infiltration flux approximately as described by Equation (1).

6.1.3 Expected Test Results

To illustrate the correct implementation of the infiltrability algorithm, the software validation test plan (Smith, et al., 2005) stated that hand calculated and KINEROS2 output values of infiltrability would be plotted as a function of cumulative infiltration for a visual comparison. The stated quantitative criteria for test acceptance was that hand calculated and KINEROS2 output of infiltrability should differ by less than 0.01 for values of infiltration greater than 10 mm/hr during the period when no runoff occurs.

6.1.4 Test Results

The quantitative criteria for test acceptance for the difference between hand calculated and KINEROS2 output results for infiltrability is too stringent. The criteria were set to a threshold of 0.01 in the software validation test plan (Smith, et al., 2005). There are several reasons why KINEROS2 results would not exactly reproduce results from Equation (1):

- The term *G'* is not only a function of the capillary drive parameter and initial water deficit, but also the surface water height. A slope of 0.09 reduces the surface water height, but ponding remains non-negligible for the calculations. The difficultly arises because the surface water height varies along the plane and over time. Thus, G' varies with time. Because it is difficult to estimate a representative water height using hand calculations for the plane for each time step, a simple approach is taken. The ponding height from a single node on the plane is chosen as the representative water height for the calculation at each time step.
- Whereas a cumulative infiltration value is recorded at the end of time steps in KINEROS2, a representative value of cumulative infiltration for the time step is needed for comparison with Equation (1). Any nonlinearity over a time step would introduce some error when using mean values of cumulative infiltration. A backward averaging scheme of the infiltration output is used for comparison with the hand calculations.
- Use of large initial water contents would amplify errors in Equation (1) for representing infiltration because the initial effective conductivity is assumed to be small. These errors are minimized by using a small value of initial water content in this test case.

Thus, a more reasonable acceptance criterion is that the difference between KINEROS2 and Equation (1) results should be less than or equal to 1 percent.

Hand calculated and KINEROS2 output values of infiltrability are plotted as a function of cumulative infiltration in Figure 1. Visual inspection of Figure 1 illustrates the close comparison of results between KINEROS2 and Equation (1). Only results from Version 1.13 are plotted on Figure 1. Results from Version 1.12 are identical to those of Version 1.13. Results from Version 1.9 are graphically indistinguishable from those of Version 1.13. Quantitative inspection shows the difference in infiltrability between Equation (1) and KINEROS2 results is greatest early and decreases with time. This trend is likely caused by two factors: (i) a representative water height is more difficult to estimate for early times as the water profile is developing, and (ii) the interpolation of the nonlinear infiltration is greatest in error. For KINEROS2 Version 1.9, the maximum difference in infiltrability is 0.7 percent. For KINEROS2 Versions 1.12 and 1.13, the maximum difference is 0.45 percent; the absolute difference is generally less than 0.01 with early-time differences ranging up to 0.1 mm/hr. Because the KINEROS2 results agree within 1 percent of those calculated using Equation (1), the results of this test case are acceptable for software validation of KINEROS2 Versions 1.9, 1.12, and 1.13.

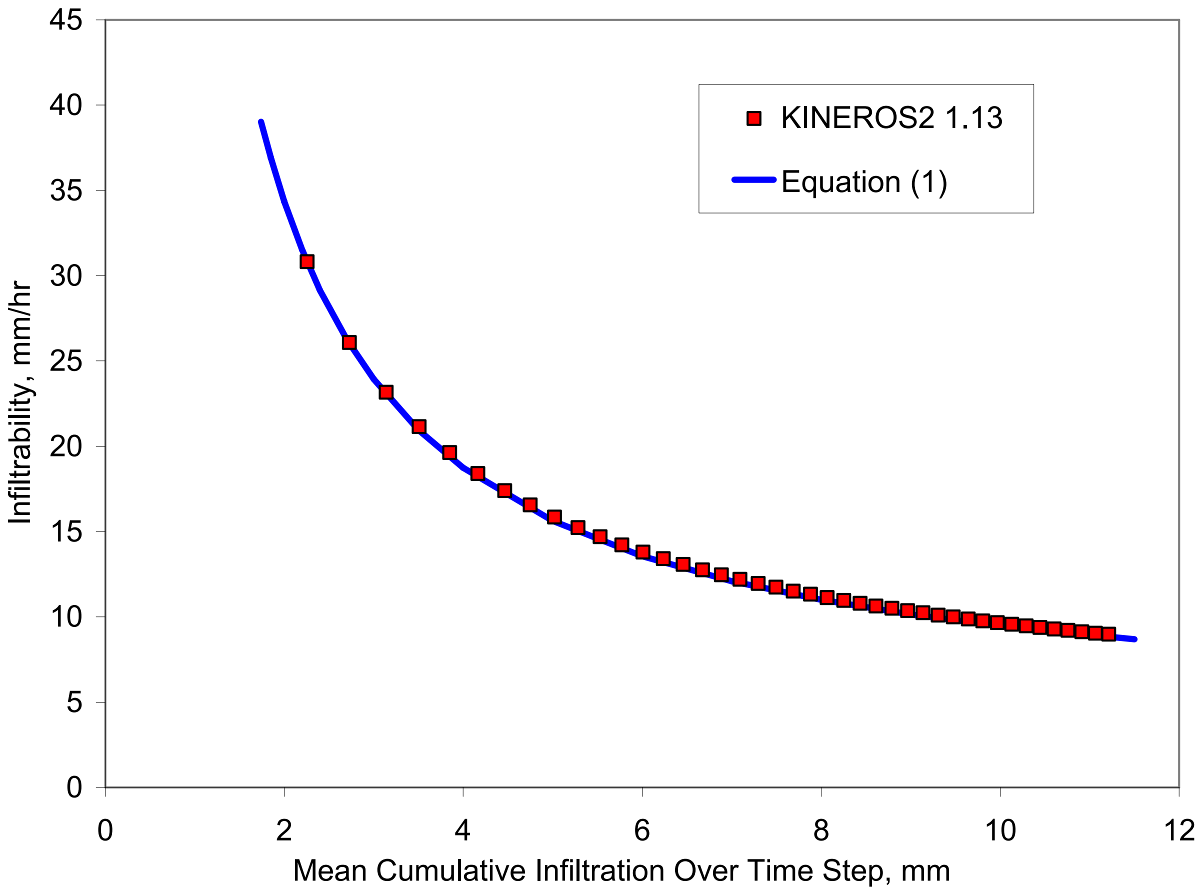

Figure 1. Comparison of Results Between Equation (1) and KINEROS2 VERSION 1.13

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 (instead of the more typical value of 5/3) for flow on a plane under constant rainfall for the Smith-Parlange infiltration model (Smith and Parlange, 1978). Also, small scale spatial variability of saturated hydraulic conductivity were not included.

