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TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis, Version 2.0

By Rex L. Baum, William Z. Savage, and Jonathan W. Godt

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
Area		
square foot (ft^2)	0.09290	square meter (m^2)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Pressure		
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
Density		
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
Hydraulic conductivity		
foot per second (ft/s)	0.3048	meter per second (m/s)

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
Area		
square meter (m^2)	10.76	square foot (ft^2)
Volume		
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
Flow rate		
meter per second (m/s)	3.281	foot per second (ft/s)
Mass		
kilogram (kg)	2.205	pound avoirdupois (lb)
Pressure		

kilopascal (kPa)	20.88	pound per square foot (lb/ft^2)

	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

	Hydraulic conductivity	
meter per second (m/s)	3.281	foot per second (ft/s)

TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis, Version 2.0

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Abstract

The *T*ransient *R*ainfall *I*nfiltration and *G*rid-Based *R*egional *S*lope-Stability Model (TRIGRS) is a Fortran program designed for modeling the timing and distribution of shallow, rainfall-induced landslides. The program computes transient pore-pressure changes, and attendant changes in the factor of safety, due to rainfall infiltration. The program models rainfall infiltration, resulting from storms that have durations ranging from hours to a few days, using analytical solutions for partial differential equations that represent one-dimensional, vertical flow in isotropic, homogeneous materials for either saturated or unsaturated conditions. Use of step-function series allows the program to represent variable rainfall input, and a simple runoff routing model allows the user to divert excess water from impervious areas onto more permeable downslope areas. The TRIGRS program uses a simple infinite-slope model to compute factor of safety on a cell-by-cell basis. An approximate formula for effective stress in unsaturated materials aids computation of the factor of safety in unsaturated soils. Horizontal heterogeneity is accounted for by allowing material properties, rainfall, and other input values to vary from cell to cell. This command-line program is used in conjunction with geographic information system (GIS) software to prepare input grids and visualize model results.

Introduction

The *T*ransient *R*ainfall *I*nfiltration and *G*rid-Based *R*egional *S*lope-Stability Model (TRIGRS) is a Fortran program for computing transient pore-pressure changes, and attendant changes in the factor of safety, due to rainfall infiltration. The original version (Baum and others, 2002) was based on the method outlined by Iverson (2000), with implementation of complex storm histories, an impermeable basal boundary at finite depth, and a simple runoff routing scheme. In version 2, we have retained the features of the original version. We have, however, expanded the model to address infiltration into a partially unsaturated surface layer above the water table by using an analytical solution of the Richards equation for vertical infiltration (given by Srivastava and Yeh, 1991). The analytical transient flow model is one-dimensional and represents the vertical infiltration in homogeneous isotropic materials that occurs during a storm. To improve usability, we have implemented property zones to simplify model input and have made numerous small changes. The program operates on a gridded elevation model of a map area and accepts input from a series of ASCII text files. Infiltration, hydraulic properties, and slope stability input parameters are allowed to vary over the grid area thus making it possible to analyze complex storm sequences over geologically complex terrain. The optional routing scheme achieves mass balance between rainfall input, infiltration, and runoff over the entire grid by allowing excess water to flow to downslope cells that are receiving less direct precipitation than they are able to absorb. The program saves output to a series of text files that can be imported to GIS software for display or further analysis.

Analyses using TRIGRS are applicable to areas that are prone to shallow precipitation-induced landslides and that satisfy other model assumptions reasonably well. These assumptions include a well-documented initial water table and steady background flux, and relatively isotropic, homogeneous hydrologic properties. The soil-water characteristic curves are approximated by an exponential function (Gardner, 1958). However, we have not evaluated the magnitude of such possible errors. Model results are very sensitive to the initial conditions, particularly the steady component of the flow field and initial depth of the water table. Consequently, the model may produce questionable results where the initial water table depth is poorly estimated.

The TRIGRS program runs from the command line or in a simple input/output window with relatively little user interaction. The user controls an analysis by means of an initialization file that contains the names of all other input and output files as well as other parameters needed to run the program. The following discussion will briefly describe system requirements for running the program, installation, and features and limitations of the program, and will provide a detailed description of the initialization file. An included tutorial helps familiarize the user with program features and operation.

System Requirements

The TRIGRS program will run on computing platforms that support Fortran 77 and Fortran 90/95. The main program is written in standard Fortran 90 and uses Fortran 90 and Fortran 77 subroutines.[1] This distribution includes the source code and executable[2] files that will run on Windows and Mac OS computers. The Windows version requires Windows 2000/XP and a Pentium-class processor. The Mac OS version requires Mac OS X (version 10.2 or later) and a PowerPC G3 (or higher) processor; TRIGRS runs from the command line, inside the Terminal application. The amount of RAM required depends on the problem size and the operating system. Analysis of a 24-period storm over a typical 30-m DEM for a USGS 7-1/2 minute quadrangle, which has about 175,000 cells, requires about 44 MB of dedicated RAM (in addition to what is required by the operating system). Analysis of the same storm over a 10-m DEM (about 1,575,000 cells) requires about 400 MB of dedicated RAM. The executable programs, source code, and tutorial/test data sets occupy about 2.2 MB of disk space. Disk space for data storage requirements depend on the problem size and output options, but can become large (hundreds to thousands of MB).

Installation

The software can be downloaded from the U.S. Geological Survey publications web server at *http://pubs.usgs.gov/of/2008/1159/*. Check *http://landslides.usgs.gov/research/software.php* for updates and bug fixes to the code. After decompressing the archive file (OF20081159_W.zip, for Windows or OF20081159_M.zip, for Mac OS X), copy the folder TRIGRS to any desired folder on your Windows PC, or Macintosh computer. Appendix 1 contains a listing of files included in this distribution. Appendix 2 gives a brief tutorial to acquaint the user with program operation.

Features

As mentioned previously, TRIGRS implements analytical solutions similar to those described by Iverson (2000) to compute both transient pore pressure due to vertical infiltration and

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[1] Some of the subroutines make use of widely implemented, but non-standard, Fortran 77 extensions for string manipulation ("adjustl()") and type declaration ("implicit none").
[2] Portions of this program include material copyrighted © by Absoft Corporation 1988–2005.

attendant changes in factor of safety in a digital landscape. We have extended Iverson's analysis by adding solutions for an impermeable basal boundary at a finite depth, an optional unsaturated zone above the water table, and a simple runoff-routing scheme to disperse excess water from cells where the application rate (rainfall intensity) exceeds the infiltrability (or infiltration capacity, Hillel, 1982). The program allows the following input parameters to vary from cell to cell throughout the model: precipitation intensity, slope, soil depth, initial water-table depth, saturated vertical hydraulic conductivity, hydraulic diffusivity, a three-parameter soil-water characteristic curve, cohesion for effective stress, angle of internal friction for effective stress, and total unit weight of soil. The precipitation rate may vary through time and may include water from other sources, if desired. The user can observe the changes in the pore pressures and factors of safety as the storm progresses (after program execution is completed). The program reads ASCII grid files in standard formats that can be output by recent versions of ArcGIS (version 9.2 and earlier) and GRASS GIS (version 6.3 and earlier). Program output is in the same ASCII grid format as the input except for an optional file that contains a listing of pore pressure and factor of safety at various depths for each grid cell. The TRIGRS program restricts the factor of safety to a maximum of 10 to facilitate plotting and eliminate division by zero in computing the factor of safety on flat slopes. To speed computation, the user can specify a minimum slope angle for computations; cells that are flatter than the minimum slope are assigned a factor of safety of 11 to distinguish them from the others.

The main program was written in Fortran 90 to take advantage of its ability to allocate arrays dynamically. Consequently, TRIGRS can be used to analyze grids of various sizes and storms having an arbitrary number of periods of different rainfall intensity without the need to recompile the program. The upper limit of the problem size that can be analyzed depends on compiler options, the operating system, and hardware being used. The interested user can find the source code in the TRIGRS folder.

Changes from Previous Version

The addition of the previously mentioned new features, primarily the unsaturated infiltration model and the introduction of property zones and a property-zone grid in place of individual grids for each physical property parameter, required major restructuring of the initialization file. Users of the previous version should consult the section on "Program Operation" for information about the new organization of the initialization file, new options, and related topics. The Mac OS version now runs from the command line, inside the Terminal application, and all input and output files now use UNIX line endings.

In the original version of TRIGRS each run analyzed the data for a single specified elapsed time in the storm sequence. To observe how pore pressures and factors of safety change during a storm, it was necessary to run TRIGRS for different values of elapsed time, t. Addition of an unsaturated zone above the water table necessitated restructuring of TRIGRS to solve for multiple elapsed times during a single program run. This restructuring now makes it possible to compute pore pressures and factors of safety for multiple elapsed times during a storm sequence; results are saved to a series of grid files for different elapsed times.

Theoretical Basis of the Program

TRIGRS combines models for infiltration and subsurface flow of storm water, routing of runoff, and slope stability to calculate the effects of storms on the stability of slopes over large areas. The following is a brief description of the basic models and formulas used by TRIGRS to

represent these processes. Formulas used in TRIGRS refer to the coordinate system depicted in figures 1 and 2.

Infiltration Models for Wet Initial Conditions

The infiltration models in TRIGRS for wet initial conditions are based on Iverson's (2000) linearized solution of the Richards equation and our own extensions to that solution (Baum and others, 2002; Savage and others, 2003, 2004). Iverson's solution consists of a steady component and a transient component. The steady seepage component depends on the initial depth to the water table and a steady infiltration rate. The steady infiltration rate, the saturated hydraulic conductivity, and the slope angle determine the steady (initial) flow direction (within the *x-z* plane). The steady vertical hydraulic gradient is a function of the slope, the initial (steady or background) infiltration rate, and the saturated hydraulic conductivity. Model results are very sensitive to the steady-seepage initial condition. Consequently, accurate initial conditions are probably the most significant input for the model. Obtaining accurate initial conditions requires a significant number of field observations possibly supplemented by steady-flow modeling to extrapolate between observations.   In the absence of accurate initial conditions, use of TRIGRS is limited to modeling hypothetical scenarios.

The transient component assumes one-dimensional, vertical downward flow, with a simple specified time-varying flux of fixed duration and intensity at the ground surface and a zero flux condition for times greater than the starting time at an infinitely deep basal boundary (fig. 3). These infiltration models apply to saturated or tension-saturated initial conditions, so that flow is in the linear range for Darcy's law and the hydraulic diffusivity is approximately constant. We have used a series of Heavyside step functions to implement Iverson's (2000) suggested summation of his original solution for rainfall of constant intensity to represent a general time-varying sequence of surface fluxes of variable intensities and durations. This generalized solution used in TRIGRS is given:

$$\psi(Z,t) = [Z-d]\beta$$

$$+2\sum_{n=1}^{N} \frac{I_{nZ}}{K_Z}\left[H(t-t_n)\left[D_1(t-t_n)\right]^{\frac{1}{2}} \operatorname{ierfc}\left[\frac{Z}{2\left[D_1(t-t_n)\right]^{\frac{1}{2}}} \right] \right]$$

$$-2\sum_{n=1}^{N} \frac{I_{nZ}}{K_Z}\left[H(t-t_{n+1})\left[D_1(t-t_{n+1})\right]^{\frac{1}{2}} \operatorname{ierfc}\left[\frac{Z}{2\left[D_1(t-t_{n+1})\right]^{\frac{1}{2}}} \right] \right] \qquad (1A)$$

In equation 1*A*,

   ψ is the ground-water pressure head;

   t is time;

   $Z = z/\cos\delta$, where Z is the vertical coordinate direction (positive downward) and depth below the ground surface, z is the slope-normal coordinate direction (also positive downward), and δ is the slope angle (figs. 1 and 2);

   d is the steady-state depth of the water table measured in the *z*-direction;

$\beta = \lambda \cos \delta$, where $\lambda = \cos \delta - [I_Z / K_Z]_{LT}$ and the subscript, LT denotes long term;

K_Z is the saturated hydraulic conductivity in the Z direction;

I_Z is the steady (initial) surface flux;

I_{nZ} is the surface flux of a given intensity for the nth time interval;

$D_1 = D_0 \cos^2 \delta$, where D_0 is the saturated hydraulic diffusivity ($D_0 = K_S / S_S$, where K_S is the saturated hydraulic conductivity and S_S is the specific storage);

N is the total number of time intervals;

$H(t - t_n)$ is the Heavyside step function.

The function *ierfc* is of the form

$$\text{ierfc}(\eta) = \frac{1}{\sqrt{\pi}} \exp(-\eta^2) - \eta \, \text{erfc}(\eta), \tag{1B}$$

where $\text{erfc}(\eta)$ is the complementary error function. The first term in equation 1A represents the steady part of the solution and the remaining terms represent the transient part. Figure 4 illustrates the kind of storm history that equation 1A is capable of modeling.

As an alternative to the solution with an infinitely deep basal boundary, we have added and implemented in TRIGRS a solution for pore pressure in the case of an impermeable basal boundary at a finite depth (fig. 3). This solution is given:

$$\psi(Z,t) = [Z - d]\beta$$

$$+2\sum_{n=1}^{N} \frac{I_{nZ}}{K_Z} H(t - t_n) \left[D_1(t - t_n) \right]^{\frac{1}{2}} \sum_{m=1}^{\infty} \left\{ \text{ierfc}\left[\frac{(2m-1)d_{LZ} - (d_{LZ} - Z)}{2\left[D_1(t - t_n) \right]^{\frac{1}{2}}} \right] + \text{ierfc}\left[\frac{(2m-1)d_{LZ} + (d_{LZ} - Z)}{2\left[D_1(t - t_n) \right]^{\frac{1}{2}}} \right] \right\}$$

$$-2\sum_{n=1}^{N} \frac{I_{nZ}}{K_Z} H(t - t_{n+1}) \left[D_1(t - t_{n+1}) \right]^{\frac{1}{2}} \sum_{m=1}^{\infty} \left\{ \text{ierfc}\left[\frac{(2m-1)d_{LZ} - (d_{LZ} - Z)}{2\left[D_1(t - t_{n+1}) \right]^{\frac{1}{2}}} \right] + \text{ierfc}\left[\frac{(2m-1)d_{LZ} + (d_{LZ} - Z)}{2\left[D_1(t - t_{n+1}) \right]^{\frac{1}{2}}} \right] \right\}$$

$$\tag{2}$$

Except for the addition of d_{LZ}, the depth of the impermeable basal boundary measured in the Z-direction, the notation in equation 2 is the same as that in equation 1. The infinite series in equations 1 and 2 converge rapidly so that in computation, only the first few terms of the series are needed. The version of TRIGRS described in this report tests these series for convergence so that the minimum number of terms needed to achieve accurate, consistent results is used at each grid cell.

Equations 1 and 2 represent two different subsurface conditions (fig. 3). Equation 1 applies where hydraulic properties are uniform with depth and equation 2 applies where a well-defined decrease in hydraulic conductivity exists at a finite depth. For example, equation 2 would apply where loose relatively permeable slope deposits overlie relatively impermeable bedrock. We considered allowing the user to specify a flux at the basal boundary; however, this would add another unknown to the problem without adding significantly to the program's analytical capabilities. Note that only one solution (either equation 1 or 2) is applied to all cells in an analysis.

Following Iverson (2000) we impose an additional physical limitation that pressure head under downward gravity-driven flow cannot exceed that which would result from having the water table at the ground surface, that is:

$$\psi(Z,t) \leq Z\beta \qquad (3A)$$

Thus, TRIGRS automatically reduces pressure head to $Z\beta$ anywhere that equation 1 or 2 has computed a value that is higher than $Z\beta$. Setting the background flux, I_{ZLT}, to zero results in a limiting pore pressure distribution equal to what occurs during slope-parallel flow. As a result of user requests, we have somewhat relaxed this requirement by allowing the user the option to specify a value of β that represents either hydrostatic ($\beta = 1$) or slope-parallel ($\beta = \cos^2 \delta$) flow conditions rather than using the more general definition used by Iverson (2000).

TRIGRS applies a modified form of equation 3A at cells where the initial flow direction is upward. If the steady water table is at the ground surface, then exfiltration occurs and any precipitation runs off along with the exfiltrating water. If the initial water table is below the ground surface and flow is upward, then TRIGRS allows precipitation to infiltrate until it raises the water table to the ground surface. This adjustment is accomplished by adding the transient and steady pressure-head components above the water table as at other cells by applying either equation 1 or 2 and by maintaining the steady upward hydraulic gradient below the water table as indicated in figure 5. The following formula applies below the water table in such cells.

$$\psi(Z,t) = (Z - d_t)\beta \; ; \; Z > d_t \qquad (3B)$$

In equation 3B, d_t is the depth to the transient water table.

Both equations 1 and 2 are generalizations of analogous heat-flow problems (Carslaw and Jaeger, 1959). Equations 1 and 2 are valid for saturated and nearly saturated soils for which the infiltrability and hydraulic conductivity approximately equal the saturated hydraulic conductivity. The solutions are strictly valid only where transient infiltration is vertically downward, but, in application, computed pore pressures will likely be accurate enough if the transient lateral flow component is relatively small. However, because the steady-flow component may have any direction consistent with possible values of β, superposition of the transient and steady components can result in flow in an arbitrary direction within the *x-z* plane. As a result of approximations made in linearizing the Richards equation, the formulas are valid for homogeneous soils and for depths that are shallow compared to the square root of the upslope contributing area (Iverson, 2000).

The formulas for both solutions of the infiltration model (equations 1 and 2) include the complementary error function. The program, TRIGRS, uses an approximation of the error function that was developed by W.J. Cody of Argonne National Laboratory (Cody, 1969). The original Fortran source code, also by W.J. Cody, is archived online at *http://www.netlib.org/specfun/erf* (accessed 10/17/2006).

Infiltration Model for Unsaturated Initial Conditions

To make the TRIGRS model applicable to a wider range of initial conditions, we have added an analytic solution for unsaturated flow as an option for estimating infiltration at the ground surface. This option treats the soil as a two-layer system consisting of a saturated zone with a

capillary fringe above the water table overlain by an unsaturated zone that extends to the ground surface (fig. 6). The unsaturated zone absorbs part of the water that infiltrates the ground surface and the remaining water passes through the unsaturated zone and accumulates at the base of the unsaturated zone above the initial water table (fig. 7*A* and 7*B*). The unsaturated zone acts like a filter that smoothes and delays the surface infiltration signal at depth (fig. 8).

This model uses four parameters to approximate the soil-water characteristic curve for wetting of the unsaturated soil (Gardner, 1958) and approximates the infiltration process as one-dimensional, vertical flow (Srivastava and Yeh, 1991; Savage and others, 2004). The infiltrating water accumulates at the base of the unsaturated zone and thus raises the water table. The load of water accumulating above the original water table propagates downward as a series of diffusive pressure waves, thus raising pore pressure at depth. For relatively thin saturated zones, like those common in hillsides, the pressure waves propagate to the basal boundary very rapidly. A separate analytical solution models propagation of these pressure waves through the saturated zone. In the following paragraphs we first describe formulas used for computing flux, hydraulic conductivity, and pore pressure distribution in the unsaturated zone. Next, we describe the procedure for estimating water-table rise from the unsaturated zone computations and then describe how pore pressure changes are computed below the original water table.

Governing Equations

A one-dimensional form of the Richards equation describes infiltration at the ground surface and vertical flow through the unsaturated zone (Freeze and Cherry, 1979).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z}\left[K(\psi)\left(\frac{\partial \psi}{\partial Z} - 1\right)\right] \qquad (4A)$$

As shown by Srivastava and Yeh (1991), the exponential hydraulic parameter model of Gardner (1958) can be used to linearize equation 4*A* and provide an analytic solution for transient infiltration through the unsaturated zone. Gardner's (1958) unsaturated conductivity model is generally considered appropriate for coarse-grained soils. In this model, dependence of hydraulic conductivity, $K(\psi)$, and fluid content, θ, on pressure head in the Richards equation is given by the following formulas:

$$K(\psi) = K_S \exp(\alpha \psi *) \qquad (4B)$$

$$\theta = \theta_r + (\theta_s - \theta_r)\exp(\alpha \psi *) \qquad (4C)$$

In equations 4*B* and 4*C*, ψ is the pressure head, $\psi* = \psi - \psi_0$, where ψ_0 is a constant defined below, K_S is the saturated hydraulic conductivity, $K(\psi)$ is the hydraulic conductivity function, θ is the volumetric water content, θ_r is the residual water content, and θ_s is the water content at saturation. The parameter α is obtained by fitting equation 4*B* to a characteristic curve for soil such as that shown in figure 9. As we recall from the discussion of figure 6, the hydraulic conductivity is constant, independent of pressure head, and equal to K_S within the capillary fringe and below the water table. Also as shown by Gardner (1958), $1/\alpha$ represents the (vertical) height of the capillary

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fringe above the water table and, thus, at the top of the capillary fringe the pressure head is $\psi_0 = -1/\alpha$. By substituting $\psi_0 = -1/\alpha$ into the formula for ψ^*, equations 4B and 4C reduce to $K(\psi) = K_S$ and $\theta = \theta_S$ at the top of the capillary fringe, and we obtain the soil water characteristic curve shown by the solid line in figure 9.

