# Grfin Tools—User Guide and Methods for Modeling Landslide Runout and Debris-Flow Growth and Inundation

Chapter 3 of
Section A, Modeling Methods
**Book 14, Landslide and Debris-Flow Assessment**

Techniques and Methods 14–A3

**U.S. Department of the Interior**
**U.S. Geological Survey**

**Cover.** Map showing potential debris-flow inundation in part of Utuado, Puerto Rico, calculated using Grfin Tools. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018). Grifin Tools logo created by Gail Reid and Tiffany Larson.

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| | |
|---|---|
| **TOOL NAMES** | All uppercase, bold. |
| ***Input fields*** | Lowercase, bold, italics. |
| *File names* | Lowercase, italics. |

# Grfin Tools—User Guide and Methods for Modeling Landslide Runout and Debris-Flow Growth and Inundation

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## Abstract

The software package, Grfin Tools, can estimate potential runout from landslides or inundation from geophysical mass flows such as debris flows, lahars from volcanoes, and rock avalanches within a digital elevation model (DEM). Grfin is an acronym of ***gr***owth + ***f***low + ***in***undation. The tools within this package apply simple, well-tested, empirical models of runout that are computationally efficient and require minimal parameters. These tools can be used individually (for example, to estimate debris-flow inundation) or in combination to represent a more complete series of linked processes, from landslide source areas, to unchannelized transport, to channelized flows. Grfin Tools can rapidly assess potential runout and inundation over large areas and the results are readily visualized in a geographic information system.

Tools for assessing areas affected by runout and flow inundation include a height-to-length ($H/L$) ratio, angle-of-reach approach for estimating open-slope, unchannelized landslide runout, and volume-area scaling relations for assessing flow inundation in channels. Potential landslide areas that constitute the sources of runout or inundation can be delineated with topographic features, such as slope and (or) curvature, derived by the software package, or by employing potential sources derived from other landslide susceptibility models. Grfin Tools also has the capability to assess inundation from flows that grow volumetrically downstream. This is a vital feature, as larger flows commonly result in longer runout and larger inundation. The software uses empirically derived growth factors applied over upslope contributing source areas or upstream channel lengths to integrate the effects of various growth processes, such as channel entrainment, streambank failures, adjacent landslides, and hillslope erosion. Inundation follows a drainage network defined with a separate tool that uses topographic curvature to identify channel initiation locations.

This document includes information on using Grfin Tools, the basis and methods underlying the tools and models, detailed descriptions of the software input and output files, and tips for handling special conditions such as roads and large water bodies. Multiple detailed examples illustrating different applications are also presented. Grfin Tools relies on the freely available TauDEM software package (Tarboton, 2005). The Grfin Tools software release is available from Cronkite-Ratcliff and others (2025).

## 1. Introduction

### 1.1. Purpose and Scope

Grfin Tools is a software package, developed by the U.S. Geological Survey, for estimating areas potentially affected by landslide runout and (or) geophysical mass-flow inundation throughout a landscape, as represented by a digital elevation model (DEM). Grfin is an acronym of ***gr***owth + ***f***low + ***in***undation, and the package includes a suite of tools to delineate different mass-movement processes. Grfin Tools focuses on landslide and flow mobility, not just landslide initiation, as fatalities and infrastructure damage commonly result from mobile landslides and flows (for example, Harp and others, 2004; McDougall, 2017). Both hazard impacts and mitigation measures can differ considerably between landslide source zones and their runout or flow-inundation zones. Here, we use the term mobility to describe the spatial extent of landslide runout or geophysical mass-flow inundation (from either debris flows, lahars, or rock avalanches), rather than velocity.

Grfin Tools enables rapid assessments of landslide runout and (or) flow inundation over large areas and allows speedy comparison of “what if” scenarios. It utilizes computationally efficient, easy-to-use empirical models with simple parameters such as an angle of reach. Material properties do not need to be specified, thereby eliminating the need for potentially difficult parameter estimations. As such, it can be used for susceptibility assessments over broad areas and (or) rapid hazard assessments where an event is imminent or has just occurred. It can also be used as a screening tool to identify areas needing more detailed field studies or sophisticated modeling studies.

We designed Grfin Tools to have a combination of features not commonly found in other available models. Typically, landslide susceptibility maps only portray potential landslide source areas or they focus exclusively on landslide runout or debris-flow inundation (for example, Dietrich and Montgomery, 1998; Dietrich and others, 2001; Baum and others, 2008; Hungr and McDougall, 2009; Christen and others, 2010; Horton and others, 2013; Mergili and others, 2014; Reid and others, 2015; Mergili and others, 2017; Reichenbach and others, 2018). In contrast, Grfin Tools enables a user to examine landslide and flow components individually (Reid and others, 2023) or in combination (Brien and others, in press). These components include landslide (or rockslide) initiation sources, landslide runout zones that may or may not extend to a downslope channel, and mass flows that follow and inundate a channel drainage network (fig. 1).

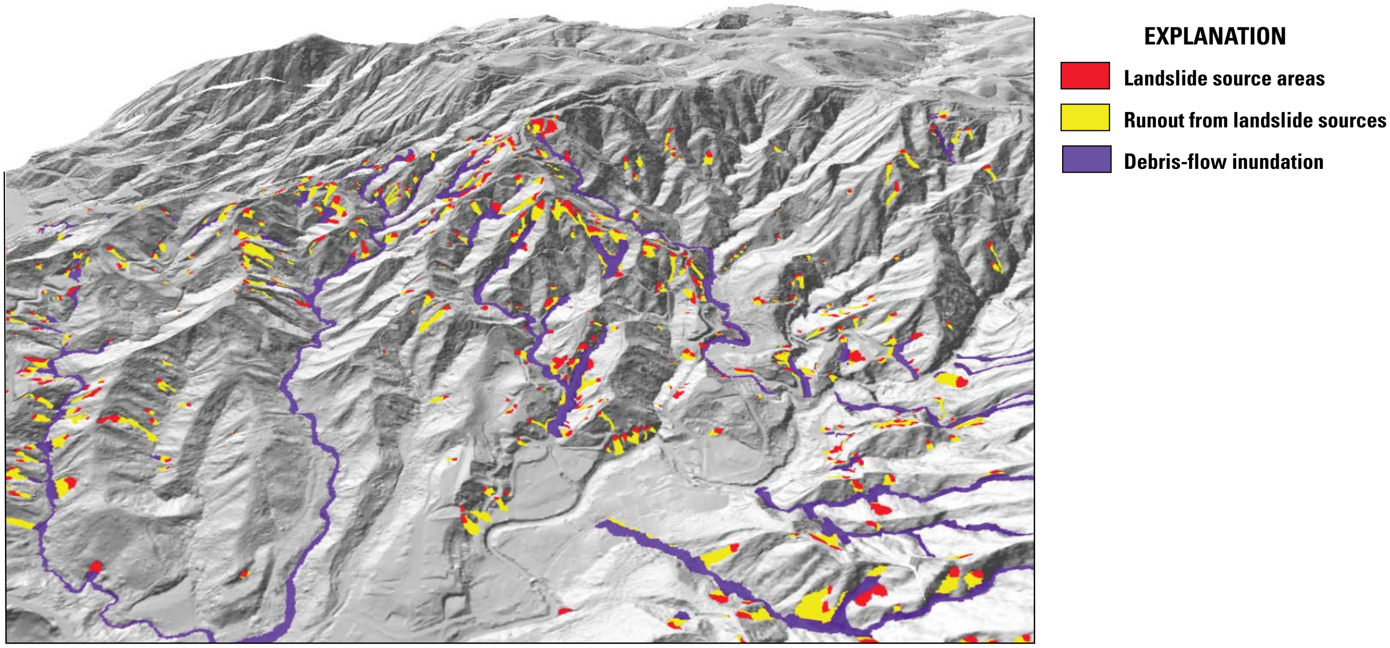


**Figure 1.** Perspective view of topography illustrating the potential locations for three types of mass movements that can be derived from a Grfin Tools analysis. Landslide source areas are located in the upper parts of steep topography and provide the source for landslide runout using a height-to-length (*H*/*L*) ratio. This runout may halt on open-slope hillsides or may continue into the channel network. Debris-flow inundation with volumetric growth from upslope landslide areas occurs in channels. A complete portrayal of these multiple processes would cover more of the topography. Image portrays observed landslides from the Hurricane Maria event in Puerto Rico (Einbund and others, 2021) divided into three movement categories. Modified from Brien and others (in press).

In addition, Grfin Tools can portray the inundation effects from geophysical mass flows that grow volumetrically as they travel downstream. This is an important feature, as volume is a fundamental control on flow mobility. Larger volumes typically result in longer runout and greater inundation (Corominas, 1996; Legros, 2002; Iverson and others, 2011; Barnhart and others, 2021). Moreover, the volumes of many geophysical mass flows commonly increase as they travel, through process such as channel-bed sediment entrainment, stream-bank failures, landslides from adjacent hillslopes, nearby hillslope erosion and rilling, and coalescence of flows from multiple tributaries (Hungr and others, 2005; Santi and others, 2008; Coe and others, 2011b; Theule and others, 2015; Reid and others, 2016; Bessette-Kirton and others, 2020). Instead of specifying the spatial effects of each growth process individually, Grfin Tools uses integrated growth factors (for example, Reid and others, 2016; Coe and others, 2021), derived over either upslope area or stream-channel length, to amalgamate all growth processes potentially affecting flow volumes. Such growth factors are similar to yield rates, erosion rates, or basin lowering rates (for example, Hungr and others, 2005; Reid and others, 2016; Reid and others, 2023).

Enabling volumetric growth of flows along a channel network allows realistic delineation of flow inundation in the upper parts of drainage networks where flows may grow in volume. This procedure also provides flow volumes that are automatically scaled to upslope or upstream conditions, thereby identifying spatially variable volumes along the channel network without the need for user-specified volumes and locations.

Grfin Tools contains the following tools for use individually or in combination:

- The **SOURCE** tool can identify potential landslide (or rockslide or distributed erosion) source areas from topographic slope and (or) curvature (computed with Grfin Tools), or from a landslide susceptibility map, such as a map derived from the distribution of factors of safety computed from other models. This tool is required for landslide runout using the **HL** tool and for some flow-growth options. (section 3.2).

- The **HL** tool uses a height (*H*) to length (*L*) ratio, *H/L*, angle-of-reach empirical model to define open-slope landslide runout zones, where material moves down unchannelized slopes and halts or reaches the downslope channel network. This angle-of-reach model utilizes the TauDEM D-Infinity Avalanche Runout tool (Tarboton and others, 2015) (section 3.3).

- The **DRAINAGE** tool creates a drainage network using topographic curvature and drainage area to identify channel initiation locations. It is required when analyzing inundation from flows that grow volumetrically downstream using the **GROWTH** tool. This tool can also create a standalone drainage network for use with geographic information system (GIS-) based analyses outside of Grfin Tools. (section 3.4).

- The **INUNDATION** tool uses volume-area scaling relations to demarcate the extent of inundation from geophysical mass flows as they travel down channels. For this empirical approach, Grfin Tools uses methods similar to Laharz (Iverson and others, 1998; Schilling, 1998, 2014) and DFLOWZ (Berti and Simoni, 2007, 2014), but with some notable differences such as more realistically delineating inundation areas where flows are unconfined. Starting volumes and locations can be user specified (section 3.5) or volumes can be determined using the **GROWTH** tool (below).

- The **GROWTH** tool computes flow volumes that increase downstream using empirical volumetric growth functions that scale with upslope source area or upstream channel length (section 3.6). Growth occurs within growth zones along the drainage network. Given these distributed flow volumes, inundation is then computed using the **INUNDATION** tool.

Grfin Tools runs as a standalone software package in a Microsoft Windows operating system (OS) command prompt window using a Settings parameter file and a DEM as the foundation for identifying potential runout and inundation areas. The resulting products can be readily viewed in any GIS software. The Grfin Tools software package and runtime documentation for Windows OS are in the Grfin Tools software release (Cronkite-Ratcliff and others, 2025), available online at https://doi.org/10.5066/P9NVKFE2.

## 1.2. Capabilities and Limitations

Grfin Tools uses empirical mobility models that do not require the complexity of estimating material parameters that might vary in time and space. Instead, it includes options that can encompass various physical processes controlling mobility behavior in different geomorphic settings, such as spatially variable source zones (section 3.2), different types of geophysical mass flows (section 3.5), and (or) different types of scalable growth factors for flows (section 3.6). Such capabilities can be advantageous for map-view susceptibility assessments over large areas. Importantly, Grfin Tools can be used for very simple analyses or more complex multi-component assessments with linked processes. Grfin Tools has the following capabilities:

- Provides a suite of tools that can be used individually or in combination to address the controls and effects of mobile mass movements, including drainage network delineation, source area identification, *H/L* landslide runout, and flow inundation with or without volumetric growth downstream.

- Utilizes easy-to-use, well tested, empirical mobility models that do not depend on material properties or subsurface characteristics.

- Does not depend on a specific GIS platform.

- Includes options to use different empirically based inundation scaling coefficients for different geophysical mass flows, such as debris flows, lahars, or rock avalanches, as well as user-specified custom values (section 3.5).

- Minimizes spikey map-view inundation artifacts in unconfined topography (section 3.5).

- Can determine landslide or flow-volume source areas from topographic attributes (such as slope or curvature) within Grfin Tools (section 3.2.2).

- Can import landslide or flow source areas from assessments performed outside Grfin Tools, including landslide susceptibility analyses, such as factor-of-safety slope-stability assessments, or mapped landslides from previous events (section 3.2.2).

- Can assess inundation from flows without landslide sources.
- Includes a wide variety of attributes to define flow growth zones within a drainage network (section 3.6.2).
- Can incorporate volumetric linear or nonlinear growth of flows using integrated growth factors for upslope contributing areas, upstream channel length, or both (section 3.6.3).

As with all modeling tools, Grfin Tools has limitations and it is not a substitute for detailed site-specific investigations. First, the underlying mobility models are empirical and have minimal underpinnings in physics; instead, these models use statistical relations typically derived from past events. For given options, both models of mobility (landslide runout and flow inundation) only portray the maximum potential affected areas—there is no delineation of the areas most likely to be affected. Analyzing multiple scenarios, however, might help assess runout likelihood. Second, there is no time evolution in the Grfin Tools models—they do not compute runout speeds, variable flow depths, or impact forces. Furthermore, these models do not bifurcate flow directions into multiple paths (also refer to section 5.2). If a more detailed analysis of geophysical mass-flow behavior is needed, then a more sophisticated dynamic routing model, such as RAMMS (Christen and others, 2010), DAN3D (Hungr and McDougall, 2009), or D-Claw (George and Iverson, 2014), could be used. More details on the limitations of the mobility calculations are contained in sections 3.3, 3.5, and 3.6.

