Theory and Technology in Natural Sciences and Watershed Management

Earth Systems Institute

Programs
for
DEM Analysis

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Earth Systems Institute is a nonprofit organization committed to interdisciplinary research in landscape interactions and applications for resource management. We explore interactions between climate, vegetation, geomorphology, hydrology, and aquatic ecology, focusing on climatic disturbances, erosion, terrestrial-channel linkages, biodiversity, and effects of land use. We transfer new field methods, models, and theories into applications for natural resource management.

Table of Contents

INTRODUCTION

Numerical simulation models play an important role in efforts to explore watershed interactions. Such models require quantification of a variety of topographic attributes, hence, analyses of digital elevation data forms an important component of our modeling efforts at ESI. We've focused on use of point elevation values provided over a regular grid, typically referred to as digital elevation models (DEMs), since data in this format are widely available. Topographic analyses prove useful for a variety of efforts beyond simulation modeling, so we've provided capabilities for output of derived quantities in raster and vector formats accessible to geographic information systems (GIS). This document provides instructions for use of these programs and descriptions of the file formats and algorithms used.

These programs form part of an active research program and undergo continuous development and testing. Updates and additions to the programs may someday be posted to the ESI website at www.earthsystems.net or to the CLAMS website at http://www.fsl.orst.edu/clams/.

What the Programs Do

Using DEMs and a set of user-specified parameters these programs will:

- delineate a routed channel network, with an option for drainage enforcement, and

- estimate certain channel and valley attributes (drainage area, channel gradient, channel length, mean annual precipitation, valley width, valley side-slope gradient).

With additional data netrace can also:

- estimate susceptibility to shallow colluvial landsliding based on user-specified relationships,

- estimate the probability for debris flow delivery to all DEM pixels, or the potential for delivery to a stream channel from all DEM pixels,

- estimate potential for debris flow scour and deposition in channels, and calculate a relative volume of debris-flow-derived sediment for each channel reach.

Channel attributes and debris-flow-scour and deposition probabilities are averaged over reaches and output to an ArcInfo Shape file. Information about tributary junctions (e.g., junction angle, tributary drainage area) may be output to a separate (point) Shape file. (Information on ArcInfo shape files is available at http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf). Landslide susceptibility and debris-flow-inundation-hazard zones are output to digital raster files.

The size of the DEM that can be examined with these programs is set in part by the types of analyses you require and by the available memory and disk space on your computer. Any debris-flow analysis adds considerably to the memory requirements and to the run time. The programs have been used successfully on DEMs containing >100 million pixels; data sets much larger than this have not been attempted.

The programs use a lot of disk space for intermediate storage of results. Depending on the analyses specified, the programs may require work space on the disk in excess of 10 times the size of the DEM.

Command-Line Implementation

We provide no graphical interface for these programs. Rather, they are run from command lines and use ASCII files for specification of adjustable parameters. This allows use of the same source code for different platforms; the programs can be compiled for a Windows machine or for a Unix machine and the implementation will be the same on both.

Caveats

You are responsible for how results from these programs are used. The accuracy of derived quantities is a function of the accuracy and resolution of input data and of the ability of the algorithms (and their implementation) to use that data to infer other quantities that have not been directly measured. Additionally, despite my utmost diligence, there may be (undoubtedly are) undetected bugs yet lurking both in the code and in the logic employed in implementation of the algorithms. You must assess the appropriateness of the algorithms for your application, my success at implementing them (source code is available), and verify the accuracy of the results.

USING THE PROGRAMS

Program Files

The programs are divided into two primary modules, Bld_grds and Netrace, and a set of five utilities. Each is described briefly here, with details provided in subsequent sections.

Bld_grds primary tasks are to determine the flow direction and contributing area for every DEM pixel. The flow direction specifies the outflow direction for surface water exiting the pixel and the contributing area specifies the surface area draining to the pixel, i.e., the pixel "watershed". In the process of calculating these quantities, Bld_grds produces auxiliary files specifying surface gradient, contour length per pixel, and the number of adjacent inflowing pixels. Bld_grds can also use a separate channel mask for drainage enforcement, derived from an existing line coverage of channel locations, for example, to aid in estimating flow directions (and channel locations) through areas of flat topography.

Netrace uses output files created by Bld_grds, along with the DEM, to trace a "routed" channel network and to estimate topographically controlled channel and valley attributes. In a "routed" network, flow directions and tributary connections are all determined so that flow can be followed (routed) up or downstream through the network. Netrace can continue to trace flow paths up hillslopes to pixels identified as landslide prone. These flow paths can then be evaluated in terms of their potential for delivery of sediment to channels by landslides and debris flows.

Adjustable parameters shared by the two programs are specified in the ASCII file parameters.dat. Parameters used only by Netrace for calculating debris flow inundation hazards are specified in the ASCII file runout_parameters.dat. Output options are specified in the ASCII file instructions.txt. By default, these files must be placed in a directory on the c: drive named \work\source\.

Both programs use the ESRI binary raster file format produced by the ARC command GRIDFLOAT. Three utilities are provided for file conversions:

Read_dem – a program to read a USGS-format DEM and produce a digital raster file.

Read_grd – a program to read an ArcInfo-format ASCII raster file and produce a digital raster file.

Grid_ASCII – a program to read a digital raster file and produce an ArcInfo-format ASCII raster file.

Two other utilities are also provides:

Merge – a program to merge multiple digital raster DEMs into a single file. This program will fill in the single-pixel gaps that sometimes occur, but currently performs no smoothing at DEM boundaries.

Splice – a program to merge multiple shape files produced by Netrace and update all attributes.

Data Files

All raster files use the ESRI binary raster file format produced by the ARC command GRIDFLOAT. This format requires two files: a binary file containing the data (8 byte floating-point array starting with the upper left DEM point and listed sequentially left to right through the columns and moving down row by row) and an ASCII header file. The binary file must have extension ".flt" and the header file extension ".hdr". All raster data files use a specific naming convention that includes an ASCII identification code that may be up to 5 characters long. For example, elevation data (the DEM) is named elev_ID.ext, where "ID" represents the (up to) 5 ASCII characters used for the identification code and "ext" refers to the file extension (.flt and .hdr).

When running the program, you'll be prompted for the directory containing the data files and the ASCII ID. Bld_grds output is written to the same director as the input DEM. Netrace requires specification of directories for both input and output data files and input and output file IDs.

A DEM alone is sufficient to run these programs. They can also use certain other types of information, if data are available, described below.

Elevation – (elev_ID, required). Digital elevation data, used by both Bld_grds and Netrace.

Mean Annual Precipitation – (prec_ID, optional) Bld_grds will read a raster file providing mean annual precipitation depth in mm and use this to determine the mean annual precipitation volume for the contributing area of each DEM pixel. This information is then used by Netrace to determine the mean annual precipitation depth for the drainage area to each channel reach. The grid size is arbitrary (e.g., PRISM data is typically available in ~1-km^2 grids), but the grid must cover the entire DEM given by elev_ID.

Vegetation Cover – (veg_ID, optional) Netrace can use a grid of vegetation classes in determining landslide susceptibility and debris-flow-runout length. The program currently recognizes four classes: 1) open stands (clear cuts); 2) mixed hardwood – conifer stands and small conifer stands; 3) large conifer stands; and 4) roads (with a buffer). The effects of vegetation cover are currently "hard-wired" into the program, but will be offered as adjustable parameters in future additions. Grid size is arbitrary, e.g., Landsat-derived landcover data is often in 25-m pixels, but the grid must cover the entire DEM.

Channel Mask – (chan_ID, optional) Bld_grds will read a raster file that flags pixels containing a channel according to a separate data source (e.g., a vector channel coverage). Channel locations determined by Netrace are based on flow directions estimated from the DEM. In many cases the

DEM provides insufficient information to determine a unique flow direction (e.g., in topographically flat areas), or there may be errors in the DEM that result in incorrect channel locations. The channel mask incorporates additional information in determination of flow directions and channel locations and serves to provide a certain level of drainage enforcement. The degree to which the channel mask is enforced is determined by the value of the flagged cells. This value specifies the maximum depth of incision (in meters) used to direct flow directions; the greater its value, the greater is the influence of the channel mask. This value may vary over the extent of the channel mask, thus allowing the user to increase the level of drainage enforcement over certain portions of the DEM. If a negative value is used to flag channel pixels, then a constant incision depth is used, equal to the value specified by the parameter "dig" in the file parameters.dat. Grid size (pixel spacing) must match the DEM.

Lake Mask – (lake_ID, optional) Netrace cannot identify lakes from the DEM, yet it is useful to flag "channel reaches" that actually cross bodies of water. The channel mask is a raster grid that identifies DEM pixels located within lakes and reservoirs; all pixels have value zero, except those falling on a body of water as identified with a separate GIS coverage. These pixels are assigned the identifier of that body of water, which is then assigned to the corresponding channel reach. Grid size must match the DEM.

Contour Interval – (contour_ID, optional) Two methods are available for estimating channel gradients, one of which is based on contour-line crossings of delineated channels and is appropriate for "Linetrace" DEMs made by interpolation of elevation values between contour lines. Lacking vector coverages for the contours, we've implemented this algorithm by estimating the contour-line locations. Since the USGS source maps come with a variety of contour intervals (20 ft, 40 ft, and 80 ft), we use a separate grid data file to specify the contour interval (in feet) over the DEM, which may span numerous quadrangles. Grid size is arbitrary, but the grid must overlay the entire DEM.

Landslide density – If debris-flow routing is done with netrace, the ASCII file dnda.txt is required in the c:\work\source directory. This file specifies the correspondence between the topographic index and landslide density, calibrated to the Oregon Coast Range. Future implementations will provide tools for regional calibration.

Order of Operation

1) Input data files must be written to the binary raster format and given the proper names. The names are specified above. Make sure that DEMs use meters for both horizontal and vertical distances. Some USGS DEMs come with vertical units of feet and horizontal units of meters; you'll have to convert the vertical units to meters prior to using these DEMs. Likewise, some DEMs use vertical units of decimeters and horizontal units of meters. These, too, must have the vertical units converted to meters prior to using them with Bld_grds.