Substitution of equations 4B and 4C into the one-dimensional version of the Richards equation 4A, leads to a linear partial differential equation with the solutions given below (Srivastava and Yeh, 1991). Note that for the coordinate transformation for the sloping ground surface we use the following: $\alpha_1 = \alpha \cos^2 \delta$.

Basic Solution for Constant Surface Flux

The flux at the base of the unsaturated zone, obtained by solving the linearized Richards equation, is given:

$$q(d_u, t) = \begin{bmatrix} I_Z - 4(I_Z - I_{ZLT}) \exp\left(\dfrac{\alpha_1 d_u}{2}\right) \exp\left[-\dfrac{t^*}{4}\right] \\[2ex] \cdot \sum_{m=1}^{\infty} \dfrac{\Lambda_m \sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left[-\Lambda_m^2 t^*\right] \end{bmatrix} \qquad (5A)$$

in which t^* is a dimensionless time defined:

$$t^* = \frac{\alpha_1 K_s t}{(\theta_s - \theta_r)} \qquad (5B)$$

In equation 5A, d_u is the depth of the unsaturated zone, I_{ZLT} is the steady, long-term background flux and the values of Λ_m are the roots of the characteristic equation shown below. All other notation is identical to that used previously.

The hydraulic conductivity in the unsaturated zone varies with time and depth according to the following formulas. The initial condition, $K(Z,0)$, is given:

$$K(Z,0) = I_{ZLT} - (I_{ZLT} - K_s \exp(\alpha_1 \psi_0)) \exp\left[-\alpha_1(d_u - Z)\right] \qquad (5C)$$

and the hydraulic conductivity solution for the unsaturated zone is given:

$$\begin{aligned} K(Z,t) = & I_{nZ} - (I_{nZ} - K_S) \exp\left(-\alpha_1(d_u - Z)\right) \\[1ex] & -4(I_{nZ} - I_{ZLT}) \exp\left(\frac{\alpha_1 Z}{2}\right) \exp\left(-\frac{t^*}{4}\right) \\[1ex] & \cdot \sum_{m=1}^{\infty} \frac{\sin \alpha_1 \Lambda_m (d_u - Z) \sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left(-\Lambda_m^2 t^*\right) \end{aligned} \qquad (5D)$$

The values of Λ_m are the positive roots of the pseudoperiodic characteristic equation,

$$\tan(\Lambda d_u) + 2\Lambda = 0. \qquad (6)$$

In TRIGRS, we solve for values of Λ_m by a combination of bracketing, bisection, and Newton-Raphson iteration (Press and others, 1986).

Early-Time Solutions for Constant Surface Flux

The Fourier series in equations 5A and 5D converge slowly for very early times, and for values of $t^* \leq 0.05$, we substitute the following expression for equation 5A:

$$q(d_u, t) = \begin{bmatrix} (I_{nZ} - I_{ZLT}) \exp\left(\dfrac{\alpha_1 Z}{2}\right) \\[2mm] \left\{ \begin{array}{l} \exp\left(\dfrac{\alpha_1 Z}{2} + \dfrac{t^*}{4}\right) \mathrm{erfc}\left(\dfrac{\alpha_1 Z}{2\sqrt{t^*}} + \sqrt{\dfrac{t^*}{4}}\right) \\[3mm] -\exp\left(\dfrac{\alpha_1(2d_u - Z)}{2} + \dfrac{t^*}{4}\right) \mathrm{erfc}\left(\dfrac{\alpha_1(2d_u - Z)}{2\sqrt{t^*}} + \sqrt{\dfrac{t^*}{4}}\right) \end{array} \right\} \end{bmatrix} \qquad (7A)$$

$$K(Z, t) = \begin{bmatrix} I_{ZLT} - (I_{ZLT} - K_s)\exp(-\alpha_1(d_u - Z)) + 2(I_{nZ} - I_{ZLT})\exp\left(\dfrac{\alpha_1 Z}{2}\right) \\[2mm] \left\{ \begin{array}{l} \mathrm{erfc}\left(\dfrac{\alpha_1 Z}{2\sqrt{t^*}}\right) \\[3mm] -\exp\left(\dfrac{\alpha_1 Z}{2} + \dfrac{t^*}{4}\right)\mathrm{erfc}\left(\dfrac{\alpha_1 Z}{2\sqrt{t^*}} + \sqrt{\dfrac{t^*}{4}}\right) \\[3mm] -\mathrm{erfc}\left(\dfrac{\alpha_1(2d_u - Z)}{2\sqrt{t^*}}\right) \\[3mm] +\exp\left(\dfrac{\alpha_1(2d_u - Z)}{2} + \dfrac{t^*}{4}\right)\mathrm{erfc}\left(\dfrac{\alpha_1(2d_u - Z)}{2\sqrt{t^*}} + \sqrt{\dfrac{t^*}{4}}\right) \end{array} \right\} \end{bmatrix} \qquad (7B)$$

Later-Time Solutions for Variable Surface Flux

To accommodate the time-varying input at the upper boundary, such as would occur during a rainstorm with varying intensity, we have put the solutions for unsaturated zone infiltration into Heavyside series expansions. In the expansions given below, t_n is the time at the nth step. In the formulas that use Heavyside series expansions, we use the appropriate time difference, $t - t_n$, or $t - t_{n+1}$, to agree with the argument of the Heavyside step function when evaluating t^*.

We use the following formula for the basal flux arriving at the base of the unsaturated zone; it is a generalized form of Srivastava and Yeh's (1991) solution given above as equation 5A.

$$q(d_u,t) = \sum_{n=1}^{N} H(t-t_n) \left[\begin{array}{c} I_{nZ} - 4(I_{nZ} - I_{ZLT})\exp\left(\dfrac{\alpha_1 d_u}{2}\right)\exp\left[-\dfrac{t_n{}^*}{4}\right] \\ \cdot \sum_{m=1}^{\infty} \dfrac{\Lambda_m \sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left[-\Lambda_m^2 t_n{}^*\right] \end{array} \right]$$

$$- \sum_{n=1}^{N} H(t-t_{n+1}) \left[\begin{array}{c} I_{nZ} - 4(I_{nZ} - I_{ZLT})\exp\left(\dfrac{\alpha_1 d_u}{2}\right)\exp\left[-\dfrac{t_{n+1}{}^*}{4}\right] \\ \cdot \sum_{m=1}^{\infty} \dfrac{\Lambda_m \sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left[-\Lambda_m^2 t_{n+1}{}^*\right] \end{array} \right] \tag{8A}$$

Computation of $K(Z,t)$ is based on a generalized form of the solution of Srivastava and Yeh (1991):

$$K(Z,t) = \sum_{n=1}^{N} H(t-t_n) \left[\begin{array}{c} I_{nZ} - (I_{nZ} - K_s)\exp\left(-\alpha_1(d_u - Z)\right) \\ -4(I_{nZ} - I_{ZLT})\exp\left(\dfrac{\alpha_1 Z}{2}\right)\exp\left[-\dfrac{t_n{}^*}{4}\right] \\ \sum_{m=1}^{\infty} \dfrac{\sin \alpha_1 \Lambda_m (d_u - Z)\sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left[-\Lambda_m^2 t_n{}^*\right] \end{array} \right]$$

$$- \sum_{n=1}^{N} H(t-t_{n+1}) \left[\begin{array}{c} I_{nZ} - (I_{nZ} - K_s)\exp\left(-\alpha_1(d_u - Z)\right) \\ -4(I_{nZ} - I_{ZLT})\exp\left(\dfrac{\alpha_1 Z}{2}\right)\exp\left[-\dfrac{t_{n+1}{}^*}{4}\right] \\ \sum_{m=1}^{\infty} \dfrac{\sin \alpha_1 \Lambda_m (d_u - Z)\sin(\alpha_1 \Lambda_m d_u)}{1 + \dfrac{d_u}{2} + 2\Lambda_m^2 d_u} \exp\left[-\Lambda_m^2 t_{n+1}{}^*\right] \end{array} \right] \tag{8B}$$

Pressure head in the unsaturated zone is obtained from equations 4B and 8B.

$$\psi(Z,t) = \frac{1}{\alpha_1} \ln\left[\frac{K(Z,t)}{K_s} + \alpha_1 \psi_0\right] \tag{9}$$

The user may specify one of two values for ψ_0, either $\psi_0 = 0$, for computation at the water table in agreement with the solutions of Srivastava and Yeh (1991), or $\psi_0 = -1/\alpha$, for computation at the

top of the capillary fringe as suggested by Savage and others (2004). When using $\psi_0 = 0$, the depth of the water table, d, is automatically substituted in place of d_u in all formulas presented here. As a result of the greater depth involved, using $\psi_0 = 0$ results in a slower rise time for the water table. The volumetric water content is computed by substituting the results of equation 9 into equation 4C.

Water Table Rise

Water-table rise occurs in response to vertical infiltration when the amount of infiltrating water reaching the water table exceeds the maximum amount that can be drained by gravity. For the one-dimensional geometry assumed by our infiltration models, the long-term vertical hydraulic gradient is $\beta - 1$, the maximum rate of drainage, $q_{Z\max}$, is

$$q_{Z\max} = K_S (\beta - 1) \tag{10A}$$

and excess flux, q_{Zex}, is determined by the following formulas:

$$q_{Zex} = 0, \text{ if } q(d_u, t) \le c_d (q_{Z\max} - I_{ZLT} \cos\delta) \tag{10B}$$

or

$$q_{Zex} = q(d_u, t) - c_d (q_{Z\max} - I_{ZLT} \cos\delta), \text{ if } q(d_u, t) > c_d (q_{Z\max} - I_{ZLT} \cos\delta) \tag{10C}$$

where the basal flux, $q(d_u, t)$, is given by equation 8A. The constant, c_d, is 1 for the case where the basal no-flow boundary is at infinite depth, and is arbitrarily set to 0.1 when the basal no-flow boundary is at finite depth. If the user selects a slope-parallel final pressure distribution, steady background flux is ignored, $I_{ZLT} = 0$; in addition, selecting hydrostatic-pressure distribution prevents all basal drainage, so that $q_{Z\max} = 0$ in equations 10A–10C.

The equations governing transient water-table rise are nonlinear and we are unaware of any techniques for solving the equations analytically to produce a continuous solution for pore pressure above and below the water table. Such problems are usually solved by numerical methods (see Freeze and Cherry, 1979; Huyakorn and Pinder, 1983). Consequently, we use approximate formulas to estimate the rate of water-table rise and pressure head in the vicinity of the rising water table.

To compute the water-table rise, we assume that the water table rise and rise of the capillary fringe resulting from infiltration are approximately equal. We integrate the excess flux arriving at the water table (equation 10B or 10C) over time to compute the volume of water (per unit area) accumulating at the base of the unsaturated zone, $V_A(t)$, and compare it to the volume of empty pore space (also per unit area) available above the initial water table (and capillary fringe) after any given time, $V_f(Z, t)$, as shown in figure 7. Numerical integration of q_{Zex} by repeating Simpson's three-point rule over successive time steps yields $V_A(t)$; numerical integration is necessary because the analytical solution for the time integral of equation 5A converges poorly. We compute the

fillable volume (available pore space) per unit (plan-view) area, $V_f(Z,t)$, above the water table by integrating the fillable porosity θ_f from the initial top of the saturated zone up to various equally spaced heights above it in the unsaturated zone. (All pore space is considered to be filled in the capillary fringe directly above the water table.) The result is shown:

$$V_f(Z,t) = (\theta_s - \theta_r)\big[(d_u - Z) + T(Z,t)\big] \tag{11}$$

In equation 11, $T(Z,t)$ is the transmissivity of a layer between the top of the saturated zone and some depth Z in the overlying unsaturated zone. In figure 7C, the roughly triangular areas between the water-content curve labeled t_1, the dashed vertical line labeled θ_s, and the dashed horizontal lines labeled Z_k or Z_{k+1} represent the volume $V_f(Z,t)$ in equation 11. We obtained formulas for $T(Z,0)$ and $T(Z,t)$ by integrating $K(Z,0)$ and $K(Z,t)$ with respect to Z, from the top of the saturated zone, d_u, to Z:

$$T(Z,0) = I_{ZLT}(d_u - Z) + \frac{1}{\alpha_1}(I_{ZLT} - K_s)\big(\exp(-\alpha_1(d_u - Z)) - 1\big) \tag{12A}$$

$$T(Z,t) = \sum_{n=1}^{N} \left\{ \begin{array}{l} H(t-t_n)\left[I_{nZ}(d_u - Z) - (I_{nZ} - K_s)\dfrac{1-\exp(-\alpha_1(d_u - Z))}{\alpha_1} \right] \\[2em] -\left[\dfrac{2(I_{nZ} - I_{ZLT})}{\alpha_1}\exp\left(-\dfrac{t_n{}^*}{4}\right) \right] \cdot \left[\begin{array}{l} \displaystyle\sum_{m=1}^{\infty} \dfrac{\sin(\alpha_1\Lambda_m d_u)\exp(-\Lambda_m^2 t_n{}^*)}{\left(\Lambda_m^2 - \dfrac{1}{4}\right)\left(1 + \dfrac{\alpha_1 d_u}{2} + \alpha_1 d_u \Lambda_m^2\right)} \\[2em] \cdot\left[\begin{array}{l} 2\Lambda_m \exp\left(\dfrac{\alpha_1 d_u}{2}\right) - \exp\left(\dfrac{\alpha_1 Z}{2}\right) \\[1em] \cdot(\sin(\alpha_1\Lambda_m(d_u - Z)) + 2\cos(\alpha_1\Lambda_m(d_u - Z))) \end{array}\right] \end{array}\right] \end{array}\right\}$$

$$-\sum_{n=1}^{N} \left\{ \begin{array}{l} H(t-t_{n+1})\left[I_{nZ}(d_u - Z) - (I_{nZ} - K_s)\dfrac{1-\exp(-\alpha_1(d_u - Z))}{\alpha_1} \right] \\[2em] -\left[\dfrac{2(I_{nZ} - I_{ZLT})}{\alpha_1}\exp\left(-\dfrac{t_{n+1}{}^*}{4}\right) \right] \cdot \left[\begin{array}{l} \displaystyle\sum_{m=1}^{\infty} \dfrac{\sin(\alpha_1\Lambda_m d_u)\exp(-\Lambda_m^2 t_{n+1}{}^*)}{\left(\Lambda_m^2 - \dfrac{1}{4}\right)\left(1 + \dfrac{\alpha_1 d_u}{2} + \alpha_1 d_u \Lambda_m^2\right)} \\[2em] \cdot\left[\begin{array}{l} 2\Lambda_m \exp\left(\dfrac{\alpha_1 d_u}{2}\right) - \exp\left(\dfrac{\alpha_1 Z}{2}\right) \\[1em] \cdot(\sin(\alpha_1\Lambda_m(d_u - Z)) + 2\cos(\alpha_1\Lambda_m(d_u - Z))) \end{array}\right] \end{array}\right] \end{array}\right\} \quad (12B)$$

No early-time equivalent of equation 12*B* is available. We use numerical integration of the results of equation 8*B* for rare cases in which early-time results are needed for computation of the water-table rise.

The water-table rise is first bracketed between the two nearest depths, Z_k and Z_{k+1}, at which the available volume has been computed, such that $V_f(Z_k, t) \geq V_A(t) \geq V_f(Z_{k+1}, t)$, and then it is estimated by linear interpolation between Z_k and Z_{k+1} (fig. 7*C*). Due to the slope of the water content curve directly above the capillary fringe (fig. 7*B*), the method outlined in figure 7*C* may slightly overestimate the actual rise of the water table, Δh. The error can be reduced by reducing the depth increment, $Z_{k+1} - Z_k$.

Pressure Diffusion Below the Water Table

Once the water-table rise has been computed at a grid cell for time increment n, we apply the load (as measured by the computed water-table rise, h_n) at the *initial* top of the saturated zone and compute the pressure head using formulas for a constant head boundary condition that have been adapted from analogous heat-flow problems (Carlslaw and Jaeger, 1959) and generalized for time-varying water-table rise, h_n. For consistency with equation 3*A*, pressure head, ψ_{hn}, applied by the newly accumulated water above the initial water table is $\psi_{hn} = \beta h_n$.

Infinite-Depth Basal Boundary, Variable Applied Head

The computer program TRIGRS uses pressure-diffusion formulas for computing head changes below a rising water table. For relatively homogeneous hillsides, a model having an impermeable basal boundary at infinite depth can approximate the pressure rise.

$$\psi\left(Z_1,t\right)=\sum_{n=1}^{N}h_n H\left(t-t_n\right)\operatorname{erfc}\left[\frac{Z_1}{2\sqrt{D_1\left(t-t_n\right)}}\right]-\sum_{n=1}^{N}h_n H\left(t-t_{n+1}\right)\operatorname{erfc}\left[\frac{Z_1}{2\sqrt{D_1\left(t-t_{n+1}\right)}}\right] \quad (13)$$

In equation 13, Z_1 is the vertical distance below the initial water table, $Z_1 = Z - d_u$.

Finite-Depth Basal Boundary, Variable Applied Head

For hillsides that have a strong permeability contrast at shallow depth, such as many hillsides that have a colluvial mantle only a few meters thick, a model that has an impermeable boundary at finite depth can estimate pressure rise.

Early-Time Formula

As with the infinite depth model, a solution that provides accurate results for early and intermediate times is based on the complementary error function:

$$\psi\left(Z_1,t\right)=\sum_{n=1}^{N}h_n H(t-t_n)\left(\begin{array}{l}\sum_{m=1}^{\infty}(-1)^{m+1}\operatorname{erfc}\left[\frac{(2m-1)d_{LZ}-Z_1}{2\sqrt{D_1\left(t-t_n\right)}}\right]\\+\sum_{m=1}^{\infty}(-1)^{m+1}\operatorname{erfc}\left[\frac{(2m-1)d_{LZ}+Z_1}{2\sqrt{D_1\left(t-t_n\right)}}\right]\end{array}\right)$$
$$-\sum_{n=1}^{N}h_n H\left(t-t_{n+1}\right)\left(\begin{array}{l}\sum_{m=1}^{\infty}(-1)^{m+1}\operatorname{erfc}\left[\frac{(2m-1)d_{LZ}-Z_1}{2\sqrt{D_1\left(t-t_{n+1}\right)}}\right]\\+\sum_{m=1}^{\infty}(-1)^{m+1}\operatorname{erfc}\left[\frac{(2m-1)d_{LZ}+Z_1}{2\sqrt{D_1\left(t-t_{n+1}\right)}}\right]\end{array}\right) \quad (14)$$

In equation 14, d_{LZ} denotes the vertical height or thickness of the saturated layer, from the initial water table down to the impermeable boundary.

Later-Time Formula

At later times, we use a formula that is based on a Fourier series solution.

$$
\begin{aligned}
\psi\left(Z_1,t\right) = \sum_{n=1}^{N} h_n H\left(t-t_n\right) & \left(\sum_{m=1}^{\infty}(-1)^{m-1} \frac{1}{2m-1} \exp\left(-\frac{(2m-1)^2 \pi^2 D_1\left(t-t_n\right)}{4d_{LZ}^2} \right) \right. \\
& \left. \cdot \cos\left(\frac{\pi}{2}(2m-1)\left(\frac{Z_1}{d_{LZ}}-1 \right) \right) \right) \\
-\sum_{n=1}^{N} h_n H(t-t_{n+1}) & \left(\sum_{m=1}^{\infty}(-1)^{m-1} \frac{1}{2m-1} \exp\left(-\frac{(2m-1)^2 \pi^2 D_1\left(t-t_{n+1}\right)}{4d_{LZ}^2} \right) \right. \\
& \left. \cdot \cos\left(\frac{\pi}{2}(2m-1)\left(\frac{Z_1}{d_{LZ}}-1 \right) \right) \right)
\end{aligned}
\tag{15}
$$

The step-function series in equations 13–15 contain N successive time steps to represent water-table rise from the initial base of the unsaturated zone. The time steps correspond to those in the unsaturated infiltration series. All time steps are completed at one grid cell before proceeding to the next cell.

Infiltration, Runoff, and Flow Routing

The program, TRIGRS, uses a simple method for routing of surface runoff from cells that have excess surface water to adjacent downslope cells where it can either infiltrate or flow farther down slope.[3] We assume that runoff occurs when the precipitation and runoff supplied to a cell exceed its infiltrability. The saturated hydraulic conductivity, K_s, generally equals the infiltrability, i, for saturated and tension-saturated soils (Hillel, 1982; Iverson, 2000). The purpose of routing the surface runoff is to prevent the loss of excess precipitation that cannot infiltrate at the cell of origin and to improve the performance of the model in urbanized or other areas where pavement or other impervious surfaces exist. However, the user may bypass the runoff routing, if desired. Running TRIGRS without routing would be appropriate where a complex system of storm drains complicates runoff routing.

We compute the infiltration, I, at each cell as the sum of the precipitation, P, plus any runoff from upslope cells, R_u, with the limitation that infiltration cannot exceed the saturated hydraulic conductivity, K_s:

$$
I = P + R_u, \text{ if } P + R_u \le K_s
\tag{16A}
$$

or

$$
I = K_s, \text{ if } P + R_u > K_s
\tag{16B}
$$

---

[3] Runoff routing is applied only to the transient part of the solution. If TRIGRS detects that the steady infiltration rate at a cell exceeds the saturated hydraulic conductivity, it reduces the value of I_s/K_s to a value that makes $\beta = 0$ at the cell, with the result that pressure head above the user-specified steady water table is zero. Cells where this occurs are identified in the log file, so that the user can go back and correct the input data.