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 Versions 1.9, 1.12, and 1.13 have not changed. No new simulations will be performed for the validation test report.

The Manning equation for open channel flow is comprised of a resistance term, a hydraulic radius term, and a slope term. Analytical solutions are not possible with the exponent 5/3, which is a common value used for the exponent of the hydraulic radius term in the Manning equation. A numerical solution along characteristic curves is possible and will serve as a test of the rectangular finite difference scheme used in both KINEROS and KINEROS2. Giráldez and Woolhiser (1996) modified KINEROS both to use an exponent 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 software 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

To evaluate the test results, the software validation test plan (Smith, et al., 2005) stated that the plots in Figure 3 of Giráldez and Woolhiser (1996) and associated conclusions would be reviewed. The comparisons were to be done visually based upon the discharge hydrographs at the lower boundary of the planes. It was expected, generally, that the KINEROS values would visually match the analytical result, although there may be conditions where the time-stepping could not adequately be resolved to match sharp changes in the hydrographs. The general shape of the hydrographs should not differ.

6.2.4 Test Results

The comparison of analytical and KINEROS numerical results in Figure 3 of Giráldez and Woolhiser (1996) are done visually based on values of the runoff generated, as determined from discharge hydrographs at the lower boundary of the planes. Generally, the KINEROS values visually matched the analytical result, although there were conditions where the time-stepping could not adequately be resolved to match sharp changes in the hydrographs. The general shape of the hydrographs did not differ. Giráldez and Woolhiser (1996) also concluded the results from the analytical solutions and KINEROS numerical solutions were in good agreement when the criteria for finite difference increments specified by Woolhiser, et al. (1990) were followed.

KINEROS underestimated the runoff hydrograph slightly in two of the five cases simulated, particularly at the sharp change in conditions when the entire plane becomes ponded. Giráldez and Woolhiser (1996, Figure 3b) note that a slight modification of the automatic time stepping criteria led to a better match of the runoff hydrographs. The slight underestimation of flow in two of the hydrographs is not expected to be significant for modeling of runoff in a watershed at Yucca Mountain. Because the shapes and magnitudes of the discharge hydrographs are visually close, the results of this test case are acceptable for software validation for KINEROS2 Versions 1.9, 1.12, and 1.13.

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, or typically dry channels receive inflows from upstream during rain events. 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, spatially-nonuniform flow to show 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 along a plane element as the flow becomes steady will be compared with analytical solutions. Three cases will be assessed.

For the first case, 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. The input parameters will be similar to those used in the first test. 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. Steady infiltration will be scaled such that the flow reaches a steady state at some distance along the surface. The position of the front occurs 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_o = 0.0005 m^3/s is applied at the downslope distance x = 0 (i.e., top of plane) on a 10-m wide impervious plane with 5-percent slope with a Manning roughness n value of 0.151. To simulate surface water flow on an impervious surface, the saturated hydraulic conductivity of the soil layer is set to zero. Time at which the front reaches the end of the plane is calculated from the velocity and plane length, where the velocity is the injection flux divided by the plane width and water depth. The normal depth is calculated to be 0.002075 m, and the shock front should reach the 50-m location in 34.588 minutes.

Shock Advance on a Flat Surface With Steady Infiltration

The linkage of surface water flow and infiltration can be evaluated by monitoring the advance of a front on a single plane element with infiltration enabled. To attain steady state infiltration, the transient simulation will be run for long times. As in the previous case, water will be injected at the top of the plane element. The timing and profile aspects of the front will be evaluated.

Output data from the diagnostic file will be compared with the simple analytic solution for runon with steady infiltration, *f*,

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

where *q* is discharge per unit width. This equation is solved to simply state that $q(x) = q_o - f \cdot x$. A parameter file for "irrigation advance" is prepared implementing the example published by Cunge and Woolhiser (1975). The maximum value of *x* is the length, *L*, of the plane.

Using a value of q_o smaller than $f \times L$ will lead to the front stabilizing at some position before the end of the plane element. Using a value q_o larger than $f \times L$ will lead to the front reaching the bottom of the plane before steady state behavior is reached.

The rate of front advance and the time when the advancing front reaches the end of the plane will be compared with the published dimensionless solution of Cunge and Woolhiser (1975)

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

in which *m* is 5/3 for the exponent in the Manning equation and *x* and *t* are normalized to account for q_o, *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.

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 Equation (2) above, by substituting the normal flow relation of the volumetric flux, *Q,* to the water depth, *h,*

$$Q = \alpha\, h^m \qquad \textbf{(4)}$$

to obtain the profile relation

$$h(x) = \left(\frac{Q_0 - f\ x\ w}{\alpha\, w}\right)^{\frac{1}{m}} \qquad \textbf{(5)}$$

where α is the roughness coefficient that includes slope and hydraulic roughness and *w* is width.

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 runon 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 2. Infiltration occurs over a rill width, $w_r(x)$. The side-slopes are symmetrical with slope:

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

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

$$\frac{dQ}{dx} = -K_s\, w_r(Q) \quad \textbf{(7)}$$

where K_s (6.25×10^{-6} m/s) is over the rill width, x is the distance downstream, and w_r 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 $R(A)$

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

where n is the Manning hydraulic roughness, and S is slope. Using the geometric terminology defined in Figure 2, it can be shown that the following expression is valid for the function $Q(w_r)$

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

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

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

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

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

to solve for the downslope position x for decreasing increments of Q. Equation (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 Equation (10) to obtain values of $w_r(Q)$ at each location.

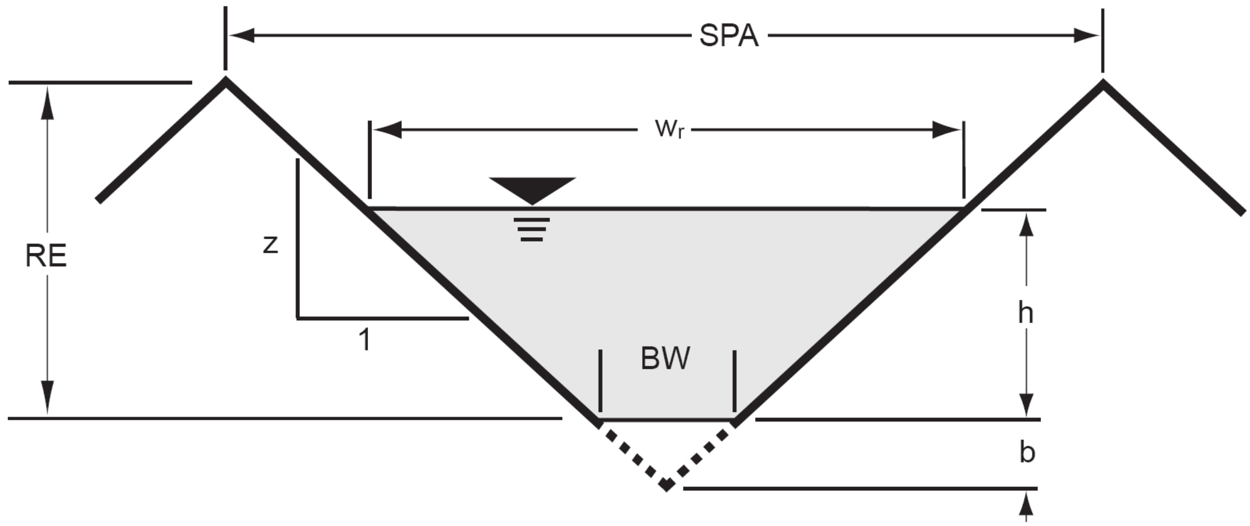

Figure 2. Definition Diagram for the Geometry of the Abstracted Rills Used in KINEROS2