Grfin Tools does not directly incorporate spatially variable angles of reach or growth factors for flow inundation, as might vary with terrain or geologic materials. However, fast runtimes for Grfin Tools enable quick comparison of multiple scenarios and such variations could be assessed using multiple runs. The multi-component aspect of Grfin Tools also allows geomorphic attributes to regulate runout and inundation over a landscape with widely varying topography and geologic materials. For example, by using area growth for flow inundation combined with spatially variable landslide sources, flow inundation will be larger in areas with abundant landslide sources and smaller in areas with limited sources. This combination can provide estimates of potential inundation zones over widely varying areas (Brien and others, in press).

Interpreting results from a Grfin Tools analysis requires a comprehensive understanding of the limits of the underlying empirical mobility models. Although we have applied Grfin Tools to a variety of types of geomorphic terrain, users should take care to determine that Grfin Tools is providing reasonable results for their applications. To aid in this determination, we suggest that users begin their analyses with simple cases (such as one tool) then progressively advance to more complicated scenarios. The examples contained in section 6 of this manual illustrate a wide range of potential applications.

# 2. Using Grfin Tools

This section provides a summary of how to use Grfin Tools, common pathways to create specific products, and some guidelines for advanced workflows. More detailed information on the underlying methods of analysis as well as the contents of input and output files are contained in subsequent sections of this document.

## 2.1. Installing and Running Grfin Tools Software

Grfin Tools software is provided as a compiled executable and installation package to run on Windows OS. Written in the C++ programming language for computational speed, it is dependent on the freely available TauDEM software package (Tarboton, 2005; available online at https://hydrology.usu.edu/taudem/taudem5/downloads.html). TauDEM creates various topographic products, such as flow directions and attributes of the drainage network, used by Grfin Tools. The TauDEM software package must be installed for Grfin Tools to function.

Information about installing and running Grfin Tools is provided in the Grfin Tools software release (Cronkite-Ratcliff and others, 2025). This repository includes an installation package with a compiled version for Windows OS, instructions on installing both TauDEM and Grfin Tools, directories for each example described in section 6, as well as source code and related materials.

Grfin Tools is run from a command prompt window (section 6). A DEM (in GeoTIFF format; section 4.2.1) in projected coordinates (for example, UTM) and a Settings file (YAML format; section 4.2.2) are always required to run Grfin Tools. The Settings file identifies the tools used as well as the parameters required for the selected options. Some options may require additional input files. To learn more about the capabilities of Grfin Tools, download and run some of the examples described in the next section and in section 6.

## 2.2. Common Pathways for Running Analyses and Examples

Grfin Tools can be used in many ways, ranging from a simple analysis of either landslide runout or flow inundation to a complete linked-process portrayal of multiple zones, including source areas, open-slope runout, and channelized flow inundation. Although the various tools create discrete results or output products, many analyses require a sequence of tools. For example, open-slope runout requires a source, and flow inundation requires point sources and (or) zones of growth. Moreover, it is possible in Grfin Tools to run either simple analyses requiring minimal parameter choices or more complex analyses where additional parameters may better target the processes and settings of interest.

Given the many analysis possibilities, here we outline common pathways to obtain specific model results or products. Figure 2 schematically illustrates these pathways, the tools required, and their key output products. Each pathway is associated with one or more detailed examples that are fully described in section 6. The Settings and DEM files for each example are available in the Grfin Tools software release (Cronkite-Ratcliff and others, 2025). Running and exploring these examples demonstrate how Grfin Tools operates and what its products provide. Each example includes additional variations to showcase some Grfin Tools options for specific situations. A user can select an example similar to their situation of interest as a basis for their own assessments. Of course, Grfin Tools can be used in other combinations beyond the pathways presented. Other sections of this document describe additional features and methods for handling special situations, such as extensive road networks and large water bodies (section 5).

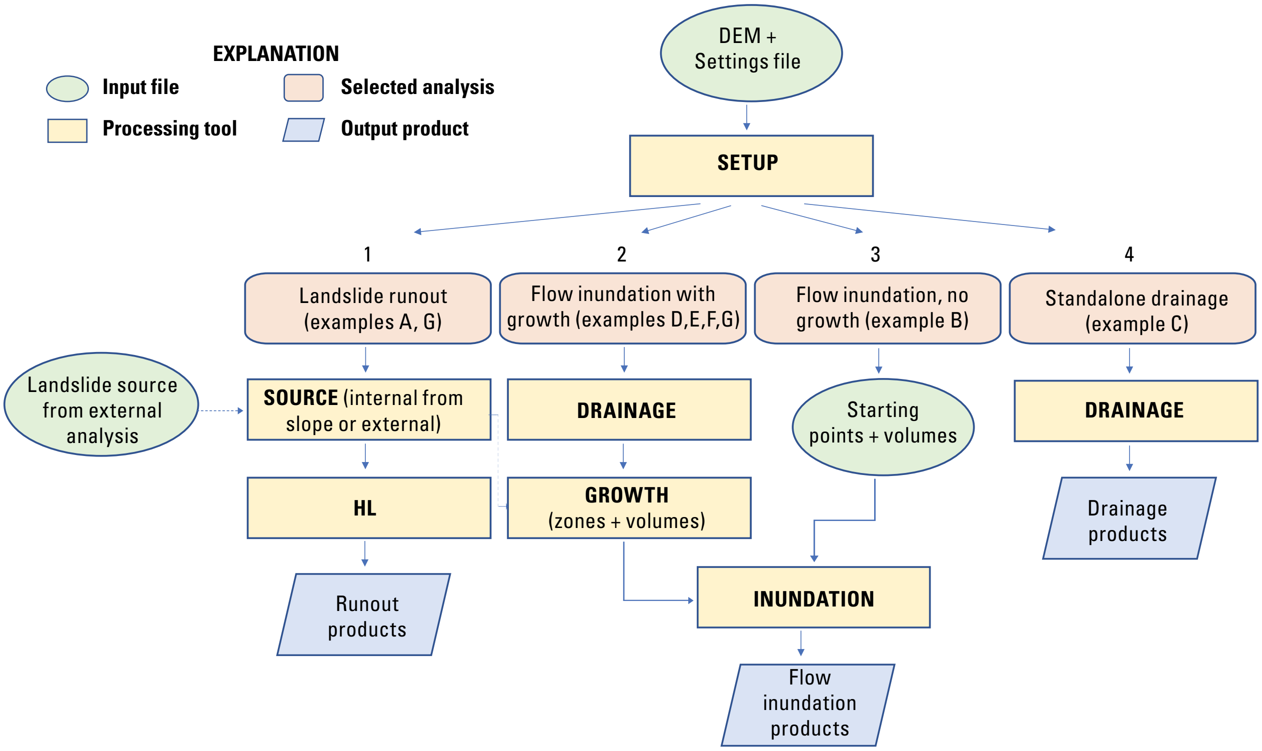


**Figure 2.** Schematic flowchart illustrating common pathways for using Grfin Tools with examples identified in orange boxes. For each analysis pathway, tools shown in yellow boxes, input files in green ellipses, and output products in blue boxes. Each tool creates many output products; only primary products are shown. Other analyses are possible and discussed in later sections. DEM, digital elevation model.

The examples described in section 6 and outlined in table 1 include both simple and complex scenarios. All examples require a setup process that uses TauDEM tools to delineate flow directions in the DEM—this setup is run as part of Grfin Tools. After the initial setup, different tools can be implemented to create different products. Simple examples include performing an *H*/*L* runout assessment from potential landslide sources (example A), determining flow inundation using known starting locations and associated flow volumes (example B), and creating a standalone curvature-based drainage network (example C). More complex examples involve obtaining flow inundation using volumetric growth from upslope contributing source areas (example D), delineating flow inundation using volumetric growth from upstream channel lengths (example E), and using multiple growth sources for flow inundation (example F). An additional example demonstrates ways to run several scenarios affected by multiple processes with different parameters and then integrate these diverse products into an overall susceptibility map showing multiple zones of mobility (example G). These examples illustrate usage of Grfin Tools in diverse topographic settings with different DEM resolutions (section 6).

**Table 1.** List of examples illustrating the use of various Grfin Tools options.

[The **GROWTH** tool invokes the **DRAINAGE** tool with default options if the **DRAINAGE** tool is not specified. *H*/*L*, height-to-length ratio]

| Example | Description | Tool(s) used |
|---|---|---|
| A | *H*/*L* runout from landslide sources only; no inundation | **SOURCE, HL** |
| B | Lahar inundation from user-specified point sources and volumes | **INUNDATION** |
| C | Standalone drainage network | **DRAINAGE** |
| D | Debris-flow inundation using growth factors based on upslope source area | **SOURCE, GROWTH** (area), **INUNDATION** |
| E | Debris-flow inundation using growth factors based on stream length | **GROWTH** (length), **INUNDATION** |
| F | Debris-flow inundation using multiple growth components based on field or remote measurements | **SOURCE, GROWTH** (combo), **INUNDATION** |
| G | Landslide susceptibility map using a combination of tools and scenarios | **SOURCE, HL, DRAINAGE, GROWTH** (area), **INUNDATION** |

## 2.3. More Advanced Workflows

The pathways and examples described above provide basic approaches for performing a Grfin Tools analysis and are a good starting point for any investigation using Grfin Tools. However, Grfin Tools offers the capability to explore topographic and parameter effects on landslide runout and flow inundation. It can accommodate a variety of workflow patterns beyond the examples listed in table 1, depending on the mass movement processes being investigated. These can be tailored to the needs of an individual user.

Two relatively easy-to-adapt advanced workflows are mentioned here. The first general approach is to analyze and fine-tune the processes separately using different tools and then combine the results. For example. If the desired goal is to create runout and inundation zones for both open-slope runout using an *H*/*L* analysis (section 3.3) and drainage-controlled flows using a flow-inundation analysis (section 3.5), then these processes can be analyzed independently in two different steps and subsequently assembled into one product.

A second general approach is to use a stepwise analysis of a given process in Grfin Tools to obtain a more relevant outcome. For example, if the desired goal is to understand the controls on debris-flow inundation with volumetric growth in a given topographic setting, a step-by-step process can highlight the significant controls. In this case, a user might first focus on evaluating the drainage network, accepting the default network or modifying governing parameters if needed (section 3.4). Then a series of runs with different growth zones and growth factors could be performed to ascertain their effects on inundation (section 3.6). By conducting a stepwise analysis, the user can acquire a better understanding of the importance of different controls for their specific situation.

# 3. Methods Underlying Different Tools

Grfin Tools contains a suite of software tools that enable the analysis pathways described in section 2 and illustrated in figure 2. The tools are selected and implemented through a Settings file (described in detail in section 4.2.2). Here, we explain the processes and procedures underlying each tool—**SETUP**, **DRAINAGE** (for delineating drainage networks), **SOURCE** (for identifying source areas), **HL** (for determining landslide runout), **INUNDATION** (for delineating flow extent), and **GROWTH** (for computing spatially distributed flow volumes that can be used in inundation). Section 4 discusses the input requirements and output results from Grfin Tools, including the implementation of control parameters and settings for each tool. Information about the basis and methods underlying each tool provided in this section can help users select appropriate tools for different study areas and better evaluate model results.

## 3.1. Setup (SETUP Tool)

Grfin Tools always requires running the **SETUP** tool before analyzing mobility. This tool uses TauDEM for a variety of calculations within the **SETUP** process; TauDEM must be installed to run Grfin Tools (refer to Cronkite-Ratcliff and others, 2025). The **SETUP** tool handles some file and directory management items (refer to section 4.2.2.1), but importantly it uses TauDEM tools to calculate the required D8 flow direction and flow accumulation for each cell in the DEM. To fully assess effects from any source areas, landslide runout zones, or flow inundation extents, it is advisable to include all areas of interest in the original DEM. Note that the DEM should be in GeoTIFF format and use a projected coordinate reference system (such as UTM or State Plane), not a geographic coordinate system. The D8 flow direction for each DEM cell identifies the adjacent cell (out of the eight surrounding cells) having the steepest descent (Tarboton and others, 2015)—this serves to route flow from one cell to the next cell. These derived raster files in GeoTIFF format are used in subsequent analyses of runout and (or) inundation. The TauDEM output files generated using the **SETUP** tool are listed in section 4.4.1.1. As creating these output files can take extensive computer runtime for larger DEMs, they are saved in a separate directory for later use. Once created, they do not need to be recreated for subsequent analyses that use the same DEM.

## 3.2. Source Areas (SOURCE Tool)

> *This section describes how to use source areas for runout and inundation and outlines approaches for constructing source-area raster files. These approaches include topographic attributes, landslide-susceptibility analyses, and (or) mapped landslides. It also describes how to filter an initial source raster file to better target specific potential source areas.*

### 3.2.1. Overview

The **SOURCE** tool is used to specify distinct source areas in analyses that require source areas (such as the **HL** tool or the source area-based **GROWTH** tool), otherwise it is ignored. Depending on the physical processes being analyzed, source areas can represent potential landslide (or rockslide) sources, or they can delineate areas where spatially distributed processes (for example, rilling or surface erosion) can contribute to flow growth. Distributed source areas can be used to create surface-runoff generated flows that do not originate from discrete landslides. Source areas are required with the **HL** tool, as this tool needs precise starting locations (section 3.2.2). Source areas are also needed for flow inundation where growth in flow volumes is controlled by part of the upslope contributing area. If the **SOURCE** tool is not used for area-growth inundation, the entire upslope area is used to compute the growth in flow volumes (section 3.6.3). If a given analysis uses both the **HL** tool and source area-based **GROWTH** tool, then both tools will use the same source areas determined from the **SOURCE** tool.

Point sources are dealt with differently and do not use the **SOURCE** tool—they can be either part of growth (***point_source_volumes_file***) as described in section 3.6 or inundation starting points (***user_specified_volumes_file***) as described in section 3.5. The parameters for the **SOURCE** tool are described further in section 4.2.2.4. Section 2 and table 1 outline examples that illustrate various uses of the **SOURCE** tool. The primary output file of the **SOURCE** tool is the *<DEMfilename>_sourcearea.tif* raster file, saved in the output directory designated by the ***dest_dir*** input field (section 4.4.2.1.2).

### 3.2.2. Obtaining Sources

The **SOURCE** tool creates a separate raster file (*<DEMfilename>_sourcearea.tif*) that delineates the source part of the DEM for use in further analyses. Source areas can be derived in many ways, but typical approaches utilize the following:

1. topographic attributes (such as slope and [or] curvature),
2. results from a slope-stability analysis (such as factors of safety), or
3. mapped locations of actual landslide sources (for back analysis of events).

The source raster can also be a combination or subset of multiple attributes—the goal is to identify appropriate source areas for a given analysis. The initial extent of the source area is derived from a user-provided file identified in the Settings file ***source_raster*** input field. To obtain source areas defined by the topographic slope of the DEM, this input field can be set to the word "slope" instead of a file name. Grfin Tools can then filter this initial raster input file as desired to extract more targeted sources, using maximum and (or) minimum values and (or) size limits (section 4.2.2.4.). A modified raster then serves as the *<DEMfilename>_sourcearea.tif* source file for further runout and inundation analyses.