At each cell where $P + R_u$ exceeds K_s the excess is considered runoff, R_d, and is diverted to adjacent downslope cells.

$$R_d = P + R_u - K_s, \text{ if } P + R_u - K_s \geq 0 \tag{17A}$$

or

$$R_d = 0, \text{ if } P + R_u - K_s < 0 \tag{17B}$$

Overland flow between adjacent cells is assumed to occur instantaneously; we have made no attempts to model the rate of overland flow. Consequently, individual storm periods should be long enough to allow surface water to flow to adjacent cells. The routing method enforces mass balance for each time step through the storm; the total precipitation at all the cells must equal the water that infiltrates at all the cells and the water that flows to edges of the problem domain (or any closed depressions) without infiltrating. Thus, excess precipitation that cannot infiltrate at its cell of origin has the opportunity to infiltrate at some point down slope. However, TRIGRS does not carry runoff over from one time step to the next, nor does it track water that enters storm drains. In other words, water that runs off a cell during any given time step will either infiltrate at another cell or reach the edge of the model (or some other sink) within that time step.

In addition to runoff from cells where precipitation exceeds the infiltrability, water is assumed to run off from any cells where the water table is initially at the ground surface and the initial (steady) rate of infiltration is negative. Water is exfiltrating from such cells and runs to the adjacent downslope cell(s). The TRIGRS program tracks exfiltrating water in the mass balance calculations.

By computing the infiltration and runoff at cells in order from the topographically highest cell(s) to the lowest, the program TRIGRS avoids the necessity of iterating to reach a solution that satisfies mass balance. Mass-balance calculations for each storm time step verify that all water applied as input is accounted for as either infiltration or runoff. Mass balance will be achieved only if the topographic data have been correctly indexed. A digital elevation model (DEM) can be indexed correctly only if it has been adjusted in GIS software to be hydrologically consistent. This adjustment is a selective smoothing process accomplished by raising the elevation of single-cell closed depressions to match surrounding cells, and slightly raising or lowering the elevation of cells in flat areas to produce flow directions that are consistent with surrounding topography. The TRIGRS program writes the results of the mass-balance calculations to a log file, named "TrigrsLog.txt", in the same folder as the application.

Topographic Indexing

We include a companion utility program, TopoIndex (Topographic Index). TopoIndex prepares a group of data files for the runoff-routing calculations. These output files contain a list of cell numbers ranked in order from highest to lowest elevation and a grid of cell numbers indicating the neighboring cell on the steepest downslope path. Figure 10 illustrates the grid cell numbering scheme. The TRIGRS program uses these data to control the order of runoff routing calculations as described above. If any of these files are missing, then TRIGRS will compute infiltration based on the rainfall input without routing any excess surface water. The output files of TopoIndex also contain a list of grid cells and their downslope neighbors, along with a list of weighting factors that determine what proportion of the runoff is transferred to each neighboring downslope cell.

The program TopoIndex uses a two-step process to index the cells from highest to lowest elevation. The first step, sorting the cell elevations, consists of defining an index using the

"Heapsort" algorithm (Press and others, 1986). The second step corrects the index by comparing the indices of neighboring cells to their relative positions along downslope paths. If the indices of two neighboring cells that have the same *apparent* elevation (due to numerical rounding or truncation) are out of order, they are swapped. This iterative step continues until the number of corrections on the last pass equals zero. Figure 11 compares grid cell elevation (fig. 11*A*) and cell index (fig. 11*B*) for a sample grid. We have successfully tested TopoIndex on a grid of a approximately 2 million cells. The TRIGRS program uses output files from TopoIndex to implement the runoff-routing scheme described in the previous paragraphs. Our tutorial (appendix 2 of this report) describes how to operate the utility program and prepare data for the analysis. Figure 12 shows the designation of D8 flow directions used by TopoIndex in contrast to the ESRI direction codes. Successful operation of TopoIndex requires the use of a hydrologically consistent DEM as input. TopoIndex does not account for storm drains and similar artificial drainage diversions that are not expressed in the topography.

TopoIndex allows the user considerable latitude in determining how excess water, R_d, will be distributed among the downslope cells. Table 1 outlines the available choices of distribution patterns, which (in this implementation) apply only to square cells. Many of the patterns depend on an exponent, ω, and the slopes between the current grid cell and its downslope neighbor cells similar to the method of Freeman (1991). The same exponent is used in computing weighting factors throughout the grid. Figure 13 illustrates how the choice of distribution patterns affects the output. Figure 13*A* and 13*B* show cell numbers and elevations from part of the sample grid. The default case ($\omega > 20$, fig. 13*C*) is to divert excess water only to the adjacent cell on the steepest downslope path (the D8 method of O'Callaghan and Mark, 1984). Letting $\omega = 0$ distributes the excess water evenly among all adjacent downslope cells; this pattern has the greatest dispersion of all the choices (fig. 13*E*). If $\omega = 1$ (fig. 13*F*), then flow is distributed among all downslope cells in proportion to the slope, which is equivalent to the method of Quinn and others (1991). Tarboton (1997) showed that this method has significant dispersion. Choosing higher exponents decreases the dispersion and diverts increasing proportions of the flow to the cell on the steepest downslope (D8) path (figs. 13*G, H*). Negative exponents are not implemented because they would concentrate flow on flatter slopes.

If the user enters a negative exponent in the TopoIndex initialization file, it acts as a flag to select a method that is similar to Tarboton's (1997) D-infinity method (fig. 13*D*). The D-infinity method assumes that water flows down the steepest slope, computes the direction of steepest slope and attempts to direct flow in that direction by partitioning the flow between the two cells nearest to the steepest slope direction. In this case, TopoIndex uses the D8 direction as a starting point and compares the slopes of the two neighboring directions to identify the triangular facet that contains the steepest slope. If the steepest slope coincides with the D8 flow direction, then all flow is diverted to the cell in that direction. Otherwise flow is distributed between the two cells that straddle the direction of the steepest slope; the weighting factors are proportional to the angles between the grid directions and the dip direction of the facet as described by Tarboton (1997).

Each of the runoff distribution patterns has its peculiar characteristics. The D8 method is the simplest and has the lowest dispersion; however, the resulting runoff distribution is irregular and somewhat unrealistic. We prefer the D-infinity method because it is physically more realistic than any of the other methods implemented in TopoIndex. The D-infinity method is used in the steady-state regional slope stability program SINMAP (Pack and others, 1998). The remaining methods, in which the weighting factors are proportional to the slope raised to an exponent, are provided to allow the user to achieve greater dispersion or smoothing of the runoff distribution if desired.

Slope Stability

Following Iverson (2000), we model slope stability using an infinite-slope stability analysis (Taylor, 1948). In his analysis, failure of an infinite slope is characterized by the ratio of resisting basal Coulomb friction to gravitationally induced downslope basal driving stress. This ratio, called the factor of safety, F_S, is calculated at a depth Z by

$$F_S = \frac{\tan \phi'}{\tan \delta} + \frac{c' - \psi(Z,t)\gamma_W \tan \phi'}{\gamma_S Z \sin \delta \cos \delta} \tag{18}$$

where c' is soil cohesion for effective stress, ϕ' is the soil friction angle for effective stress, γ_W is unit weight of groundwater, and γ_S is soil unit weight. The pressure head, $\psi(Z,t)$, in equation 18 is subject to the limitation imposed by equation 3 and is obtained from either equations 1, 2, 9, or 13–15 depending on the particular conditions modeled.

Factors of safety, F_S, are calculated by equation 18 for transient pressure heads at multiple depths Z (fig. 14). Failure is predicted when $F_S < 1$ and stability holds where $F_S \geq 1$. The state of limiting equilibrium exists where $F_S = 1$. Thus, the depth Z where F_S first drops below 1 will be the depth of landslide initiation. This initiation depth depends on soil properties and the time and depth variation of pressure head, which, in turn, depends on rainfall history.

In the unsaturated zone we use a simple approximation for Bishop's (1959) effective stress parameter, χ, in computing the factor of safety. Vanapalli and Fredlund (2000) defined the approximation, $\chi = (\theta - \theta_r)/(\theta_s - \theta_r)$, which has subsequently been adopted by others (see Lu and Likos, 2004). To compute the factor of safety above the water table, the matric suction, $\psi(Z,t)\gamma_W$, is multiplied by χ. In TRIGRS, we compute a depth-averaged soil unit weight for use in equation 18 to account for the lower unit weight of partially saturated soil above the water table.

Limitations

All numerical and analytical models of ground water flow and slope stability are subject to limitations imposed by simplifying assumptions, approximations, and other shortcomings in the underlying theories. The TRIGRS program is based on transient vertical infiltration models combined with a simple slope stability model and is subject to the same limitations that are inherent in the original models (Srivastava and Yeh, 1991; Iverson, 2000; Savage and others 2003):

- The model assumes flow in homogeneous, isotropic soil; thus, application to areas with marked soil anisotropy or heterogeneity in hydrologic properties may cause errors in the solution.

- The TRIGRS program models only one-dimensional vertical infiltration, which is dominant in determining pore pressure change early in a storm. During longer storms and periods between storms, lateral flow also has a significant influence on the magnitude and distribution of pore pressure. Estimates of pore pressure using the TRIGRS model may be in error once lateral flow begins to respond to the storm. Consequently, TRIGRS is *not* suitable for modeling long-term effects of alternating periods of rainfall and evapotranspiration, and choosing the correct initial conditions for a given storm is critical to obtaining accurate results. The most suitable method for handling lateral flow within the TRIGRS framework is currently under investigation. Users

may estimate "worst-case" pressure-head conditions resulting from late-storm slope-parallel flow by setting the initial water table at the ground surface and setting the steady background flux to zero or by using the slope-parallel option (tables 2 and 3) to obtain a pore pressure distribution equivalent to slope-parallel flow.

- The results are very sensitive to the initial conditions. Ideally, the user should know the initial water-table depth and something about the initial flow field throughout the study area. The user must specify the initial depth of the water table and steady infiltration or exfiltration rate at each cell or estimated values for the entire area. The initial water-table depth and rate allow the user to represent fairly general initial flow conditions. In urban and suburban areas, data from geotechnical borings and monitoring wells for environmental remediation projects may provide estimates of the initial conditions. In the absence of detailed information, simple ground-water flow models that can be adapted to hill-slope conditions might provide reasonable estimates (Beven and others, 1984; Beven, 2004).

- The program uses a simple method for routing surface runoff from cells where precipitation exceeds the infiltrability (K_s for saturated and tension-saturated soils) to neighboring downslope cells. This method does not account for evapotranspiration, which is expected to be low during most storms. Furthermore, the runoff routing model cannot be used to estimate stream flow because runoff from cell to cell is assumed to happen instantaneously and the runoff receives no contributions from subsurface flow, except for cells where steady exfiltration is specified in the initial conditions.

- Procedures for correcting and preprocessing digital elevation models (filling pit artifacts or one-cell depressions, and computing flow directions) are not included in TRIGRS or TopoIndex. However, such procedures are available in modern GIS software. TopoIndex and TRIGRS require a DEM that has been corrected to remove noise, such as one-cell depressions.

- Model results are sensitive to the engineering properties of geologic units in the model area, some of which may vary over orders of magnitude. For any geologic material the hydraulic conductivity and diffusivity may vary over several orders of magnitude.

- The slope-stability model is based on an infinite slope analysis, which assumes uniform slope, thickness, physical properties, and that pore-water pressure is a function of only depth and time. Applying this method over a grid that represents three-dimensional topography may result in errors where slope, thickness, physical properties or pore pressure changes abruptly. Non-uniform lateral stresses (or inter-cell forces) and non-planar failures may occur in areas where the infinite slope assumptions are violated. Thus, the model is more accurate where conditions favor planar failure, which typically occur at depths that are shallow compared to the width of the grid cells and in areas where slopes are smooth and have a relatively uniform mantle of weathered material. Based on published comparisons of various methods of slope stability analysis, we expect the model to compute lower factors of safety than more rigorous methods of stability analysis would in areas where failures tend to be non-planar (Duncan, 1996).

- The TRIGRS model is not recommended for use on slopes steeper than 60°. For slopes steeper than about 50°–60°, depending on the depth, cohesion, and other parameters, equation 18 predicts increasing, rather than decreasing, values of F_S for *constant* depth. The safety factor increases for slopes steeper than 50°–60° because the thickness of the sliding mass, $Z \cos \delta$, decreases as the slope becomes steeper, with the result that the proportion of shearing resistance contributed by cohesion increases significantly over that contributed by friction. Although this difficulty can be overcome by dividing a depth grid by $\cos \delta$ to effectively transform it to a

thickness grid and using the transformed grid with TRIGRS, this transformation will not overcome the uncertainty resulting from use of a one-dimensional model to represent the infiltration process on slopes steeper than 60°–70°.

• The program does not check for consistent units of measurement between the different input parameters. However, we have provided a simple utility program called UnitConvert that can be used to convert data contained in grid files between different systems of units.

• A lack of information about how conditions change once a slope has failed limits the ability of TRIGRS to forecast what happens after the factor of safety has fallen below unity (failure) at any particular grid cell. Although it is feasible to modify TRIGRS to update the properties and hill-slope geometry after failure occurs, the main difficulty lies in predicting what the updated properties and geometry should be. In many instances, the scars of shallow failures expose more competent material, and considerable time (years to decades) must pass before sufficient weathered material accumulates to allow failure at the same location. However, depending on cell size, successive failures might occur at neighboring locations within the same cell during a storm or later storms. Consequently, for computational purposes, we have treated cells as if they are unchanged by failures during a given simulation—in other words, TRIGRS does not modify the soil thickness or properties when $F_S < 1$.

Program Operation

The Windows versions of the programs TRIGRS, TopoIndex, Gridmatch, and UnitConvert are launched by double clicking their icons. These programs have a command line interface, and run in their own console windows. Mac OS versions are started from the command line in the Terminal application.[4] Upon starting, TRIGRS opens a user-supplied initialization file found in the present working directory, and reads a list of file names and parameters needed to compute the pore pressures and factors of safety in each cell. The program then opens and reads files of input data, computes the results, and saves the output to a series of files. The program exits automatically when it is finished. The TRIGRS program writes a brief log file that may be useful in troubleshooting or in keeping a record of successive analyses. The log file includes a record of the starting and ending time, any errors that occurred, a copy of data from the initialization file, statistics on convergence of series solutions, and other information useful in interpreting program output. The utility programs, TopoIndex, GridMatch, and UnitConvert, operate in the same manner. Successful operation of the programs requires that the initialization file and other input files be organized and formatted correctly. Therefore, we describe the format and contents of these files before presenting a brief tutorial (appendix 2).

TRIGRS Initialization File

The initialization file (table 2) controls input and output. Use of an initialization file accelerates analysis when compared to the alternative of repeatedly choosing input files from interactive dialog boxes. The initialization file is in ASCII text format and contains a list of header

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[4] To run TRIGRS from the command line, start Terminal, type cd and drag the (main) TRIGRS folder icon to the Terminal window. After the path name of the folder appears on the command line, press return. Drag the TRIGRS program icon (in the folder TRIGRS/bin) to the terminal window and press return. TRIGRS will launch immediately and look for the initialization file in the present working directory, which in this case is the folder selected using the cd command.

lines, input file names, and constants needed to complete the analysis. To change problem parameters, the user edits the initialization file using a text editor. Consequently, most runtime errors result from mistakes in editing the initialization file or errors in the input grids. To reduce errors in editing the file, a descriptive or explanatory heading precedes each line (or in one case a group of related lines) of data in the initialization file. The first line of data contains a project title. It is followed by several lines of numeric data including program parameters, properties for each zone, rainfall infiltration rates and times; the second group of lines contains names of input files; and the third group of lines specifies which output files will be saved, as well as their file names and paths. The fourth and final group contains user options that affect how the analysis is performed. Table 2 shows the organization of the initialization file and defines the input file names using partial path names (starting at the current folder). The next few paragraphs describe the structure of the initialization file and general characteristics of the data. We have provided a more detailed explanation of the initialization data needed to perform a simulation in the tutorial (appendix 2).

Numeric data.—The file contains several lines of numeric data needed to determine array sizes, model parameters, precipitation history, initial conditions, and physical properties. An explanatory heading precedes each line of data. The file is organized with a project title and heading on the first two lines, numerical input data and headings on the next six lines, followed by two lines of headings, one line of data for each property zone, and two more lines each for rainfall rate, corresponding times, and their respective headings (table 2). The user may set physical parameters, such as soil and water table depths, background flux, and rainfall (infiltration) rates to a constant value over the entire grid by specifying a positive value. A negative value for any of these parameters prompts the program to read an input grid for spatially variable data. The user determines the number of property zones and assigns physical properties (soil strength parameters and hydraulic properties) to each zone (one line per zone). A single property-zone grid maps all these properties to the model. Table 3 defines the numeric variables listed in table 2 and indicates appropriate ranges of values.

Input files.—The user must specify a file name for each input file. The TRIGRS program automatically reads a name for each potential input file; therefore the user must provide a placeholder for any input file that either does not exist or will not be used for a given simulation. The TRIGRS program can accept either full or partial path names[5] as long as 255 characters; however, the rules for specifying path names vary between operating systems. If the paths are typed incorrectly, the program will report an error. To minimize errors in specifying file path names, the user may place all the input data files needed for a given simulation into a specific folder. On Windows systems, placing a copy of the executable program (TRIGRS.exe) and initialization file into the folder where the data reside will further simplify operation. By doing so, the user needs only to specify the file names and does not need to worry about the paths.

In table 2, path names of input files are on the next group of lines after the numeric data described previously. Each file name occupies a single line in the file. The total number of lines in the file depends on the number of property zones and number of periods of different rainfall intensity. Be sure to include a file path name, rifil(), for each period, but only one heading for this group of file names. In this example, the rainfall rates during the storm are set constant over the grid. Two storm periods are specified, so two lines are needed for the rainfall rate input file names (placeholders in this case).

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[5] The full path is the concatenation of the drive name, the folder name(s), and the file name. For example, C:\\Program Files\TRIGRS\TRIGRS.EXE is a full path name and TRIGRS\TRIGRS.EXE is a partial path name. Parent directories can be specified by typing "..\" in Windows or ".." in Mac OS and UNIX.

Output files.—Table 4 lists the names and describes the contents of the output files that TRIGRS can generate. A series of eight logical values (true or false) determines which output grid files are saved to disk. These are listed directly after the input file names (table 2). A numeric flag at the end of the list of output file choices determines whether the cell-by-cell list file is saved and whether it contains optional data. *Note that this file can become very large, particularly if the analysis includes multiple time steps. This option should be reserved for use with small test grids to prevent filling the disk drive.* The user may specify an identification code to group files from a particular simulation. Users may also specify a separate folder where the output files can be saved. Certain output grids can be saved at selected times during the simulated storm.

Model options.—The last few lines of the initialization file (table 2) allow the user to select options that control how the model performs certain functions in the unsaturated zone (appendix 2). These options allow the user to compute the fillable porosity either analytically or numerically, compute positive pressures above the original water table as water accumulates at the base of the unsaturated zone, and determine how the capillary fringe is treated. The final option allows the user to select the slope of the beta line, which determines maximum pore pressure at each depth.

On start-up, TRIGRS will look for the default initialization file, "tr_in.txt", in the same folder where the program file resides. If it is not present, then TRIGRS prompts the user to enter the name of the initialization file. TopoIndex, GridMatch, and UnitConvert follow a similar convention.

Input File Format

Most input files contain gridded data and all grid files use the same basic format, consisting of a short list of file parameters followed by the grid data. File parameters can be entered in formats that support either ESRI ArcGIS or the open-source GRASS GIS. The files are in space-delimited ASCII text format and can be viewed or edited with a text editor.

The first six lines of the ArcGIS ASCII grid file contain parameters defining the grid. Table 5*A* shows an elevation grid from the tutorial data folder. The first two lines define the number of columns and rows in the grid. The third and fourth lines indicate the coordinates of the lower-left (southwest) corner of the grid, the fifth line indicates the grid spacing, and the sixth line defines the value used to identify cells where no data exists. Each parameter is preceded by a text label up to 14 characters long (table 5*A*). Text labels for the ArcGIS ASCII grid format should appear exactly as shown in table 5*A*. The remaining lines (line 7 and beyond) contain the value (topographic elevation in this example) of each grid cell. The grid data begins at the northwest corner cell in the upper left-hand corner of grid and the cells are listed from left to right (west to east), and row-by-row from top to bottom (north to south). The grid data may be written in either decimal or scientific floating-point format. Single-precision arrays hold the grid data. Spaces, commas, or tabs may be used as delimiters. The default "no data" (null) value for cells to be excluded from the analysis is -9999.

The header for a GRASS GIS two-dimensional ASCII grid format also lists six lines (table 5*B*). The first four lines list the north, south, east, and west boundaries of the grid in UTM or similar coordinates, and the last two lines contain the number of rows and columns in the grid. Grid values are arranged and formatted the same way as for the ArcGIS files. The GRASS GIS software allows the user to specify the value for no-data cells, but the header does not specify this value, so we suggest setting the no-data (null) value to -9999 to agree with the default value in TRIGRS.