6.3.3 Expected Test Results

The expected results for each of the three parts of this test case are described next. The criteria were set in the software validation test plan (Smith, et al., 2005).

Shock Advance Approximation Without Infiltration

The criteria for evaluating this test case consider the simulated time of arrival of the sharp front compared with the analytical result, and mass balance in the computations. 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 consider 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 consider 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.

6.3.4 Test Results

The results for each of the three parts of this test case are described next. In each case, the criteria specified in the software validation test plan (Smith, et al., 2005) were attained.

Shock Advance Approximation Without Infiltration

Figure 3 illustrates the ability of KINEROS2 to treat the difficult case of shock advance on an impervious plane. Numerical dispersion is expected to smooth the front in the KINEROS2 simulation.

The 50-percent breakthrough times for Versions 1.9, 1.12, and 1.13 are 33.6, 32.7, and 33.4 minutes, respectively. Based on the input, the front should reach the end of the plane in 34.588 minutes. The breakthrough times were visually estimated from the plots of flux leaving the plane element over time. The errors in the front reaching the end of the plane are 2.9, 5.5, and 3.4 percent for versions 1.9, 1.12, and 1.13, respectively.

KINEROS2 Versions 1.12 and 1.13 each exhibited a volume balance error of 2 percent for the event, indicating flow is simulated to move slightly faster than the analytical shock (i.e., water is numerically created). Version 1.9 exhibited a mass balance error of 3 percent for the event simulation. Some mass balance error is expected, due the inability of the model to find depths intermediate to those at the few fixed nodes KINEROS2 employs.

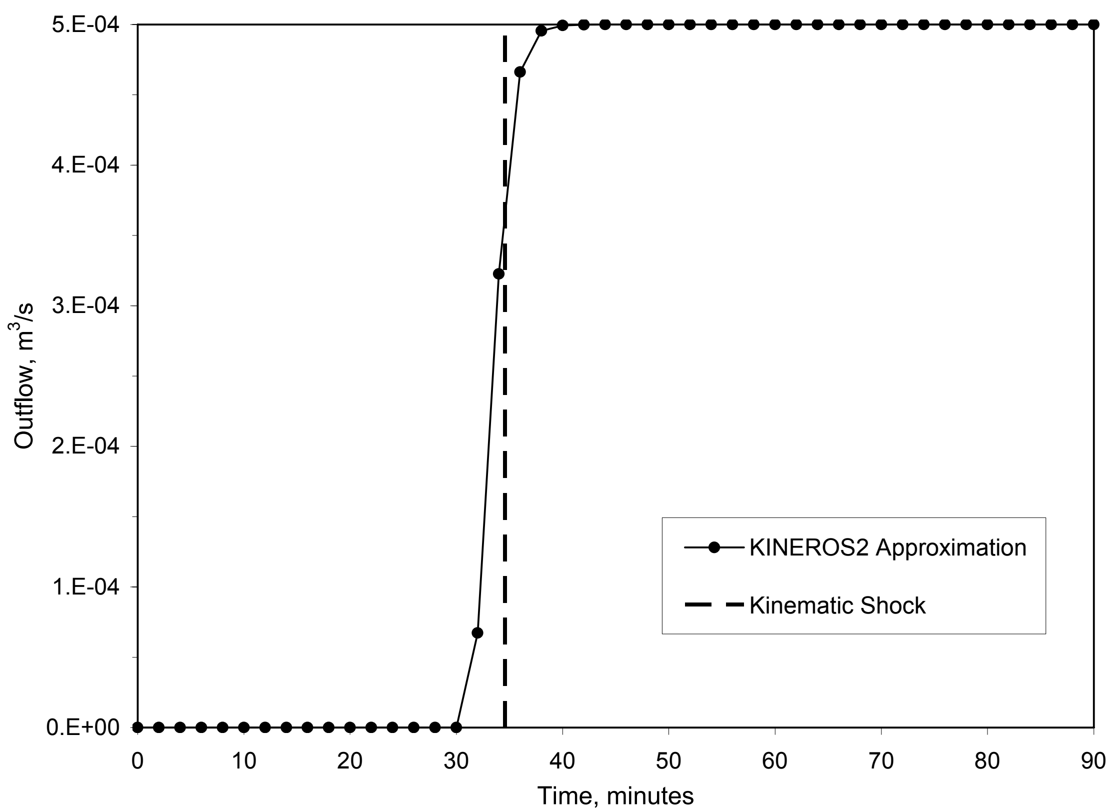

Figure 3. Comparison of Analytical and KINEROS2 Results for Flow Along an Impervious Plane (No Infiltration) Using Results From KINEROS2 Version 1.13

Because the time to 50-percent breakthrough is within 10 percent of the expected 34.588 minutes and the mass balance error for the simulation is less than 5 percent, the results of this test case are acceptable for software validation for KINEROS2 Versions 1.9, 1.12, and 1.13.

Shock Advance on a Flat Surface With Steady Infiltration

For the low-flux case ($q_o < f \times L$), a comparison of KINEROS2 and analytical results for the case of flow advance over a steadily infiltrating plane is made graphically in Figure 4. The front stabilizes at a position of approximately 50 m down the plane, both using KINEROS2 and analytical results. The spatial resolution of the KINEROS2 plane element nodes does not allow further resolution of the profile near the 50-m position. Figure 4 shows that the water heights and fluxes along the plane agree closely with the analytical results. Differences gleaned from the output data of KINEROS2 and analytical equations are attributed to round-off error by KINEROS2 output, except at the toe of the front. At the toe, the water height is 0.3 percent of the water height at the top of the plane where, according to the analytical result, the water height should be zero. The error at the toe is likely caused by smoothing of the front by KINEROS2. Simulated water height results along the plane from KINEROS2 Versions 1.9, 1.12, and 1.13 are identical except for extremely small differences at the toe of the front.