2) Set all parameter values in the ASCII file "parameters.dat" and, if you are including debris-flow-inundation hazards, in "runout_parameters.dat". Make sure that these files are placed on the c: drive in the directory \work\source\, as this is where Bld_grds and Netrace will look for them. Currently, if debris-flow probabilities are to be calculated, the file dnda.dat also needs to be placed in the c:\work\source\ directory. This file provides a relationship between a topographic index of slope stability and landslide density. The supplied file is calibrated for

the Oregon Coast Range. Future versions of these programs will include options for calibration to other data sets.

3) Process the DEM (and other optional input files) using Bld_grds to create topographic outputs. This step will produce several binary raster files on your hard disk.

4) Specify the analyses required for Netrace in the ASCII file "instructions.txt".

5) Run Netrace to create the output Shape files.

6) Use Splice to merge Shape files, if needed.

7) Delete unneeded raster files.

Batch files can be created to automate these tasks, an example of which is provided in a later section.

UTILITIES

Read_dem

This program reads an ASCII USGS-format DEM and creates a floating-point binary raster file, consisting of a floating-point (single-precision real) binary raster file with extension ".flt" and an ASCII header file with extension ".hdr".

The program is initiated by typing "read_dem" at a command-line prompt from the directory containing the executable file. It will prompt you for the "Root directory:", for which you specify the location of the DEM file, specifying the full path (including the final "\"). You'll then be prompted for the DEM-file name, including any extension. For a USGS-format DEM named mydata.dem in directory c:\Washington\dems\, you'd type "c:\washington\dems\" after the "root directory:" prompt and then type "mydata.dem" when prompted for the DEM-file name. You'll then be prompted for an output file name. If the file is intended for use with Bld_grds, name it elev_ID, where "ID" indicates an ASCII identifier up to five characters long.

Read_grd

Readgrd will read an ASCII raster file created by ArcInfo and create a binary raster file. The program is initiated by typing "read_grd" at a command line from the directory containing the executable file. You'll then be prompted for the "root directory:" and for the name of the ASCII grid, which requires the extension ".grd". When specifying the name, do not type the extension. For an ASCII grid file named dem1.grd in directory c:\washington\dems\, you'd type "c:\washington\dems\" after the "root directory:" prompt, and you'd type "dem1" when asked for the name of the file.

You'll then be asked for an output file name, which if you're planning on using the file with Bld_grds, should be elev_ID, where ID is an ASCII identifier up to five characters long. You'll then be asked to specify a "Grid multiplication factor:". This allows you to convert vertical units in the output file; for example, if the DEM uses vertical units of decimeters and horizontal units of meters, specify a multiplication factor of 10.0. If the units are the same, simply specify 1.0.

Grid_ASCII

Grid_ASCII will create an ASCII file using the ArcInfo raster format. Invoke the program by typing "grid_ASCII" at a command prompt in the directory containing the executable file. You'll then be asked for the "root directory:" and for a list of file name. Type file names with no extension. A blank return indicates the end of the list.

Merge

Merge will combine a set of DEMs (in IDRISI format) into a single file. You must specify the root directory and then a list of file names (with no extension). The program will check that all files use the same units and horizontal resolution and will fill in single-cell gaps that sometimes occur between DEMs. You also have the option of creating an ASCII output file.

Splice

Splice will take a set of shape files produced by Netrace and combine them into a single file with corrected reach attributes (e.g., drainage area). With this facility, a large DEM may be divided into a set of smaller tiles, shape files produced for each, and then the shape files merged to provide a single file for an entire large drainage, with the correct LLIDs, drainage areas, mean annual precipitation values, and channel lengths carried through. Note that there MUST be overlap between the shape files (and, therefore, between the DEM tiles), otherwise splice has no way of knowing how the shape files are connected.

Splice will prompt you for the number of shape files to merge and then for the name of each, including the full path. This allows you to merge shape files held in different directories. You'll then be asked for the name of the output shape file, including the full path.

BLD_GRDS

Command-Line Prompts

Bld_grds is invoked by typing "Bld_grds" at a command line from the directory holding the executable file. It asks for the "Root Directory:" (the path to the data files) and for the file identifier (an ASCII sequence from one to five characters long).

It then asks if "Zero values indicate nodata (y/n):" Some DEMs have used a value of zero over areas covered by ocean. Since zero values are sometimes legitimate elevations in low-lying coastal areas, it is impossible to distinguish between oceanic and terrestrial portions of the DEM. Bld_grds will attempt to define a flow direction for every pixel with data in the DEM. Doing so over large portions of ocean is both time consuming and meaningless, and in some instances will cause the program to crash as it runs out of stack space in memory. Hence, you'll see the question posed at the beginning of the program run "Zero values indicate nodata (y/n):". If you indicate "y", any pixels with an elevation value of zero will be ignored.

If Bld_grds finds a file with the name ang_ID, it will ask if you want to use the existing flow direction file. If you don't, simply type "n".

Outputs

Bld_grds creates a series of raster files. These are:

Accum_ID: A flow accumulation grid, giving an estimate of the drainage area to each pixel. Drainage area in accum_ID is given in units of DEM pixels. Negative values indicate edge contamination, i.e., potentially underestimated drainage area because the watershed intersected the DEM boundary.

Slope_ID: Estimated surface gradient at each DEM point.

Bcont_ID: Estimated total contour length crossed by flow out of each pixel, in units of DEM cells. Values can vary from 0 to 4. Low values of Bcont indicate local flow convergence; high values indicate local flow divergence. Note that accum/bcont gives specific drainage area (drainage area per unit length of contour) in units of pixel length.

Pin_ID: The area of the eight adjacent cells flowing into each pixel. Values vary from 0 to 8. Pin provides an estimate of local flow convergence.

Ang_ID: Flow direction for each pixel, calculated using the algorithm described by Tarboton (1997). Values vary from 0 to 2*PI radians.

Dir_ID: D8 flow direction for each pixel, with flow directions confined to one of the eight adjacent pixels (i.e., N, NE, E, SE, S, SW, W, NW).

Pval_ID: Mean annual precipitation value for the drainage area to each pixel, created only if a precipitation data grid (prec_ID) is provided.

SA_ID: Slope-area product, aS^b (optional). A command-line prompt asks if you want the slope-area product calculated. If so, you'll be prompted for the slope exponent value. The specific area (area per unit contour) is used for this product.

Algorithms

The first step is to read the input grids. The elevation grid is loaded into memory and zero-shifted (the minimum elevation is subtracted from all values). The program checks to see if the channel mask and the precipitation grids are present in the data directory. Subsequent tasks are described below. Alterations to the DEM are stored in a temporary raster file, named etmp_ID, which is deleted upon successful completion of the program.

Creation of a Depression-Less DEM

It is assumed that the DEM contains no closed depressions – that all pixels eventually drain to a DEM edge. However, most DEMs contain closed depressions that must somehow be removed so that drainage directions can be defined. These depressions arise both from actual errors in the DEM (e.g., poor edge matching between USGS quadrangles) and because pour points may be missed by the point samples of elevation. I use two algorithms to remove closed depressions: filling of depressions to the level of the lowest pour point and incision of probable channel locations to drain closed depressions.

Filling: This is the standard algorithm, described by Jenson and Domingue (1988): find the lowest pour point and raise all pixels in the depression to this level. Unfortunately, this procedure tends to obscure potentially useful information that elevations within the depression may actually provide. Hence, I first try another strategy, cutting of channels along the lowest pour point.

Cutting: I find the lowest pour point and then try to infer drainage away from the depression by tracing a path that proceeds to the lowest adjacent pixel. If a drainage path can be found with a

length of five pixels or less, and that requires excavation of no more than 10 DEM units (meters), I'll lower the pixel elevations along the drainage path to the level of the pour point. If a drainage path meeting these requirements cannot be found, the depression is filled to the level of the pour point.

Flow Directions

A flow direction must be defined for every pixel within the DEM. Where elevation differences between adjacent pixels allow determination of a flow direction, I use an algorithm presented by Tarboton, (1997). This algorithm represents the ground surface local to the DEM point in terms of 8 triangular facets, with corner elevations defined by the DEM point and its eight adjacent points. Flow directions are defined for each facet; the steepest outgoing flow path is then assigned to the pixel. Note that this algorithm defines flow directions that may be in any direction and are not limited to one of the eight directions directed to an adjacent DEM point. Flow direction values, in radians of azimuth from north, are stored in raster file ang_ID.

Flow directions determined as described above allow flow into, at most, two downslope pixels, thus allowing flow dispersion over topographically divergent areas. Once the criterion for channel initiation has been met, dispersion is no longer allowed and alternative algorithms are used to determine flow direction into one of the adjacent pixels, as discussed below.

Two other quantities are derived with the calculation of flow direction: 1) a measure of local flow convergence, specified by the area (in terms of DEM pixels) of the eight adjacent pixels that flow into each pixel, stored in raster file pin_ID, and 2) a measure of the contour length traversed by incoming flow to each pixel, stored in raster file bcont_ID. I'll discuss this quantity at greater length below.

For pixels that have no adjacent pixels of lower elevation, a flow direction is undefined. These are flat areas within the DEM. To define flow directions over flat areas I use an algorithm described by Garbrecht and Martz (1997), which tends to direct flow away from adjacent higher elevations and towards adjacent lower elevations. Flow directions within flats are then directed toward one of the eight adjacent pixels.

A D8-flow direction grid (with flow direction an integer multiple of PI/4 radians, so that all flow is directed towards only one adjacent pixel) is also created during the calculation of flow directions. This grid is named dir_ID and is used for routing of debris flows, for which downslope dispersion is also not allowed. For pixels meeting the criteria for channels, the D8 flow direction will match that written to ang_ID. For all other pixels, the flow direction specified in dir_ID and ang_ID may diverge slightly. To compensate for the limited number of flow directions allowed with the D8 method, there is an option to allow a random element into determination of D8 flow direction. I use the partitioning of flow indicated by the flow direction (Tarboton, 1997) specified in ang_ID as a measure of the probability that flow (or a debris flow) will enter each adjacent downstream pixel. Sampling each downslope pixel in turn, if a random sample from a uniform distribution spanning 0 to 1 is less than the probability of incoming flow, all flow is directed to that pixel. In general, the D8 flow direction will correspond to the pixel receiving the majority of flow as determined with Tarboton's method, but with sufficient perturbations to allow downslope travel paths to better follow flow directions as indicated by elevation contours. One drawback with this method is that different runs can produce different D8 flow directions for the same pixel. Averaged over large areas, this is of no consequence and

the overall accuracy in flow direction is improved, but this method may cause individual debris flow paths to diverge slightly between different runs of the program.