An additional filter to control the minimum source area size can be applied to any of these source area approaches. The Settings file ***min_source_area*** input field (section 4.2.2.4.) defines the minimum contiguous source area and can be used to screen out isolated, small areas unlikely to become a landslide source. Refer to example A (section 6.1) for an illustration of this process.

#### 3.2.2.1. Topographic Approach

Topographic characteristics, such as ground-surface slope and (or) curvature, are well known to influence the location of landslides and are commonly used to identify terrain susceptible to future landsliding (for example, Montgomery and Dietrich, 1994; Iverson and others, 1997; Dai and Lee, 2002; Corominas and others, 2003; Sorbino and others, 2010). Topographic attributes such as slope can also demarcate ground vulnerable to other forms of erosion (for example, Chaplot and Le Bissonnais, 2000; Fox and Bryan, 2000; Staley and others, 2014).

Grfin Tools can directly utilize slope (fig. 3*A*) and curvature derived from the primary DEM to create a more targeted source raster file (section 4.2.2.4.). This can provide a very quick and rational method for defining source areas. By setting the ***source_raster*** input field to the word "slope" instead of a file name, a slope range can be extracted by Grfin Tools using

***min_source_value*** and (or) ***max_source_value*** input fields. Optionally, planform curvature, which is derived from the same process as the drainage network, can be used to filter any initial source raster (slope or other) by setting a ***min_curvature_source*** value. This filter can delineate topographic swales. Examples using a minimum slope and a minimum curvature filter to extract susceptible ground are shown in figure 3, parts *B* and *C*. Other cases that use topographic characteristics to delineate source areas are presented in example A (for *H*/*L* runout, section 6.1) and example D (for inundation using area growth, section 6.4).

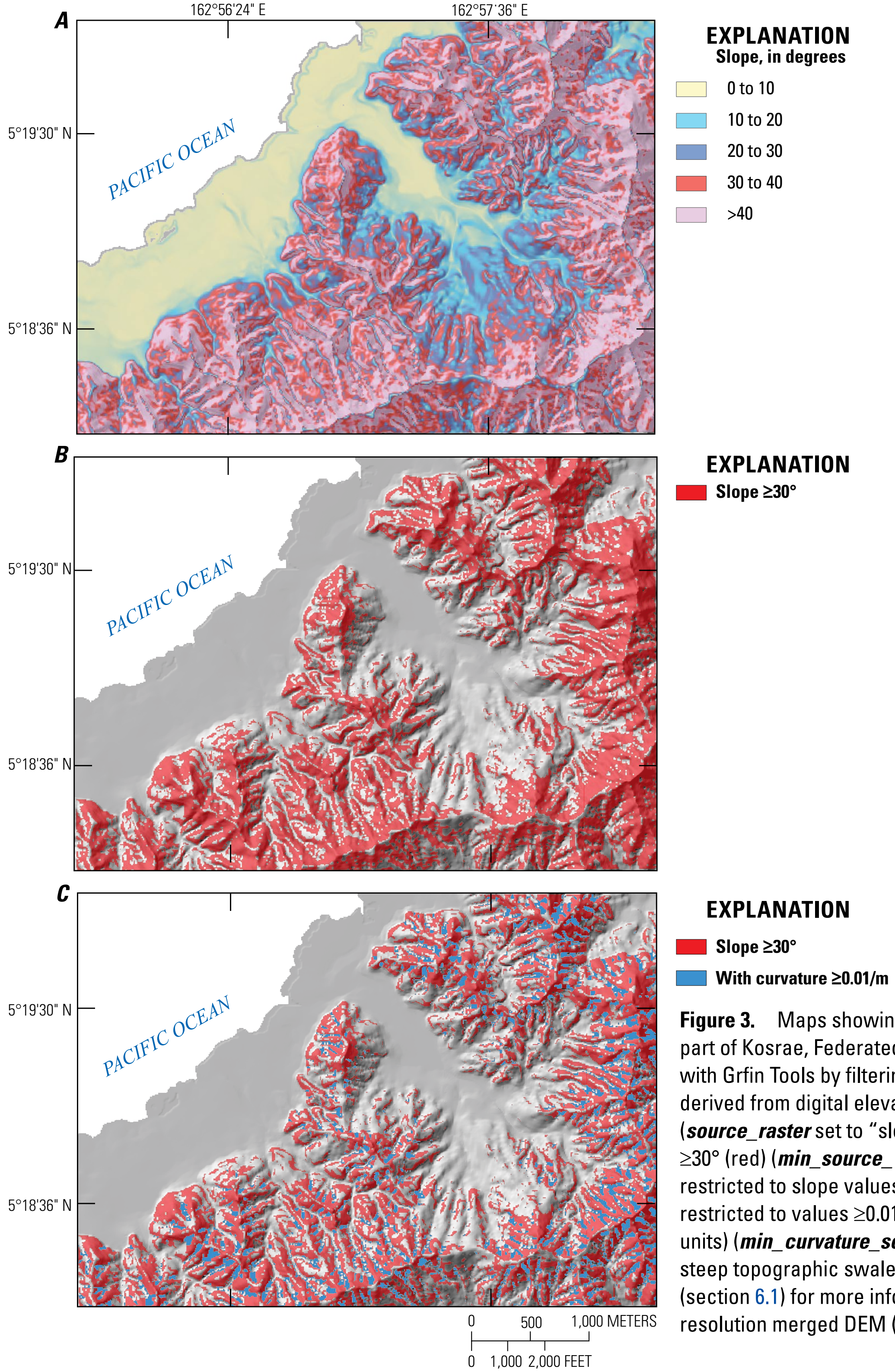


**Figure 3.** Maps showing more targeted source areas in part of Kosrae, Federated States of Micronesia, identified with Grfin Tools by filtering topographic attributes. *A*, Slope derived from digital elevation model (DEM) in Grfin Tools (***source_raster*** set to "slope"). *B*, Slope restricted to values ≥30° (red) (***min_source_value*** set to "30"). *C*, Source areas restricted to slope values ≥30° and planform curvature restricted to values ≥0.01/meter (/m, reciprocal DEM length units) (***min_curvature_source*** set to "0.01"), which highlights steep topographic swales (blue). Refer to example A (section 6.1) for more information. Hillshade from 10-meter-resolution merged DEM (U.S. Geological Survey, 2013a, b).

#### 3.2.2.2. Landslide-susceptibility Approach

Another approach to identifying source areas utilizes spatially distributed landslide susceptibility analyses performed outside of Grfin Tools. Landslide susceptibility methods can be based on statistical examination (using techniques such as logistic regression or frequency ratios) of attributes associated with mapped landslide events, such as soil type (for example, Nandi and Shakoor, 2010; Reichenbach and others, 2018). Alternatively, susceptibility assessments can employ physics-based slope-stability methods such as limit-equilibrium using one-dimensional cell-by-cell methods (for example, Montgomery and Dietrich, 1994; Pack and others, 1998; Baum and others, 2008) or three-dimensional areas (Mergili and others, 2014; Reid and others, 2015), provided results can be portrayed over a DEM.

The resulting raster files of susceptibility or factor of safety computed from these slope-stability analyses can identify areas prone to future landsliding. Here again, the ***min_source_value*** and (or) ***max_source_value*** input fields can be used in Grfin Tools to extract a range of values defining potential source areas of interest; this process creates a source area raster for further analyses. Maximum and minimum values will depend on the values contained in the initial source raster. An example demonstrating the use of factor-of-safety results from other slope-stability analyses to obtain source areas is presented in Example G (section 6.7.a).

#### 3.2.2.3. Mapped Landslide Approach

Mapped landslide source areas (not including their runout zones) can also be used as a source in Grfin Tools. This may be useful for back analysis of specific landslide events to determine Grfin Tools parameters such as growth factors or reach angles. Mapped landslide sources may also be useful for examining a variety of plausible runout scenarios from an individual landslide. As in the previous two approaches, a source raster file containing the mapped landslide source areas is needed, as well as appropriate filters. For example, a raster of zeros and ones (where a value of one indicates a mapped landslide source area) could be filtered using a minimum source value of one to obtain the source areas. Example F (section 6.6) in this document illustrates the use of a mapped landslide source area for back analysis.

## 3.3. Landslide Runout using H/L Relations (HL Tool)

*This section describes the method underlying an H/L ratio landslide runout analysis in digital topography. It also discusses the selection of an angle of reach (**min_reach_angle**) to identify runout areas.*

### 3.3.1. Overview

The **HL** tool uses a simple *H*/*L* ratio, in the form of an angle of reach (arctan(*H*/*L*)), to define areas potentially affected by runout downslope of defined landslide (or rockslide) source areas (figs. 4, 5). Results from this tool are generally referred to as *H*/*L* runout or landslide runout in this document: areas affected by this runout may represent downslope movement of less mobile landslides, open-slope or unconfined flows, and (or) transport zones affected by flows before they reach a drainage network. Typically, areas affected by channelized flows will be identified using the **INUNDATION** tool (section 3.5). This discussion provides guidance on selecting an angle of reach and interpreting patterns of runout from the **HL** tool. The parameters for the **HL** tool are described further in section 4.2.2.5. Section 2 outlines pathways for using the **HL** tool.

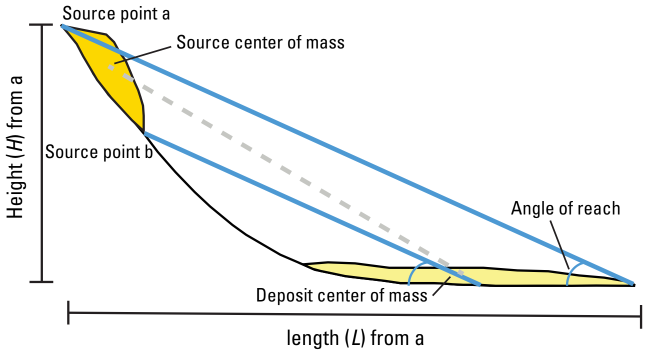


**Figure 4.** Diagram defining angle of reach, height (*H*), and length (*L*) for landslide runout computations. Height and length are shown relative to source point a. The same angle of reach is shown extending from source points a and b (blue lines). Note that upslope source points (such as a) will typically lead to farther runout and overlap the runout from downslope source points (such as b). Angle between the source and deposit centers of mass (dashed gray line) also shown for comparison.

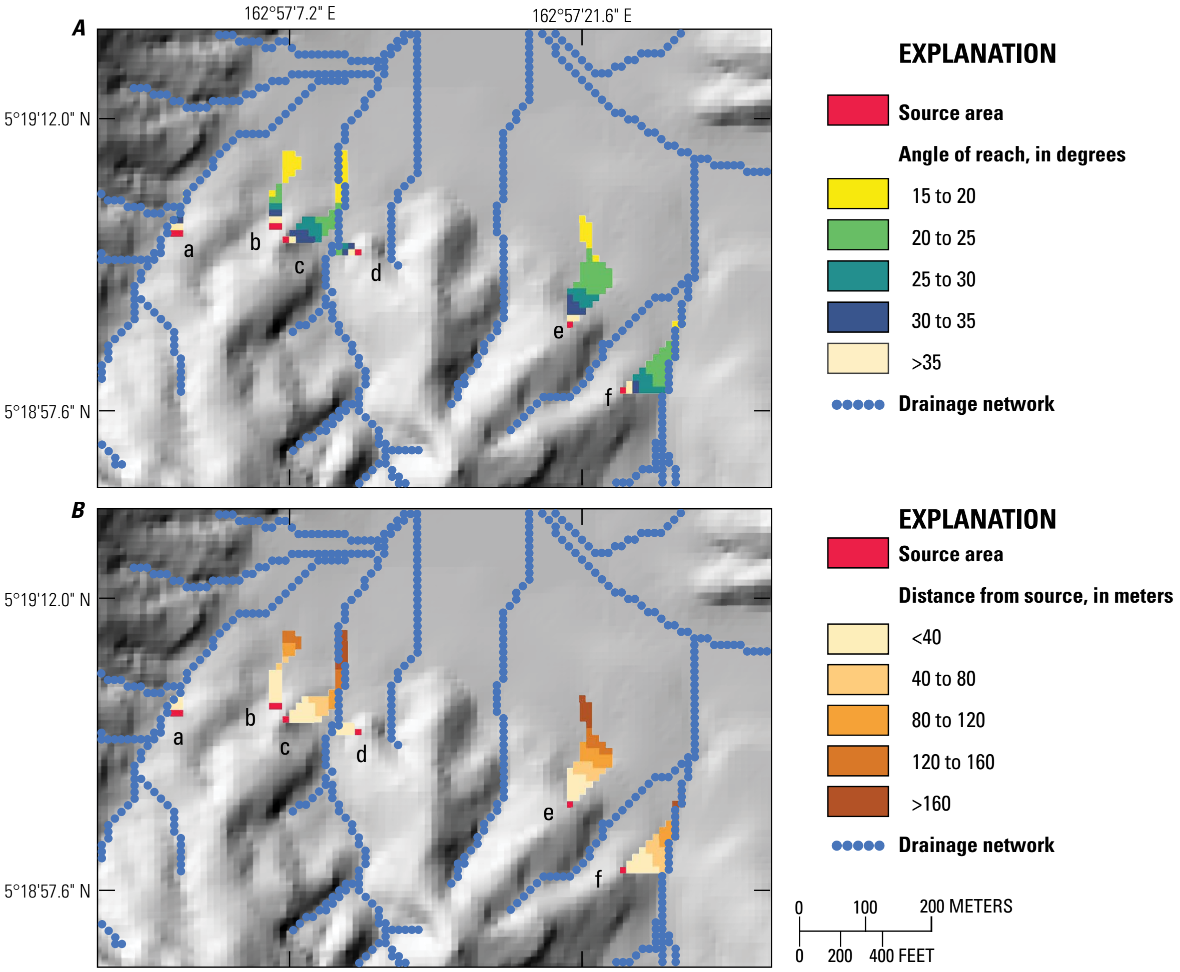


**Figure 5.** Maps showing runout zones starting from limited source areas (red) in part of Kosrae, Federated States of Micronesia, computed using the Grfin Tools **HL** tool for angles of reach ≥15°. *A,* Runout zones by angle of reach, grouped into 5° intervals. Low angles of reach, combined with spreading, create more extensive runout. Note that some runout zones transition from adjacent hillslopes into the stream network (starting at locations a, c, d, f) whereas others terminate on open hillslopes (starting at locations b, e). *B*, Runout zone by distance from source cells, grouped into 40-meter (m) intervals. Hillshade from 10-m-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

Runout from a source is demarcated in the DEM using an angle of reach (also known as a minimum shadow angle or Fahrböschung angle)—this very simple mobility ratio was proposed by Heim (1932) for rock avalanches and has been expanded upon and utilized by many investigators (for example, Hsü, 1975; Iverson, 1997; Legros, 2002; Wallace and Santi, 2021). The minimum reach angle defines the limits of runout. The **HL** tool directly uses the D-Infinity Avalanche Runout tool from TauDEM, with its assumptions and default settings (Tarboton and others, 2015). These include the use of D-Infinity algorithm to partition flow from one DEM cell into multiple downslope cells, the use of a fixed proportion threshold (0.2) to control this dispersion of downslope flow, and a runout length defined along a flow path (rather than straight horizontal distance). These assumptions dictate that runout will be identified along flow paths with modest dispersion. The **HL** tool needs two items to be specified:

1. the delineation of specific source areas (section 3.2) as starting points, and
2. a threshold angle of reach (***min_reach_angle***).