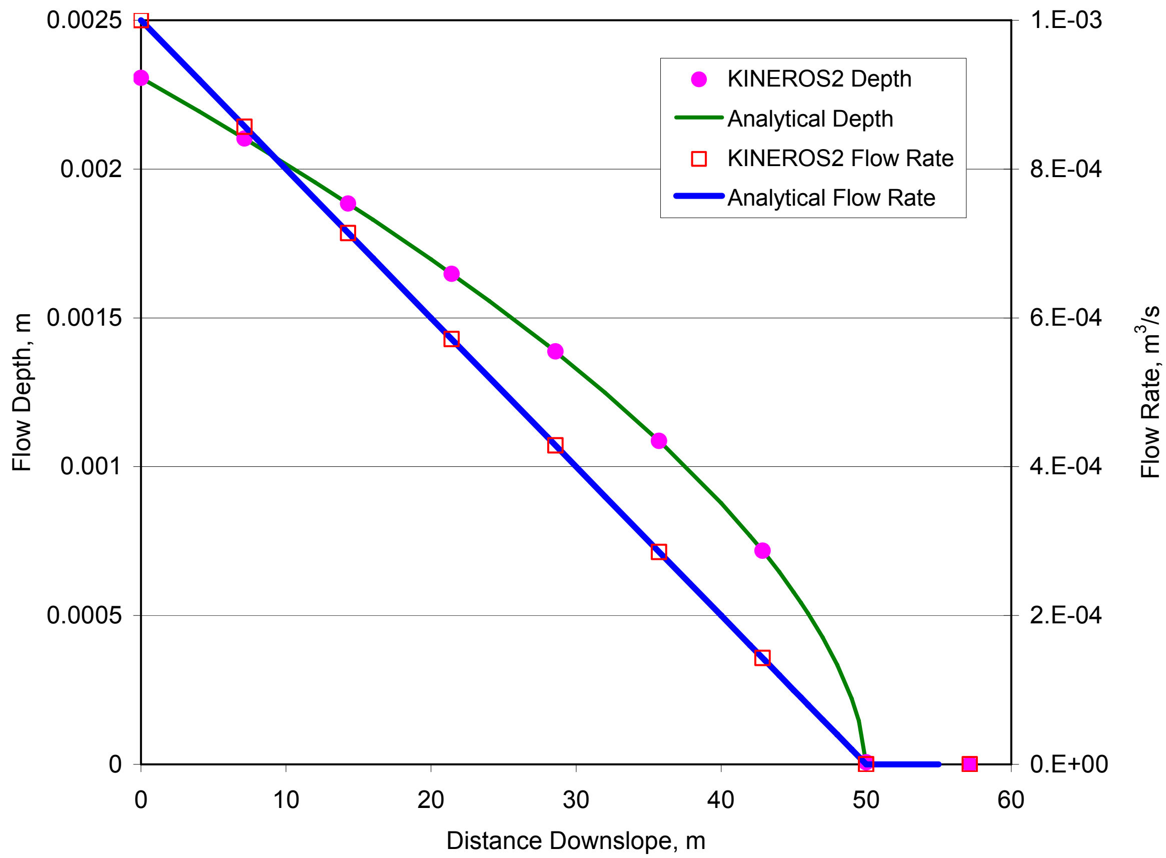

Figure 4. Water Depth and Flux Profiles Along a Uniformly Infiltrating Plane When Steady Flow Has Been Achieved. KINEROS2 Version 1.9 Results Are Plotted. KINEROS2 Version 1.12 and 1.13 Results for Water Depth Are the Same.

For the high-flux case *($q_o > f \times L$)*, comparison of KINEROS2 and Equation (3) results can use a criterion similar to that used for the first case of Section 6.3.3, *Shock Advance Approximation Without Infiltration*. Criteria were not mentioned in section 6.3.3 for the case with infiltration, though the description included an analytical model for estimating the time at which the front reaches the end of the plane. Thus, a criterion of 10 percent was set for the timing of the front reaching the end of the plane. For the case of *Shock Advance on a Flat Surface With Infiltration*, Equation (3) leads to an estimate of 39 minutes for the front to reach the end of the plane. KINEROS2 Version 1.9, 1.12, and 1.13 each produce estimates of approximately 36.5, 36, and 36 minutes, respectively, for the front, as delineated by the 50 percent breakthrough for flux. These times represent less than 10 percent error for the time it takes the front to reach the end of the plane element.

For the low-flux case, because water depth and flux along the plane for each version are within 1 percent of the analytical estimates, the results of this test case are acceptable for software validation for KINEROS2 Versions 1.9, 1.12, and 1.13. For the high-flux case, because the timing of the front reaching the end of the plane for each version is with 10 percent of the analytical estimate, the results of this test case are acceptable for software validation for KINEROS2 Versions 1.9, 1.12, and 1.13.

Shock Advance on a Rilled Surface with Steady Infiltration

The results for the case of steady flow advance on a rilled, infiltrating surface are shown in Figures 5a and 5b. For all three versions, the KINEROS2 simulations are sufficiently accurate in comparison to the analytic model solutions. Small errors are noted at the leading edge of the front for KINEROS2 Version 1.9 results (Figure 5a,b).

Because flux values along the plane element are not part of the intermediate output for Versions 1.12 and 1.13, a comparison of water depths is made to show that these versions are performing similar to Version 1.9. Plotted water depths along the plane for KINEROS2 Versions 1.12 and 1.13 visually matched those from Version 1.9. Quantitatively, all differences in water depth are less than 0.04 percent for most of the profile. At the leading edge of the profile, when water depths are less than 0.1 of the depth at the top of the plane element, errors are sometimes larger. Note that percentage differences of increasing small numbers are not meaningful.

Because the results for each version are within 5 percent at all locations and within 1 percent at most locations as compared to the analytical results, the results of this test case are acceptable for software validation of KINEROS2 Versions 1.9, 1.12, and 1.13.

6.4 Saturation Induced Runoff for a Layered Soil Profile

KINEROS2 has the ability to simulate 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.