The only exceptions to the grid-file format are files used to control the routing of excess water. These text files include three lists as shown in tables 6, 7, and 8. Table 6 illustrates the

format of a file containing a list of cells downslope from each grid cell. Table 7 follows a similar format and contains the weighting factors for the corresponding cells listed in table 6. Table 8 illustrates the format of the index file that indicates the order in which cells are analyzed to correctly partition infiltration and runoff. The input routing method also uses a grid file that indicates which neighboring cell is on the steepest downslope path.

Output File Formats

The TRIGRS program automatically generates a log file and can generate optional output files (if specified in the initialization file, table 2). The log file (always named "TrigrsLog.txt") contains information about program operation and repeats the data from the initialization file. By renaming the file (add the identification code applied to the other output files from the simulation), the user can save a record of the simulation to keep with the other output files. Most of the optional output files follow the same grid format as the input files. Three of the files contain (1) the minimum factor of safety, (2) the pressure head, and (3) the depth at which the minimum occurs. In case of runoff, TRIGRS saves a file showing runoff at the end of each storm period.

Another optional output file contains a cell-by-cell listing of the pore pressure and factor of safety at each depth in the profile (fig. 14 and table 9). This file can become quite large because its size increases with the user-specified number of vertical increments (fig. 14) and with the number of cells in the grid. For example, on a grid with 20,522 cells, the profile data using five vertical increments (six points per cell) occupied about 5 MB, where the ASCII grid output files occupied 368 KB each. The suggested use of this file is for tracking time histories of a few representative cells organized into a small grid for model calibration.

TopoIndex Initialization File

TopoIndex requires less input than TRIGRS, but its initialization file is similar in design. Table 10 shows an example initialization file for TopoIndex. The first two lines contain numeric data needed to control program operation and establish array sizes. The next two contain the names of input files and the remaining lines control output. Table 11 lists the output files. TRIGRS uses four of the seven output files that TopoIndex is capable of generating (indicated by * in table 11). The other three are provided as a convenience for the user in visualizing the data.

Troubleshooting

The following suggestions will help to ensure that TRIGRS and associated programs work as expected.

- Use GIS software to hydrologically correct (remove pit artifacts from) the digital elevation model (DEM).
- Make sure that all grid files (1) are in one of the specified formats, (2) have the same numbers of rows and columns, and (3) have the same number of no-data cells in the same locations (fig. 10). We have provided a utility program "GridMatch" to help the user verify that all input grids have the same structure. It checks the number and locations of no-data cells as well as verifying that the number of rows and columns are the same. Table 12 is a sample listing of the initialization file for GridMatch. Results of the file comparison are saved in the file gridmatchLog.txt. Sample mismatching grid files, used to demonstrate the operation of GridMatch, are found in the folder Data/gridmatch/ within the TRIGRS distribution.

- Check the path names of all files listed in the initialization file for correct location and spelling.
- Be sure that the initialization file is in the same folder as the program file on Windows systems or in the present working directory on Mac OS X and other UNIX-based systems.
- Save and close the initialization file and all other input files before attempting to run TRIGRS or one of the associated utility programs

A list of common problems and solutions appears in table 13.

Comparison of Computed Results with Published Analyses

We tested TRIGRS against Iverson's (2000) examples from the Minor Creek landslide and from an experiment at the USGS debris-flow flume and were able to reproduce his results for pore pressure and factor of safety profiles. Thus, we were able to verify that the computer code accurately implements Iverson's (2000) formulas for pore pressure and factor of safety. After publishing the original version of TRIGRS, students of Ricardo Rigon (University of Trento, Trento, Italy) pointed out an error in the coordinate transformation in Iverson's (2000) original paper. Correction of that simple error causes our numerical results to differ somewhat from Iverson's (2000) published values, though preserving their basic form. Folders named "MinorCreek" and "flume" contain files with necessary data to reproduce these results. By varying elapsed time, t, in the initialization file, the user can compute pressure head and factor of safety profiles like those of figures 7, 8, 10, and 11 of Iverson (2000). Note that the computed profiles conform to the limit imposed by equation 3. We have also verified that the new version of TRIGRS described in this report reproduces the published results of Srivastava and Yeh (1991). Data in the folder "sy91" produce profiles that allow the user to reproduce the curves plotted in figure 3 of Srivastava and Yeh (1991).

Acknowledgments

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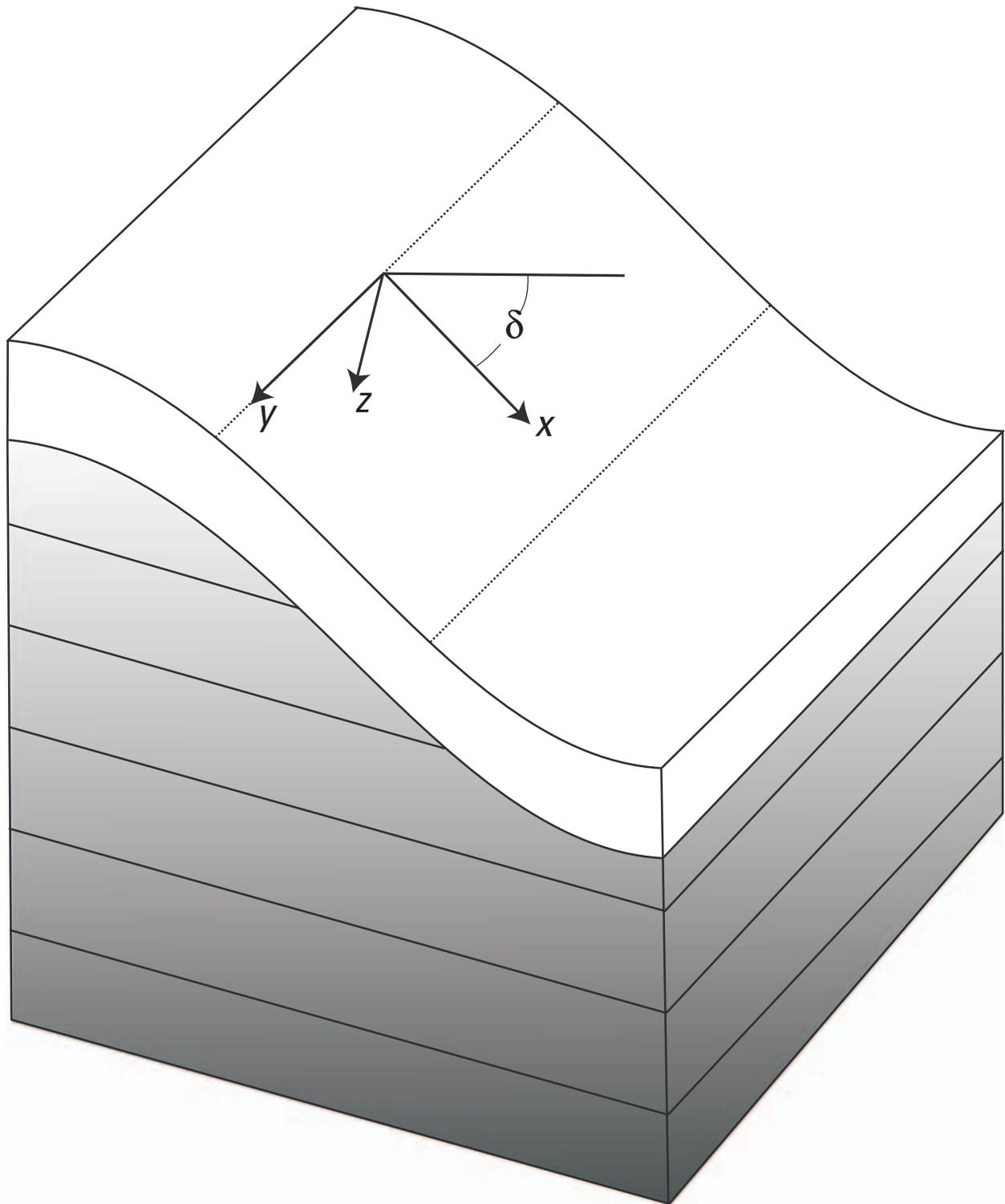
Figure 1. Sketch showing local xyz coordinate system with x tangent to the local surface slope, y tangent to the local topographic contour and z normal to the x-y plane; the slope angle, δ, is with respect to the horizontal.
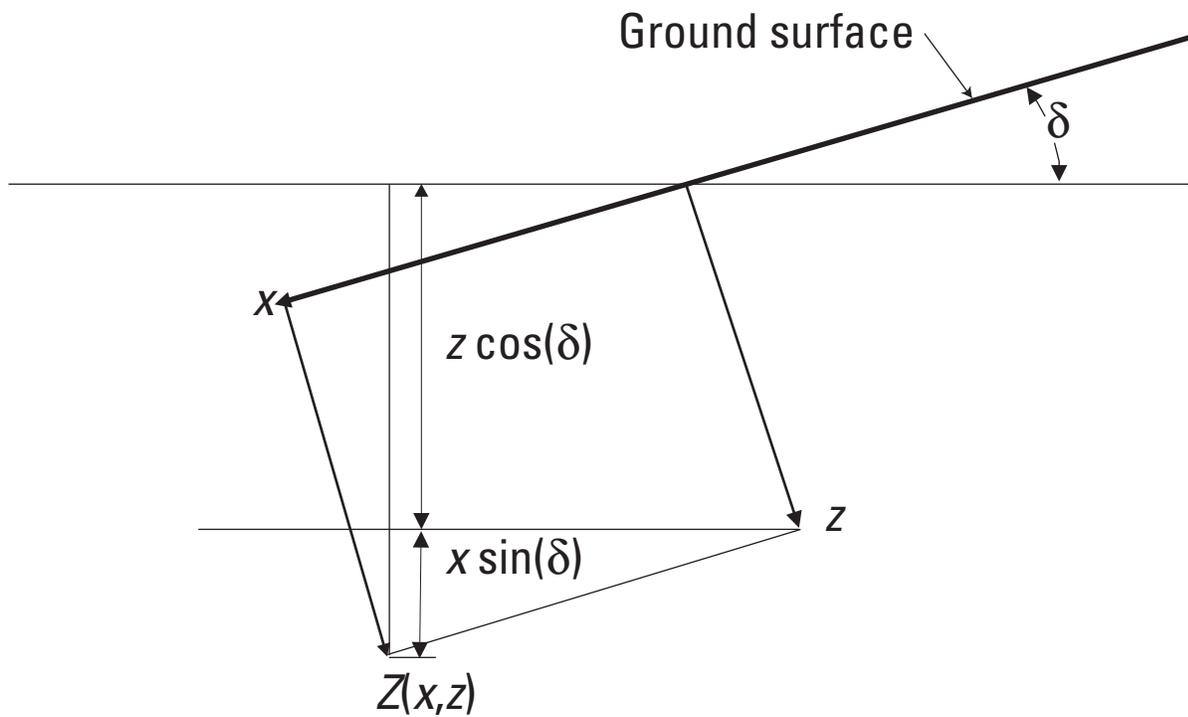
Figure 2. Sketch showing the definition of the vertical coordinate, $Z = x\sin\delta + z\cos\delta$, used to compute the depth at an arbitrary location. If Z and z have a common origin, then $Z = z/\cos\delta$ (after Iverson, 2000).
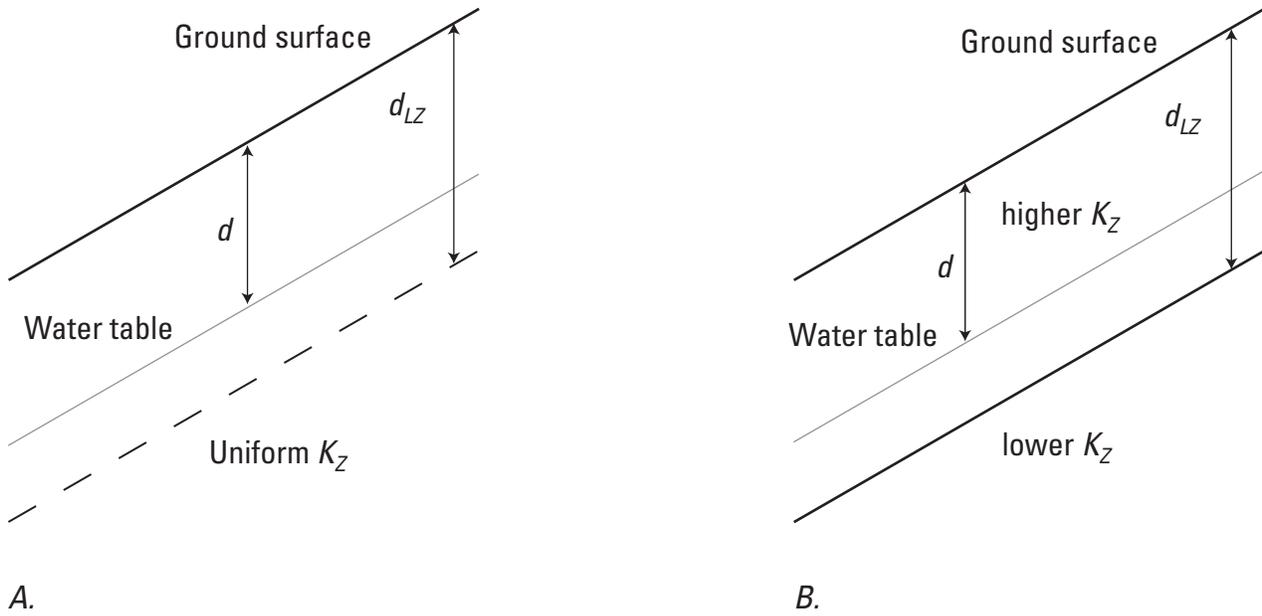
Figure 3. Schematic cross sections showing boundary conditions assumed in deriving the two infiltration formulas (equations 1 and 2). The dimension Z_{max} corresponds to the input variable *zmax*, and the initial depth to the water table, d, corresponds to the input variable *cdep* (table 3). *A*, The infinite-depth boundary condition, which is assumed in equation 1, is appropriate for areas where the vertical hydraulic conductivity is relatively uniform with depth, *B*, The finite-depth boundary condition, which is assumed in equation 2, is appropriate where a more permeable surficial layer overlies a less permeable substrate, such as regolith over bedrock.
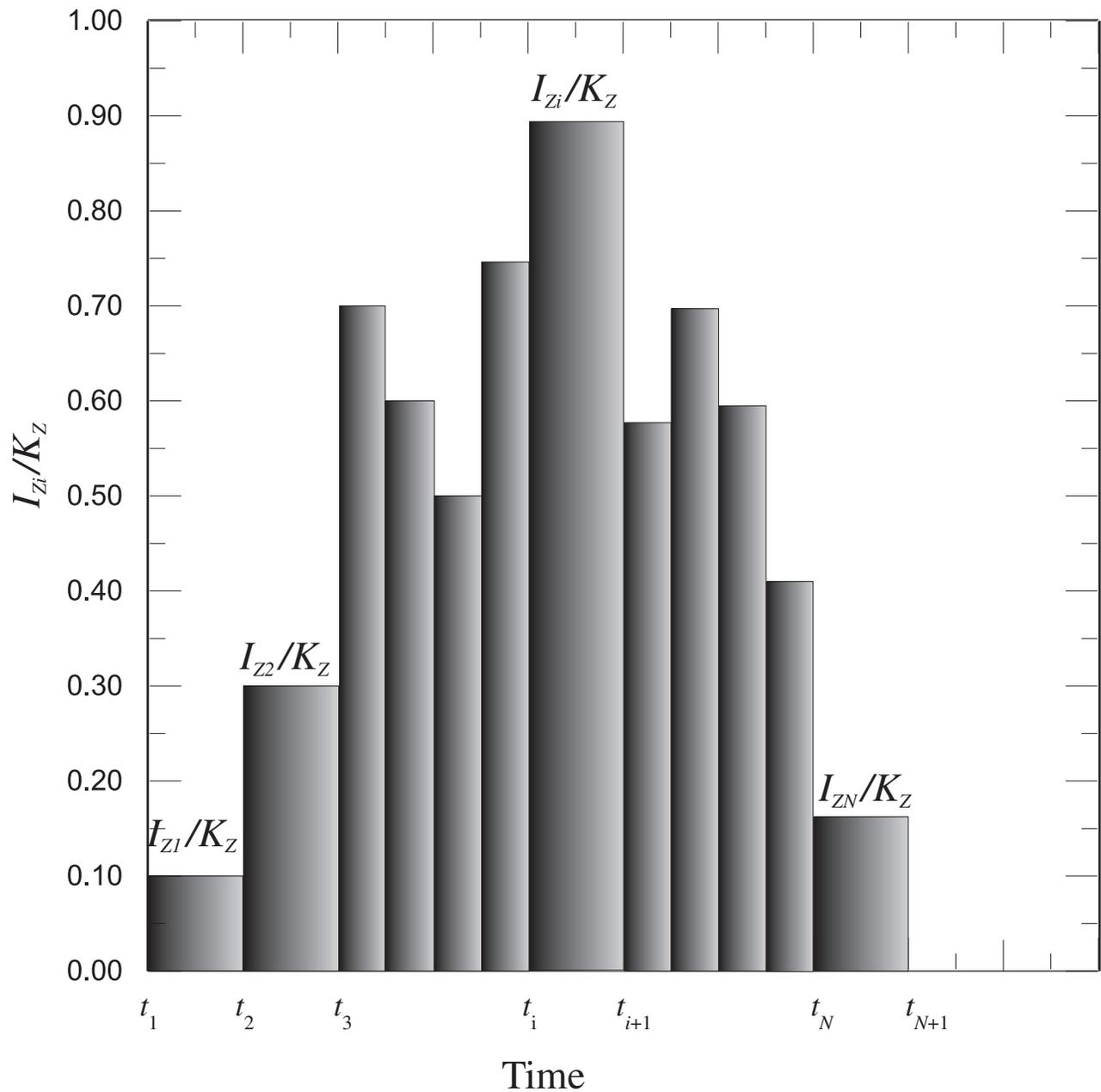
Figure 4. Hypothetical rainfall history of varying duration and intensity. In practice, the initial time, t_1 is set to zero. Times t_1, ..., t_{N+1} are stored in the array capt() (see tables 2 and 3). The first rainfall period begins at time t_1 and ends at time t_2; the ith rainfall period begins at time t_i and ends at time t_{i+1}. Rainfall intensities for each period are stored either in the array cri(), if constant over the study area, or in the files rifil(1), ..., rifil(nper) if intensity during each period varies over the study area (table 2).
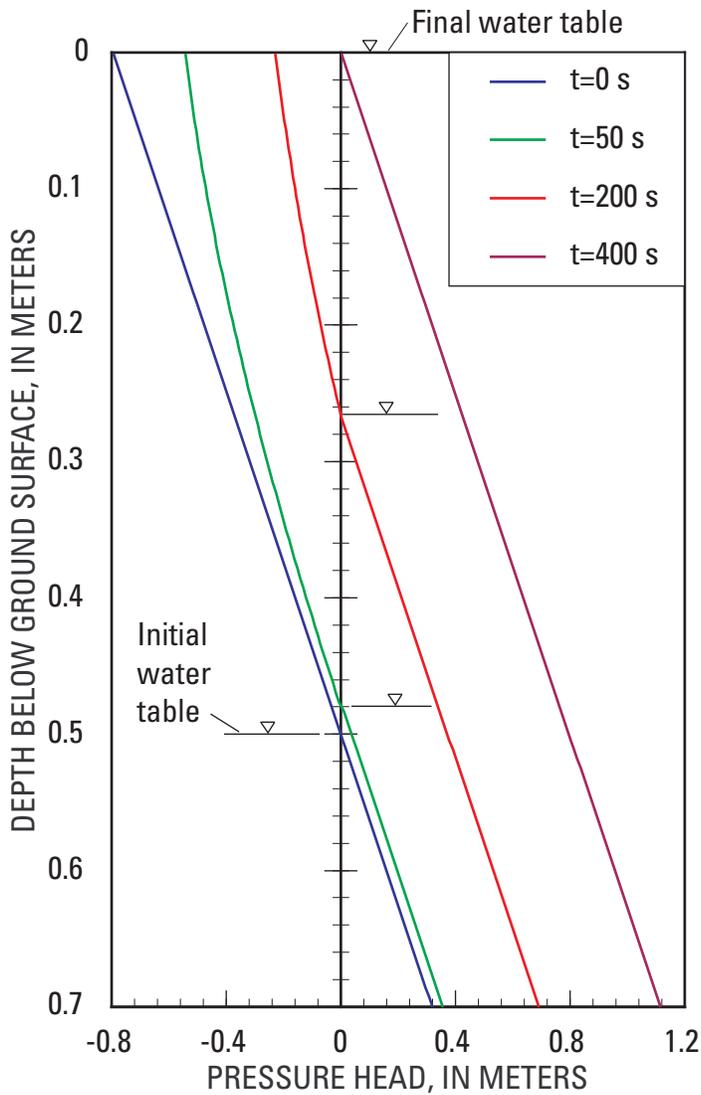
Figure 5. Example of transient water-table rise and pressure-head changes in response to precipitation at a cell where steady upward flow occurs but the water table is initially beneath the ground surface. The TRIGRS program maintains the initial upward hydraulic gradient below the water table and adds the transient infiltration solution to the initial condition above the water table. In the example shown here: K_s=1 x 10^{-4} m/s, D_0=1 x 10^{-3} m^2/s, δ = 31°, I_{ZLT} =-1.0 x 10^{-5}, I_{nZ} =5 x 10^{-5} m/s (see equations 1*A*, 2, and 3*B*).
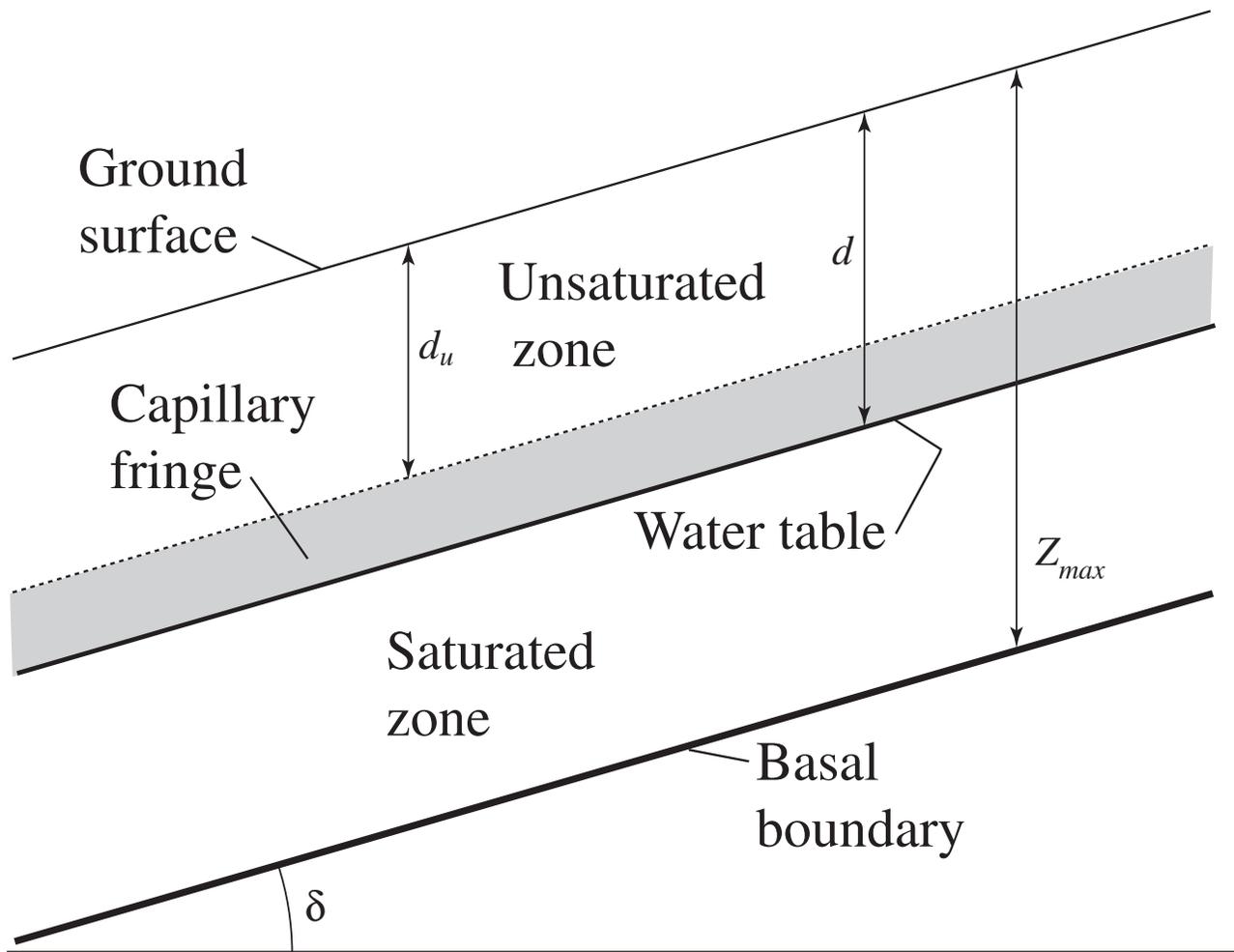
Figure 6. Shallow ground-water conditions in hillside soils. The unsaturated zone above the water table has depth d_u. The capillary fringe is between the unsaturated zone and the water table at depth, d. The lower boundary, which is treated as impervious in this model, is at depth Z_{max}.
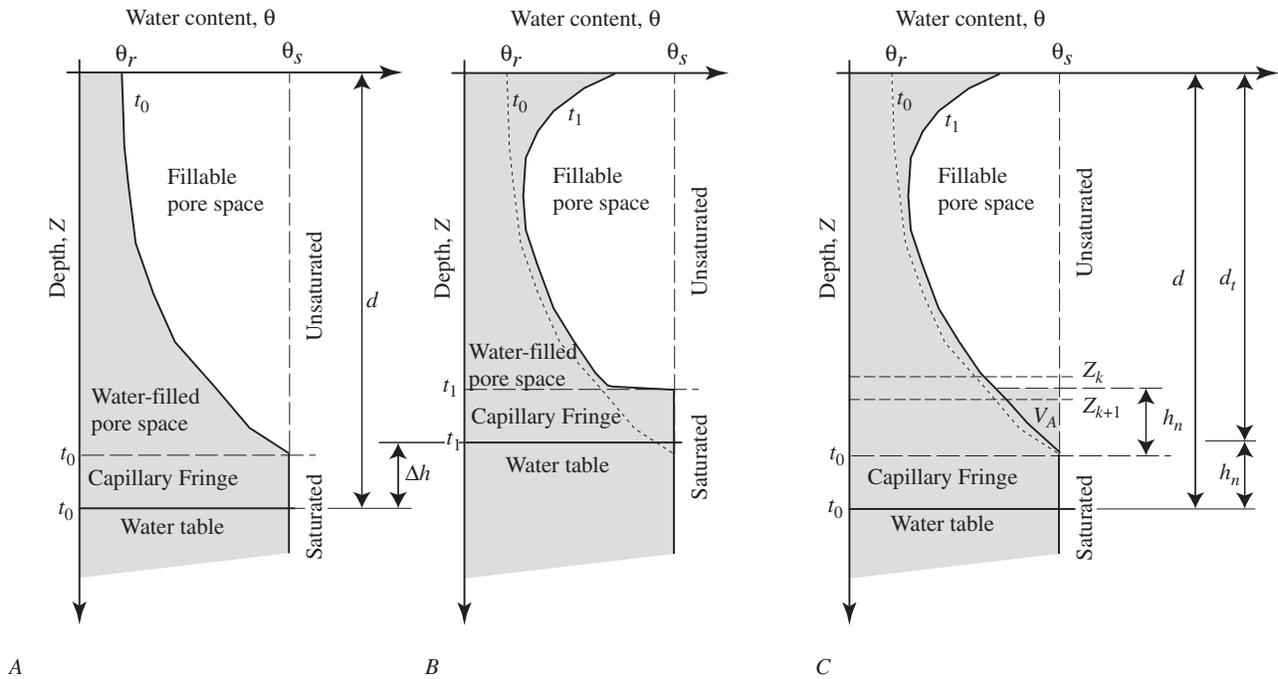
Figure 7. Vertical soil water-content profiles from the ground surface down to an arbitrary depth, Z, showing the water-table rise as a result of infiltration. A, Initial conditions at time t_0; soil water content increases with depth above the top of the capillary fringe as indicated by width of shaded area. B, Conditions at a later time, t_1, showing water-table rise of amount Δh. The shaded area between dotted line t_0 and solid line t_1 indicates the water absorbed by the soil. C, Approximations used in estimating water-table rise at the later time. The shaded area between dashed line t_0 and solid line t_1 represents the computed volume of water absorbed by the soil (change in water content from t_0 to t_1, see equations 4B, 4C, and 8B). The triangular area labeled V_A represents the cumulative volume of water (minus drainage, equations 10B, 10C) computed to reach the water table or base of the unsaturated zone between t_0 and t_1. The amount of fillable pore space above the top of the capillary fringe is computed at evenly spaced depths $Z_1, Z_2, ..., Z_k, ...$ (equations 10–12). The water table rise, Δh, is assumed to equal the rise in the capillary fringe, h_n, which is estimated by interpolating the volume of fillable pore space between depths Z_k and Z_{k+1} to estimate the height filled by volume V_A.
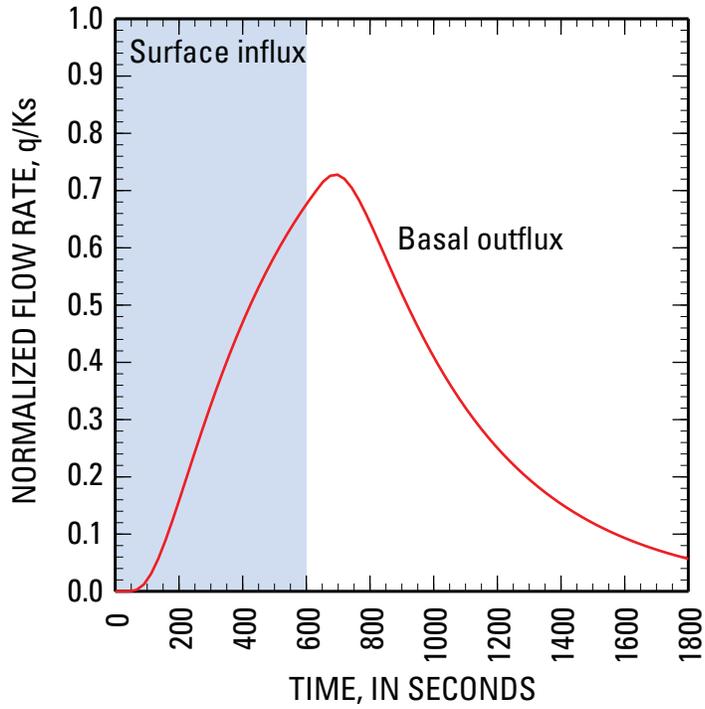
Figure 8. Plot of example input and output of unsaturated zone infiltration model. Partial absorption of water infiltrating at the surface results in damping and smoothing of the signal at the base of the unsaturated zone.
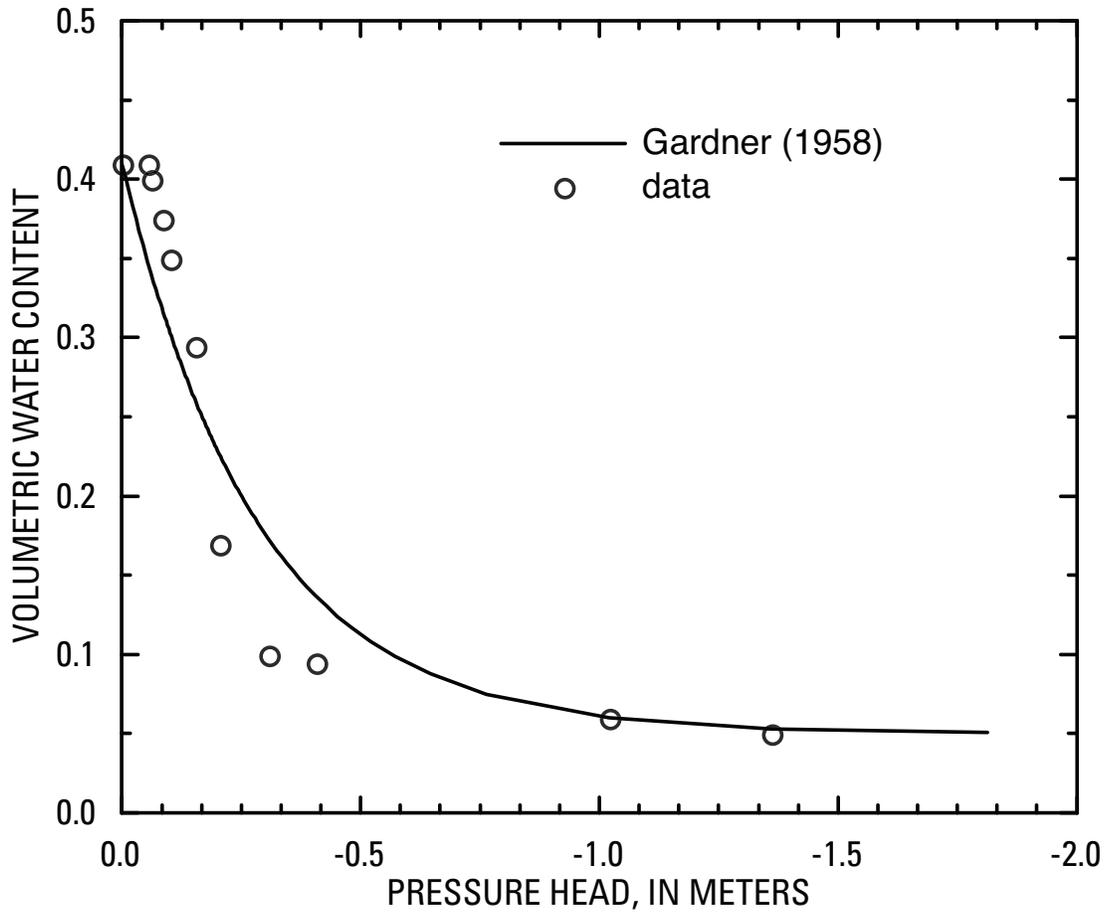
Figure 9. Graph showing example of Gardner (1958) models for soil water characteristics. The model was fit to soil-water retention data for sandy colluvium derived from glacial outwash sand near Everett, Wash. Gardner parameters: $\alpha = 3.5$, $\theta_S = 0.41$, $\theta_R = 0.05$.