Flow Accumulation

Once flow directions are defined for each pixel, drainage area (flow accumulation) to each pixel can be determined. I use the algorithm described by Tarboton (1997) for flow accumulation, which allows drainage to two lower adjacent pixels. This allows some dispersion of downslope drainage.

It is important to understand that a DEM provides insufficient information to unambiguously define drainage area. The lack of information between DEM points requires that assumptions be made about the shape of the ground surface. Once these assumptions are made, it is possible to define flow lines, but the iterative algorithms employed for estimating flow accumulation do not construct flow lines explicitly. Rather a variety of schemes are used to partition flow to downslope pixels (see e.g., (Wilson and Gallant, 2000). I am unaware of any assessment of the accuracy of the different schemes, and have chosen one that is both easy to implement and that provides results consistent with expected dispersion and convergence of flow in topographically complex areas (Tarboton, 1997).

Once the criteria for channelization (described below) is met, downstream dispersion is no longer allowed and all flow is directed toward one of the downslope pixels. Thus, if need be, the flow direction is altered to align with one of the D8 flow directions (i.e., it must be an integer multiple of PI/4).

I've tried several criteria for determining which of the adjacent pixels to direct *channelized* flow to. The first is the standard algorithm in which flow is directed to the pixel with the path of steepest descent (e.g., (Wilson and Gallant, 2000). I've found, however, that this strategy can result in misdirected streams in some instances, particularly over areas of relatively uniform surface gradient.

The second criteria is to direct flow to one of the two downslope pixels that would have received flow using the Tarboton algorithm, choosing the one with the greatest topographic convergence, which may or may not coincide with the path of steepest descent. The reasoning for this choice is that stream channels are commonly delineated on contour maps via crenulations in the contour lines, which indicates local topographic convergence. I use the value of *pin* (read from file pin_ID that was created during calculation of flow directions) as an estimate of topographic convergence. This strategy results in better alignment of some DEM-inferred stream channels with contour crenulations, but not always. The primary factor causing misdirected streams in this case is an artifact arising in creation of the DEM. The USGS's use of a distance-weighting interpolation algorithm results in high surface curvature values at contour crenulations, but low curvature between contour lines. Where contours are widely spaced, traced stream locations may diverge from the contour crenulations.

None of these strategies are foolproof; all result in misdirected channels. I've had best results using topographic convergence as the criteria for directing flow, but results may vary from one DEM to another.

Drainage Enforcement Using a Channel Mask

Bld_grds can use an optional channel mask to guide channel tracing in areas where the DEM provides insufficient information for determining channel location, e.g., over flat areas. The channel mask is provided as a raster grid, created from a vector line coverage. To guide subsequent tracing of the channel network, elevations within a certain distance of the channel locations specified in the channel mask are lowered. The extent of lowering is a function of distance from the masked channel, and varies linearly from zero for pixels greater than 100 meters from the channel to a maximum at pixels corresponding to the channel mask. The maximum extent of lowering is specified by the value of "dig" in the parameters.dat file. The value of "dig" is added to the elevation drop over the pixel to achieve greater drainage enforcement over steep slopes.

Lowering of elevations along specified channel pathways is done after the filling of the DEM and prior to determination of flow directions. The sequence followed is 1) create a depressionless DEM, 2) lower elevations along channel pathways, and 3) again create a depressionless DEM using the new elevations, since the lowering of elevations along the specified channel pathways will create new closed depressions.

The degree to which the channel mask is enforced is controlled to some extent by the maximum depth of allowed incision. This depth is specified by the cell value in the channel mask (in integer decimeters). If the value is negative, a constant specified by the value of the parameter "dig" in parameters.dat is used. The larger the allowed incision, the greater is the influence of the channel mask on derived flow directions. However, as the channel mask exerts greater control, locational errors between the line coverage used to create the channel mask and the DEM can result in the placement of channels in inappropriate places – up valley walls, over islands, etc. The topographic attributes derived by Netrace are based on the original DEM elevations (not those altered for removing depressions and enforcing drainage) and are referenced from the channel locations determined by Bld_grds. Hence, misplacement of the channels relative to the DEM will result in incorrect channel gradients, valley-floor widths, valley side slopes, etc.

Mean Annual Precipitation

At the same time that flow accumulation is being calculated, Bld_grds can also accumulate mean annual upstream precipitation. This requires an additional input grid of mean annual precipitation for each DEM point (from e.g., PRISM, available at http://www.climatesource.com). The resulting mean annual precipitation volume for each pixel is stored in the raster file pval_ID. This file will be used by Netrace to report mean-annual precipitation depth for the drainage area to each reach.

Bld_grds will look for an input grid named "prec_ID", in either IDRISI raster format, ArcView binary raster export format, or as a BIL file. Units are assumed to be in millimeters of precipitation per year. If such a file is not found, no pval_ID file will be produced.

Determination of Channel Initiation Points

There are a variety of published strategies for estimating the location of channel heads using DEMs, e.g., (Wilson and Gallant, 2000; Tarboton and Ames, 2001). All employ calculation of some topographic threshold, typically a function of drainage area, that when exceeded indicates presence of a channel. Bld_grds currently employs two criteria, one applied on low-gradient

areas where channel expansion occurs primarily through fluvial processes and another applied on high-gradient areas where channel expansion may occur via mass wasting processes. For low-gradient areas we employ a slope-dependent drainage area threshold proposed by Montgomery and Dietrich (1992) and Dietrich et al. (1993);

$$a_{cr}S^{\alpha} = C,$$

where a_{cr} is a critical specific drainage area (drainage area per unit contour) required for channel initiation, S is surface gradient, α is an exponent that varies between 1 and 2, and C a constant. The value of α is set by the value specified for c_exp in the parameter.dat file. For steeper areas we employ a simple drainage area threshold. Both criteria may be implemented using either specific drainage area (drainage area per unit contour) or drainage area alone, determined by the "channel threshold criteria" specified in the parameters.dat file.

The surface gradient cutoff dictating the choice of methods is specified by the value of S_max in the parameters.dat file. For areas with gradients less than S_max, the slope-dependent criterion is used.

In addition to drainage-area-dependent thresholds for channel initiation we also require a minimum topographic convergence at channel heads (specified by the value of P_min in parameters.dat). This corresponds to enforcing a threshold in contour-line curvature for channel initiation. It may be set to zero to preclude any dependence on local convergence.

Choice of appropriate thresholds (*C* for low-gradient areas, critical drainage area for high-gradient areas, and S_max for separating the two) is confounded by the fact that channel-head locations are dictated by factors other than topography. Moreover, channel heads may migrate up or down stream over time in response to flood and mass-wasting events. The goal, therefore, is to set threshold values that reproduce appropriate channel densities, since accurate reproduction of individual channel-head locations is probably not feasible. I'll discuss strategies for each.

An important point to remember is that the channel density resulting from any choice of threshold parameters is also a function of the horizontal and vertical resolution of the DEM and of its accuracy. Recall also that DEM accuracy reflects the accuracy of the source data. We've found that channel density estimated from 10-meter (horizontal resolution) DEMs with 1-decimeter vertical resolution interpolated from 40-foot contour lines on 1:24,000-scale USGS 7.5-minute quadrangles can vary dramatically from one quadrangle to another depending on the degree to which topographic texture is preserved in the contour crenulations depicted on the maps.

S_max: S_max separates channel initiation into two process domains, fluvial erosion of surface material and mass wasting. This delineation is not precise: other processes may also be active (e.g., seepage erosion) and these two process types are not cleanly separated by a difference in surface gradient (e.g., gullies form on steep slopes). It is useful to separate channel initiation processes in terms of slope gradient, however, because use of a single criteria across both low- and high-gradient slopes leads to either an under or over-estimate of channel density on one or the other.

To estimate an appropriate value for S_max I use observed mass wasting locations as a guide. The range of slope values over which mass wasting occurs may be found by overlying a point coverage of landslide initiation sites over a grid of slope values estimated from the DEM.
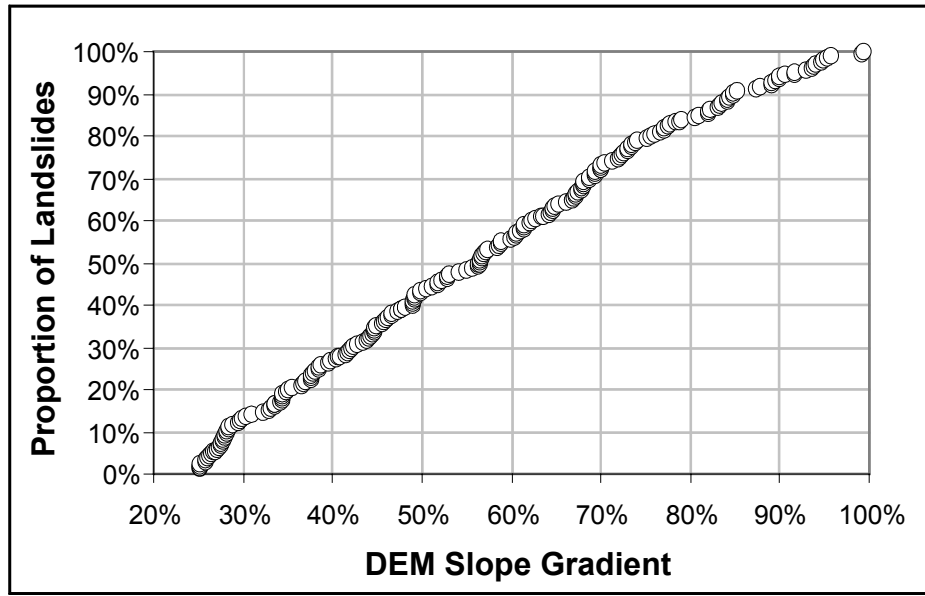
Figure 1. Distribution of surface gradients estimated with a 10-meter DEM at landslide initiation points, Knowles Creek Basin (60km^2), Oregon Coast Range.