(a)

(b)

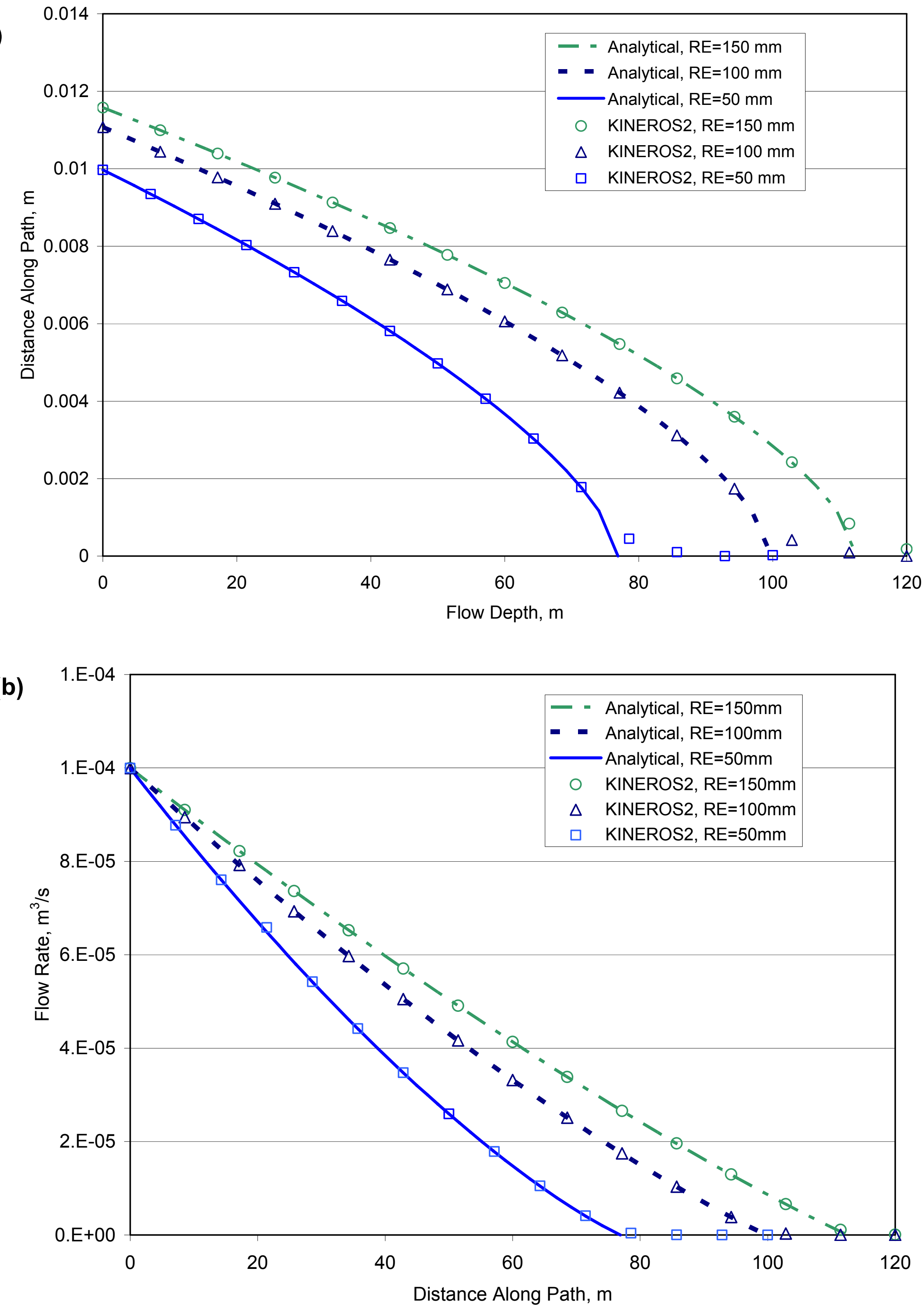

Figure 5. Spatial Pattern of (a) Depth and (b) Flux for Steady Runon When Infiltration is Enabled for Three Different Rill Depths (RE) Using Theoretical (Analytical) Equations and KINEROS2 Version 1.9 Results

6.4.1 Test Input

A steady rainfall of 20 mm/hr 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/hr (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 saturate 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/hr. The asymptotic rate 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. The onset time of saturated-induced runoff will be estimated from the results and compared with the hand-calculated value. The magnitude of the runoff after steady behavior is reached will be compared with the expected value.

6.4.3 Expected Test Results

The criteria for test acceptance were established in the software validation test plan (Smith, et al., 2005). Hand-calculated values for this test case include the timing and asymptotic rate of runoff. The initial storage in the soil is calculated as the porosity minus the initial water content multiplied times the soil depth {(0.323 - 0.1314)*200 mm}; thus, the soil storage is 38.3 mm. Using this soil storage and a rainfall rate of 20 mm/hr, the soil should saturate in approximately 115 minutes. With the infiltration constrained to 0.5 mm/hr, the asymptotic runoff amount should be 19.5 mm/hr. The criteria for acceptance are that the onset of KINEROS2 simulated 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/hr.

6.4.4 Test Results

Figure 6 illustrates that KINEROS2 Version 1.13 results visually attain the required accuracy. Figure 6 shows the soil storage is depleted after 115 minutes and runoff is initiated between 115 and 116 minutes. The onset time of runoff for each version (KINEROS2 Versions 1.9, 1.12, and 1.13) is the same. A smaller computational time step could have been used to better resolve the onset of runoff, but this calculation would not change the conclusion for this test. Using the 1 minute time steps, the maximum possible error in the onset of runoff already is less than 1 percent.

A leakage rate of 0.5 mm/h is attained upon reaching steady runoff approximately 15 minutes after the onset of runoff, thus reaching an asymptotic runoff rate of 19.5 mm/hr. The percent error for outflow (runoff) from Versions 1.9 and 1.12 results is 0.01 percent, and the error from Version 1.13 is 0.0001 percent.

Because the timing of runoff initiation and magnitude of runoff rate for each version are within 2 percent of the hand-calculated values, the results of this test are acceptable for software validation of KINEROS2 Versions 1.9, 1.12, and 1.13.