For a given angle of reach, the primary product is an output raster, covering the same extent as the DEM, that contains runout distance (*<DEMfilename>_hlrunout_distance.tif*). Any positive values in this raster file delineate areas affected by runout from the combined sources. An additional output file contains the specific angle of reach at each DEM cell affected by runout back to its source cell (*<DEMfilename>_hlreachangle.tif*). The contents of these two raster files are further described in section 4.4.2.1.

The simple *H*/*L* approach with an angle of reach as implemented in the **HL** tool has several limitations. It uses the maximum runout extent and does not incorporate the angle between the source and deposit centers of mass (fig. 4). It does not utilize the volume of material transported. *H*/*L* relations incorporating volumes tend to better match empirical observations of runout, where the angle of reach decreases (or mobility increases) with increasing volume (for example, Scheidegger, 1973; Davies, 1982; Corominas, 1996; Iverson and others, 2015). There is no volumetric growth calculated by the **HL** tool. It does not account for variations in landslide type, geologic material, travel path morphology, or the presence of liquefiable substrates. This approach does not forecast movement speeds or impact forces, as might be determined using other landslide dynamics models (for example, McDougall and Hungr, 2005; George and Iverson, 2014; Iverson and George, 2014; McDougall, 2017; Mergili and others, 2017; Melo and others, 2018). Despite these limitations, it does assess potential runout along flow paths in a digital landscape; its advantage is computational speed and simplicity. As such, it is suitable for rapid assessments over large areas.

### 3.3.2. Angle of Reach Controlling Runout

In a simple context, the angle of reach is calculated from the length of the farthest deposit runout location (*L*) and the height of the highest source location (*H*) (fig. 4). The D-Infinity Avalanche Runout tool in TauDEM (as used in the **HL** tool) treats each source cell independently, so the highest elevation (*H*) is defined for each source cell. Lower reach angles can extend runout, whereas reach angles steeper than the local ground slope result in no runout. However, variations in local topography can exert a primary control on runout. In digital topography, runout can be more complex than what might appear in a simple cross section (fig. 4), as the extent of runout follows continuous flow paths (fig. 5). Thus, runout computed using a low angle of reach may curve and extend from hillslopes into stream channels (locations c, d, f in fig. 5). Runout does not encompass areas on hillslopes opposite the source slope. In some cases, runout may be limited to only open hillslopes (locations b, e in fig. 5). Limited dispersion or spreading occurs as well, so that depending on local topography, runout may not just follow a single track in the DEM (locations e, f in fig. 5).

Using the same angle of reach, runout from upslope source cells will typically overlap runout from downslope source cells (fig. 4). Thus, greatly expanding source areas to cover gentler slopes may have a limited effect on the overall pattern of runout (refer to example A, section 6.1). Runout from many source cells is superimposed and aggregated into a composite runout raster, but sources do not necessarily combine to create even greater runout. Instead, each cell affected by runout can be traced to an individual source cell. In steeper, dissected terrain, runout from many source cells often extends into stream channels whereas flatter downslope topography can lead to broad aprons of runout (fig. 6). In many types of dissected terrain, a reach angle between 20° and 30° will allow runout to extend from source areas to the drainage network. Lower angles of reach will extend runout aprons onto adjacent flatter ground. Output raster files from the **HL** tool enable the visualization of both reach angles and runout distances from specified source areas (figs. 5, 6).

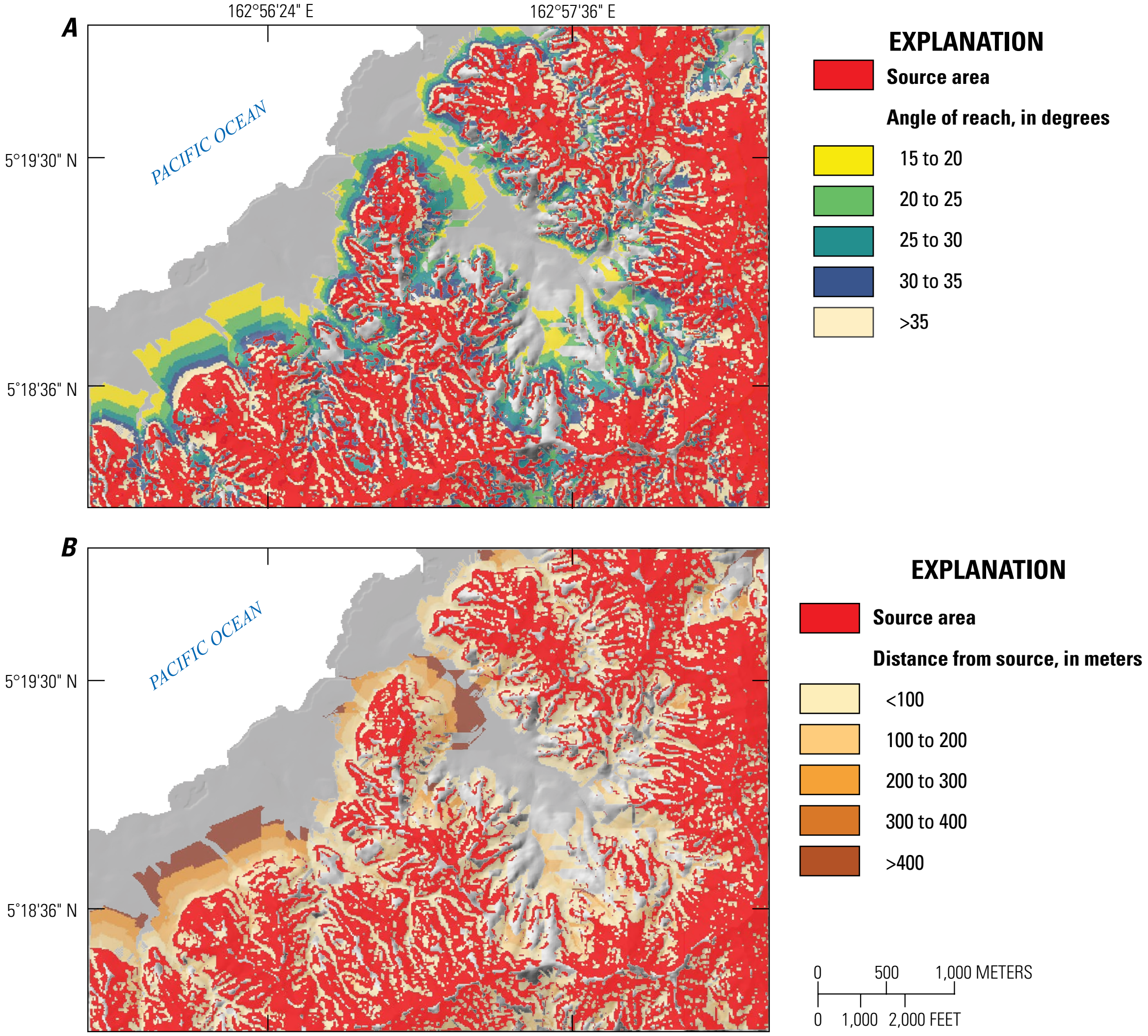


**Figure 6.** Maps showing landslide runout zones starting from extensive source areas in part of Kosrae, Federated States of Micronesia, computed using the Grfin Tools **HL** tool for angles of reach ≥15° (***min_reach_angle*** set to "15"). *A*, Runout zones by angle of reach, grouped into 5° intervals. Low angles of reach commonly create more extensive runout on adjacent gentle ground. *B*, Runout zones by distance from source cells, grouped into 100-meter (m) intervals. Hillshade from 10-m-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

## 3.4. Drainage Networks (DRAINAGE Tool)

> *This section describes the creation of a curvature-based drainage network within a DEM. Such a network is required for analyzing flow inundation with growth. Typically, the default drainage network parameters work well; however, guidance is provided for fine-tuning parameters, if needed.*

### 3.4.1. Overview

The **DRAINAGE** tool is used to delineate a drainage network for use with the **GROWTH** and **INUNDATION** tools or to create a stand-alone drainage network. A drainage network is not required for analyzing flow inundation with user-specified starting points using the **INUNDATION** tool or for the **HL** tool. The parameters for the drainage network tool are described further in section 4.2.2.3. Typically, the default parameters for the **DRAINAGE** tool work well for many DEMs and will not need to be adjusted. Note that the **GROWTH** tool will automatically invoke the **DRAINAGE** tool using default parameters if the **DRAINAGE** tool is not explicitly specified. Section 2 outlines pathways for using the **DRAINAGE** tool; example C (section 6.3) illustrates fine-tuning of drainage parameters as well as creating standalone drainage networks.

To create a drainage network, the **DRAINAGE** tool identifies the approximate location of channel initiation using topographic curvature-based criteria, rather than a fixed, pre-defined contributing-area threshold method as is commonly used (for example, Mark, 1984; Montgomery and Foufoula-Georgiou, 1993). Although a fixed contributing-area threshold may work well for small areas or individual drainage basins, a single threshold rarely produces realistic drainage networks over large areas (Pelletier, 2013; Clubb and others, 2014; Tarboton and Ames, 2001). To avoid interdependency between drainage density and contributing-area thresholds, Grfin Tools uses a curvature-based method inspired by Tarboton and Ames (2001). A curvature-based contributing-area threshold is used to identify topographic concavities (hollows) that represent likely locations of channel initiation. The contributing area included for the channel initiation threshold includes only these concavities. Downstream of these channel-initiation points, the derived drainage network and corresponding debris-flow inundation follows D8 flow directions from the user-specified DEM using the ***demfilename*** input field (refer to section 3.1).

The difference between a fixed flow-accumulation threshold and a curvature-based flow-accumulation threshold is illustrated using drainage networks constructed for the vicinity of Letz Creek, Oregon (fig. 7). With a specified flow-accumulation threshold for the Coast Range in Oregon of 1,500 square meters (m$^2$) (Reid and others, 2016), a reasonable approximation of the drainage network is created in drainage basins northwest of the ridgeline (fig. 7*A*). However, this fixed flow-accumulation threshold in adjacent basins southeast of the ridgeline produces unrealistic results not representative of areas subject to surface-water flow. Using default settings for the Grfin Tools curvature-based method results in a more realistic channel network (fig. 7*B*).

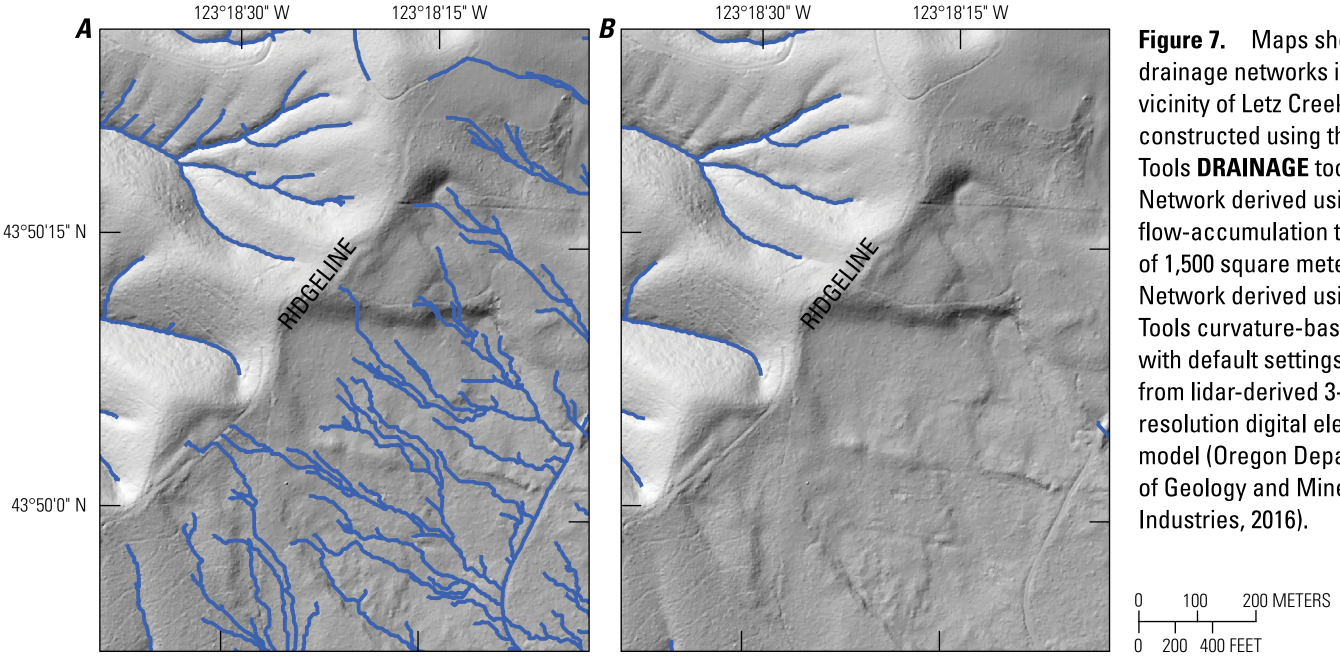


**Figure 7.** Maps showing drainage networks in the vicinity of Letz Creek, Oregon, constructed using the Grfin Tools **DRAINAGE** tool. *A*, Network derived using a fixed flow-accumulation threshold of 1,500 square meters. *B*, Network derived using Grfin Tools curvature-based method with default settings. Hillshade from lidar-derived 3-foot-resolution digital elevation model (Oregon Department of Geology and Mineral Industries, 2016).

Many drainage delineation algorithms, including those used by TauDEM in Grfin Tools, can create unrealistic drainages on flat ground, with long spurious segments heading in one of the D8 directions before abruptly changing direction. Moreover, defining drainage networks on flat ground can detrimentally affect runtimes (section 5.4). Fortunately, flow inundation typically occurs in steeper, well-defined parts of a drainage network. A user should examine any flow inundation on flat ground for unrealistic flow directions.