Using the distribution of gradients observed for landslides at Knowles Creek basin (Figure 1), for example, I've chosen a value of 25% for S_max. The minimum end of this distribution is an arbitrary choice; one could just as well argue that catching 85% of the distribution (at a gradient of 35%) is the appropriate level. In any case, use of S_max allows division of the landscape into low- and high-gradient areas over which to apply different criteria for channel initiation.

Low-Gradient Threshold, *C*: Physically, the value of *C* reflects regional properties of soil, bedrock, and climate. This is a complex mix, however, confounded by limits in DEM resolution and accuracy and by heterogeneity in the factors affecting channel formation, so that an *a priori* estimate of *C* is probably not feasible. Hence, we must estimate *C* based on field observations. Montgomery and Foufoula-Georgiou (1993) report a relationship $C \sim 10^6/R_a$ for study areas in California and Oregon, where *C* is in square meters and R_a is mean annual rainfall in millimeters. If you have data on regional channel densities, you can calibrate *C* to your DEMs directly. Another approach, suggested by Montgomery and Foufoula-Georgiou (1993), is to reduce *C* until "feathering" occurs, i.e., extension of the channel network onto unchannelized hillslopes. This method essentially sets *C* to maximize the channel density resolved with the DEM.

A simple means for doing this is to create a slope grid and a flow accumulation grid (with no channelization of flow allowed, i.e., set the *C* value extremely high in parameters.dat) with Bld_grds, from which to create a grid of $A*S^\alpha$ values. Then separate out those pixels with gradient less than S_max, which can be binned and displayed as a cumulative distribution from which to estimate channel density as a function of the threshold *C*.

In Figure 2 I multiplied the number of pixels within a bin by 12 meters (the average channel length within a pixel) to get the total channel length corresponding to the number of pixels in a bin and then divided by the total number of pixels with gradient less than S_max in the DEM, multiplied by 100 meters (the area of a pixel). This provided an estimate of channel density. As expected, channel density increases as the value of *C* decreases. At a *C* value of about 1500 square meters the rate at which channel density changes with decreasing *C* increases, shown by the change in slope on the log-log plot. This is where inferred channels start to extend up
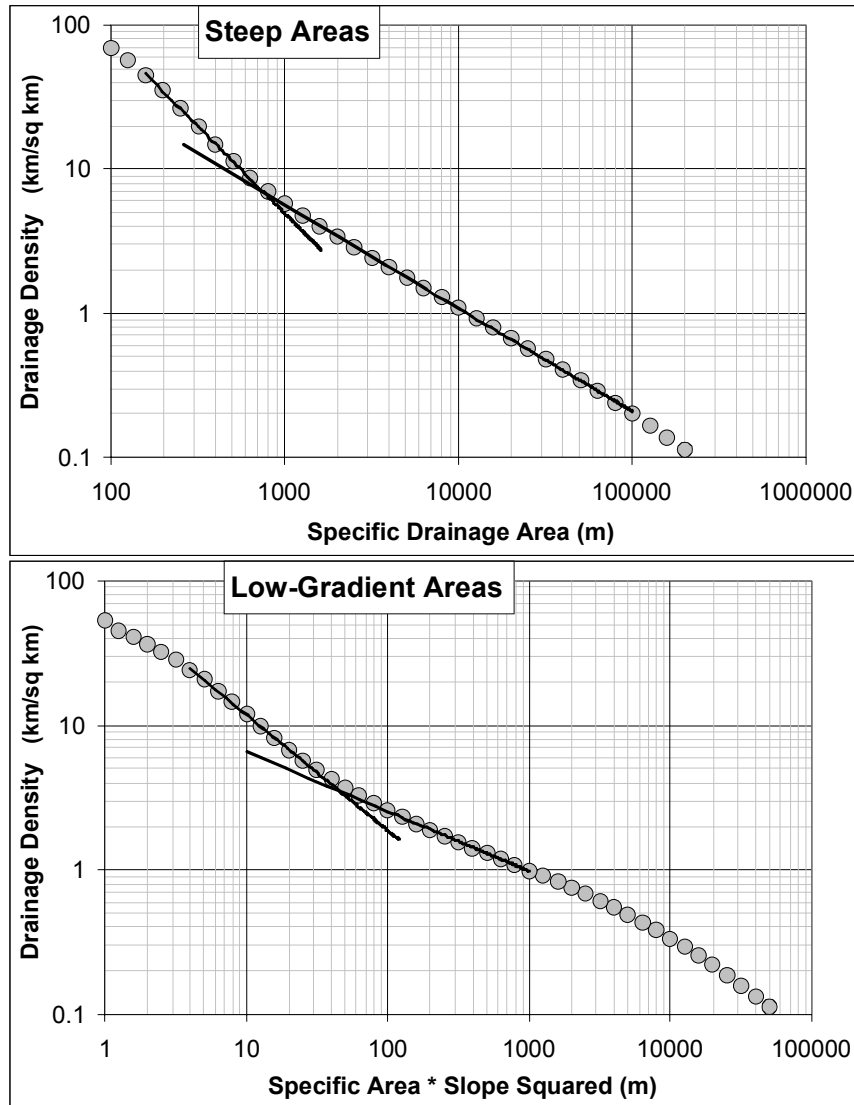
Figure 2. Thresholds for channel initiation. Inflections in the curve of drainage density as a function of the specific-area threshold show the threshold value below which delineated channels extend onto planar hillslopes. These values indicate the most dense channel network resolved by the topograpic information in the DEM. We apply different thresholds for steep, landslide-prone topography and for lower-gradient lands to accomodate the different channel-forming processes active in these two areas

portions of the hillslope with no contour crenulations – channel "feathering" – leading to a dramatic increase in channel density. I thus chose 1500 square meters as an appropriate value of *C* for this DEM, which gives a channel density of about 6 km/km^2, a value in line with observed channel densities in the Oregon Coast Range.

High-Gradient Areas: The intent here is to find a drainage-area threshold appropriate for mass wasting processes. A more process-based strategy could be employed, something that employed slope as well, but I expect that mass-wasting controls on channel initiation vary dramatically (with each storm season), so I've opted for the simplest criterion.

Again, the goal is to set a threshold value that reproduces an appropriate channel density, not to accurately replicate specific channel-head locations. For that purpose, the same strategy described above for low-gradient areas may be used. Create a flow accumulation grid with Bld_grds (with the channel_area_threshold set to an extremely high value in parameters.dat, to preclude flow channelization); bin pixels with gradients greater than or equal to S_max, and plot a cumulative distribution in terms of number of pixels verses accumulation area.

13

Surface Gradient

Surface gradient for each DEM pixel is calculated using a finite difference scheme as described in Wilson and Gallant (2000). The equation for slope is equivalent to that described by Zevenbergen and Thorn (1987) and uses adjacent pixels in the four cardinal directions.

Dietrich et al. (2001) point out that this method for estimating surface gradient produces an error that varies with slope azimuth and therefore advocate another method that utilizes more of the adjacent pixels. In testing these algorithms against a synthetic DEM, with known surface gradients at every point, I've found that there is indeed a directional anisotropy in the error associated with the finite difference calculation of slope. The anisotropy is reduced by using all eight adjacent pixels, however, the absolute error is increased. I have chosen to use the method that exhibits directional variance, but has greater accuracy.

Specific Drainage Area: Contour Length

Specific drainage area (drainage area per unit length of contour) is used in some algorithms for estimating water flux (both overland and sub-surface). Drainage area for each pixel is estimated as described above, the contour length for each pixel is estimated as described here and stored in raster file bcont_ID in units of number of pixel lengths. Contour length is estimated during the calculation of flow directions using the Tarboton algorithm (Tarboton, 1997). A flow direction is calculated for each of the eight triangular facets defined by the current DEM pixel and its eight neighbors. For facets with flow exiting the pixel, contour length is estimated as the projection of the flow on the edge of the facet. Thus flow at an angle of θ to the edge spans a contour of length ½ Sin(θ) pixel lengths; flow perpendicular to the edge crosses a contour of ½ pixel length. The equivalent contour length for each facet with flow exiting the pixel is summed and this value is written to bcont_ID. This provides an estimate of the total contour length crossed by flow exiting the pixel. The total drainage area for the pixel divided by this value provides an estimate of specific drainage area.

NETRACE

Netrace uses the raster files created by Bld_grds to trace a channel network, which if requested, is extended to estimated shallow landslide initiation sites. The DEM is then used to estimate a variety of topographic attributes for each pixel identified as a channel. These are written to an ArcView shape file. The methods used for calculating these attributes are described below.

Command-Line Prompts

Netrace requires specification of an "Input directory" (path to the data files) and an "Input ID". All input raster files are stored in this directory. You will also be prompted for an "Output directory" and an "Output_ID". Derived shape and raster files are placed in the output directory using the output_ID. Use of separate input and output directories allows creation of multiple output files for a single watershed, e.g., using different forest-cover grids. You are then offered four options for delineation of the watershed:

1) Delineate the maximum drainage area

2) Specify the drainage area to delineate

3) Specify a single pour point

4) Iterate over DEM to get all channels

Since a single DEM may contain any number of separate watersheds, these options provide ability to chose which one(s) to trace. Options 1 and 4 require no further user input; option 2 requires input of the drainage area (in square kilometers) to delineate; option 3 requires input of the DEM column and row numbers of the pour point (the mouth of the basin you want to analyze). You'll be prompted for any additional information required.

If you've specified debris-flow analyses in the instructions.txt file, you'll be prompted for creation of additional raster files, described below.

Netrace then performs the set of operations specified in the instructions.txt file. Screen output reports on program progress.

Outputs

Vector Files. There are options for three shape files. These are:

Reach_ID: The channel network is divided into a series of reaches with locations and topographic attributes output to this file. Available attributes and options for specifying reach end points are described below.