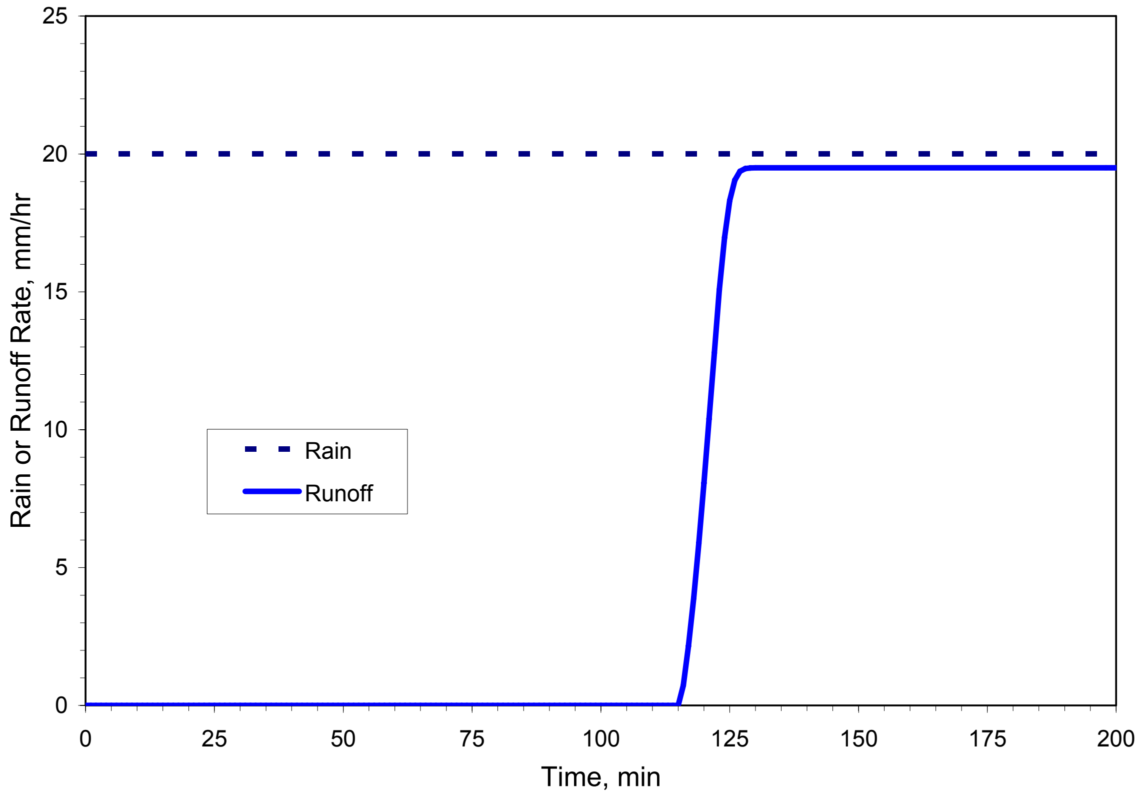

Figure 6. Saturation-Induced Runoff Response to Steady Rainfall for a Two-Layer Soil Using KINEROS2 Version 1.13

6.5 Measurements in the Walnut Gulch Watershed

The last test case for KINEROS2 will be to simulate actual runoff measured in the Walnut Gulch Watershed in the semi-arid southwestern United States. The KINEROS model, an earlier version of KINEROS2 has been thoroughly tested over a range of catchment sizes in a semiarid environment where Hortonian runoff occurs (Goodrich, 1990). KINEROS2 Versions 1.9, 1.12, and 1.13 will be used to simulate runoff from a small subwatershed called Lucky Hills located in 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

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. The subwatershed is called Lucky Hills. These are the same files used in Goodrich (1990). Measured rainfall and runoff were obtained from http://www.tucson.ars.ag.gov/dap/ for four events (event numbers 50, 62. 63, and 75 in their index system). The data bases of precipitation and runoff are described in Stone, et al. (2008) and Goodrich, et al. (2008).

6.5.2 Test Procedure

Using the same input files as used by Goodrich (1990), simulation results from KINEROS2 Versions 1.9, 1.12, and 1.13 will be used to plot precipitation profile and simulated runoff hydrograph for visual 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

The criteria for test acceptance were established in the software validation test plan (Smith, et al., 2005). The criteria for evaluating this test case consider the visual comparison of measured and computed hydrographs, primarily for the number of peaks, relative timing and 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 simulated results with measured values from the watershed (Goodrich, 1990) will be sufficient.

6.5.4 Test Results

Figures 7 through 10 illustrate the comparison of KINEROS2 simulation results and measured data for a range of events measured at the Lucky Hills #106 subwatershed of the Walnut Gulch Experimental Watershed in southeastern Arizona. These events represent a range of storm sizes, both amount of rain and duration of the event. The parameters describing the soil and surface conditions are taken directly from Goodrich (1990), and have not been adjusted for any differences between the older KINEROS used by Goodrich, and the newer KINEROS2.

Uncertainties that could lead to differences between simulated and measured runoff include: (i) initial conditions, (ii) timing of rain over the watershed compared to that at the rain gages; and (iii) calibrated hydrological properties from KINEROS, the precursor to KINEROS2. Hence, close matches of simulated and measured values should not be expected.

Simulation of the event on July 12, 1975 (Figure 8) exhibits the best match with only a slight shift in the timing of the runoff hydrograph. Simulations of the July 17, 1975 and September 26, 1977 events closely matched the timing, but not the magnitudes of runoff. In general, KINEROS2 simulations of the events produced the correct number of peaks, relative timing and magnitude of peaks, but did less well on reproducing the absolute timing and magnitudes of runoff.

Because the number of peaks and relative timing and magnitude of peaks were matched, the results from this test are considered acceptable for software validation of KNIEROS2 Versions 1.9, 1.12, and 1.13.

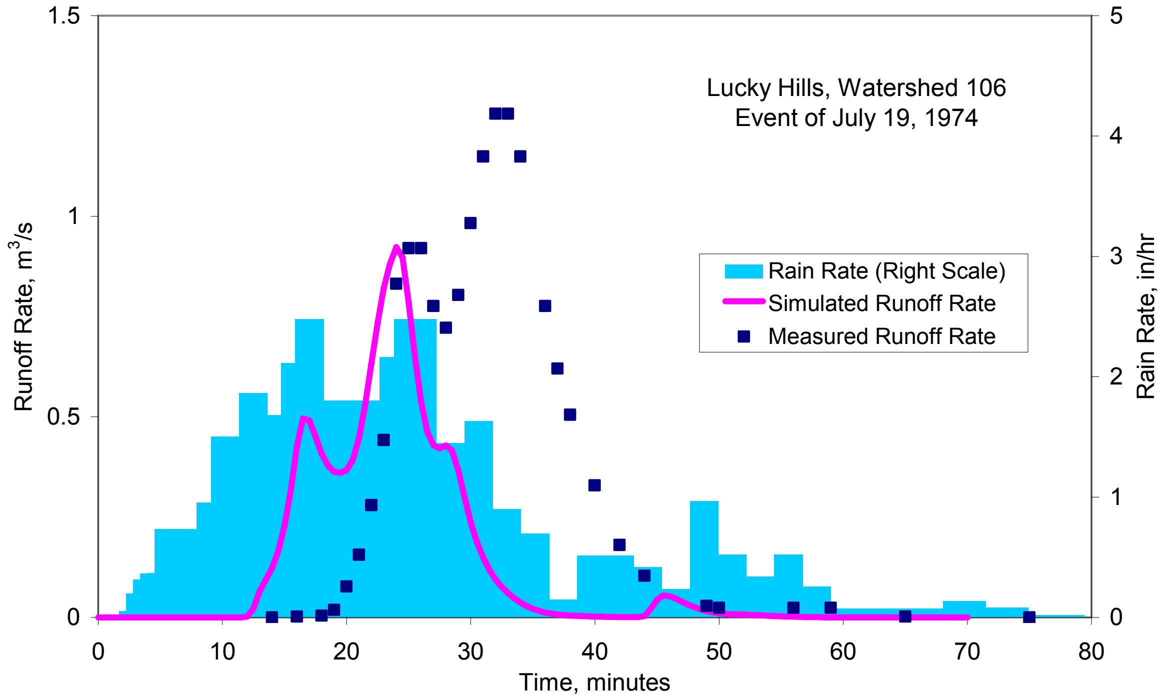

Figure 7. Comparison of KINEROS2 Version 1.13 Results with Measured Data for an Event (07/19/74) at Lucky Hills Subwatershed at Walnut Gulch Research Watershed, Tombstone, Arizona