Figure 10. TRIGRS grid cell numbering scheme. Numbering begins at upper left (northwest) corner of a grid and increases from left to right, row by row. No-data cells (shaded) are not numbered.

103	102	102	101	100	99	97	95	94	92
100	100	100	99	97	96	94	92	90	88
97	97	96	95	93	92	91	88	85	82
94	93	92	90	89	87	84	82	79	76
90	89	87	86	84	81	78	75	74	72
86	84	83	80	77	75	72	70	69	69
81	79	76	74	72	69	68	67	68	71
76	73	71	69	68	66	67	68	71	73
71	69	68	66	65	66	68	71	74	76
68	66	65	65	66	68	71	74	77	81

A

1	2	3	4	5	9	13	17	20	26
6	7	8	10	14	15	19	25	30	34
11	12	16	18	23	27	28	35	40	46
21	22	24	29	32	36	41	45	51	57
31	33	37	38	42	47	53	60	65	68
39	43	44	50	55	61	70	77	82	79
49	52	59	62	69	78	90	91	88	72
56	66	71	80	89	94	92	86	74	67
76	81	85	95	98	96	84	75	64	58
83	93	100	99	97	87	73	63	54	48

B

Figure 11. Diagram of an elevation grid file, comparing values of (*A*) elevation and (*B*) topographic index.
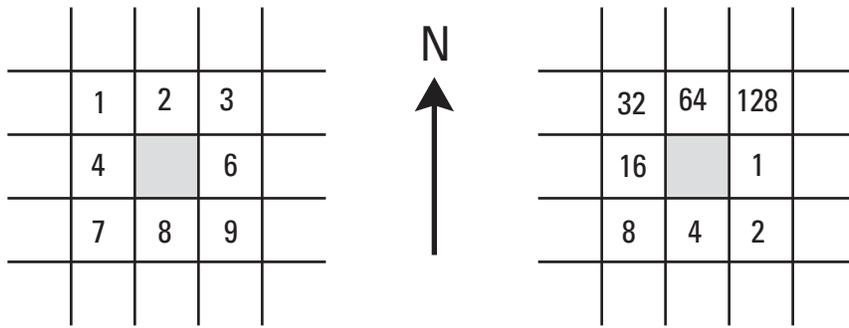
TopoIndex direction codes   ESRI direction codes

Figure 12. Diagram comparing numeric codes for D8 flow directions used by the utility program TopoIndex with those used by ESRI Arc/Info.
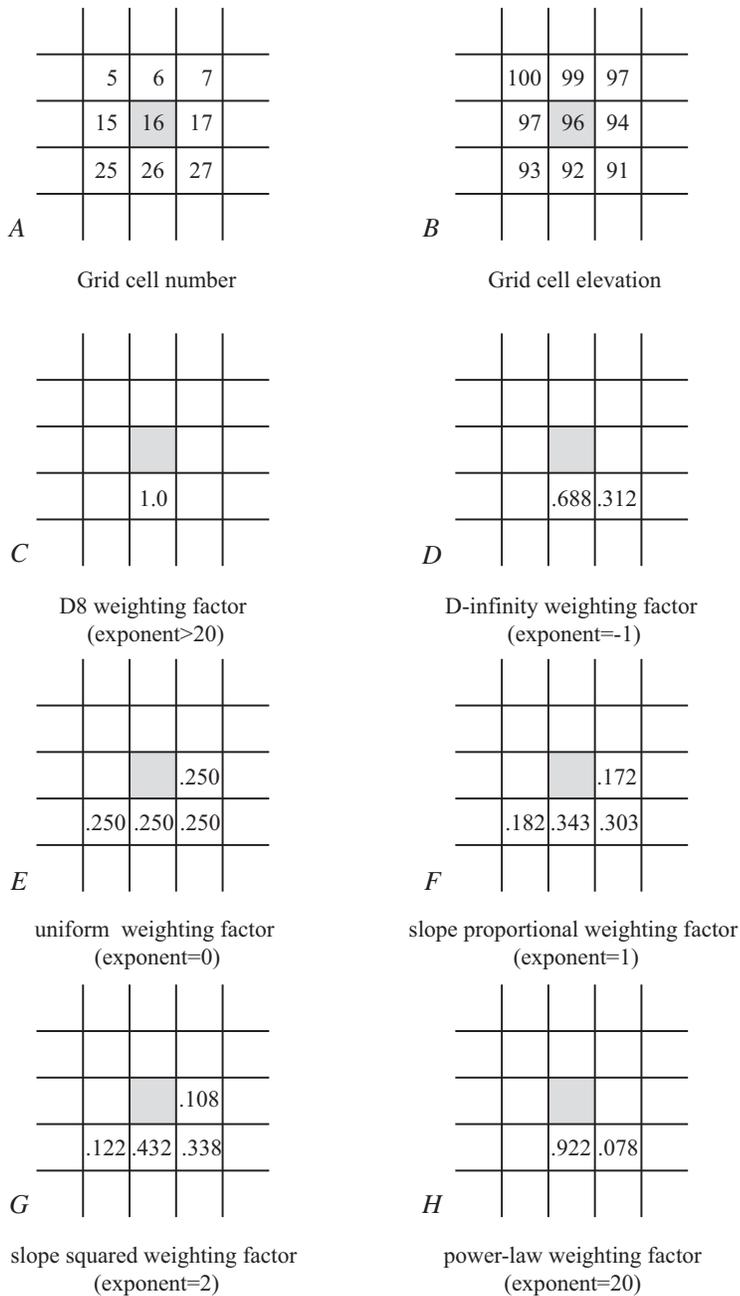
Figure 13. Example weighting factors for runoff distribution from an arbitrary cell (no. 16 of the tutorial grid file). *A*, Grid cell numbers. *B*, Elevation at cell 16 (shaded) and its nearest neighbor cells. *C*, Weighting factor for D8 method. *D*, Weighting factors for the D-infinity method. *E–H*, Slope power-law weighting factors for various exponents. Note that weighting factors of flatter cells approach zero as the exponent increases. *E*, Uniform distribution to all adjacent downslope cells. *F*, Distribution to all adjacent downslope cells, with weighting factor proportional to slope. *G*, Distribution to adjacent downslope cells, with weighting factor proportional to square of slope. *H*, Distribution to adjacent downslope cells, with weighting factor proportional to slope raised to 20th power. Weighting factors for cells 17 and 25 are zero.

Figure 14. Vertical spacing for computing infiltration and factor of safety. The user specifies the upper limit, zmin, the lower limit, zmax, and the number of steps, nzs, (table 3). To prevent division by zero, the upper limit, zmin, should be a small, finite depth below the ground surface. The TRIGRS program will compute the pore pressure and factor of safety at equally spaced depths between zmin and zmax.

Table 1. Weighting factors for runoff distribution.