Link_ID: The channel network is also output to a second shape file, link_ID, with nodes at every channel junction and all channel links given as continuous arcs. This file can be used within Arc to create a routed channel coverage, with the "reach_ID" file used to define "events". A comma-delimited ASCII file is also created, named "routes_ID.txt", which lists the LLID, beginning channel length (which is always zero), and the final channel length for each channel. This file expedites creation of a routed channel coverage from the shape file in Arc.

Trib_ID: A shape file with information about tributary junctions.

Netrace has options for creating a variety of raster files as well.

Vmask_ID.flt: A raster file to delineate valley-floor pixels. A pixel is identified as part of the valley floor if it is within some specified elevation above the elevation of the channel pixel it drains to and its surface gradient is less than the channel gradient plus some specified amount. The elevation range is determined as a specified number (vh in parameters.dat) of estimated bank-full depths, with bank-full depth calculated as a power function of drainage area. Coefficients for bank-full depth are also specified in parameters.dat. The gradient threshold is determined as the sum of channel gradient and ds_v (given in parameters.dat). Each valley-floor pixel is assigned the ID of the channel reach it drains to (ID of the reach in the reach_ID shape file). The option for creation of vmask_ID is specified in instructions.txt.

Topo_ID.flt: Each pixel is assigned a topographic weighting factor that indicates the intrinsic topographic control on landslide susceptibility. The regional landslide density is multiplied by this factor to provide a spatially distributed, topographically dependent estimate of landslide susceptibility. If "debris-flow delivery" is specified in instruction.txt, the topo_ID file will be created.

ID_ID.flt: Each pixel is given the ID of the channel reach that flow originating from the pixel delivers to. This delineates the drainage area of each reach. The option for creation of the ID_ID file is specified in instructions.txt.

Dist_ID.flt: Each pixel is assigned the flow distance to the delivered-to channel reach. The option for creation of the dist_ID file is specified in instructions.txt.

Deliv_i ID.flt: Each pixel is assigned the probability that a debris flow originating in the pixel will travel to a stream channel. Subsets of the channel network can be chosen using the max_grad_d value – the maximum downstream gradient – which is used to estimate gradient-imposed barriers to fish passage. Hence, deliv_i_ID can show the probability for debris-flow delivery only to channels with no downstream reaches greater than 8%, for example. The threshold gradient is specified in the parameters.dat file. Multiple gradients may be specified, with consequent output of multiple deliv_i_ID files. The integer value of "i" in the name indicates which of the specified gradient values, in sequential order, the file is associated with. If "debris-flow delivery" is specified in instructions.txt and options are given for "RASTER file generation" in parameters.txt, you will be prompted for creation of the deliv raster files.

Trav_I_ID.flt: Each pixel is assigned the probability that it will be traversed by a debris-flow from upslope that delivers to a stream channel. As with deliv_i_ID, subsets of the channel network can be delineated based on the max_grad_d value. If "debris-flow delivery" is specified in instructions.txt and options are given for "RASTER file generation" in parameters.txt, you will be prompted for creation of the trav raster files.

Rdif_j_i_ID.flt: These files provide information for estimating the influence that changes in landslide susceptibility caused by vegetation changes on a hillslope pose for the probability of debris-flow delivery to stream channels. As with deliv_i_ID, results can be specific to a subset of the channel network as delineated by the threshold value of max_grad_d. The integer value of "i" indicates which max_grad_d value the file is associated with. Four different vegetation-change options are provided for creation of rdif files: 1) Mature forest to clear cut, 2) Mature forest to current conditions, 3) Current conditions to clear cut, and 4) Pixel-level current conditions to clear cut. The choice of options is entered following command-line prompts after the program is started and the value of "j" in the output file indicates which option the file is associated with. The first three options show the relative change in debris-flow probability for the delivered-to channel reach for debris flows initiating in each pixel, given the indicated change in forest cover over the entire DEM. The fourth option shows the relative change in probability associated with a change of vegetation cover in each pixel alone. These grids are intended to show where changes in forest cover pose a high potential for affecting stream channels, incorporating both initiation probability and the probability of debris-flow delivery. If "debris-flow delivery" is specified in instructions.txt and options are given for "RASTER file generation" in parameters.txt, you will be prompted for creation of the rdif raster files.

Netrace, as discussed further in the following section, also includes a set of subroutines for estimating debris-flow inundation areas. Results from these routines are provided as a raster file that identifies landslide source areas, zones susceptible to debris-flow traverse, and areas susceptible to inundation by debris flow deposits.

Options for Specifying Reach Length

Two strategies are used for determining reach end points for the reach_ID shape file: 1) Fixed-length reaches, with endpoints set at pre-determined points, and 2) Homogeneous reaches, with end points positioned to create reaches with relatively uniform attributes. The strategy used is specified in the instructions.txt ASCII file. For both cases, reach length may vary with position in the channel network so that longer reaches can be used for larger channels. Two options are provided for determining reach length: 1) a set number of channel widths, or 2) a linear function of drainage area. These are specified in the ASCII file parameters.dat. For fixed-length reaches, endpoints are determined uniquely by the specified function (although reaches at the upstream end of the channel network may vary from the specified length by ±sqrt(2) pixel lengths). For homogeneous reaches, end-point positions vary to minimize variance of channel gradient, valley width, and drainage area within a reach, while still seeking to keep mean reach lengths near the specified limits.

Shape File Attributes for Channel Reaches

Output shape files are named "reach_ID" and include the following attributes.

Length: Reach length in meters. Note that the reach length specified here may not match exactly the reach length measured from node to node in the vector file. The vector-file vertices are placed at pixel centerpoints, where as Netrace estimates channel length using channel locations that may not cross the DEM pixel midpoint, in an attempt to provide a more accurate estimate of total channel length.

Area: Drainage area in square kilometers to the downstream end of the reach.

LLID: Each channel is assigned a unique identifier, based on the latitude and longitude at the mouth. At channel junctions, the identifier is assigned to the channel with the largest drainage area and the smaller channel is assigned a new LLID. LLIDs are calculated using pixel corners to differentiate cases where two tributaries enter the mainstem at a single DEM node.

From_Dist: The distance from the channel mouth to the downstream end of the reach (in meters).

To_Dist: The distance from the channel mouth to the upstream end of the reach (in meters).

Azimuth_deg: Average flow direction for the reach in degrees azimuth.

Order: Strahler stream order. Note that stream order is a function of where the channel head is defined.

Mean_Grad: Mean gradient through the reach (vertical change/horizontal length).

Max_Grad_D: Maximum gradient encountered downstream through the network.

Min_Grad: Minimum gradient within the reach (at the scale of DEM pixels).

Max_Grad: Maximum gradient within the reach.

AveDevGrad: Average deviation of gradient through the reach.

ValWidth_L: Valley width in meters on the left side of the channel (facing downstream).

ValWidth_R: Valley width in meters on the right side of the channel.

Width_Min: Minimum valley width within the reach.

Midth_Max: Maximum valley width within the reach.

WdthAveDev: Average deviation of valley width through the reach.

ValSlp1_L: Estimated surface gradient at the base of the valley wall on the left side of the channel (facing downstream), over a horizontal length of ~10 meters.

ValSlp1_R: Estimated surface gradient at the base of the valley wall on the right side of the channel, over a horizontal length of ~10 meters.

ValSlp2_L: Estimated surface gradient of the valley wall on the left side of the channel over a horizontal length of ~100 meters.

ValSlp2_R: Estimated surface gradient of the valley wall on the right side of the channel over a horizontal length of ~100 meters.

Lake: ID of any lake (specified in the raster mask lake_ID) crossed by the reach; zero if there is no lake.

MnAnPrc_mm: Mean annual precipitation depth in millimeters, averaged over the drainage area to the downstream end of the reach.

P_Dep_Ave: Estimated average probability of debris-flow deposition in the reach.

P_Dep_Max: Estimated maximum probability of debris-flow deposition within the reach.

P_Scr_Ave: Estimated average probability of debris-flow scour through the reach.

P_DF_Ave: Estimated average probability of debris-flow traversal (including scour, deposition, or transitional flow) for pixels within the reach.

P_DF_Max: Estimated maximum probability of debris-flow traversal within the reach.

Dep_Sm_ave: Average volume estimate of debris-flow-deposited material found in the reach. Relative units: large values indicate high probability of finding a large volume of debris flow material.

Dep_Sm_Max: Maximum volume estimate of debris-flow-deposited material for pixels within the reach.

P_DF_OPEN: Maximum probability of debris-flow traversal within the reach for uniform OPEN vegetation coverage.

P_DF_LARGE: Maximum probability of debris-flow traversal within the reach for uniform LARGE vegetation coverage.

MeanAnncfs: Mean annual discharge for the downstream end of the reach based on a regression equation for western Oregon.

Shape File Attributes for Tributary Junctions

LLID_main: LLID of the mainstem

MstmAr(km2): Drainage area of the mainstem, in square kilometers (assumes 10-meter DEM), upstream of the tributary junction.

MStmLn(m): Distance from the channel mouth to the tributary junction along the mainstem.

MstmGrad_u: Channel gradient of the mainstem upstream of the tributary junction.

MstmGrad_d: Channel gradient of the mainstrem downstream of the tributary junction.

MstmValWth: Estimated valley width of the mainstem at the tributary junction.

LLID_trib: LLID of the tributary channel.

Trib_grad: Channel gradient of the tributary.

JnAngl(deg): Junction angle of the tributary with the mainstem, in degrees

Expctd_LS: The expected number of landslides to be found in the tributary basin, based on integrating landslide density (summing pixel by pixel) over the drainage area of the tributary

LS_delivry: A relative volume estimate for debris flows at the tributary mouth, same as *Dep_Sum* above, but at the tributary mouth.

Trib_Area: Drainage area of the tributary basin in square kilometers.

Algorithms

LLID

A unique 13-digit identifier, derived from the digital latitude and longitude (to a precision of 1-ten-thousanth of a degree) of the mouth of the channel, is assigned to each reach. The identity of the "mainstem" at tributary junctions is based on drainage area: a new LLID is assigned to the channel with the smaller of the two drainage areas. Use of the LLID allows grouping of all reaches belonging to a single channel and is required by Arc for creation of a routed channel network.