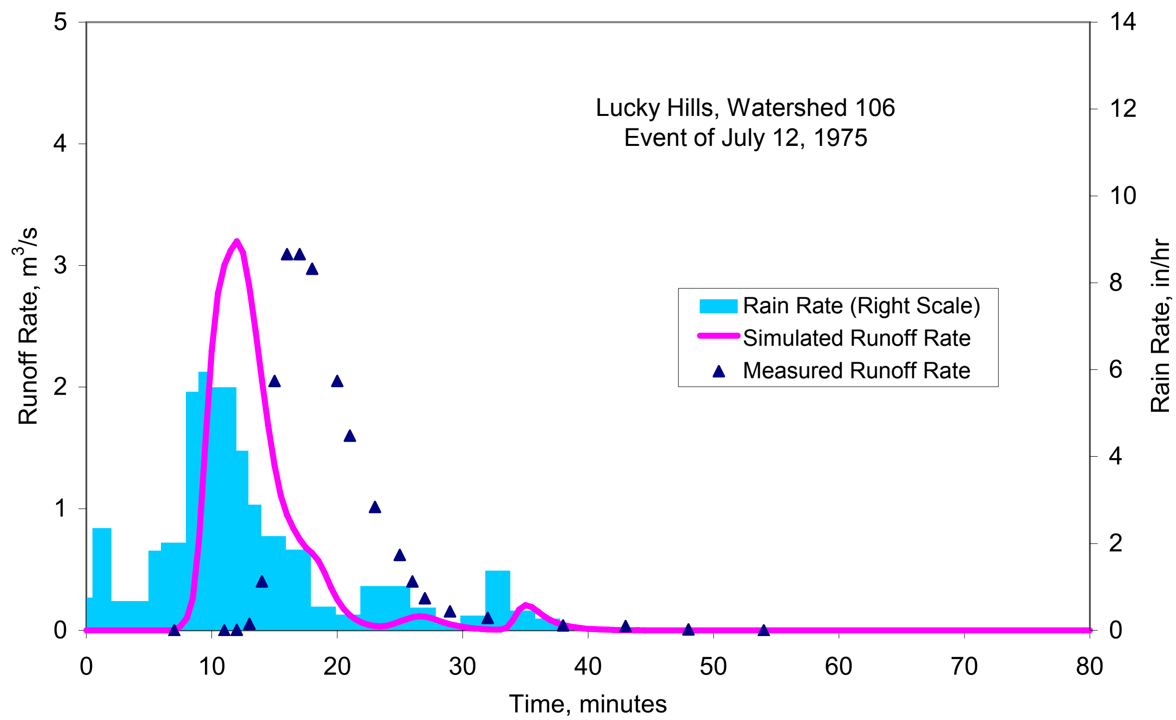

Figure 8 . Comparison of KINEROS2 Version 1.13 Results with Measured Data for an Event (07/12/75) at Lucky Hills Subwatershed at Walnut Gulch Research Watershed, Tombstone, Arizona

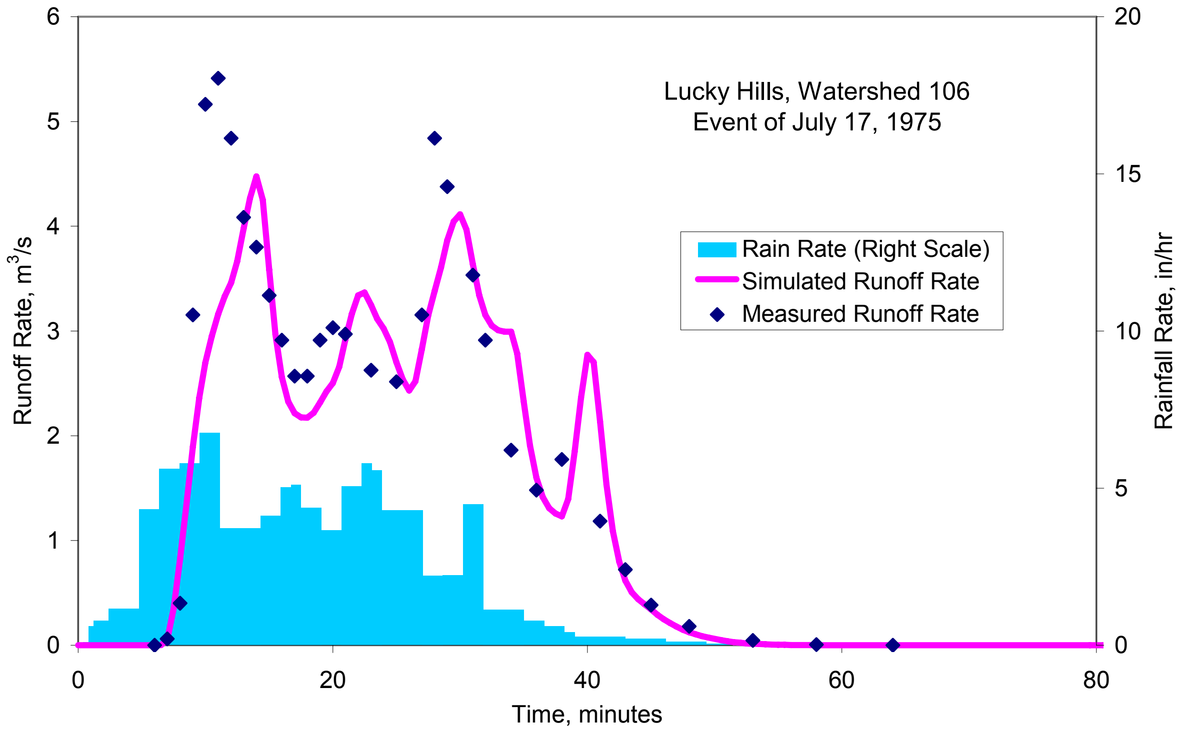

Figure 9. Comparison of KINEROS2 Version 1.13 Results with Measured Data for an Event (07/17/75) at Lucky Hills Subwatershed at Walnut Gulch Research Watershed, Tombstone, Arizona