[The weighting factors, w_{ij}, are a function of the slope, s_{ij}, between grid cell i and each neighboring downslope cell, j; the number of neighboring grid cells, n, that are downslope from cell i, and an exponent selected by the user, ω. The program automatically rounds all weighting factors to three decimal places and adjusts them so that the sum of weighting factors at each cell equals 1. The default pattern is to divert flow only to the adjacent cell on the steepest downslope path. Weighting factors computed by TopoIndex are valid only for square cells (distance between rows equal to distance between columns)]

Exponent	Weighting factor	Distribution pattern
$\omega < 0$	$w_{i1} = \left(\dfrac{\pi}{4} - \delta_d\right)\bigg/\left(\dfrac{\pi}{4}\right)$ $w_{i2} = \delta_d\bigg/\left(\dfrac{\pi}{4}\right)$; if two cells $w_{ij} = 1$; if only one cell	Narrow; flow is diverted only to the one or two neighboring downslope cells, j and k, that straddle the steepest downslope path. If the steepest downslope path is aligned with a grid direction or diagonal, then flow is diverted only to the neighboring cell in that direction. The weighting factors depend on the angle δ_d between the D8 flow direction and the steepest slope. Here the exponent, ω, serves only as a flag.
$\omega = 0$	$w_{ij} = \dfrac{1}{n}$	Fan-shaped; uniform distribution among adjacent downslope cells regardless of slope.
$0 < \omega \le 20$	$w_{ij} = s_{ij}{}^{\omega}\bigg/\displaystyle\sum_{j=1}^{j=n} s_{ij}{}^{\omega}$	Fan-shaped; the positive value of ω results in weighting factors that favor steeper flow paths. The pattern becomes more strongly skewed toward the steepest downslope path as slope angle increases.
$\omega > 20$	$w_{ij} = 1$; cell on steepest path $w_{ij} = 0$; other downslope cells	Narrow; flow is diverted only to the neighboring cell that is on the steepest downslope path (D8 method, O'Callaghan and Mark, 1984)

Table 2. Sample listing of the initialization file "tr_in.txt".

[An explanatory heading precedes each line of data, and each heading occupies a single line. Some of the longer headings appear to occupy two lines in the table below; however they occupy only one line in the actual file. These long headings are distinguished by a hanging indent. The total number of lines in the file depends on the number of property zones and number of periods of different rainfall intensity. Units in this example, time, s; length, m; force, N (kg-m/s^2); pressure and stress, Pa (=N/m^2); unit weight, N/m^3]

```
Name of project (up to 255 characters)
TRIGRS, version 2, Tutorial
imax, row, col, nwf, tx, nmax
100,  10,  10,  154,  1,  30
nzs, mmax, nper,  zmin,  uww,     t, zones
10,   -100,  2,   0.001, 9.8e3, 216000,  2
zmax,   depth,   rizero,  Min_Slope_Angle (degrees)
-3.001,  -2.4,  -1.0e-9,       0.
zone, 1
cohesion,phi,  uws,   diffus,   K-sat, Theta-sat,Theta-res,Alpha
3.5e+03, 35., 2.2e+04, 6.0e-06, 1.0e-07,  0.45,    0.05,    -0.5
zone, 2
cohesion,phi,  uws,   diffus,   K-sat, Theta-sat,Theta-res,Alpha
8.0e+03, 31., 2.2e+04, 8.0e-4, 1.0e-04,   0.45,    0.06,    -8.
cri(1), cri(2), ..., cri(nper)
3.e-7,  9.e-5
capt(1), capt(2), ..., capt(n), capt(n+1)
0,       172800, 216000
File name of slope angle grid (slofil)
Data/tutorial/slope.asc
File name of property zone grid (zonfil)
Data/tutorial/zones.asc
File name of depth grid (zfil)
Data/tutorial/zmax.asc
File name of initial depth of water table grid   (depfil)
Data/tutorial/depthwt.asc
File name of initial infiltration rate grid   (rizerofil)
Data/tutorial/rizero.asc
List of file name(s) of rainfall intensity for each period, (rifil())
Data/tutorial/ri1.asc
Data/tutorial/ri2.asc
File name of grid of D8 runoff receptor cell numbers (nxtfil)
Data/tutorial/TIdscelGrid_tutorial.asc
File name of list of defining runoff computation order (ndxfil)
Data/tutorial/TIcelindxList_tutorial.txt
File name of list of all runoff receptor cells  (dscfil)
Data/tutorial/TIdscelList_tutorial.txt
File name of list of runoff weighting factors  (wffil)
Data/tutorial/TIwfactorList_tutorial.txt
Folder where output grid files will be stored  (folder)
Data/tutorial/
Identification code to be added to names of output files (suffix)
itx1
Save grid files of runoff? Enter T (.true.) or F (.false.)
T
Save grid of minimum factor of safety? Enter Enter T (.true.) or F (.false.)
T
Save grid of depth of minimum factor of safety? Enter Enter T (.true.) or F (.false.)
T
Save grid of pore pressure at depth of minimum factor of safety? Enter Enter T (.true.) or F
       (.false.)
T
Save grid files of actual infiltration rate? Enter T (.true.) or F (.false.)
T
Save grid files of unsaturated zone basal flux? Enter T (.true.) or F (.false.)
F
Save listing of pressure head and factor of safety ("flag")? (Enter -2 detailed, -1 normal, 0 none)
-2
Number of times to save output grids
1
Times of output grids
216000.
Skip other timesteps? Enter T (.true.) or F (.false.)
F
Use analytic solution for fillable porosity?  Enter T (.true.) or F (.false.)
T
Estimate positive pressure head in rising water table zone (i.e. in lower part of unsat zone)?
       Enter T (.true.) or F (.false.)
T
```

Table 2. Continued

```
Use psi0=-1/alpha? Enter T (.true.) or F (.false.) (False selects the default value, psi0=0)
F
Log mass balance results?   Enter T (.true.) or F (.false.)
T
Flow direction (enter "gener", "slope", or "hydro")
slope
```

Table 3. Definitions of input variables, excluding file path names, found in the initialization file and related input files.

[See table 2 for location of each variable in the initialization file, "tr_in.txt". Integers are assumed to be 4-byte integers]

Program Control

Variable name	Type	Description	Range of values
imax	integer	Number of grid cells (excluding no-data cells).	imax>0
row	integer	Number of grid rows.	0<row<imax
col	integer	Number of grid columns.	0<col<imax
nwf	integer	Length of arrays to store flow routing locations and weighting factors. Set equal to total number of runoff weighting factors computed by TopoIndex.	imax≤nwf≤8*imax
tx	integer	A multiplier that, in combination with nper, determines how many time steps are used in the computations. Computational effort and storage requirements increase directly with tx.	tx≥1
nmax	integer	Maximum number of roots, Λ_n, (equation 6) and corresponding terms in series solutions for unsaturated zone.	nmax≥1; the series normally converges with a few tens of terms or less.
nzs	integer	Number of vertical increments.	nzs≥1
mmax	integer	Maximum number of terms in series solution for impermeable base at finite depth, maximum value of m in equation 2; also a flag to choose between a finite (eq. 2) or infinite depth (eq. 1) solution.	mmax≥1; typically 10<mmax<25; setting mmax<1 chooses the original Iverson solution (equation 1) for infinite depth
zones	integer	Number of physical property zones used to model the problem domain. An integer property zone grid must be supplied if more than one zone is used.	zones≥1
flag	integer	Output flag used to specify how depth profiles are saved.	flag = -1 or -2; output depth profile at all cells, any other value, no profile output
slomin	real	Minimum slope angle; no computations of pore pressure or factor of safety on slopes lower than slomin.	slomin≥0
flowdir	character, (length=5)	Assumed flow direction for computing slope of the beta line, which determines the maximum pore pressure. Also determines maximum drainage rate computed by equations 10A–10C.	flowdir="gener," general, maximum pressure head determined by equation 3A; or "slope," slope parallel, maximum pressure head equals that for slope-parallel flow; or "hydro," hydrostatic conditions, maximum pressure head equals depth

Table 3. Continued

Mechanical and Hydrologic Properties and Dimensions

Variable name	Type	Description	Range of values
zmin	real	Shallowest depth at which to compute pore pressures, Z_{min}	zmin>0; typically .01≤zmin≤0.1
czmax	real	Maximum depth at with to compute pore pressures and factor of safety, Z_{max}	czmax> zmin; read values from grid file if negative
cdep	real	Initial depth of water table, d	0<cdep≤zmax; read values from grid file if negative
crizero	real	Steady, pre-storm infiltration rate, I_Z	crizero>0; read values from grid file if negative
uww	real	Unit weight of water, γ_w	uww>0
c()	real array	Soil cohesion, c	c≥0
phi()	real array	Angle of internal friction, ϕ	phi>0; read values from grid file if negative
uws()	real array	Total unit weight of soil, γ_s	uws>0; read values from grid file if negative
dif()	real array	Hydraulic diffusivity, D_0	dif>zmin; read values from grid file if negative
ks()	real array	Vertical hydraulic conductivity of saturated soil, K_Z	ks>0; read values from grid file if negative
ths()	real array	Soil saturated volumetric water content, θ_s	ths>0
thr()	real array	Soil residual volumetric water content, θ_r	ths>thr≥0
alp()	real array	A fitting parameter for soil size distribution, α, approximately equal to the inverse of the height of capillary rise.	alp>0; negative value causes TRIGRS to treat the zone as tension saturated

Table 3. Continued

Storm Properties

Variable name	Type	Description	Range of values
nper	integer	Number of periods of different rainfall rates during a storm, N	nper≥1
t	real	Elapsed time since start of storm, t	t>0
cri()	real array	Rate of application (rainfall intensity) during each storm increment, I_{nZ}	cri()>0; read values from grid file if negative
capt()	real array	Cumulative duration of storm at end of each increment, t_n	capt(1)=0; capt(1)<capt(2)<, …, capt(n)<capt(n+1)

Runoff-Routing Parameters (found only in data files, not in initialization file)

Variable name	Type	Description	Range of values
nxt()	integer array	Cell that is downslope along the steepest path from the present cell	1≤ nxt ≤imax
indx()	integer array	Index of cell numbers from (topographically) highest to lowest	1≤ indx ≤imax
dsctr()	integer array	Counter array to keep track of downslope cells	dsctr≤nwf
dsc()	integer array	Cell numbers of downslope cells	dsc≤nwf
wf()	real array	Weighting factors for distributing runoff to downslope cells	0≤wf≤1

Map Grid Data

Variable name	Type	Description	Range of values
zmax()	real array	Depth of basal boundary for each cell	zmax>0
slo()	real array	Slope angles	slo≥0
depth()	real array	Initial depth of water table	depth≥0
rizero()	real array	Steady, background infiltration rate	All real values
ri()	real array	Storm infiltration rate	ri>0
zo()	integer array	Property zone numbers	zo>0

Table 4. Output files generated by TRIGRS.

[The abbreviation "TR" at the beginning of a file name identifies a file generated by the program TRIGRS; XXXXXXXX denotes the user-defined identification code (as many as eight characters) used to group files from the same run. Numerals in parentheses indicate the order in which optional files are selected in the initialization file (table 2)]

File Name	Description
TrigrsLog.txt	Log file; TRIGRS overwrites this file every time it runs.
TRrunoffPer###XXXXXXXX.asc	Grid of computed runoff during a given storm period; ### designates the storm period ending at time capt(###) (1).
TRfs_min_XXXXXXXX.asc	Grid of the minimum computed factor of safety at each cell for time, t (2).
TRz_at_fs_min_XXXXXXXX.asc	Grid of depths at which the minimum factor of safety was computed for time t (3).
TRp_at_fs_min_XXXXXXXX.asc	Grid of pressure head at the depth corresponding to minimum factor of safety for time t (4).
TRinfilratPer###XXXXXXXX.asc	Grid of actual infiltration rates during a given storm period; ### designates the storm period ending at time capt(###) (5).
TRunszfluxTS###XXXXXXXX.asc	Grid or unsaturated zone basal flux for a given storm period; ### designates the storm period ending at time capt(###) (6).
TRlist_z_p_fs_XXXXXXXX.txt	Cell by cell list of pressure head and factor of safety at each depth increment (see table 9). Use output flag to select abbreviated, expanded, or no output (7).
TRnon_convrg_UZ_XXXXXXXX.asc TRnon_convrg_SZ_XXXXXXXX.asc	Grid files locating non-convergent cells. Generated automatically if infinite series computations at any cells do not converge. UZ denotes unsaturated zone, SZ denotes saturated zone.

Table 5. Example listings of a grid file for a 10-row by 10-column grid. *A*, Heading is for ESRI's ASCII grid format.

```
ncols       10
nrows       10
xllcorner    563435
yllcorner    5258305
cellsize    10
NODATA_value  -9999
103 102 102 101 100 99 97 95 94 92
100 100 100 99 97 96 94 92 90 88
97 97 96 95 93 92 91 88 85 82
94 93 92 90 89 87 84 82 79 76
90 89 87 86 84 81 78 75 74 72
86 84 83 80 77 75 72 70 69 69
81 79 76 74 72 69 68 67 68 71
76 73 71 69 68 66 67 68 71 73
71 69 68 66 65 66 68 71 74 76
68 66 65 65 66 68 71 74 77 81
```

Table 5. Continued *B*, Heading is for GRASS GIS two-dimensional raster ASCII format.

north: 5258405
south: 5258305
east: 563535
west: 563435
rows: 10
cols: 10
103 102 102 101 100 99 97 95 94 92
100 100 100 99 97 96 94 92 90 88
97 97 96 95 93 92 91 88 85 82
94 93 92 90 89 87 84 82 79 76
90 89 87 86 84 81 78 75 74 72
86 84 83 80 77 75 72 70 69 69
81 79 76 74 72 69 68 67 68 71
76 73 71 69 68 66 67 68 71 73
71 69 68 66 65 66 68 71 74 76
68 66 65 65 66 68 71 74 77 81

Table 6. Partial listing of the file "TIdscelList_tutorial.txt", which contains the cell numbers of downslope receptor cells.

[The number -9999 indicates the beginning of a new cell, the next line contains the number of the grid cell, and the following lines list as many as eight adjacent cells that are downslope from the grid cell designated at the beginning of the list. The sequence repeats for each cell in the grid. If no other cells are downslope from a particular cell, such as cells 93 and 94, its cell number is indicated as the only downslope cell. Text in the column to the right of the numbers identifies each line of data, but does not appear in the actual output files]

-9999	separator
1	cell number
11	neighboring downslope cell number
-9999	separator
2	cell number
12	neighboring downslope cell number
-9999	separator
3	cell number
13	neighboring downslope cell number
14	neighboring downslope cell number
-9999	separator
4	cell number
15	neighboring downslope cell number

…

-9999	separator
92	cell number
93	neighboring downslope cell number
-9999	separator
93	cell number
93	neighboring downslope cell number
-9999	separator
94	cell number
94	neighboring downslope cell number
-9999	separator
95	cell number
94	neighboring downslope cell number

…

Table 7. Partial listing of the file " TlwfactorList_tutorial.txt ", which contains the weighting factors of downslope cells. In this example, the weighting factors are based on the D-infinity method (Tarboton, 1997).

[The number -9999. indicates the beginning of a new cell, and the separator is followed by a decimal point, because the weighting factors are floating point values. The next line contains the number of the grid cell, and the following lines list weighting factors corresponding to cells listed in table 6. The sequence repeats for each cell in the grid. If no other cells are downslope from a particular cell, such as cells 93 and 94, it receives a weighting factor of 1.000. Text in the column to the right of the numbers identifies each line of data, but does not appear in the actual output files]

```
-9999.          separator
   1            cell number
 1.000          weighting factor for neighboring downslope cell
-9999.          separator
   2            cell number
 1.000          weighting factor for neighboring downslope cell
-9999.          separator
   3            cell number
 0.410          weighting factor for neighboring downslope cell
 0.590          weighting factor for neighboring downslope cell
-9999.          separator
   4            cell number
 1.000          weighting factor for neighboring downslope cell

…

-9999.          separator
  92            cell number
 1.000          weighting factor for neighboring downslope cell
-9999.          separator
  93            cell number
 1.000          weighting factor for neighboring downslope cell
-9999.          separator
  94            cell number
 1.000          weighting factor for neighboring downslope cell
-9999.          separator
  95            cell number
 1.000          weighting factor for neighboring downslope cell

  …
```

Table 8. Partial listing of the file "TIcelindxList_tutorial.txt," which contains the cell index for a grid of 100 cells taken from the tutorial data set.

[The first column indicates the index to each cell number listed in the second column. Cell numbers are assigned beginning at the upper left corner of the grid from left to right across rows and from top to bottom (figs. 10 and 11). No-data cells are unnumbered. Refer to section of the text titled "Topographic Indexing" for further information]

```
 1  1
 2  2
 3  3
 4  4
 5  5
 6  11
 7  12
 8  13
 9  6
10  14
11  21
12  22

…

88  69
89  75
90  67
91  68
92  77
93  92
94  76
95  84
96  86
97  95
98  85
99  94
100  93
```

Table 9. Partial listing of the TRIGRS output file " TRlist_z_p_fs_XXXXXXXX.txt ", depth profile of pressure head and factor of safety for each cell.

[Values appearing in the actual file may differ from those listed here, depending upon the user's choice of input parameters. The file has a three-line header to identify the numeric data that follow. The first line after the header contains the cell number and the slope angle in degrees; the next six lines contain six columns of fixed-width output. The first column lists the depth, Z; the next three list the pore pressure, as pressure head at depth Z (column two, total pressure head; column three, initial pressure head; column four, transient pressure head); column 5 lists the steady flow pressure cutoff; and the sixth lists the factor of safety. The sequence repeats for the next cell starting on the eighth line after the header. The number of lines of (six-column) output for each cell is one plus the number of vertical increments (1+nzs, see fig. 14). Output shown below results when flag is set to -2; if flag is set to -1, then the third, fourth and fifth columns are omitted]

```
TRIGRS depth profiles at each cell
Cell Number, Slope angle
Z               P         Pzero       Ptran        Pbeta          FS
 1  16.7000
 0.10000E-02  0.91741E-03 -0.91650     5.5674      0.91741E-03   10.000
 0.48080      0.44109    -0.47632      5.1009      0.44109       0.86418
 0.96060      0.88127    -0.36146E-01  4.6608      0.88127       0.84360
  1.4404       1.3214      0.40403     4.2470       1.3214       0.83672
  1.9202       1.7616      0.84420     3.8590       1.7616       0.83329
  2.4000       2.2018      1.2844      3.4965       2.2018       0.83122
   2  11.3000
 0.10000E-02  0.96160E-03 -0.96063     5.6999      0.96160E-03   10.000
 0.48080      0.46233    -0.49926      5.2331      0.46233       1.2947
 0.96060      0.92371    -0.37887E-01  4.7921      0.92371       1.2652
  1.4404       1.3851      0.42349     4.3767       1.3851       1.2553
  1.9202       1.8465      0.88486     3.9867       1.8465       1.2504
  2.4000       2.3078      1.3462      3.6216       2.3078       1.2474
   3  12.0000
 0.10000E-02  0.95676E-03 -0.95581     5.6856      0.95676E-03   10.000
 0.48080      0.46001    -0.49675      5.2188      0.46001       1.2174
 0.96060      0.91907    -0.37696E-01  4.7779      0.91907       1.1895
  1.4404       1.3781      0.42136     4.3627       1.3781       1.1802
  1.9202       1.8372      0.88041     3.9728       1.8372       1.1755
  2.4000       2.2962      1.3395      3.6080       2.2962       1.1728
```

Table 10. Example listing of entries in the initialization file for the program TopoIndex, "tpx_in.txt"

[File path names are limited to 255 characters; "Rows", "Columns", and "Number of iterations" are positive integers. "Exponent" is a real number as defined in table 1. The default folder for storing output is the folder where the program TopoIndex resides]

```
Name of project (up to 255 characters)
Tutorial data for TopoIndex analysis
Rows, Columns, flow-direction numbering scheme (ESRI=1, TopoIndex=2)
10,     10,     2
Exponent, Number of iterations
25,        10
Name of elevation grid file
data/tutorial/dem.txt
Name of direction grid
data/tutorial/directions.txt
Save listing of D8 downslope neighbor cells?  Enter T (.true.) or F (.false.)
T
Save grid of D8 downslope neighbor cells? Enter T (.true.) or F (.false.)
T
Save cell index number grid?  Enter T (.true.) or F (.false.)
T
Save list of cell number and corresponding index number? Enter T (.true.) or F (.false.)
T
Save flow-direction grid remapped from ESRI to TopoIndex? Enter T (.true.) or F (.false.)
T
Name of folder to store output? Leave blank to use default folder
data/tutorial/
Identification code for output files? (8 characters or less)
tutorial
```

Table 11. Names of TopoIndex output files.

[The abbreviation "TI" at the beginning of the file name identifies a file generated by the program TopoIndex; XXXXXXXX denotes the user-defined identification code used to group files from the same run. Numerals in parenthesis indicate the order in which optional files are selected in the initialization file (table 10)]

File Name	Description
TopoIndexLog.txt	Log file; TopoIndex overwrites this file every time it runs.
TIdsneiList_XXXXXXXX.txt	List of downslope receptor cells in D8 flow direction (1).
TIdscelGrid_XXXXXXXX.asc	*Grid of downslope receptor cells in D8 flow direction (2).
TIcelindxGrid_XXXXXXXX.asc	Grid of cell index numbers that specify computation order for runoff routing in TRIGRS (3).
TIcelindxList_XXXXXXXX.txt	*List of cell numbers and corresponding index number (computation order) (4).
TIflodirGrid_XXXXXXXX.asc	Flow-direction grid in terms of the TopoIndex numbering scheme shown in figure 12 (5).
TIdscelList_XXXXXXXX.txt	*Cell by cell list of downslope cells for which non-zero weighting factors have been computed.
TIwfactorList_XXXXXXXX.txt	*Cell by cell list of weighting factors for downslope receptor cells.

*Required by TRIGRS for runoff routing.

Table 12. Listing of GridMatch initialization file, "gm_in.txt."