Since most DEMs are provided in UTM coordinates, the projection to latitude and longitude is different for the two horizontal datums commonly used. The correct datum for the DEM (NAD27 or NAD83), along with the UTM zone number of the DEM, is specified in the parameters.dat file.

Channel Length

Channel orientations are estimated point-by-point by fitting of a quadratic through a window centered over the channel (DEM) point. The length of the window is twice the "junction length" specified in parameters.dat. Hence, a 50-meter junction length will result in fitting of a 2nd-order curve through 100-meters of channel, which will include 7 to 10 points (in a 10-meter DEM), depending on the channel orientation. The intersection of this curve through the center pixel is then used as an estimate of channel length through the pixel. This gives on average shorter lengths than obtained by assuming that channels cross directly through the center of the pixel. This procedure also provides an estimate of channel orientation (flow direction) through each pixel.

Channel lengths show up in three fields of the dBase file that is produced: the length of the reach (in meters) and the "from" distance and "to" distance, which specify the distance from the mouth of the channel for the downstream and upstream-ends of the reach, respectively. The "from" and

"to" distances are used by Arc to create a routed coverage. Note that these lengths will vary from those calculated by ARC from locations of nodes and vertices, since they align with the DEM points, whereas channel lengths have been estimated as described above.

Channel Gradient

Two algorithms are used to estimate channel gradients: 1) Using estimated contour-line crossings along the delineated channels, and 2) fit of a polynomial over a centered window of DEM elevations along the delineated channels. The algorithm used is specified in the ASCII file instructions.txt.

Contour-line crossings: Many of the DEMs provided by the USGS are produced by interpolation of elevation values between contour lines on the 7.5-minute quadrangle maps. If the contour interval of the source map is known, contour-line crossings provide points of known elevation along channels. Channel gradient is then estimated as the contour interval divided by the channel distance between contours. This produces a stepped gradient profile: constant values between contours with step changes at contour crossings. I've chosen not to interpolate gradients (e.g., from midpoints between the contours) since this method better preserves gradient estimates in areas where gradient changes rapidly, as where a small, steep channel intersects a low-gradient valley floor. Implementation of this algorithm requires the contour_ID grid.

Centered Window: Channel gradients are estimated using a polynomial fit to channel pixel elevations over a centered window. Window length is varied as a function of channel slope and channel points falling below the fitting curve are weighted preferentially (assuming that these DEM points fall closer to the actual channel). This procedure is iterated until successive estimates of gradient converge (to some small tolerance) at all points.

The distances over which to apply the centered window are specified by the values of Xmin and Xmax in parameters.dat. These distances are applied at channel gradients specified by Smin and Smax; the length of the window varies linearly as a function of channel gradient between the values specified by Smin and Smax and are held constant for gradients greater or less than these limits. The order of the polynomial used for the fit is also specified in parameters.dat.

It is important to ensure that the length of the window is sufficient to include a number of DEM pixels greater than the number of points required for the polynomial fit. The polynomial must be *over* fit. The longer the window specified, the greater will be the number of included points, and the greater will be the amount of smoothing applied to the fit channel profile. It is also appropriate to use polynomials of relatively low order, e.g., no greater than 3. Higher-order polynomials tend to result in spurious high-gradient reaches.

An estimated channel gradient is obtained for each channel pixel. These are then averaged over the length of the reach and reported in the field "Mean_Grad" in the dBase file. The largest gradient encountered downstream (to the edge of the DEM) is also recorded, in the field "Max_Grad_D". This value may be useful for culling reaches that lack fish presence because of a downstream gradient barrier.

Valley-Floor Width

Width of the valley floor is estimated as the length of a transect that intersects the valley walls at a specified height above the channel. Since the orientation of the valley is unknown, transect orientation is varied to find that which provides the minimum length. The height above the

channel is specified as a number of estimated bank-full depths. The number of bank-full depths is determined by the parameter *vh*, specified in the parameters.dat file. The appropriate value is probably dependent on the quality of the DEMs and may vary regionally. Preliminary analyses using data from the Oregon Coast Range indicate that a value for *vh* of 2.5 works well, although larger values (up to 20) have been found to work better elsewhere.

Bank-full depth is estimated as a function of drainage area as

$$H_{bf} = depth\_coefficient\_1 * A^{depth\_coefficient\_2}$$

where H_{bf} is bank-full depth and A is drainage area in square kilometers. The two coefficients are specified in parameters.dat. Elevations are linearly interpolated between DEM points. The accuracy of these estimated widths is directly dependent on the resolution and accuracy of the DEM.

An estimated valley-floor width is obtained for every channel pixel, one for each side of the channel. Since there are occasionally some pixels where this strategy fails – the transect may be incorrectly oriented at tributary junctions, for example – I then check for outliers in the estimated width over a centered window that spans 10 pixels. Any values exceeding 2.5 times the median are considered in error and are replaced by a linear fit through the remaining points. The resulting widths are then averaged over the length of the reach.

Valley-Wall Gradients

Two estimates of surface gradient are made for each side of the valley wall. One estimate applies to the base of the wall and is calculated from the change in elevation over a 10-meter distance from the intersection of the transect used for estimating valley width. This value roughly approximates the steepness of the valley wall adjacent to the valley floor. The other estimate is based on the change in elevation over a 100-meter distance from the base of the wall. This provides a mean slope over a longer length and may be useful as a predictor of channel-adjacent mass-wasting potential. To determine the orientation of the valley wall (so that the elevation change is taken parallel to the aspect of the slope), I sample two points along a transect oriented normal to the estimated slope azimuth, each 50 meters from the midpoint of the 100-meter line extended up from the base of the valley wall. Orientation of the azimuth is varied to minimize the difference in elevation of these two points. This provides an estimate of valley-wall aspect over a length scale of 100 meters.

These two estimates of surface gradient are made for each side of the valley for each channel pixel. Again, there are opportunities for mistakes, particularly at tributary junctions. Hence, the procedure for culling outliers is repeated with each of the slope measurements. The values reported for each reach then represent the average of the remaining points.

Tributary Junction Angles

The angle with which tributary channels enter the mainstem is estimated from the channel orientations found when fitting quadratics through windowed lengths of channel for estimating channel length (see the section, "Channel Length", above). Through the mainstem, this window is centered about the junction pixel. Through the tributary the window extends upstream from the junction.

Debris-Flow Potential

Subroutines that implement an empirical model for estimating probability of debris flows for stream channels are included in Netrace. Two quantities must be derived to estimate potential for debris-flow impacts: 1) the upslope susceptibility to debris-flow-triggering landslides and 2) the probability that a debris flow initiated upslope will travel to the channel reach.

Within Netrace, landslide susceptibility is treated in terms of the probability of encountering a landslide scar within a pixel. This probability may be derived from an estimate of landslide density (number of landslides per unit area). A high density implies a high susceptibility to landsliding. For the current implementation, landslide density is empirically calibrated as a function of topography and vegetation cover for the Oregon Coast Range and no user-specified parameters are included.

The probability that a debris flow will travel from any specific landslide source pixel to a downslope channel reach is estimated from an empirical model currently calibrated to the Oregon Department of Forestry data for debris flow impacts from the 1996 storm (Robison et al., 1999). This model, derived from the Benda-Cundy model (Benda and Cundy, 1990), specifies a probability of runout from any specific landslide initiation site as a function of four topographic parameters and as a function of riparian stand type. The topographic parameters are 1) channel gradient, 3) valley width, 3) cumulative upstream scour length, and 4) junction angles at tributary junctions. These are derived from the input DEM. Additionally, the probability that the debris flow erodes material from the bed and the probability that it deposits material are also estimated. Riparian stand type is based on the CLAMS vegetation coverage. This model is described in Miller et al., (in prep). The current implementation has no adjustable parameters. Future updates will include programs for calibrating the model and ability to adjust model parameters within Netrace.

Once probabilities of landslide initiation and debris flow runout are made for every potential landslide initiation site, these can be routed to the channel and summed to provide an estimate of the probability of debris flow scour of the reach. The scour probability averaged over each reach is stored in the field "P_Scr_Ave" of the dBase file. Similarly, the average probability of debris flow deposition in the reach is stored in field "P_Dep_Ave". The maximum probability of deposition encountered within a reach is stored in the field "P_Dep_Max". In many cases, debris flows are predicted to stop on fans at tributary junctions which may span only a small proportion of the total reach length. The P_Dep_Max field shows which reaches may be affected by locally restricted debris-flow deposition on fans. Two additional fields, P_DF_Ave and P_DF_Max, indicate the probability for debris flow traversal, including processes of scour, deposition, and transitional flow. A relative estimate of the volume of debris-flow-derived sediment to be found in the reach is provided by the values of "Dep_Sum_Ave and "Dep_Sum_Max". These values are calculated using the cumulative scour length of all debris flow tracks leading to the reach times the probability of initiation and the probability of runout to and deposition in the reach. Its units are length, in terms of the cumulative number of pixels of scour length, but should be interpreted as relative volume, e.g., large values indicate a greater probability of finding a large volume of debris-flow-transported material in a reach.

We've added two fields that aid in assessing the relative change in the probability of debris flow impacts associated with changes in forest cover. The field P_DF_OPEN gives the maximum probability of debris flow impacts within the reach obtained with a uniform OPEN forest type

(clear-cut). The field P_DF_LARGE gives the maximum probability of debris flow impacts within the reach obtained with a uniform LARGE forest type.

Debris Flow Inundation Hazards

With the help of Jon Hofmeister (Oregon Department of Geology and Mineral Industries), a model for estimating a relative potential for debris flow inundation is implemented in Netrace. The model is based on that of Iverson et al. (1998), which was originally presented for estimating lahar inundation hazards. Iverson et al. showed that lahar cross section and inundation area can be estimated with the equations

$$A_{cs} = aV^{2/3},$$
$$B = bV^{2/3};$$

where A_{cs} is cross-sectional flow area of the lahar, B is the area inundated by the lahar, V is total lahar volume, and a and b are empirical coefficients. Iverson et al. suggest that these same equations may be applied for colluvial landslide-triggered debris flows, with proper calibration of the two coefficients. Schilling et al. (1998) describe an implementation of the model in Arc. Building on the work of Iverson et al. and Schilling et al., we've implemented this model for estimating debris flow inundation hazards using a DEM.