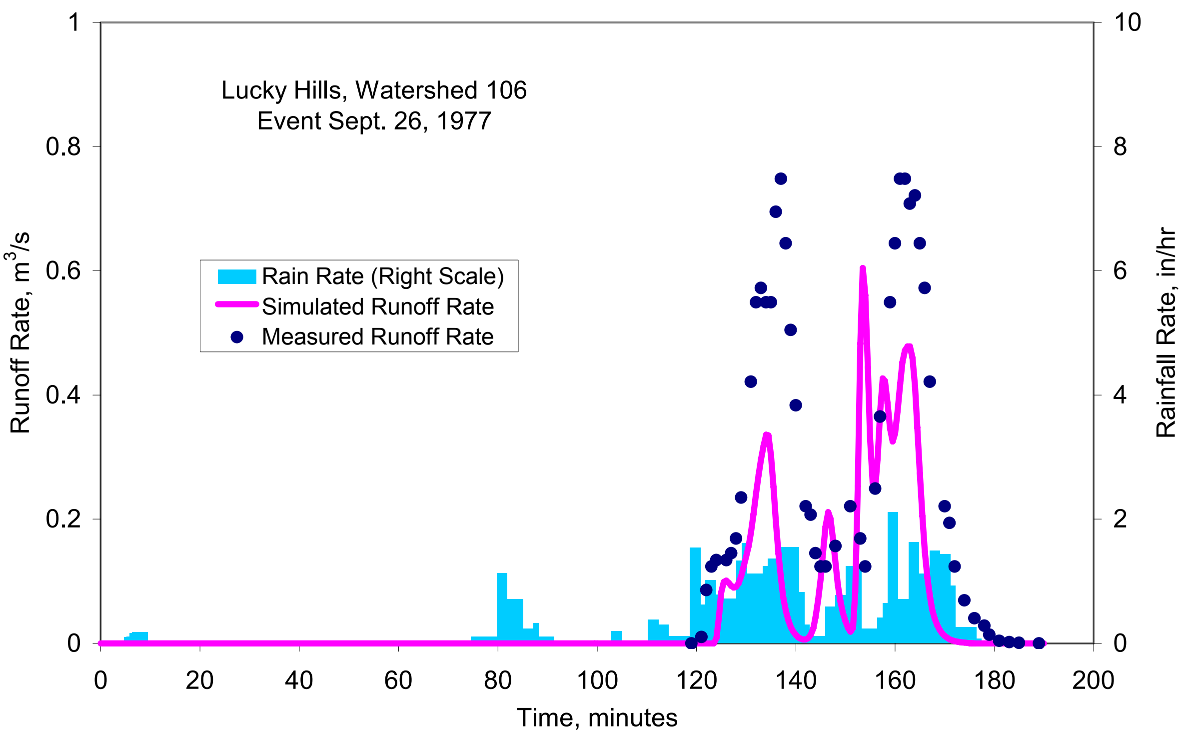

Figure 10. Comparison of KINEROS2 Version 1.13 Results with Measured Data for an Event (09/26/77) at Lucky Hills Subwatershed at Walnut Gulch Research Watershed, Tombstone, Arizona

7.0 SUMMARY AND CONCLUSIONS

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. Whereas KINEROS2 was designed by the U.S. Department of Agriculture 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 30 years because of continued use, testing, and comparison with measured data, and thus, should be considered to be a mature code.

Five software validation tests were performed to ensure that relevant portions of KINEROS2 Versions 1.9, 1.12, and 1.13 performed as expected. The first test determined that the infiltration equation is implemented as intended. The second test compared KINEROS2 results with an analytical expression for runoff under a simple rainfall. The third test determined that the KINEROS2 results for flow on a single plane satisfy the continuity equations and are asymptotically correct for steady nonuniform flow. The third test was 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 determined that KINEROS2 can accurately represent features associated with saturation-induced runoff, which is an important phenomena at Yucca Mountain. The fifth test compared KINEROS2 results with measurements made at the Walnut Gulch Watershed in Arizona. The last four tests readily met the acceptance criteria specified in the software validation test plan (Smith, et al., 2005). The first test did not meet the criteria specified in the test plan, but justification was provided for the unreasonableness of the original acceptance criteria specified in the test plan (Smith, et al., 2005).

All three versions of KINEROS2 (Versions 1.9. 1.12, and 1.13) are considered acceptable for use in analyses covering areas similar to the desert southwest (United States), in terms of semi-arid climatic conditions and topography.

8.0 FILES

Parameter and data files are included in the accompanying cdrom so that computer runs described in the text can be repeated. Files are in directories TEST1, TEST3a, TEST3b, TEST3c, TEST4, and TEST5. Note that directory pathways in control files will need corrections for the specific directory pathway needed for other computer hard disks. Unless otherwise stated, these are the input files for KINEROS2.

TEST 1, Section 6.1

File Name:	Purpose
infilvalid.fil	Control file for infiltration model test
infilvalid.par	Parameter file
R40mmh.PRE	Precipitation input file

TEST 3, Section 6.3

Test 3a File Name:	Purpose
ronzero.fil	Control file for impervious runon test
ronvalid0n.par	Parameter input file
norain.pre	Precipitation input file (no rain, in this case)
inject2.dat	Water injection input file

Test 3b File Name:	Purpose
ronflatval.fil	Control file for impervious runon test
ronvalid.par	Parameter input file
norain.pre	Precipitation input file (no rain, in this case)
injectry.dat	Water injection input file, modify for large flux

Test 3c File Name:	Purpose
ronmicv50.fil	Control file for impervious runon test
ronmicv100.fil	Control file for impervious runon test
ronmicv150.fil	Control file for impervious runon test
ronvalidm50.par	Parameter input file for Rill=50mm
ronvalidm100.par	Parameter input file for Rill=100mm
ronvalidm150.par	Parameter input file for Rill=150mm
norain.pre	Precipitation input file (no rain for this case)
inject4.dat	Water injection input file
TEST3.CON	Rill=50mm input file for INTEGRATE.f95 fortran 95 code
TEST4.CON	Rill=100mm input file for INTEGRATE.f95 fortran 95 code
TEST5.CON	Rill=150mm input file for INTEGRATE.f95 fortran 95 code

TEST 4, Section 6.4

File Name:	Purpose
SAT_TEST3.FIL	Control file for saturated runoff on 0.5mm/h subsoil
SAT_TEST1.PRE	Precipitation input file, steady rain at 20 mm/hr
SAT_TEST2L.PAR	Parameter input file, single plane, 2-layers

TEST 5, Section 6.5

File Name:	Purpose
LH106R50.fil	Control file for event of July 19, 1974
LH106R62.fil	Control file for event of July 12, 1975
LH106R63.fil	Control file for event of July 17, 1975
LH106R75.fil	Control file for event of Sept 26, 1977
LH106x2.PAR	Parameter file for watershed LH106
19Jul74.pcp	Rainfall file for event of July 19, 1974
12Jul75.pcp	Rainfall file for event of July 12, 1975
17Jul75.pcp	Rainfall file for event of July 17, 1975
26Sep77.pcp	Rainfall file for event of Sept 26, 1977