### 3.4.2. Methods and Default Drainage Parameters

Grfin Tools utilizes default settings, based on topographic scaling factors and published values for curvature thresholds (Pelletier, 2013; Mudd and others, 2019), to define the drainage network parameters that identify channel-initiation points. These default values are shown in section 4.2.2.3. With default values, the location of channel initiation is assigned where the contributing concave area (planform curvature ≥0.02/meter [/m, reciprocal DEM length units]) is approximately 200 m$^2$. With 0.5- to 10-meter (m)-resolution DEMs, the default settings in Grfin Tools work well to define drainage networks in a wide variety of terrain with variable drainage density, including the Federated States of Micronesia, California, Oregon, and Puerto Rico (fig. 8). Fine-tuning the drainage network parameters may slightly improve the results for an individual drainage basin but is rarely optimal over large areas. For coarse-resolution DEMs, such as 30-m Shuttle Radar Topography Mission DEMs, the default values will likely need adjustment (refer to section 3.4.3 for suggestions). Note that a DEM resolution finer than 30 m is required to accurately identify the transition from hillslope to valley (Montgomery and Foufoula-Georgiou, 1993) and accurate locations of channel initiation will be unlikely with coarse-resolution DEMs.

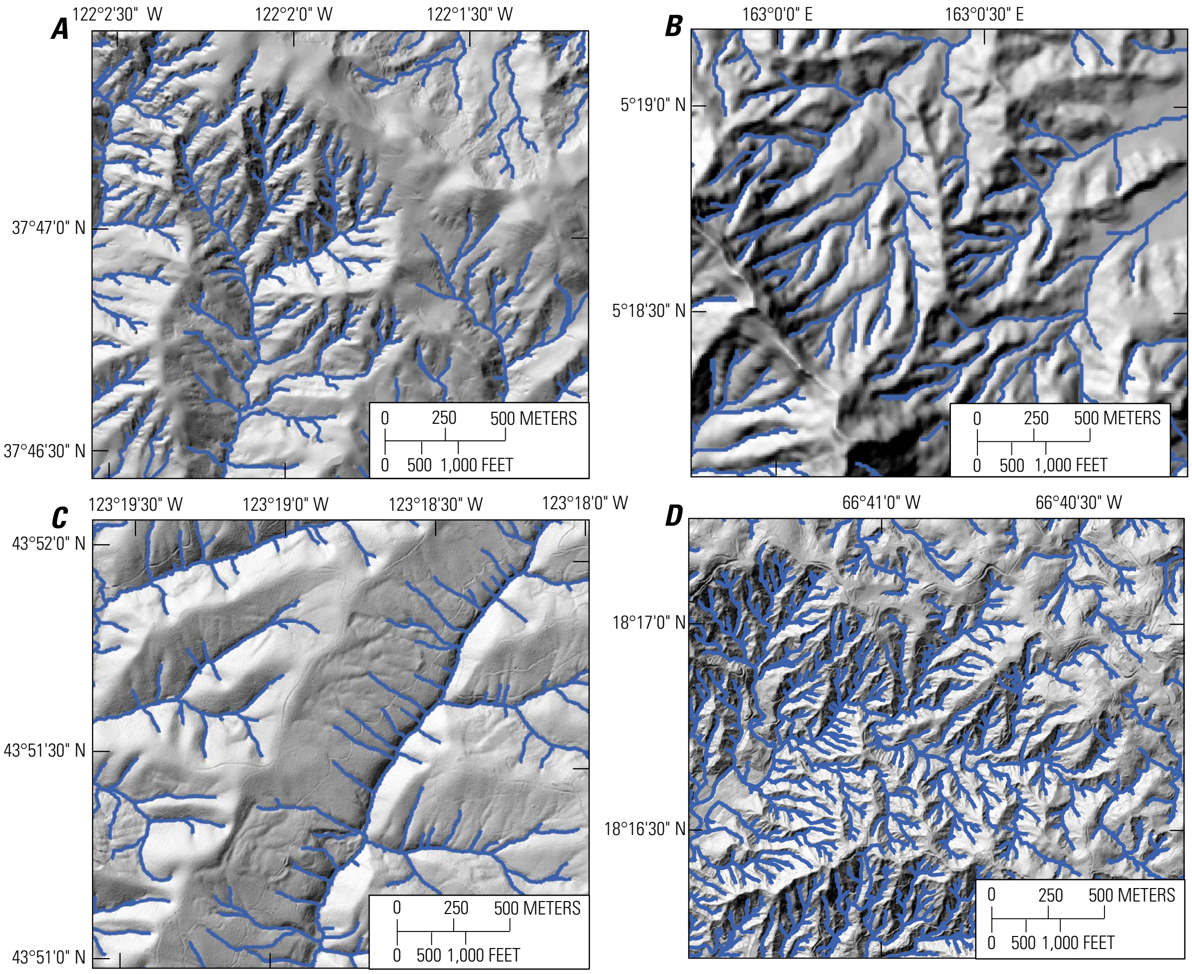


**Figure 8.** Maps showing example drainage networks constructed using the Grfin Tools **DRAINAGE** tool and default ***drainage_options*** settings. *A*, Eastern San Francisco Bay area, California, 2-meter (m)-resolution digital-elevation model (DEM) (OCM Partners, 2023). *B*, Kosrae, Federated States of Micronesia, 10-m-resolution DEM (U.S. Geological Survey, 2013a, b). *C*, Letz Creek, Oregon, 3-foot-resolution DEM (Oregon Department of Geology and Mineral Industries, 2016). *D*, Utuado, Puerto Rico, 1-m-resolution DEM (U.S. Geological Survey, 2018).

The Grfin Tools curvature-based method identifies channel-initiation points of the drainage network using the following sequence of steps. If the default settings are used, no user input is needed for these steps:

1. smooth the DEM using the mean elevation of a circular smoothing window (***dem_neighborhood***);
2. calculate planform curvature using the method of Zevenbergen and Thorne (1987)—Grfin Tools then smooths the resulting curvature values using a local mean in a 3×3-cell-square window;
3. apply a curvature threshold (***min_curvature_drainage***) to identify concavities in the topography;
4. apply an area threshold (***min_concav_area***), to eliminate small, typically isolated concavities;
5. calculate the contributing area of the remaining concavities; and
6. apply a specified area threshold (***min_drainage_area***) to identify channel-initiation points, based on the contributing area of only concave topography.

Figure 9 illustrates the intermediate steps used to identify the approximate location of channel initiation. The smoothed planform curvature output file, *<DEMfilename>_smoothplancurv.tif* (step 2, fig. 9*A*), shows the smoothed planform curvature created from a smoothed DEM within a digital landscape. With the application of a curvature threshold (step 3), only areas with a curvature less than ***min_curvature_drainage*** (concavities; combined brown and red areas in fig. 9*B*) are added to the contributing area for identification of channel initiation. Step 4 eliminates the smallest concavities (area less than ***min_concav_area*** of 200 $m^2$), which are highlighted in red in parts *B* and *C* of figure 9. These areas will not be included in the contributing area used in step 6. The blue lines in part *C* of figure 9 show the resulting drainage network with Grfin Tools default parameters. For this example, the default parameters provide a good representation of channel-initiation points that is applicable over large areas.

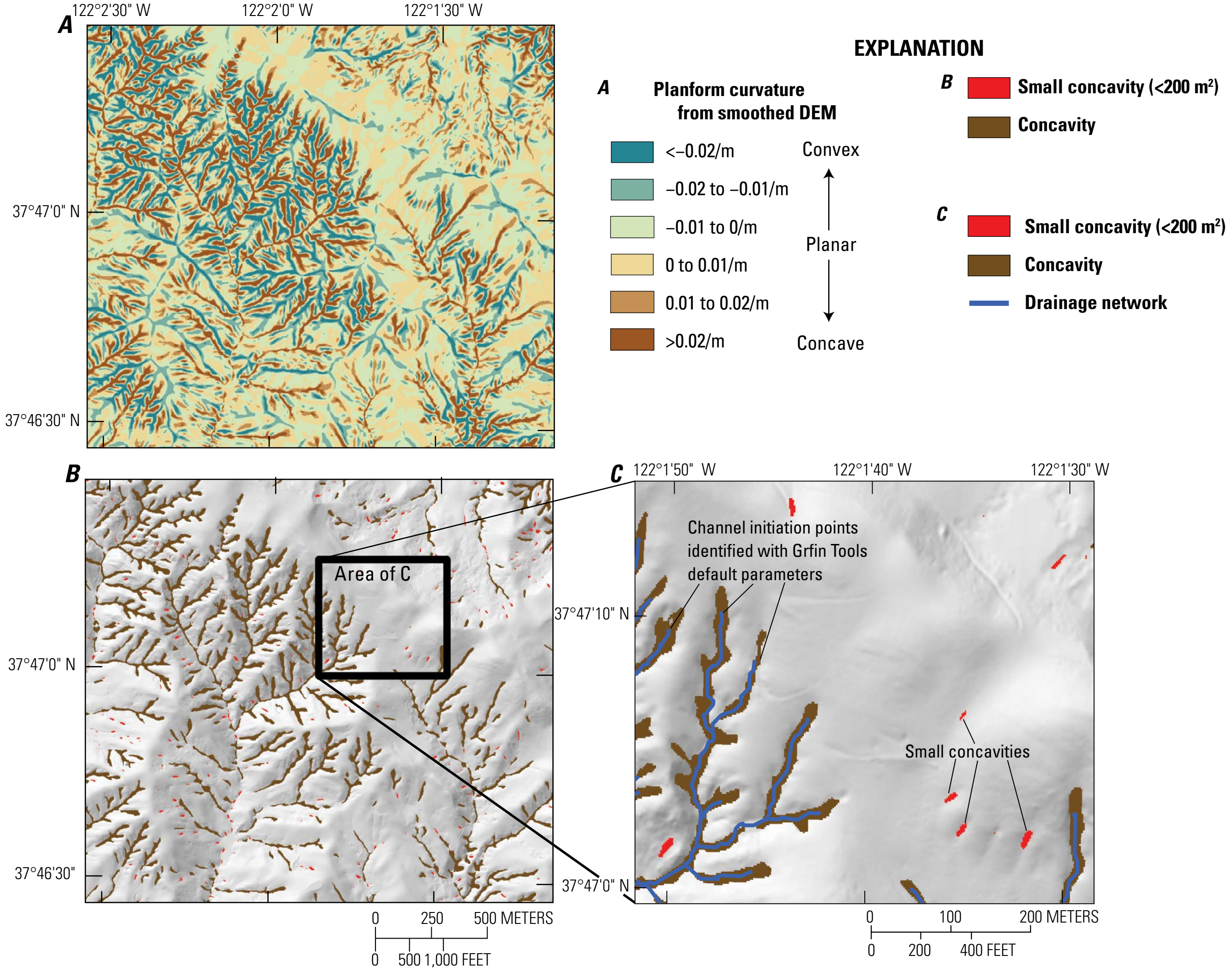


**Figure 9.** Maps showing planform curvature in the eastern San Francisco Bay area, California, calculated using the Grfin Tools **DRAINAGE** tool with a smoothed digital elevation model (DEM) to illustrate the process of locating channel-initiation points. *A*, Planform curvature (<*DEMfilename*>*_smoothplancurv.tif*) showing a range of values from concave to convex. *B*, Curvature with a threshold applied using ***min_curvature_drainage*** to show only concave areas. *C*, Zoomed-in curvature showing small concavities, channel-initiation points identified with Grfin Tools default parameters, and resulting drainage network. m, meter (/m, reciprocal DEM length units); $m^2$, square meter. Hillshade from 2-meter-resolution DEM (OCM Partners, 2023).

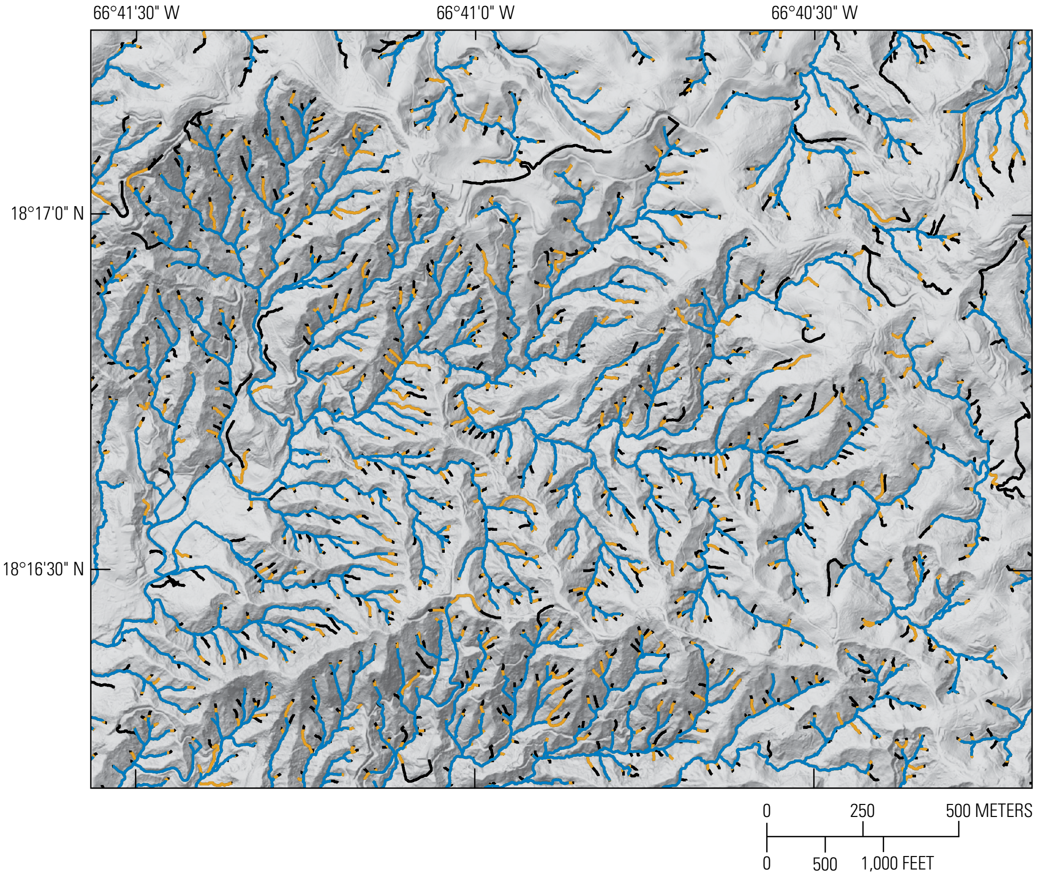
## 3.4.3. Adjusting Drainage Parameters

In special cases, such as DEMs with coarse resolution (for example, with a 30-m cell size), default settings can create drainage networks that start lower in the channel than desired or too high on the hillslope (typically due to isolated concavities or prevalent ridge-top roads). In these cases, minor adjustments to the default settings may be desirable. Adjustment of drainage parameters is intended for advanced users and can require in-depth understanding of the inter-relationship between parameters in the ***drainage_options*** section (refer to section 4.2.2.3). One strategy for adjustments, as illustrated in part *A* of figure 9 and example C (section 6.3), is to first examine the raster file of planform curvature created from a smoothed DEM (<*DEMfilename*>*_smoothplancurv.tif*) in combination with a shaded relief image (fig. 9*A* or section 6.3) or 10-m contours lines to (1) determine if the DEM smoothing window is suitable for the terrain and (2) examine the range of curvature values before making adjustments. The suggested strategies described below often involve adjustment of multiple input parameters in combination. These strategies cannot remedy issues of inaccurate or hydrologically incorrect DEMs.