To address debris flow hazards requires examination of a multitude of potential landslide initiation sites and runout tracks and estimation of deposit volume for each. Initiation sites are empirically identified as functions of a topographic index. Two choices for this index are currently provided: surface gradient and output from SHALSTAB. Currently the index is used simply to provide a threshold value for identifying pixels susceptible to landsliding, i.e., using slope, if surface gradient exceeds the threshold, the pixel is considered susceptible to landsliding; for SHALSTAB, landslide susceptibility is assumed if the steady-state precipitation value for failure is less than a specified threshold. The threshold value is specified by the parameter Istar_max in parameters.dat. The choice of index to use is specified in the instructions.txt file.

Lacking data other than elevations, we've chosen to estimate potential deposit volume based on the cumulative scour length of each track, multiplied by the estimated mean volume of colluvium available for scour per unit length (specified in parameters.dat). Using the model presented by Benda and Cundy (1990), potential debris flow tracks are divided into zones of scour, transport (with no net scour or deposition), and deposition. Parameter values for this model are specified in parameters.dat. Every debris flow track thus has an estimate of the maximum deposit volume that might traverse it, based on the cumulative upstream scour length.

Once a depositional zone is reached, valley cross-sectional area is estimated as a function of inundation depth (using the DEM). This is then translated to an estimate of debris flow volume as a function of inundation depth using the equation above. On debris flow fans and on large valley floors, cross-sectional area is estimated as a function of deposit width by assuming a constant surface slope normal to the flow direction. Every DEM pixel within vicinity of a potential debris flow track thus has an estimated minimum debris flow volume required for inundation.

Then, moving downslope along each debris flow track, we accumulate a sum of all pixels as a function of volume, i.e., we create a cumulative distribution of the volume of pixels potentially inundated so far. If the area inundated exceeds that corresponding to the volume assigned to a

particular pixel (*B* in the equation above), the pixel is assigned the next largest volume for which the area inundated is still less than that corresponding to the maximum volume available. Each pixel is then assigned a value equal to its assigned or reset volume divided by the maximum potential volume of a debris flow deposit reaching that point. This ratio serves as an index of relative inundation hazard; the smaller its value, the greater the likelihood of that location being impacted by deposition from a debris flow. This procedure is repeated for all potential debris flow tracks and all channels. Where deposit zones overlap, the smallest value (highest hazard) is maintained.

Output is to an ASCII raster file named hazard_ID.grd. Values are coded differently depending on the choice of topographic index for instability. Codes are as follows.

Slope

0-99: Surface gradient in percent. Higher values imply greater landslide susceptibility. To translate to hazard ratings requires an empirical calibration, as described above.

100: Debris flow transport (with a 1-pixel buffer).

101-200: Relative inundation ratio times 100 plus 100. Lower values imply greater hazard. Interpretation requires field calibration, but for example: 101-115 – high hazard; 116-150 – moderate hazard; 151-200 – low hazard.

SHALSTAB

0-100: Ratio of minimum inundation volume to maximum potential volume times 100. This provides a measure of debris flow inundation hazard – the lower the value, the higher the hazard. Interpretation requires field calibration, but an example would be: 0-15 high hazard, 16-50 moderate hazard, 50-100 low hazard.

107: Debris flow transport zone, with a 1-pixel buffer.

116-9999: Istar (topographic index) value, lower values correspond to higher landslide susceptibility. Interpretation requires field calibration to a landslide inventory.

INPUT PARAMETER FILES

Parameters.dat

Adjustable parameters for Bld_grds and Netrace are held in the ASCII file parameters.dat. A description of each parameter is provided below.

Flow-direction algorithm Option 1 implements the standard steepest descent algorithm; option 2 implements the "greatest convergence" algorithm described previously

Sl   the number of pixels over which slope is calculated (> 1 to address "pocket terracing"). The weighted-distance algorithm used by the USGS and many contractors to interpolate line-trace 10-meter DEM elevations between contour lines results in spurious variations in the first and higher-order derivatives of elevation. Interpolated elevations tend toward flatter topography in the vicinity of a contour line (where data density is greater) with much of the variation occurring between contours. When estimating derivatives such as slope or topographic convergence, this artifact results in bands of high slope, or high convergence, parallel to the contours. These bands can be seen in shaded relief images

produced from these DEMs and are particularly apparent as a set of apparent pits, or "pocket terraces" along lower-gradient channel courses. These artifacts are troublesome for algorithms that use estimates of slope and topographic convergence, such as estimates of relative soil saturation and slope stability. To address this issue, I've added the option for some smoothing of the derived slope estimate. The value of *sl* specifies the number of pixels to use as the length increment for calculating surface gradient. I've typically used values of 2 or 3. Too many, and you loose resolution; too few and you're plagued with bands of anomalously high slope gradient. Use as low a number as you can.

Dig　maximum depth of incision used for drainage enforcement. This parameter is used by bld_grds only if the channel mask raster file is present and only if channels are flagged by a negative integer value. Larger "*dig*" values result in greater enforcement to the channel mask, but may also result in spurious channel elevations where errors in the vector channel coverage used to create the mask direct channels onto hillslopes. Values around 1 meters.

Channel-threshold criterion　Option 1 implements a channel threshold based on drainage area; option 2 implements a channel threshold using specific drainage area (drainage area per unit contour length). The choice influences the appropriate values used for the next two parameter values.

channel_area_threshold　the contributing-area threshold for channel initiation in high-gradient areas (areas with surface gradient greater than or equal to *S_max*). Methods for estimating this value using the DEM are discussed in the section above "Determination of Channel Initiation Points". Given in the same units as used for the DEM, e.g., square meters if drainage area is specified, meters if specific drainage area is specified. Typical values for western Washington and Oregon fall within the range of a few hectares or less (for 10-meter DEMs). Lower values result in higher estimated channel density.

C_min　Used to determine the contributing-area threshold as a function of surface gradient for low-gradient areas (those with surface gradient less than *S_max*): $A = C\_min/S^{C\_exp}$, where *A* is threshold contributing area and *S* is surface gradient. Typical values for western Washington and Oregon fall within the range of a few thousand square meters or less (for 10-meter DEMs). Lower values result in higher estimated channel density.

C_exp　the exponent on slope used for determining channel thresholds in low-gradient areas (~2.0)

S_max　The minimum surface gradient for landslide potential, calibrated to a DEM with a landslide inventory. This value is used to separate low-gradient areas, for which a slope-dependent drainage threshold (*C_min*) is used for channel initiation, from high-gradient areas, for which a drainage area threshold (*channel_area_threshold*) alone is used for channel initiation. Typical values for DEM-derived slope gradients are around 25%.

P_min　The minimum number of inflowing cells required for channel initiation. This value enforces a topographic convergence threshold, in addition to the drainage-area threshold discussed above, for channel initiation. Lower values resulting in higher estimated channel density. A value of zero removes any convergence criterion.

lstop_max　Specifies the maximum length for unchannelized, low-gradient (less than *s_max*, above) debris flow runout. If the distance from a source pixel to a channel exceeds

lstop_max with no gradient greater than s_max, the source pixel is assumed incapable of producing a debris flow that will travel to a channel, i.e., any landslides stop prior to encountering a channel. Since the final item is debris-flow delivery to channels (for creation of the output shape files), there is no need to keep track of these debris-flow sources. A typical value for *lstop_max* is 50 meters for a 10-meter DEM (*lstop_max* must be correspondingly longer for DEMs of lower resolution). Longer values can be specified to ensure that nothing is missed, but processing times and memory requirements will increase. Note that for estimating debris flow inundation areas, *lstop_max* should be set very high, 5000 meters say, to ensure that all potential landslide runout tracks are included, even those that do not enter a channel.

Xmin   Specifies the minimum window length used for channel gradient estimation, in DEM units. Typically on the order of 100 meters for a 10-meter DEM. *Xmin, Xmax, Smin, Smax*, and *Fit_Order* are only used if the "poly fit over centered window" option is specified in instructions.txt for gradient calculation.

Xmax Specifies the maximum window length used for estimating channel gradient. Typically on the order of 300 meters for a 10-meter DEM

Smin   Specifies the channel gradient at and below which *Xmax* applies. Typically set to 0.01 or lower.

Smax   Specifies the channel gradient at and above which *Xmin* applies. Typically set to 0.20. Window length varies linearly from *Xmin* to *Xmax,* as a function of channel gradient*,* for gradients between *Smax* and *Smin*.

Fit_Order   The (integer) order of the polynomial used for fitting channel profiles. Values of 1 to 3 work well.

junction_length   The channel length used to estimate channel flow direction and tributary junction angles, in DEM units. Typical value: 50 meters.

width_coefficient_1   Used for estimating channel width: $W = w_1 + w_2A^2$, where w_1 is *width_coefficient_1* and w_2 is *width_coefficient_2*. This equation is based on a regression to regional data in coastal Oregon (Sharon Clark), for which w1 = 1.6066. Channel widths are only used as a minimum for valley-floor width estimates.

width_coefficient_2   Sharon's regression gives $w_2 = 2.05183$

depth_coefficient_1 for estimation of bank-full depth:
bank-full depth = *depth_coefficient_1**Area$^{depth\_coefficient\_2}$

depth_coefficient_2 exponent used for estimating bank-full depth as a power function of drainage area

Reach_method: specifies the method for determining reach length 1) as a certain number of bank-full widths (which is estimated using the width_coefficients above), or 2) with specified lengths that may vary linearly with drainage area

Number of channel widths: used with reach method 1

Minimum_reach_length   Used with method 2. Reach lengths will try to be maintained within the guidelines specified by the *minimum* and *maximum_reach_lenth* parameters. The choice of fixed-length reaches, which are set to be exactly the specified length, or homogeneous

reaches, which are adjusted to minimize variance within a reach, is made in the instructions.txt file. The preferred reach length is allowed to vary linearly between *minimum_reach_length* and *maximum_reach_length* as a function of drainage area. Given in DEM units (e.g., meters).

maximum reach length   As above, in DEM units.

Amin   The area in square kilometers at and below which *minimum_reach_length* is used.