[This listing shows an example of three files to be compared. A line of descriptive text precedes each line of numeric data and the list of input files. The first file listed is always treated as the master file and all subsequent files are compared to the master file.]

```
Number of grid files to test
3
Rows, columns
10,10
Names of input files (text string, up to 255 characters per line; one file per line, list master
      grid first)
data/gridmatch/master.asc
data/gridmatch/test1.asc
data/gridmatch/test2.asc
```

Table 13. Common problems and solutions for users of the TRIGRS and TopoIndex programs

Problem	Things to check
The program displays the message "Cannot locate default initialization file, type name of initialization file and press RETURN to continue."	1. Make sure the initialization file is in the working directory. 2. If you have been editing the initialization file, save and close the file. 3. Make sure the initialization file is named correctly.
TopoIndex does not converge or exits without generating the expected output files.	Check the log file "TopoIndexLog.txt" to see if the corrections converged rapidly during the first several iterations and then stuck at a constant number of corrections during the remaining iterations until the program terminated. If so, then, 1. Use GIS software to verify that the DEM was hydrologically corrected by filling single-cell depressions. (Genuine depressions such as lakes may be included in the analysis if adequate bathymetric data exist or they can be excluded from the analysis by designating such areas as no-data cells in all grids). 2. Verify that the number and locations of no-data cells in the DEM and flow direction grids match. 3. Verify that similar values are used to represent no-data cells and integer and floating-point grids. 4. Verify the format and spelling in the headings (check spelling and capitalization of labels) of grid cells.
TRIGRS displays an error message referencing a file name.	1. Check the path name of the file, as entered in the initialization file, to be sure it is typed correctly and that the folder exists. 2. Confirm that the file is not locked or open in another application.
TRIGRS or TopoIndex displays a message that says "Error reading file *filename.*"	1. Check file format; grid files should follow the format shown in tables 5*A* and 5*B*. 2. Check end of file. Open the offending data file and position the cursor at the end of the file. If the end of the file is directly after the last value, press return/enter to type an "end-of line" character, then save and close the data file. (If no return character exists at the end of the last line data, an error occurs when the programs try to read the last line). 3. Check file type (line endings). Different operating systems use different line endings for text files. Use a text editor to confirm that the data files are of the correct type for your operating system (DOS for PC or UNIX for MacOS X, Linux, and other UNIX systems).
TRIGRS displays an error message referencing a program line number.	This may result from errors in reading or writing a file. 1. Identify and open the corresponding file, correct any errors, and try again. 2. In case the program reports array boundary errors, check the initialization file for incorrect values (tables 2, 3, and 4) and for input or output files listed in the wrong order. 3. Check the input grids for mismatched no-data cells.
The arrangement of cells in the output grids does not match that in the original DEM.	1. Check the input grids for mismatched no-data cells. 2. Check GIS coverages for differences in boundaries used to assign properties or to define no-data cells of mismatching grids. For example, if using geologic map coverage to generate grids of physical properties and applying a shoreline from a different coverage to define no-data cells in the elevation grid, a mismatch may occur along the shoreline. In other words, one grid may contain no-data cells at the same (row-column) locations as data cells in the other grid.

Appendix 1. Listing of Files Included in This Distribution

Folder names appear below in boldface type and slashes indicate folder hierarchy. File suffixes for make files and compiled programs vary between operating systems; the ".exe" and ".amk" suffixes used below correspond to the Windows convention.

TRIGRS/
gm_in.txt
memoryReq.xls
tpx_in.txt
tr_in.txt
tr_in_flume.txt
tr_in_mc.txt
tr_in_sy.txt
uc_in.txt

TRIGRS/bin/
GridMatch.exe
TopoIndex.exe
TRIGRS.exe
unitconvert.exe

TRIGRS/data/flume/
slope.asc
TIcelindxList_flume.txt
TIdscelGrid_flume.asc
TIdscelList_flume.txt
TIwfactorList_flume.txt
zones_flume.asc

TRIGRS/data/gridmatch/
master.asc
test1.asc
test2.asc

TRIGRS/data/MinorCreek/
slope.asc
TIcelindxList_MC.txt
TIdscelGrid_MC.asc
TIdscelList_MC.txt
TIwfactorList_MC.txt
zones_MC.asc

TRIGRS/data/sy91/
slope.asc
zones.asc

TRIGRS/data/tutorial/

dem.asc
depthwt.asc
directions.asc
ri1.asc
ri2.asc
rizero.asc
slope.asc
TIcelindxList_tutorial.txt
TIdscelGrid_tutorial.asc
TIdscelList_tutorial.txt
TIwfactorList_tutorial.txt
zmax.asc
zones.asc

TRIGRS/doc/
Readme.txt

TRIGRS/src/GridMatch/
GridMatch.amk
gridmatch.f90
srdgrd.f

TRIGRS/src/TopoIndex/
isvgrd.f
mpfldr.f
nxtcel.f90
rdflodir.f
sindex.f
slofac.f
srdgrd1.f
TopoIndex.amk
tpindx.f90

TRIGRS/src/TRIGRS/
calerf.f
dbsct.f
derfc.f
dsimps.f95
flux.f90
grids.f95
input_file_defs.f95
input_vars.f95
irdgrd.f
irdswm.f
isvgrd.f
iverson.f95
ivestp.f95
model_vars.f95

pstpf.f95
pstpi.f95
rnoff.f95
roots.f
satfin.f95
satinf.f95
savage.f95
smallt.f95
srdgrd.f
srdswm.f
ssvgrd.f
steady.f95
svgstp.f95
TRIGRS.amk
trigrs.f90
trini.f95
unsfin.f95
unsinf.f95
unsth.f95

TRIGRS/src/UnitConvert/
srdgrd.f
ssvgrd.f
UnitConvert.amk
unitconvert.f90

Appendix 2. Tutorial

We have provided a data set for a 100-cell (10 cells wide by 10 cells long) grid to demonstrate use of TRIGRS, along with separate single-cell grids for reproducing Iverson's (2000) flume and Minor Creek landslide analyses and Srivastava and Yeh's (1991) infiltration analysis. These data sets are found in separate folders within the folder "data" and include a complete set of files for topographic, precipitation, and physical properties data, along with necessary data for routing runoff, where applicable (appendix 1). The following paragraphs describe use of the programs TopoIndex and TRIGRS and how a user controls an analysis by editing the initialization files. Data for this exercise are found in the folder "tutorial," within the "data" folder. By following the instructions in this tutorial, the user will analyze a small sample problem that illustrates many of the features of TRIGRS. The sample data set includes spatially variable geometry and physical properties data, a spring, and two-stage (spatially uniform) rainfall. The tutorial analysis illustrates development of local runoff, gradual build-up of pore pressure as a result of infiltration, and local slope failure at the end of the storm. Before starting, make sure that your system preferences are set to show file extensions[1] and that you have a text editor installed on your system.

Using TopoIndex to Prepare Data for Runoff Routing

Use the program TopoIndex at the beginning of a project to prepare data needed for runoff routing in TRIGRS. Once a topographic data set and routing method are selected for a study area, the output of TopoIndex can be reused for multiple analyses of that area by TRIGRS.

First, we will examine the necessary input files for TopoIndex. In the folder TRIGRS, open the file "tpx_in.txt"; the contents should resemble table 10*A* in the main text. Table 2-1 lists the contents of the file with line numbers to aid discussion. A line of explanatory text precedes each line of data. For example, the text on line 1 describes the data on line 2. The project title appearing on line 2 (tables 10 and 2-1) may include letters, numbers, and spaces. The succeeding paragraphs describe the other information appearing in the file "tpx_in.txt." and the names of input files. The user may also select certain output files, enter an identification code that will help group the files from a given run, and may specify the folder where the files will be stored.

The first two values on line 4 specify the number of rows and columns in the elevation grid file. The number of rows and columns appears in the heading of the grid files. Open the elevation grid file "dem.asc" in the folder "TRIGRS/data/tutorial" to verify that the number of rows and columns listed in "tpx_in.txt" agrees with corresponding numbers in the grid file (fig. 2-1 and table 2-1, lines 3–4). If necessary, correct the number of rows and columns in the initialization file and then close the grid file.

The numbering scheme of the (input) direction grid (fig. 12) is the third value listed on line 4 (table 2-1); the example data uses the TopoIndex numbering scheme. Open the direction grid file, "directions.asc" (in the same folder), to determine which grid-direction numbering scheme is used in the file. Compare the values listed in the grid to figure 12. If the grid values range from 1

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[1] If Windows is not set to display file extensions, select "Folder Options" from the "View" menu (Windows XP or the "Tools" menu in Windows 2000) at the top of the "TRIGRS" folder window. Click on the "View" tab in the "Folder Options" window and uncheck the box next to "Hide file extensions for known file types" and then click "OK" to save the change. To show extensions in Mac OS X, click the pointer on a vacant spot on the desktop to make the "Finder" active and then select "Preferences" from the "Finder" menu. Check the box next to "Always show file extensions" and then click the red button in the upper left corner of the "Finder Preferences" window to save the change and close the window.

to 9, then the initialization file should contain the numeral 2 at the end of its second line of data to indicate that the grid uses the TopoIndex numbering scheme. If the numbers in the grid are powers of two ranging from 1 to 128, then the initialization file should contain the numeral 1 at the end of the second line of data (the project title constitutes the first line of data) to indicate that the grid uses the ESRI numbering scheme. When finished checking the numbering scheme, close the direction-grid file and enter the correct value on line 4 of the initialization file.

The first value on line 6 is an exponent (ω, table 1) that determines the flow distribution weighting factors as described previously (fig. 13). The exponent selects one of the runoff routing methods defined in table 1. Figure 13 shows example results for various exponents. Return to the initialization file "tpx_in.txt" and look at the exponent, on the third line of data (table 2-1, lines 5–6). We suggest starting with any negative exponent, which selects the D-infinity method. If greater dispersion is needed to distribute water more smoothly across the slope, then choose a small positive exponent. Use a large positive exponent to minimize the dispersion. Enter -1 as the initial value for the exponent in the initialization file (table 2-1, line 6).

The second value on line 6 specifies the maximum number of iterations for indexing the cells. As we described previously, TopoIndex uses an iterative process to determine the order in which runoff calculations should proceed. The maximum number of iterations needed to complete the indexing process varies with the size of the grid. Our limited experience with grids of various sizes indicates that the following formula can estimate the maximum number of iterations.

$$iterations \leq 1 + \frac{rows + columns}{20}$$

Verify that the maximum number of iterations listed in the initialization file (table 2-1, lines 5–6) is at least as large as indicated by the above formula. For a 10x10 grid, allow at least two iterations. The purpose in setting the maximum number of iterations is to allow TopoIndex to stop after a reasonable time in case the DEM is not hydrologically consistent and indexing cannot converge. TopoIndex will stop after the index solution converges or the maximum number of iterations is reached. Consequently, in certain cases the user may need to try a larger number of iterations than suggested above in order to achieve convergence.

Text on line 8 and 10 of the initialization file identifies input files. Verify the names of the input files that are listed in the initialization file (table 2-1, lines 7–10). The tutorial folder ("TRIGRS/data/tutorial") should contain files named "dem.asc" and "directions.asc". In the initialization file, the name (path) consists of the folder name followed by a separator and the file name. The separator is a slash (/) for Mac OSX[2] or a backslash (\) for Windows. The combination of folder and file name can be as long as 255 characters. To avoid using folder or path names, the user can copy the executable file and initialization file to the folder that contains the input data files. Please consult the documentation for your computer's operating system to learn more about rules for specifying file path names.

Letters on lines 12, 14, 16, 18, and 20 determine which of the five possible output files are saved. The letter "T" stands for "true", and answers as "yes," while "F" stands for "false" and answers as "no." Verify that the necessary output files are selected for output. A "T" should appear on the line below the question "Save grid of D8 downslope receptor cells?" and the question "Save list of cell number and corresponding index number?" (table 2-1, lines 14, 18). These two files are needed to run TRIGRS later in the tutorial. For now, an "F" should appear below the other three questions that ask about saving files.

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[2] TRIGRS and related programs use the POSIX path names on Mac OSX. Note also that the files use UNIX line endings, rather than traditional Mac OS line endings.

Text on line 22 of the initialization file identifies the output folder. Verify that the specified output folder is "data\tutorial" (second to last line of data in the initialization file). The folder name should be typed "data\tutorial\" for a Windows PC or "data/tutorial/" for a Mac OS computer. Type an identification code of eight characters or less on the last line of the initialization file (in this case we have used "tutorial", see line 24, table 2-1). Be sure to use only characters that your computer's operating system allows for file and folder naming.

Close the file "tpx_in.txt" and double-click the program icon for TopoIndex (see instructions in the section "Program Operation" if using Mac OSX). The program will run and then exit, closing its window. Open the folder "Tutorial" and then open the files "TIdscelList_tutorial.txt", "TIwfactorList_tutorial.txt", and "TIcelindxList_tutorial.txt" to examine their contents. Partial listings of these files appear in tables 6, 7, and 8. The file "TIcelindxList_tutorial.txt" lists cells in their correct order from highest to lowest elevation; the left column contains the index, or pointer, and the right column contains the cell number for each index value (table 8). Cell numbers increase from left to right, row by row from top to bottom, skipping any no-data cells (fig. 10). Cell numbers in the file "TIdscelList_tutorial.txt" (table 6) correspond to weighting factors in the file "TIwfactorList_tutorial.txt" (table 7 and fig. 13). When finished studying the output, close the files. At this point, either experiment with calculating the weighting factors by different methods (by changing the value of the exponent in "tpx_in.txt") or proceed with the tutorial.

Preparing the TRIGRS Initialization File for an Analysis

We will now perform a sample analysis of slope stability using TRIGRS for the same grid we processed using TopoIndex. Return to the folder TRIGRS and double click the icon "tr_in.txt" to view its contents; it should resemble table 2. Notice that an explanatory heading precedes each line of data, except that the names of the rainfall-intensity files are listed on succeeding lines under a single heading. Tables 2 and 3 define the entries in the initialization file and indicate permissible ranges of values. Table 4 identifies output files, most of which are optional and can be selected in the initialization file. Table 2-2 contains the same information as table 2, with the addition of line numbers to aid the reader in locating some of the entries in the table. Note that changing the number of property zones or the number of rainfall intensity periods will change the number of lines in the initialization file, but the relative locations of the entries remain the same.

Array sizes.—Compare the array parameters on line 4 (second line of input data) of the initialization file against values that were computed by the program TopoIndex (figure 2-2 and table 2-2). In the TRIGRS folder, open the file TopoIndexLog.txt and find the line of text "Data cells, Rows, Columns, Downslope cells" near the bottom of the list. Compare the corresponding numerical values in the line following with the four values on the corresponding data in "tr_in.txt" (table 2-2, lines 3–4). If any of the numbers differ, change the values in "tr_in.txt" to agree with their corresponding values in "TopoIndexLog.txt". The TRIGRS program uses these numbers to allocate storage and the program will quit spontaneously or report an array-boundary error if these numbers are too small.

Simulation parameters.—Several other parameters that control the nature of a given simulation are included near the beginning of the initialization file (table 2-2, lines 3–6). These parameters are defined in table 3. The number of vertical increments (nzs, fig. 14) determines how detailed the simulation is with depth. Choose the smallest number of increments that gives sufficient vertical detail when analyzing large grids, because computation time increases directly with the number of vertical increments.

The sign of mmax (table 2-2, lines 5–6) determines whether pore pressures are computed using equation 1 or equation 2 for saturated infiltration. Setting mmax to a negative value selects Iverson's (2000) solution for infinite depth (equation 1) and a positive value selects the solution for finite depth (equation 2). A positive value of mmax determines how many terms of the infinite series in equation 2 will be used in computing the pore pressures. Our tests indicate that the series converges rapidly and that 20 terms yield sufficient accuracy for most purposes. If convergence does not occur at one or more cells, then mmax can be increased. A corresponding parameter, nmax, (table 2-2, lines 3–4) controls series solutions for unsaturated infiltration. The parameter nmax controls the number of roots found for equation 6 and the maximum number of terms used in computing any infinite series where the roots appear. A value of nmax=30 is usually more than adequate to insure convergence the series.

Both saturated and unsaturated formulations are able to compute pore pressures for multi-stage storms. The rainfall periods, nper, correspond to individual bars in the rainfall histogram of figure 4. Two values of rainfall intensity are listed on line 16 of the initialization file (table 2-2), corresponding to the two periods in this example (nper=2). The rainfall intensities are in meters per second. More details are provided in a later paragraph titled "Rainfall Intensities."

Set the minimum depth, zmin, to a small positive value (0.001 m in this example, table 2) to investigate transient infiltration and slope-stability from just below the surface downward to the maximum depth. Enter a value for the unit weight of water, uww, to establish the units of measurement for your other data. In this case, we are using meter-kilogram-second units, and the unit weight of water is approximately 9800 kg-m/s^2 m^3 (or N/m^3). Finally, enter the elapsed time, t, since the beginning of the storm. We have entered 216,000 s to compute conditions at the end of the storm. Enter the time as "216000" without the comma, because commas are used to delimit values in the input file.

The value tx (lines 3–4) determines how many intermediate time steps are used in the calculations. When using the saturated infiltration solutions (equations 1 and 2), tx may be set to 1 to allow TRIGRS to compute a solution as rapidly as possible for a particular elapsed time. To produce a time series, tx can be set to a larger number to achieve the desired number of time steps; however, increasing the number of time steps does not affect accuracy of the solution. The number of time steps is the product of tx and nper. When using unsaturated infiltration solutions, tx can be set to a small positive number (usually 10 or less) to compute pore pressure response. Increasing the time steps for unsaturated infiltration may increase accuracy of the results because numerical integration is employed in solving for the water-table rise.

Physical parameters.—Many of the input parameters for geometry, initial conditions, physical properties, and precipitation input can be set to constants or read from grids. Maximum depth, Z_{max}, water table depth, d, and initial or background infiltration rate, I_Z, are specified in lines 7 and 8 (table 2-2); negative values indicate that these will be read from grids (lines 23–28, table 2-2), rather than using spatially constant values. The TRIGRS program now uses property zones to assign physical properties, so that a single grid file (lines 21–22) can be used for all property values. Lists of properties for each zone are contained in the initialization file (table 2-2, lines 9–14). The parameters must be listed in the following order: c, ϕ, γ_s, D_0, K_Z, θ_s, θ_r, and α. Enter a positive value for each parameter in each property zone, the property zone grid determines how the properties vary spatially by mapping the parameters to their respective zones. If properties are uniform throughout the problem domain, then specify only one property zone. No property zone grid will be needed and the word "none" can be entered as a placeholder for the file name (table 2-2, lines 21–22). Use a positive value of alpha to use the *unsaturated* infiltration

solution; a negative value will cause TRIGRS to use the *saturated* infiltration model for that property zone.

  Rainfall intensities.—The line of data immediately after the property zone data lists rainfall intensities corresponding to the number of periods (nper, table 2-2, line 6) of distinct rainfall intensity (table 2-2, lines15–16). The intensities should be listed in their correct temporal order. An array of spatially constant rainfall values, cri(:), (lines 15–16 of table 2-2) or grids of spatially variable rainfall must exist for each period (table 2-2, lines 29–31). To use spatially constant rainfall values, list nper positive values on line 16 in the initialization file and placeholders for file names, one per line, for a total of nper lines. To use spatially variable rainfall values, list nper negative values on line 16 in the initialization file and file names for the rainfall grids, one per line, for a total of nper lines. As with the background flux, entering a negative intensity, cri(), causes TRIGRS to read rainfall intensity from a grid file for the corresponding time period (table 2-2, lines 29–31).

  Time increments.—The next line of numerical data in the initialization file (table 2-2, lines 17–18) contains times that define the rainfall periods as defined in figure 4. These should be listed in their correct temporal order so that the numbers increase from left to right. Three times are listed in "tr_in.txt" for this example (table 2-2). The first time, 0 s, is at the beginning of the rainfall; the remaining times correspond to the end of each rainfall period and beginning of the next. Thus, period one, which has an intensity of 6 x 10^{-7} m/s (2.16 mm/h) ends after 172,800 s (48 h) and period two begins. After 216,000 s, (60 h) period two, which has an intensity of $2x10^{-5}$ m/s, ends. Thus period two lasts 43,200 s (216,000–172,800) or 12 h. Times and rainfall intensities used in this example were selected arbitrarily, but are within the observed ranges of rainfall duration and intensity.

  Input files.—The next group of lines lists the names of the input files in the order in which TRIGRS expects them (table 2-2, lines 19–39). All the files are in the tutorial data folder, so the folder name precedes the name of each file as described previously. Verify that the folder name agrees with the location of the input files. In addition to a file corresponding to each physical parameter listed on line 8 (maximum depth, initial water table depth, and steady pre-storm infiltration rate), the listing includes files for slope angle, rainfall intensity, and runoff routing data. Note that the number of files for rainfall intensity must equal the number of storm periods and that all are grouped under one heading. Two rainfall intensity files are listed in this example. Supply a placeholder, such as "none" for the names of any file names that do not exist. For example, if you assume that the initial water-table depth is constant over the entire area, you would not need to create a grid file for water-table depth. In that case, you would enter a positive constant for the water table depth (table 2-2, line 7–8) and type "none" below the heading that asks for the name of the water table grid file (table 2-2, lines 25–26).