Coarse resolution DEMs will likely require adjustment of the default parameters, including disabling smoothing (set ***dem_neighborhood*** to zero), decreasing the curvature threshold (***min_curvature_drainage***) on the basis of values in <*DEMfilename*>*_smoothplancurv.tif*, including all concavities (set ***min_concav_area*** to zero, and setting the area threshold (***min_drainage_area***) to a value equal to or greater than the DEM cell size.

In cases where the drainage network starts lower in the drainage basin than desired and the curvature raster shows that concavities in the DEM have been oversmoothed (example C, section 6.3, “Discussion of Output Results” section), it may be necessary to first decrease ***dem_neighborhood*** and ***min_curvature_drainage***. Example C demonstrates a sequence of these adjustments. If oversmoothing is not apparent, a decrease in ***min_drainage_area*** can move the channel-initiation points up slightly higher, improving the results in some drainage basins, although this may introduce unrealistic straight drainage segments in other basins.

In areas with prevalent ridge-top roads, topographic smoothing windows (***dem_neighborhood***) slightly larger than the default values (such as 15 m) may help if drainage networks start too high on hillslopes. This adjustment will result in some loss of fine-scale details in the topography and resultant drainage network. Figure 10 compares the resulting drainage network using different smoothing windows (***dem_neighborhood*** values of 5, 10, and 15 m). Smaller smoothing windows result in channels initiating higher in the topography. The supplement to example G (section 6.7.b) illustrates an example where a smoothing window of 15 m is applied as one step of a procedure to eliminate road-related artifacts.



**EXPLANATION**

**Drainage network**—DEM smoothing window for curvature calculation, in meters

| | |
|---|---|
| ▬ | 5 |
| ▬ | 10 |
| ▬ | 15 |

**Figure 10.** Map showing drainage networks in part of Utuado, Puerto Rico, constructed using the Grfin Tools **DRAINAGE** tool comparing topographic smoothing windows (***dem_neighborhood***) of 5, 10, and 15 meters (m) applied before calculation of planform curvature to identify concavities in the topography. Hillshade from lidar-derived 1-m-resolution digital elevation model (DEM) (U.S. Geological Survey, 2018).

In cases where the drainage network with default settings appears to start too high in the basin or unrealistic straight channel segments are present, the first recommended strategy is to increase the minimum concave area threshold (***min_concav_area***). Alternative strategies are to increase the minimum curvature threshold (***min_curvature_drainage***) and (or) the minimum drainage area threshold (***min_drainage_area***). Suggested ranges of values for all parameters in the ***drainage_option*** section are provided in section 4.2.2.3.

## 3.5. Flow Inundation (INUNDATION Tool)

*This section describes the volume-area scaling relations controlling inundation for a predefined or custom mass-flow type (**flowtype**). It also discusses the ramifications of delineating inundation with or without flow growth within a DEM and the options for guiding inundation in unconfined topography (such as using **hbar**).*

### 3.5.1. Overview

Using simple empirical flow volume-area relations, the **INUNDATION** tool allows users to delineate the spatial extent of potential flow inundation from various geophysical mass flows, including debris flows, lahars from volcanoes, and rock avalanches. The parameters for this tool are described further in section 4.2.2.7. Section 2 outlines the pathways for using this tool.

The underlying method has three stages:

1. Inundation area is determined as a function of flow volume using volume-area relations to translate a given volume into cross-sectional and planimetric inundation areas.
2. Flow volumes are defined in one of two ways:
   A. Specified volumes are assigned at known points in the digital landscape. This is similar to other flow-routing models as well as Laharz (Iverson and others, 1998; Schilling, 1998, 2014) and DFLOWZ (Berti and Simoni, 2014).
   B. Flow volume is allowed to grow systematically downstream. This does not require assigning known volumes; instead, growth-zone attributes and growth factors are defined. Enabling flow-volume growth requires the use of the **GROWTH** tool (section 3.6.) and results in a spatial distribution of flow volumes in the drainage network that can better represent inundation in upper sections of a drainage network.
3. Flow volumes coupled with the volume-area relations are used in the **INUNDATION** tool to map target inundation areas following topographically derived flow directions.

The main output of the **INUNDATION** tool is a raster file, covering the same area as the DEM, that delineates the extent of flow inundation (*<DEMfilename>_inundation.tif*). It is saved in the output directory designated by the ***dest_dir*** input field; contents of this raster file are further described in section 4.4.2.1.5.

There are limitations to the **INUNDATION** tool. It is empirical, based on volume-area scaling relations from observed events. It does not incorporate time and, thus, does not simulate or route dynamic flows moving through topography. It does not compute flow speeds, flow hydrographs, or flow-impact forces, as might be performed in landslide-dynamics models (for example, Hungr and McDougall, 2009; Christen and others, 2010; George and Iverson, 2014; Iverson and George, 2014; McDougall, 2017). It also does not delineate inundation from flows that diverge into multiple channels. It does, however, define the extent of potentially hazardous areas along a single channel; its advantages are computational speed and simplicity. Therefore, the **INUNDATION** tool can be used to rapidly evaluate a wide range of potentially hazardous scenarios over large areas.

### 3.5.2. Volume-Area Relations Controlling Inundation

In Grfin Tools, selecting appropriate coefficients for volume-area equations is crucial for portraying realistic inundation zones—this is handled by the input field ***flowtype***. The underlying basis for mapping the extent of flow inundation comes from two empirically derived power-law equations that relate a given flow volume to both cross-sectional and planimetric inundation areas. This approach has been thoroughly described in earlier work about the models Laharz (Iverson and others, 1998; Schilling, 1998, 2014; Griswold and Iverson, 2008) and DFLOWZ (Berti and Simoni, 2007, 2014). Grfin Tools, however, can also utilize these relations for situations where flows grow as they travel downstream—a departure from the Laharz and DFLOWZ approaches. Because of this modified application, we discuss the underlying origin of these relations, and we illustrate how flow growth functions in section 3.6. Other significant differences in Grfin Tools from these earlier approaches are also discussed below. For example, our methods greatly reduce spikey map-view inundation artifacts that sometimes occur using other volume-area models in situations where flows are unconstrained by valley walls.

Two governing volume-area power-law equations can be obtained from the calibration of empirical observations of cross-sectional and planimetric inundation using previous flow events having diverse volumes. These flows are typically aggregated by the type of mass flow, such as debris flow, lahar, rock avalanche, or pyroclastic flow (for example, Iverson and others, 1998; Berti and Simoni, 2007; Griswold and Iverson, 2008; Widiwijayanti and others, 2009). Figure 11 illustrates the definition of cross-sectional and planimetric areas. In most previous studies, cross-sectional area, $A$, is determined at locations with the maximum flow volume. Some analyses use the entire planimetric inundation area from the start of flow or headscarp of the initiating landslide (here designated $B0$) and some use the area of primary deposition after the maximum flow volume has been achieved (here designated $B1$).

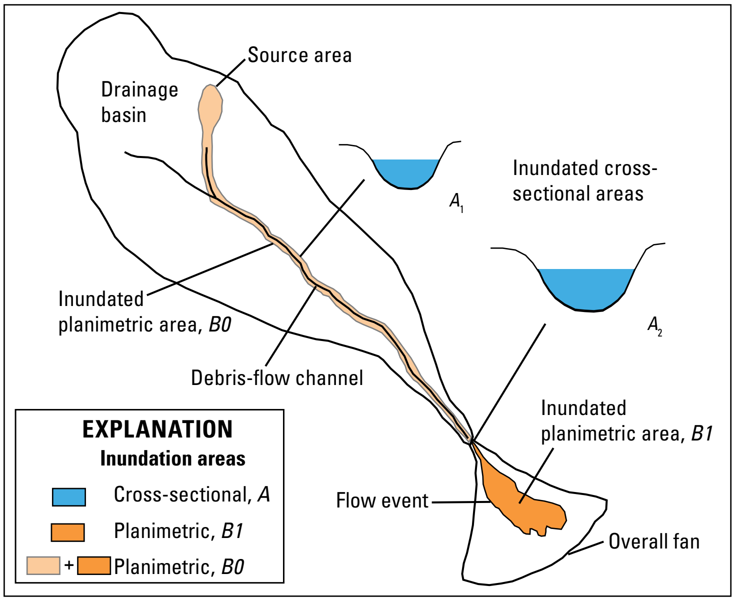


**Figure 11.** Schematic diagram showing drainage basin with debris-flow inundation zone from source into channel and onto fan. Examples of cross-sectional area (*A*) and planimetric area (*B*) used to calibrate the volume-area equations are also illustrated. Two different planimetric areas are commonly used in these analyses: either the entire inundated area including the growth zones as well as transport and depositional areas (*B0*) or the primarily depositional area (*B1*). In a growth zone using Grfin Tools, inundated cross-sectional areas increase downstream, as illustrated by the $A_1$ and $A_2$ cross sections. Flow growth is discussed in section 3.6. Modified from Berti and Simoni (2007).

Although coefficients in volume-area equations can be determined by best-fit regressions of observations to a generalized power-law form, statistical testing indicates that most geophysical mass-flow datasets can be fit well with a volume exponent of 2/3 (for example, Iverson and others, 1998; Berti and Simoni, 2007; Griswold and Iverson, 2008). These fits result in the following generalized equations:

$$A = \alpha_1 V^{2/3} \text{, and} \tag{1}$$

$$B = \alpha_2 V^{2/3} \text{,} \tag{2}$$

where

$V$ is known volume,
$A$ is cross-sectional inundation area,
$B$ (either *B0* or *B1*) is planimetric inundation area, and
$\alpha_1$ and $\alpha_2$ are the fit coefficients.

These equations are linear with log-transformed data and imply that observational data scatter is roughly proportional to volume magnitude. Importantly, flow volume is the fundamental parameter controlling inundation.

A volume exponent of 2/3 is attractive, as it conforms to physical scaling (area is proportional to volume$^{2/3}$), reduces the number of parameters needed to one per volume-area equation ($\alpha_1$ for cross-sectional area and $\alpha_2$ for planimetric area), and results in scale-invariant coefficients that facilitate ready comparison between different types of geophysical mass flows. Table 2 lists previous studies where empirical observations of flows have been fit with a power-law volume exponent of 2/3. In these studies, datasets were derived either from worldwide compilations, regional events, or a combination of the two with flow volumes typically spanning many orders of magnitude. Volume-area coefficients range from small cross-sectional and large planimetric values for more mobile, liquid-rich flows such as lahars to larger cross-sectional and smaller planimetric values for less mobile rock avalanches. The distribution of these coefficients for various types of geophysical mass flows are illustrated in figure 12.

**Table 2.** Studies of volume-area relations for geophysical mass flows, grouped by type.

[Estimated uncertainties in the coefficients available from sources listed in the “Reference” column. $\alpha_1$ and $\alpha_2$ are coefficients fit with $V^{2/3}$ (refer to eq. 1 and 2). Approx., approximate; $m^3$, cubic meters; $\alpha_1$, cross-sectional coefficient; $\alpha_2$, planimetric coefficient; $V$, volume; $A$, cross-sectional area; $B$, planimetric area; NA, not applicable]

| Data area | Number of events | Number of pairs[1] | Approx. range of volumes ($m^3$) | $\alpha_1$ | $\alpha_2$ | *B0/B1* [2] | Reference |
|---|---|---|---|---|---|---|---|
| | | | Debris flows | | | | |
| 1. Central Alps (Italy) | 116 | 116 $V$–$B$ pairs | $10^1$ to $10^5$ | NA | NA[3] | *B1* | Crosta and others (2003) |
| 2. Worldwide | 64 | 44 $V$–$B$ pairs;<br>50 $V$–$A$ pairs | $10^1$ to $10^7$ | 0.1 | 20 | *B0* | Griswold and Iverson (2008) |
| 3. Combo of areas 1 + 2 + Italy | 90 | Unknown | $10^1$ to $10^7$ | 0.08 | 17 | Mix | Berti and Simoni (2007) |
| 4. Combo of areas 1 + 2 + 3 + more Italy | >100 | 115 $V$–$B$ pairs;<br>85 $V$–$A$ pairs | $10^1$ to $10^7$ | 0.07 | 18 | Mix | Simoni and others (2011); used in DFLOWZ (Bert and Simoni, 2014) |
| | | | Post-fire debris flows | | | | |
| 5. Arizona, USA | 6 | 6 $V$–$B$ pairs;<br>6 $V$–$A$ pairs | $10^2$ to $10^6$ | 0.1 | 40 | Mix | Magirl and others (2010); Webb and others (2008) |
| 6a. Southern California, USA[4] | 23 | 21 $V$–$B$ pairs;<br>21 $V$–$A$ pairs | $10^2$ to $10^6$ | 0.02 | 28 | *B1* | Bernard and others (2021) |
| 6b. Southern California, USA[4] | 23 | 21 $V$–$B$ pairs;<br>21 $V$–$A$ pairs | $10^2$ to $10^6$ | 0.02 | 42 | *B1* (upstream) | Bernard and others (2021) |
| | | | Lahars | | | | |
| 7. Worldwide | 27 | 27 $V$–$B$ pairs;<br>18 $V$–$A$ pairs | $10^5$ to $10^{10}$ | 0.05 | 200 | *B1* | Iverson and others (1998) |
| 8. Southern Andes + subset of areas 1–7 | 15 | 15 $V$–$A$ pairs | $10^6$ to $10^8$ | 0.02 | -- | *B1* | Castuccio and Clavero (2015) |
| | | | Rock avalanches | | | | |
| 9. Worldwide | 143 | 142 $V$–$B$ pairs;<br>13 $V$–$A$ pairs | $10^5$ to $10^{11}$ | 0.2 | 20 | Unknown | Griswold and Iverson (2008) |
| | | | Pyroclastic flows | | | | |
| 10. Worldwide | 29 | 29 $V$–$B$ pairs;<br>21 $V$–$A$ pairs | $10^4$ to $10^8$ | 0.05 | 35 | *B1* | Widiwijayanti and others (2009) |
| 11. Montserrat | 11 | 11 $V$–$B$ pairs;<br>11 $V$–$A$ pairs | $10^4$ to $10^8$ | 0.1 | 40 | *B1* | Widiwijayanti and others (2009) |

[1] Number of pairs is the number of measured flow events used to fit the volume-area relations. $V$–$A$ pairs used for equation 1. $V$–$B$ pairs used for equation 2. Not all events have both types of pairs.