Amax   The area in square kilometers at and above which *maximum_reach_length* is used. The preferred reach length varies linearly from *minimum_reach_length* to *maximum_reach_length* for drainage areas between *Amin* and *Amax*. Common values may be *minimum_reach_length* = 100 (m), *Amin* = 1 (km^2); *maximum_reach_length* = 300 (m); *Amax* = 100 (km^2).

Minimum reach length for adjusting max_grad_d   Max_grad_d is a field in the reach shape file that indicates the maximum channel gradient encountered downstream. This attribute is used to identify reaches upstream of a natural barrier to fish use. Certain species tend not to be found upstream of channels having a gradient steeper than some threshold. This and the next three parameters are used to specify the length over which the max_grad_d is calculated. Reaches are constructed from the basin outlet upstream following the rules specified for setting reach lengths above. The gradient calculated for each reach is compared to the value of max_grad_d. If the reach gradient is greater, the value of max_grad_d is updated. If the length of the reach is less than that specified by the criterion specified with these parameters, the reach used for comparing to max_grad_d is extended up and downstream until it reaches the specified length.

Maximum reach length for adjusting max_grad_d   The reach length for max_grad_d can vary as a linear function of drainage area between the limits specified by minimum and maximum reach lengths.

Area for minimum reach length (max_grad_d)   Drainage area at and below which the minimum reach length for max_grad_d is applied

Area for maximum reach length (max_grad_d)   Drainage area at and above which the maximum reach length for max_grad_d is applied

Area weighting for reach breaks   used to adjust the influence of tributary junctions in setting reach end points for homogeneous reaches. Larger values cause reach breaks to occur with smaller tributaries.

Vh   The number of bank-full depths above the channel elevation used for estimating valley-floor width.

Ds_v   The increase above the channel gradient allowed for "valley-floor" pixels in the valley-floor raster mask. If the gradient (tangent) of the pixel is more than ds_v above the gradient of the channel pixel it drains to, the pixel is not masked as part of the valley floor.

UTM grid information. These values are needed for calculating the LLID – the latitude and longitude of the channel mouths – for each channel. Each reach is assigned the LLID of the channel it belongs to.

Datum 83 for NAD83, 27 for NAD27

UTM zone number e.g., 10

SHALSTAB: Parameters.dat also specifies values for use with the SHALSTAB algorithm when it is used as the topographic index for slope instability. These are used only to translate the topographic index to units of mm/day steady-state rainfall so that output can be compared directly to other implementations of SHALSTAB. Soil parameters are assumed uniform over the entire

Soil Saturated Bulk Density (kilograms per cubic meter)

Soil Friction Angle (degrees)

Soil Cohesion (Pascals)

Saturated hydraulic conductivity (meters per day)

Soil depth (m)

Soil porosity

RASTER file generation for probability of debris-flow delivery   These parameters specify the maximum channel gradient(s) (max_grad_d values) to use for precluding upper portions of the channel network for determining debris-flow delivery in construction of the deliv_ID, trav_ID, and rdif_ID raster files. Multiple values may be specified, which will result in construction of multiple raster files, one set for each value. The number of gradient values is specified followed by the gradient values to use.

Runout_parameters.txt

debris_flow_slope   Used in the Benda-Cundy (Benda and Cundy, 1990) model for estimating debris flow runout. This value specifies the channel gradient above which channelized flows don't stop at tributary junctions. Typically set to TAN20° (0.364).

erode_slope   Used in the Benda-Cundy model for debris flow runout. Specifies the channel gradient above which debris flows erode the channel bed. Typically set to TAN10° (0.176)

thetamin   Used for the Benda-Cundy model for debris flow runout. *Thetamin* specifies the channel gradient at and below which debris flows deposit material. Unlike the Benda-Cundy model, the gradient for debris flow deposition is made a function of estimated valley-floor width. This allows a steeper slope to be specified for unchannelized areas, such as where debris flow channels enter steep, unchannelized debris fans. *Thetamin* is typically set to a value of TAN3.5°(0.06).

wmin   Used for the Benda-Cundy model for debris flow runout. The valley-floor width at and below which *thetamin* applies. Given in DEM units (e.g., meters). Typically set to a value of 30 meters.

thetamax   Used for the Benda-Cundy model for debris flow runout. *Thetamax* specifies the channel gradient at and below which debris flows deposit material where valley-floor width is greater than *wmax* (below). Typically set to a value of 0.15.

wmax   Used for the Benda-Cundy model for debris flow runout. Specifies the valley width at and above which *thetamax* applies. For valley widths between *wmin* and *wmax*, the channel gradient for debris flow deposition is varied linearly between *thetamin* and *thetamax*.

colluvial_volume Used for estimating debris flow inundation areas. Specifies the average colluvial volume available for debris-flow scour per unit length of low-order channel. Given in DEM units, e.g., m^3/m. A typical value is in the range of 6 to 8 m^3/m.

colluvial_volume_0 Used for estimating debris flow inundation areas. Specifies the average volume available for debris flow scour per unit length of traverse over unchannelized hillslopes.

junction_angle   Used with the Benda-Cundy model for debris flow runout. Specifies the tributary junction angle above which debris flows deposit (unless the receiving channel gradient exceeds *debris_flow_slope*). Typical value: Tan70° (2.745)

trigger_angle   Used with the Benda-Cundy model for debris flow runout. Specifies the junction angle for 1st-order tributary channels above which debris flows deposit. Typcial value: TAN45° (1.0).

Istar_index   Specifies the index to use 1) SHALSTAB, 2) slope gradient

Istar_max   Threshold value of the topographic index for slope instability. Pixels with index values less than (if SHALSTAB is used, or greater than if slope gradient is used) are considered source areas for landsliding.

a_coef_0: The coefficient for cross-sectional flow area. Different coefficients may be used for channelized and unchannelized debris flows; a_coef_0 is used for debris flow tracks traversing hillslope pixels that are not classified as channels. Values less than 0.5 are found to work acceptably well, but field verification is required.

b_coef_0: The coefficient for debris flow inundation area. Here too different coefficients may be used for channelized and unchannelized debris flows: b_coef_0 is used for debris flows traversing hillslope pixels that are not classified as channels. Values less than 100 work acceptably well.

a_coef_c: The coefficient for cross-sectional flow area for debris flow tracks traversing pixels classified as channels.

b_coef_c: The coefficient for debris flow inundation area for pixels classified as channels.

Radius: Used in creating transects for calculating valley cross-sectional area. First, every hillslope pixel is associated to the nearest channel pixel. Then a circle with a radius of the specified number of pixels is constructed about every channel point. Pixels intersected by the edge of this circle serve as endpoints for the transects. This is done both for a circle of the specified radius and for a circle with radius given by *radius*/5. This procedure produces multiple potential valley-crossing transects for every channel point. The one producing the smallest cross-sectional area is used. With 10-meter DEMs, I've found a *radius* of 25 pixels works well.

Max_bin: The largest ratio of inundation volume to maximum potential debris flow volume to continue estimating inundation hazards for. The larger this value, the greater will be the

number of pixels for which the ratio is calculated, however, a large number of them will be for a very low hazard potential. I've found a max_bin value of 1.0 works well.

Nbins: The number of bins to use for tracking the cumulative distribution of debris flow volumes associated with pixels inundated as we follow a debris flow track downstream. A larger number of bins provides greater resolution of hazard variation, but requires greater processing time. I use a value of 256, since this is (for most plotters) the maximum number of color variations that can be plotted.

de_min_0: Used for estimating deposit cross sectional area as a function of inundation width over flat areas. Cross sectional area is estimated as

$$A_{cs} = de\_min \cdot W^{rp}$$

where *W* is deposit width, measured from the channel, and *rp* is another adjustable parameter, usually set to 1.0 (in which case, cross sectional area corresponds to a deposit with a constant surface slope equal to *de_min*). Separate values for *de_min* may be specified for channelized and nonchannelized debris flows; *de_min_0* applies to hillslope pixels not classified as channels. Values of *de_min* are typically in the range of 0.05 to 0.15.

de_min_c: The value of *de_min* to use for pixels classified as channels.

de_max: Valley transects are terminated if elevation along the transect decreases by an amount greater than de_max, in which case it is assumed we've crossed a drainage divide. I typically set de_max to 5 meters.

rp: The exponent on W in the equation above for estimating cross sectional area through flat areas. A value of 1 corresponds to a deposit with a constant surface slope equal to *de_min.*

smooth_output: (y/n) Specifies whether the inundation ratio is smoothed prior to output. Smoothing is done over a three-by-three pixel weighted average excluding pixels with zero or nodata values. Weighting is based on (1-*B*), where *B* is the inundation ratio of the pixel. Hence, high-hazard pixels are preferentially weighted.

Buffer: The size of the buffer to add around inundation hazard areas, in pixels. Buffer pixels are added based on the average inundation-ratio value of adjacent pixels with nonzero values.

The Instruction File

The file instructions.txt tells program Netrace which attributes to calculate and write to output files. Note that when a shape file for reaches is created, certain attributes are automatically written to the output dBase file, while others are optional. Those that are automatically written are: reach ID, LLID, reach length, drainage area to the downstream end of the reach, to distance, and from distance.

SOURCE LISTINGS

Source files for these programs are available. All code is written in Fortran, with a mix of fixed-format Fortran 77 and free-format Fortran 90. To compile these programs requires linking of object files created from the following files.

Bld_grds

  Big_grds.f90
  Doc_file.f90
  Flood.f90
  Flow.f90
  Nr.f90
  Nrtype.f90
  Nrutil.f0
  Ran.f90
  slope_div.f90
  Sort.f90

Note that the underlined files are from Numerical Recipes (Press et al., 1996) (www.nr.com).

Newtrace

  Brent.f90
  chnslp.for
  convert.f90
  dBASE_record.f90
  grad.f90
  gully.f90
  indexx.f90
  locate.f90
  mainhead.f90
  medfit.f90
  nr.f90,
  nrtype.f90
  nrutil.f90
  polint.f90
  pythag.f90
  runout.f90
  runtrace.f90
  select.f90
  svbksb.f90
  svdcmp2.f90
  svdfit.f90
  trace.f90
  tracks.f90.

Here too the underlined files are from Numerical Recipes.

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