  Output files.—The log file, "TrigrsLog.txt", is generated automatically, all others are optional. Table 2-2 shows the group of lines in the initialization file that control output (lines 40–63). If desired, you may supply the name of a folder where the output files will be stored. In this case, TRIGRS will write the files in the folder named "data/tutorial/" ("data\tutorial" for the Windows version) within the TRIGRS folder (lines 40–41). Leave the line blank if you wish to put the files in the same folder where the TRIGRS executable program file resides (or present working directory on Mac OSX or UNIX). If desired, provide an identification code (as many as 8 characters) for output files, otherwise leave a blank line (table 2-2, lines 42–43). For this example, the code "t=216000" corresponds the time since rainfall began, specified earlier. Be sure to change the code before running the next simulation. Generation of individual output grid files can be turned on or off by typing "T" or "F" on the corresponding lines of the initialization file (table 2-2, lines 44–55). Table 4 of the main text describes the various output files. An output flag in the

initialization file controls output of a detailed listing of pressure head and factor of safety by depth for each grid cell (table 2-2, lines 56–57). For this tutorial, make sure that all of the grid files are turned on (T) and that the output flag is set to -2 to generate a full list, like that in table 9. When working with large grids, it is best to suppress output of the detailed listing by setting the flag to 0 (zero) to save disk space.

When using the unsaturated infiltration model or multiple time steps for the saturated infiltration model (tx>1, table 2-2, lines 3–4), it is possible to save output grids at more than one elapsed time during the storm. Specify the number of times for saving the grids (table 2-2, lines 58–59), the specific times for output (lines 60–61) and whether to skip the intervening time steps (lines 62–63). If the specified output times do not correspond to increments of the time step size, then TRIGRS will automatically adjust the output time to the nearest time step.

Other user options.—A few other user options exist in the current version of TRIGRS (table 2-2, lines 64–73. The option to use an analytic solution for fillable porosity (lines 64–65) allows the user to choose the efficient analytic solution which converges rapidly for intermediate and later times or a numerical integration for very early times. The option of estimating positive pressure head in the rising water table zone (lines 66–67) allows the user to save to disk either the positive pressure estimate below the rising water table (enter "T") or the negative pore pressure computations above the initial water table (enter "F"). Negative pressure computations can be used to compare model results with published numerical solutions (Srivastava and Yeh, 1991). The next option (table 2-2, lines 68–69) allows TRIGRS to use the unsaturated computations either in the entire zone above the initial water table, $\psi_0 = 0$, or only above the capillary fringe $\psi_0 = -1/\alpha$ (Savage and others, 2004). Using the second option (only above the capillary fringe) tends to produce more rapid water-table rise, because the unsaturated infiltration models operate on a thinner layer, but it may produce a better approximation of the soil-water characteristic curve.

The option of logging mass-balance results (table 2-2, lines 70–71) allows the user to check behavior of the unsaturated zone solution for particular combinations of parameters. This option is mainly for use in the early stages of modeling on trial cells. Logging mass balance during simulations on large grids will slow down computations and greatly increase disk storage requirements.

The flow direction option (table 2-2, lines 72–73) allows the user to override the default slope of the line that determines the maximum allowable values of computed pore pressures given in equation 3*A* (see also Iverson, 2000). Table 3 of the main text describes the choices and their results under the program control variable "flowdir."

Using TRIGRS to Analyze Slope Stability during a Simple Storm

After studying and editing the initialization file, close the file and double-click the TRIGRS application icon to perform an analysis. (If using Mac OSX, follow instructions in the Program Operation section of the main text.) The TRIGRS program will attempt to open an initialization file named "tr_in.txt" in the same folder as the TRIGRS application resides. If TRIGRS does not find the file, it will prompt the user to enter the name of the initialization file. After finding the initialization file, TRIGRS should run without any additional intervention by the user. After TRIGRS completes execution, you can open the output files in the folder "data/tutorial" to see the results. In this analysis, time was set to compute conditions at the end of the storm. To save these results before conducting another analysis, add the identification code to the name of the log file (change it to "TrigrsLogt=216000.txt") and move it to the folder with the output data so you have a record of what input parameters were used. Next, edit the initialization file to change the time, identification code, and any other parameters before running TRIGRS again. The TRIGRS

program does not have any display capabilities. To observe your results graphically, import the ASCII grid output files into graphics or GIS software.

Time steps.—A typical analysis will involve running TRIGRS for several different times throughout the duration of a storm to observe how pore pressure and slope stability vary as the storm progresses. To observe pore pressures at an earlier time, open "tr_in.txt" and edit the time (table 2-2, lines 5–6). For example, change the elapsed time from 216000 s to 43200 s and run TRIGRS again to observe the pore pressure and factor of safety at the middle of the first storm period. Then repeat for 86400 s and 100800 s to compute pressure head at the end of the first and second storm periods. After each analysis, be sure to save the log file by renaming and moving it as described above. Alternately, one can leave the value of t=216000 and set the value of tx to 4 (table 2-2 lines 3–4), to get output at even time increments. Using this option requires the user to specify output times (table 2-2, lines 58–63).

Figure 2-3 shows graphical representations of the input data and the results of the analysis for the hypothetical study area that is represented by the tutorial data grids.

Input data.—The digital elevation model (DEM, fig. 2-3) represents part of a small canyon that drains to the southwest. Geologic material that underlies the upper left part of the area has higher shear strength parameters (cohesion and phi, fig. 2-3), and lower hydraulic conductivity, K_S, and diffusivity, D_0, than material in the remainder of the area. The depth to firm bedrock is assumed to be 2 m everywhere except on slopes that are steeper than 30°, where depth decreases linearly with increasing slope angle. The precipitation data represent a hypothetical 28-hour storm that consists of 24 hours of steady, light precipitation followed by four hours of heavy precipitation. We have assumed uniform precipitation over this small area. The steady infiltration rate (not shown) is also uniform across the area, except at a spring located in the channel bottom. A negative infiltration rate in the seventh column and eighth row of the grid file "rizero.asc," which is found in the folder "TRIGRS/data/tutorial/" represents discharge from the spring.

Results. –Three series of plots in figure 2-3 show the runoff and progressive changes in pressure head, ψ, and factor of safety, F_S. Runoff occurred during both phases of the storm (RUNOFF 1 and 2 in fig. 2-3). The precipitation rate is higher than the hydraulic conductivity of material in the upper left so that water runs off this area and infiltrates into the more permeable material down slope, as reflected by the higher infiltration rates directly downslope from the contact between materials of higher and lower conductivity (INFILTRATION 1 and 2, Fig. 2-3). As a result, pressure head increased more rapidly downslope from the contact between the two materials. A spring exists at the channel bottom in the lower left corner of the area, which also produces runoff during both storm periods. Pressure head increased very little in the less permeable material, in the upper left corner of the area, but increased steadily throughout the storm in the more permeable material. Likewise, factor of safety changed gradually during the storm, and many of the steep cells become unstable by the end of the storm (Fig. 2-3).

Starting a new problem.—Having completed the tutorial, you should now be ready to set up and solve a new problem. Use GIS software to create the input grids and save them in the required ASCII format. Create a new folder for all the input data (preferably in the TRIGRS "Data" folder) and copy all of the data files for the new problem into the new folder. Use the utility GridMatch to make sure that all the grid files are compatible before proceeding. If you plan to use the simple runoff routing features in TRIGRS, then use TopoIndex to generate the necessary files.

Once all the grid and routing files are ready, make a copy of the TRIGRS initialization file and rename both the original file and the copy. If any of the initialization files in the TRIGRS folder are named "tr_in.txt," be sure that it is the active (new) one. However, to avoid confusion, it might be best to give all the initialization files descriptive names and enter the name of the one you

want to use at run time. After creating and naming a new initialization file, open it in a text editor and enter the correct folder and file names for your new problem into the new initialization file. Also, be sure to edit the project title and all the other input parameters to suit the new problem.

Using the unsaturated infiltration model.—Once you are confident using the model to simulate saturated infiltration, you are ready to begin experimenting with the unsaturated infiltration model. Successful use of the infiltration model requires initial testing of parameters on single-cell grids to learn how the model will behave with particular combinations of soil properties and model or program control parameters. Results of these tests will guide selection of program control parameters, such as nmax, nzs, and tx, as well as ranges of physical properties to achieve accurate results with efficient computation.
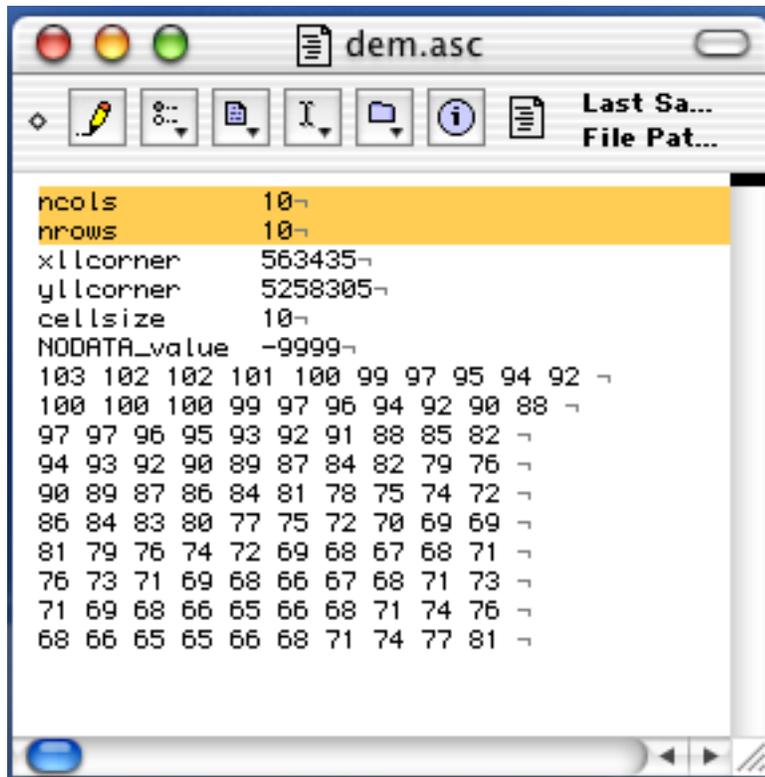
Figure 2-1. Screen image of the file "dem.asc" with grid dimensions highlighted.

```
  ● ● ●                    📄 TopoIndexLog.txt                              ⬭

        Starting TopoIndex
        Date: 10/28/2002
        Time: 15:20:44

        -- LISTING OF INITIALIZATION DATA --
        Name of project (up to 255 characters)
        Tutorial example data for TopoIndex analysis
        Rows, Columns, flow-direction numbering scheme (ESRI=1, TopoIndex=2)
          10  10  2
        Exponent, Number of iterations
         -1.00000  10
        Name of elevation grid file
        :data:tutorial:dem.asc
        Name of direction grid
        :data:tutorial:directions.asc
        Save listing of D8 downslope receptor cells?  Enter T (.true.) or F (.false.)
         F
        Save grid of D8 downslope receptor cells? Enter T (.true.) or F (.false.)
         T
        Save cell index number grid?  Enter T (.true.) or F (.false.)
         F
        Save list of cell number and corresponding index number? Enter T (.true.) or F (.false.)
         T
        Save flow-direction grid remapped from ESRI to TopoIndex? Enter T (.true.) or F (.false.)
         F
        Name of folder to store output?
        :data:tutorial:
        ID code for output files? (8 characters or less)
        tutorial
        -- END OF INITIALIZATION DATA --

        Tutorial example data for TopoIndex analysis

        Reading flow-direction data
        subroutine nxtcel2 completed normally
        iteration   1  corrections   1
        iteration   2  corrections   0
        Parameters for file--> :data:tutorial:dem.asc
        Exponent  -1.00000
        Data cells, Rows, Columns, Downslope cells
          100  10  10  154

        TopoIndex finished normally
        Date: 10/28/2002
        Time: 15:20:45
```

Figure 2-2. Screen image of the file "TopoIndexLog.txt" with array length parameters highlighted.
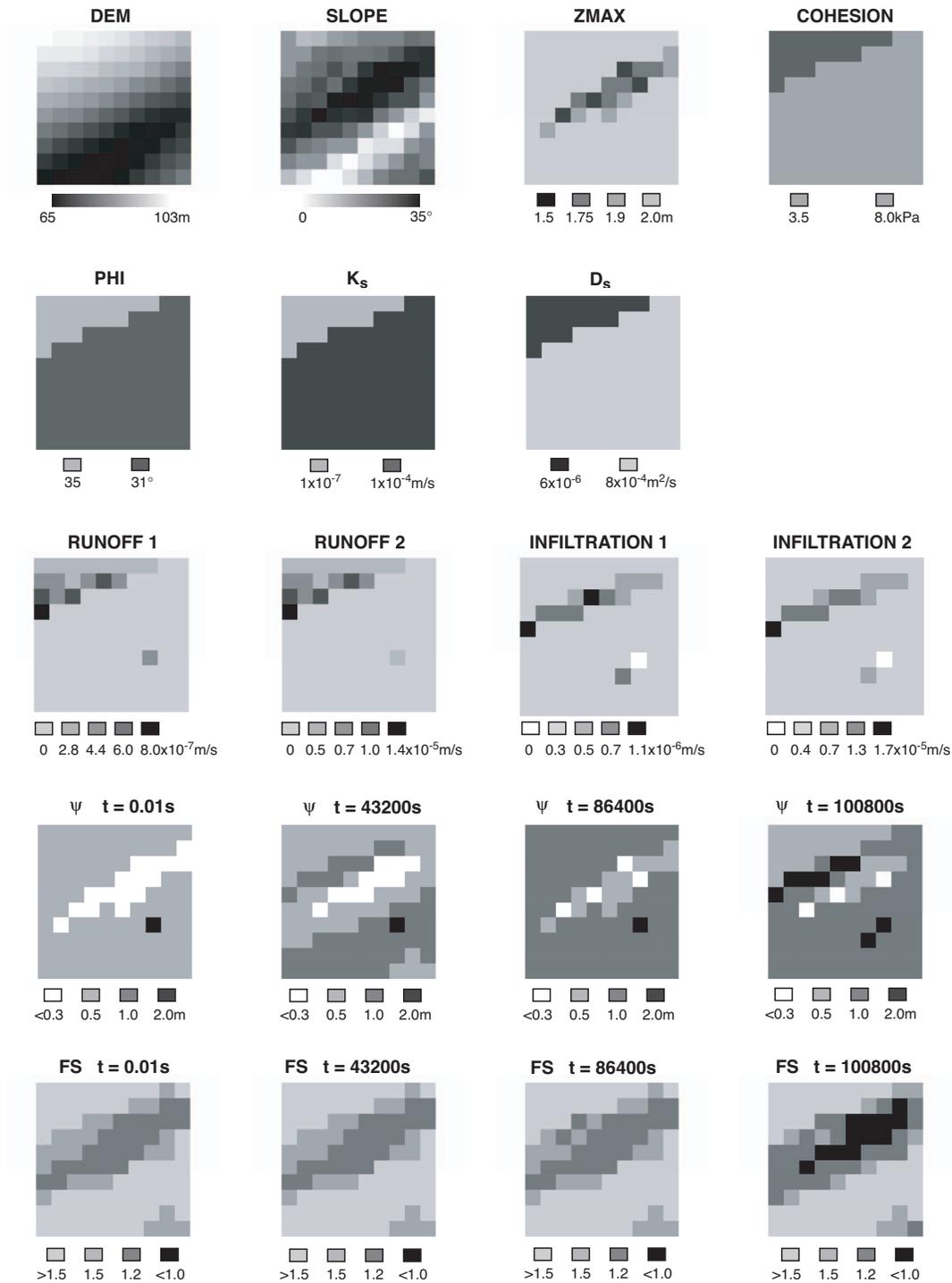
Figure 2-3. Sample analysis of data from the folder "TRIGRS/data/tutorial". The first two rows represent input data (elevation, slope angle, depth of soil, soil cohesion, internal angle of friction, hydraulic conductivity, and hydraulic diffusivity). The third row shows runoff and infiltration rates during the two storm periods. The fourth row shows pressure head at the base of the soil through time, and the bottom row shows the factor of safety through time.

Table 2-1. Contents of the initialization file "tpx_in.txt" for tutorial problem, listed by line number.

[File path names are limited to 255 characters; "Rows", "Columns", and "Number of iterations" are positive integers. "Exponent" is a real number as defined in table 1. The default folder for storing output is the folder where the program TopoIndex resides]

Line number	Text
1	Name of project (up to 255 characters)
2	Tutorial data for TopoIndex analysis
3	Rows, Columns, flow-direction numbering scheme (ESRI=1, TopoIndex=2)
4	10, 10, 2
5	Exponent, Number of iterations
6	25, 10
7	Name of elevation grid file
8	data/tutorial/dem.txt
9	Name of direction grid
10	data/tutorial/directions.txt
11	Save listing of D8 downslope neighbor cells? Enter T (.true.) or F (.false.)
12	T
13	Save grid of D8 downslope neighbor cells? Enter T (.true.) or F (.false.)
14	T
15	Save cell index number grid? Enter T (.true.) or F (.false.)
16	T
17	Save list of cell number and corresponding index number? Enter T (.true.) or F (.false.)
18	T
19	Save flow-direction grid remapped from ESRI to TopoIndex? Enter T (.true.) or F (.false.)
20	T
21	Name of folder to store output? Leave blank to use default folder
22	data/tutorial/
23	Identification code for output files? (8 characters or less)
24	tutorial

Table 2-2. Contents of initialization file "tr_in.txt" for tutorial problem, listed by line number.

Line number	Text
1	Name of project (up to 255 characters)
2	TRIGRS, version 2, Tutorial
3	imax, row, col, nwf, tx, nmax
4	100, 10, 10, 154, 1, 30
5	nzs, mmax, nper, zmin, uww, t, zones
6	10, -100, 2, 0.001, 9.8e3, 216000, 2
7	zmax, depth, rizero, Min_Slope_Angle (degrees)
8	-3.001, -2.4, -1.0e-9, 0.
9	zone, 1
10	cohesion,phi, uws, diffus, K-sat, Theta-sat,Theta-res,Alpha
11	3.5e+03, 35., 2.2e+04, 6.0e-06, 1.0e-07, 0.45, 0.05, -0.5
12	zone, 2
13	cohesion,phi, uws, diffus, K-sat, Theta-sat,Theta-res,Alpha
14	8.0e+03, 31., 2.2e+04, 8.0e-4, 1.0e-04, 0.45, 0.06, -8.
15	cri(1), cri(2), ..., cri(nper)
16	3.e-7, 9.e-5
17	capt(1), capt(2), ..., capt(n), capt(n+1)
18	0, 172800, 216000
19	File name of slope angle grid (slofil)
20	Data/tutorial/slope.asc
21	File name of property zone grid (zonfil)
22	Data/tutorial/zones.asc
23	File name of depth grid (zfil)
24	Data/tutorial/zmax.asc
25	File name of initial depth of water table grid (depfil)
26	Data/tutorial/depthwt.asc
27	File name of initial infiltration rate grid (rizerofil)
28	Data/tutorial/rizero.asc
29	List of file name(s) of rainfall intensity for each period, (rifil())
30	Data/tutorial/ri1.asc
31	Data/tutorial/ri2.asc
32	File name of grid of D8 runoff receptor cell numbers (nxtfil)
33	Data/tutorial/TIdscelGrid_tutorial.asc
34	File name of list of defining runoff computation order (ndxfil)
35	Data/tutorial/TIcelindxList_tutorial.txt
36	File name of list of all runoff receptor cells (dscfil)
37	Data/tutorial/TIdscelList_tutorial.txt
38	File name of list of runoff weighting factors (wffil)
39	Data/tutorial/TIwfactorList_tutorial.txt
40	Folder where output grid files will be stored (folder)
41	Data/tutorial/
42	Identification code to be added to names of output files (suffix)
43	itx1
44	Save grid files of runoff? Enter T (.true.) or F (.false.)
45	T
46	Save grid of minimum factor of safety? Enter Enter T (.true.) or F (.false.)
47	T

Table 2-2. Continued.

Line number	Text
48	Save grid of depth of minimum factor of safety? Enter Enter T (.true.) or F (.false.)
49	T
50	Save grid of pore pressure at depth of minimum factor of safety? Enter Enter T (.true.) or F (.false.)
51	T
52	Save grid files of actual infiltration rate? Enter T (.true.) or F (.false.)
53	T
54	Save grid files of unsaturated zone basal flux? Enter T (.true.) or F (.false.)
55	F
56	Save listing of pressure head and factor of safety ("flag")? (Enter -2 detailed, -1 normal, 0 none)
57	-2
58	Number of times to save output grids
59	1
60	Times of output grids
61	216000.
62	Skip other timesteps? Enter T (.true.) or F (.false.)
63	F
64	Use analytic solution for fillable porosity? Enter T (.true.) or F (.false.)
65	T
66	Estimate positive pressure head in rising water table zone (i.e. in lower part of unsat zone)? Enter T (.true.) or F (.false.)
67	T
68	Use psi0=-1/alpha? Enter T (.true.) or F (.false.) (False selects the default value, psi0=0)
69	F
70	Log mass balance results? Enter T (.true.) or F (.false.)
71	T
72	Flow direction (enter "gener", "slope", or "hydro")
73	slope