[2] *B0* analysis computes planimetric area from headscarp down; *B1* analysis computes planimetric area typically from start of deposition (refer to fig. 11); “mix” uses both types of planimetric area observations.

[3] Coefficients from these studies were not fit with $V^{2/3}$. However, these events used in other studies.

[4] Two analyses having different planimetric areas were performed with this postfire-related dataset, one planimetric area starts farther upstream than the other.

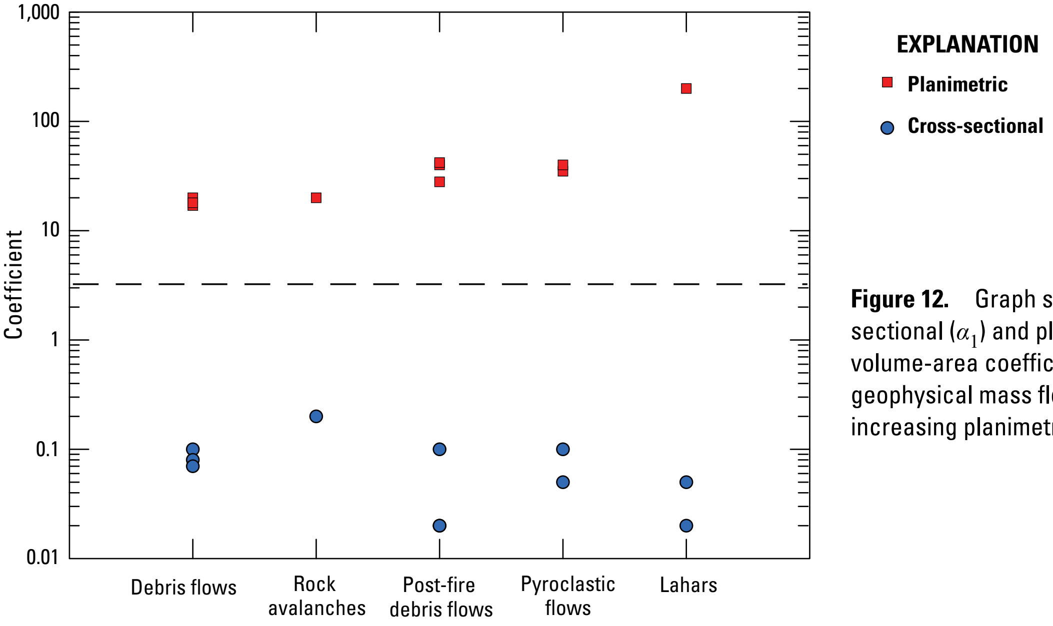


**Figure 12.** Graph showing cross-sectional ($\alpha_1$) and planimetric ($\alpha_2$) volume-area coefficients for different geophysical mass flows, in order of increasing planimetric coefficient.

Given the scatter in observational data from mass flows, generalized volume-area equations are useful but may not provide precise inundation prediction for a given topography. Coefficients of determination, $r^2$, for linear regression models of log-transformed values of volume and area commonly range from about 0.7 to 0.98 for many types of mass flows (Iverson and others, 1998; Berti and Simoni, 2007; Griswold and Iverson, 2008; Widiwijayanti and others, 2009). However, the 95- or 99-percent-confidence intervals for prediction of inundation areas tend to be large, varying between about ±0.5 to 1 order of magnitude depending on the dataset (Iverson and others, 1998; Berti and Simoni, 2007; Griswold and Iverson, 2008).

Previous analyses of these volume-area relations typically assumed fixed, maximum flow volumes with constant cross-sectional areas having no growth or deposition (Iverson and others, 1998; Schilling, 1998; Berti and Simoni, 2007; Griswold and Iverson, 2008; Berti and Simoni, 2014). The coefficient values used in these curve fits are commonly derived from maximum volumes—that is, volumes attained after all growth has occurred. Moreover, cross-sectional areas of inundation are commonly derived from these maximum volumes and thus are conservative (large) and suitable for hazard assessments. Some studies have directly examined differences in overall planimetric inundation area with and without flow bulking, noting some differences (for example, Dorta and others, 2007). However, several factors indicate that general volume-area equations can be used to also estimate inundation from flows that grow volumetrically as they travel (refer to section 3.6).

For studies that used complete inundation area (*B0* examples in table 2), such as the debris-flow analysis of Griswold and Iverson (2008), many of the observations are from flows that grew as they traveled. In these studies, planimetric areas incorporated areas affected by flow growth. On the other hand, studies that just analyzed distal depositional areas (*B1* examples in table 2), effectively assumed that all growth had already occurred before planimetric inundation. Importantly, statistical assessments of data from many debris flows show minor differences between planimetric coefficients for *B1* and mixed (*B0* and *B1*) inundation areas (Berti and Simoni, 2007; Simoni and others, 2011). This may be due to the relatively large uncertainties in the observations as well as channel morphologies (the area of upstream narrow channels may be small compared to overall planimetric area); nevertheless, it indicates that similar coefficients could be used for flows that grow as they travel provided volumes were reasonably estimated. Given that many debris flows can increase in volume as they travel, Grfin Tools has several methods for computing flow volumes during growth using the **GROWTH** tool described in section 3.6.

The Grfin Tools ***flowtype*** input field (section 4.2.2.7) allows a user to select between standard volume-area parameters ($\alpha_1$and $\alpha_2$ ) derived for three types of geophysical mass flow phenomena—debris flow (“debrisflow”), lahar (“lahar”), or rock avalanche (“rockavalanche”) (table 3)—as analyzed by Iverson and others (1998) and Griswold and Iverson (2008). Entering “custom” in this input field allows a user to specify values for $\alpha_1$ and $\alpha_2$ in the volume-area equations, such as those presented in table 2. Differences in flow inundation using different volume-area relations are illustrated in figure 13. Note that larger $\alpha_1$ values (such as for rock avalanches) can result in wider inundation, and larger $\alpha_2$ values (such as for lahars) produce more extensive overall inundation.

**Table 3.** Volume-area coefficients $\alpha_1$ and $\alpha_2$ for standard geophysical mass flow types used in Grfin Tools.

[Coefficients from Iverson and others (1998) and Griswold and Iverson (2008). $\alpha_1$ , cross-sectional coefficient; $\alpha_2$ , planimetric coefficient.]

| ***flowtype*** **name** | $\alpha_1$ | $\alpha_2$ |
|---|---|---|
| “debrisflow” | 0.1 | 20 |
| “lahar” | 0.05 | 200 |
| “rockavalanche” | 0.2 | 20 |

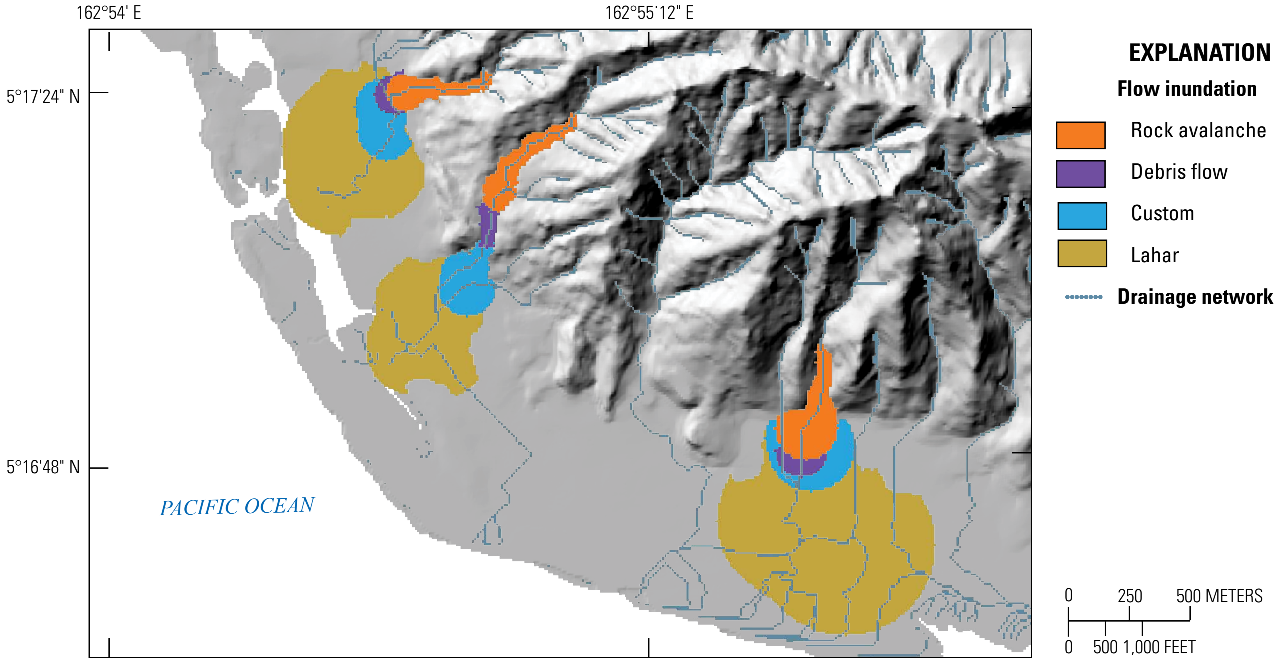


**Figure 13.** Map showing flow inundation in part of Kosrae, Federated States of Micronesia, computed using different parameters in the Grfin Tools ***flowtype*** input field for different geophysical mass flows. The worldwide relations for rock avalanche, debris flow, and lahar used in this figure are from Iverson and others (1998) and Griswold and Iverson (2008). The custom relations used in this figure are for post-fire debris flows (item 5 in table 2) from Magirl and others (2010). Computations use the same fixed volumes starting at three specified starting locations. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

## 3.5.3. Mapping Inundation in a Digital Topography

The volume-area equations (eqs. 1, 2) are integral to mapping flow inundation in digital topography. For a given flow volume, these relations are used to both construct inundation cross sections along a drainage path and to define the planimetric area inundated. Constructing cross sections along a flow path is the fundamental approach defining the lateral extent of inundation, with each section having a cross-sectional inundation area, $A$, from equation 1. The flow paths used to guide the construction of these cross sections always follow the D8 flow directions identified by TauDEM while using the **SETUP** tool (section 3.1). The starting locations for inundation depend on the Grfin Tools options selected. For example, inundation can start from user-specified points (refer to the ***user_specified_volumes_file*** input field description in section 4.2.2.7) or from Grfin-identified growth zones located in the curvature-based drainage network (using the **GROWTH** tool discussed in section 3.6).

Without growth, the starting locations are designated AB points (both $A$ and $B$ in eqs. 1, 2 are computed)—this AB designation is shown in input and output files containing flow volume information (for example, sections 4.3.4 and 4.4.2.2.3). Flow volume does not change (implying no growth or deposition) in areas downstream from AB points, as is also assumed in Laharz (Iverson and others, 1998); this is a relatively conservative assumption. Cross-sectional inundation area, $A$, is a function of the computed flow volume at any cell along a drainage path. A fixed-volume cross-sectional area may limit downstream extent as planimetric area is expended upstream in larger cross sections. Planimetric inundation area, $B$, is then computed and accumulated downstream of these AB points.

At each DEM cell along a flow path, an inundation cross section is defined perpendicular to the cell's flow direction (fig. 14). This cross section extends outward from the starting flow cell (commonly the channel thalweg), in a manner similar to Laharz (Schilling, 1998). Along the direction of each cross section, the method steps out sequentially cell by cell on each side of the starting cell (fig. 15), and compares the DEM cell elevations to the starting flow-cell elevation. If a DEM cell elevation on either side is greater than the starting cell elevation (as is typical in a valley with confining walls), this elevation denotes a temporary fill level. The method then seeks topography at a similar fill-level elevation on the opposite side of the starting flow cell and computes the cross-sectional area between this fill-level elevation and the DEM surface (fig. 15*A*). If this computed cross-sectional area, $A$, is greater than or equal to the target cross-sectional area, $A_t$, then no additional fill is needed, and the cross-section extent defines the lateral range of inundation. If the computed area is smaller than the target area, then the process continues to search for a higher fill level until the target area is reached; this will result in a wider cross section. Two additional cross sections oriented at 45° to each side of the perpendicular section (fig. 14) are assessed in the same manner. Therefore, at each flow cell, Grfin Tools assesses a total of three cross sections to better smooth inundation and account for irregularities in the DEM that would not be well captured by just one cross section.

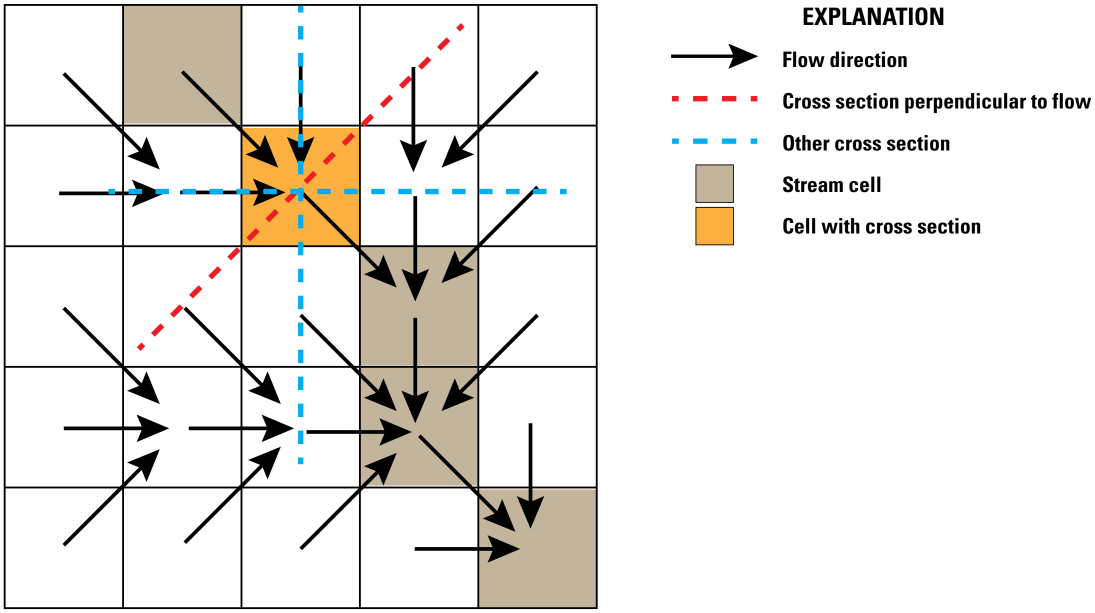


**Figure 14.** Schematic diagram showing computed flow directions between cells of a digital elevation model based on elevation differences. Flow from a cell is routed to one of the surrounding eight directions defined by D8 flow directions (black arrows). Nonwhite cells represent stream cells defined by a flow-accumulation threshold—Grfin Tools uses a curvature-based method (section 3.2). Cross-section directions used to delineate flow inundation are shown for one cell in the stream network. One section is oriented perpendicular to the primary flow direction of the cell; the other two sections are oriented 45° to either side of the perpendicular section. Modified from Schilling (1998).

**Figure 15.** Schematic cross sections of flow inundation. *A*, Confined flow bounded by topography. *B*, Partially confined flow bounded by topography on left side. *C*, Unconfined flow—in this case, height controlled by average flow height, $\bar{h}$, and not topographic barriers. Cross-sectional inundation areas, $A$, are the same in each case.

In cases where DEM elevations on one side of the cross section are below the fill-level elevation (a partially confined flow), the cross section is terminated on that side when the computed area is greater than or equal to the target area, $A_t$ (fig. 15*B*). If a cross section extends to a DEM boundary or to NODATA values within a DEM before this area target is achieved, the cross section is extrapolated using the last elevation encountered. Occurrences affected by these cross sections are attributed with special values in the inundation raster output file (section 4.4.2.1.5) and noted in an inundation output log file (section 4.4.2.1.6). Methods for computing flow planimetric inundation given these conditions are discussed below. In rare cases where a cross section does not encounter any topography in the default mode (if input field ***hbar*** is set to “no”), the section will extend to the maximum allowable width, which is equal to the maximum dimension of the DEM.

To determine the planimetric area inundated from each cell along a flow path, Grfin Tools first computes a circle with a diameter of the average of the three cross-section widths (fig. 16). The elevation of this fill circle is set at the highest elevation of the three sections and its center is the average $x$ and $y$ locations of the mid-points of the three sections. Then, the part of this circle elevated above the encompassed DEM cells is considered inundated. Circle filling is performed using a breadth-first search (BFS) method (Cormen and others, 2022) for efficiency. The extent of inundation results from the series of overlapping circles progressing down the flow path. This average-circle method systematically smooths inundation areas and eliminates spikey map-view artifacts such as those sometimes generated by Laharz (fig. 16*A*) in unconfined or partially confined areas (for example, Muñoz-Salinas and others, 2009; Reid and others, 2016). Moreover, a circle shape reasonably approximates part of an elastica curve minimizing bending energy (Levien, 2008), which is similar to typical observed flow-front shapes.

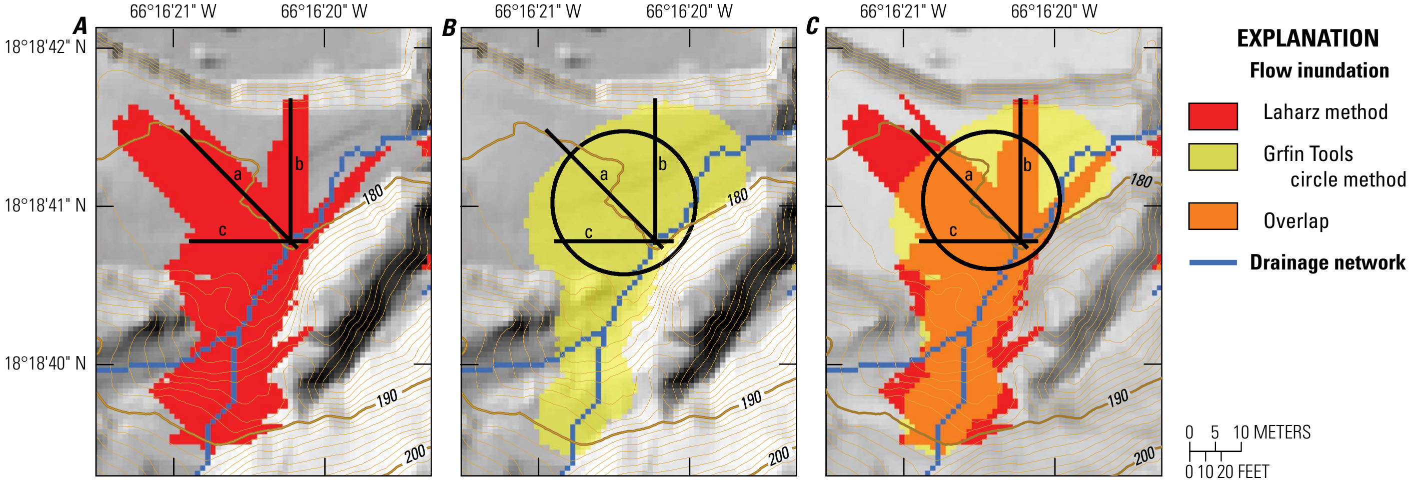


**Figure 16.** Maps comparing flow inundation patterns in part of Utuado, Puerto Rico, from two different methods. Cross section a is perpendicular to flow; cross sections b and c are oriented 45° from a. *A*, Inundation using method from Laharz (Schilling, 2014). *B*, Inundation using Grfin Tools average-circle method (circle shown using the average width of the three cross sections). *C*, Comparison of methods. Orange indicates overlap between the two methods. Total planimetric inundation area is similar with the two methods, but the spatial distribution differs. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

To compute the overall planimetric inundation area, $B$, equation 2 is used to define a target planimetric inundation area, $B_t$, based on a given volume. The cross-section approach described above defines the lateral extent of inundation, whereas the target planimetric-area approach controls the overall downstream extent of inundation. As cross sections and circles are constructed progressively down a flow path, the resulting planimetric inundation is accumulated for each incremental step. When the cumulative amount equals or exceeds the target area $B_t$, inundation halts.

In more unconfined areas, large inundation circles can engulf large planimetric areas and, thus, tend to rapidly halt inundation as cumulative inundation reaches or exceeds the target planimetric area. However, it is possible for these circles of inundation to significantly overshoot the target area, especially in DEMs with larger cell sizes and smaller flow volumes. In these situations, Grfin Tools iteratively reduces the circle radius until the cumulative planimetric inundation area is within 20 percent of the target area. This 20-percent tolerance enables matching the target inundation area in coarse DEMs with small flows without adverse effects.

In most cases, cross sections will encounter some topography that is at least slightly higher than the starting flow-cell elevation (as channels tend to be at lower elevations), thereby allowing fill elevations to define a cross-sectional area. Because the **INUNDATION** tool uses the average of three sections, most flows transiting from mountainous topography onto gentler ground will likely encounter some elevated topography. With fewer topographic restrictions in gentler ground, expanding circular areas mimic spreading (fig. 17). The resulting inundation is generally conservative (affecting more area near the transition to gentler ground; fig. 17*A*) and may be appropriate for many hazard assessments.

In cases where a cross section extending from a DEM cell along a flow path reaches a DEM boundary or NODATA cells (no active DEM cell present), the cross section is extrapolated using the last elevation encountered in the active DEM area. If the resulting circle of inundation (from three cross sections) has a center located within the active DEM, planimetric inundation is delineated as described above. On the other hand, if the center is in an inactive area, the cross section is recomputed using the ***hbar*** option described below, and the circle of inundation and its center recomputed. Inundation is then delineated using the recomputed circle. These steps help ensure that inundation is not based on unrealistically wide cross-sections in areas close to the boundary of an inactive DEM area. The resulting planimetric inundation area may be less than the target area, as no inundation occurs beyond the DEM boundary or within NODATA areas.

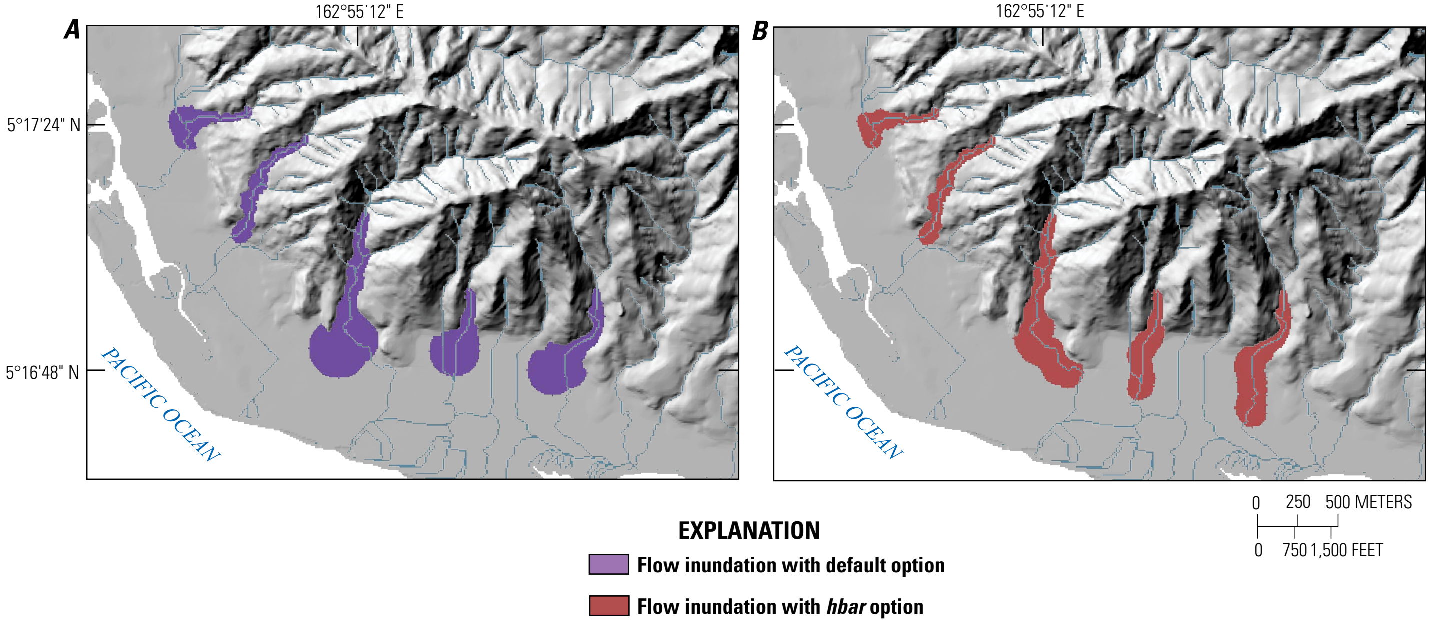


**Figure 17.** Maps comparing flow inundation options in part of Kosrae, Federated States of Micronesia, computed in Grfin Tools using debris-flow relations with fixed volumes starting at five specified locations. Inundation extends onto relatively unconfined flat topography beyond a mountainous range front. *A*, Inundation using default average-circle method. *B,* Inundation using the ***hbar*** option. Planimetric inundation areas are similar in both *A* and *B*. Blues lines represent stream network. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

For situations with completely flat or highly divergent topography where flow is not confined within a valley, cross sections cannot be rationally constructed and can potentially be unrealistically wide. Grfin Tools includes a selectable input field (***hbar***) to effectively restrict cross-sectional width using the average inundation height, $\bar{h}$, defined as $V/B$ for a given flow volume (fig. 17*B*). This assumes that $\bar{h}\big/\sqrt{B}$ is essentially constant with changing volume, as posited in Iverson and others (1998). Figure 18 shows the relation between average height and volume, assuming the default worldwide volume-area equations (Iverson and others, 1998; Griswold and Iverson, 2008); as expected, average height increases with increasing volume. As an example, the default assumption for debris flows implies that

$$\bar{h} = 0.05V^{1/3}, \tag{3}$$

Berti and Simoni (2007) used average height to estimate debris-flow inundation originating in channels but overflowing onto unconfined depositional fans. Grfin Tools expands on this idea—if the ***hbar*** option is selected then all cross sections (confined or unconfined) and thus the corresponding average circle must have at least an overall average fill height of $\bar{h}$ (fig. 15*C*).

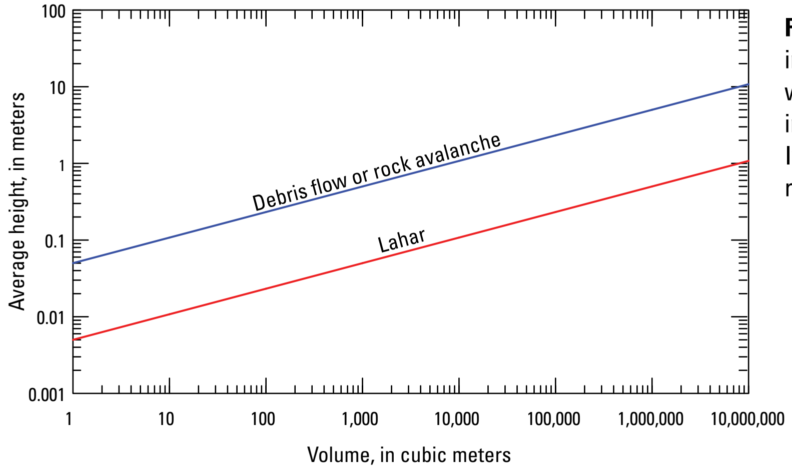


**Figure 18.** Graph showing average height of inundation, $\overline{h}$ , versus flow volume, $V$, using the worldwide debris-flow and rock-avalanche planimetric inundation volume-area relations from Griswold and Iverson (2008) and the lahar inundation volume-area relation from Iverson and others (1998).

The average fill height restriction has little effect where cross sections are narrower in confined topography with higher flow-fill elevations (for example, the two western drainages in fig. 17*B*). However, it does effectively control both inundation height and thus width in more unconfined, typically gentler, topography. In these situations, the ***hbar*** option enforces less lateral spreading to achieve the target area and thereby leads to a more extended, tongue-like planimetric inundation geometry (for example, the three southern drainages in fig. 17*B*). Total planimetric inundation areas with or without the ***hbar*** option are similar (compare parts *A* and *B* of fig. 17). A potential downside of the ***hbar*** option is that tongue-like inundation can more closely follow poorly defined and unrealistic drainages across gentle terrain. In actual physical settings with unconfined areas, more circular inundation has been observed with more fluid flows (for example, Tsai, 2006), whereas more tongue-like inundation can occur in the presence of strong lateral levee development and greater flow momentum (for example, George and Iverson, 2014). In addition, the effects of the ***hbar*** option can be reduced when using lahar volume-area relations (fig 18).

## 3.6. Growth of Flows (GROWTH Tool)

*This section describes the selection of one or multiple methods to define growth zones and the selection of components and methods to compute flow volumes within those growth zones. It provides guidance on selecting methods for defining growth zones and computing growth volumes using upslope source area- or channel length-dependent growth factors.*

### 3.6.1. Overview

Many geophysical mass flows grow as they travel downslope and downstream—this growth can lead to larger volume flows with greater inundation areas. As flows grow, their increased volume enhances speed, mobility, and destructiveness (Corominas, 1996; Iverson and others, 2011; Barnhart and others, 2021). Flows can grow by more than an order of magnitude compared to their initial volume (Hungr and others, 2005; Santi and others, 2008). As an alternative to initially specifying these flow volumes and locations (section 4.2.2.7), Grfin Tools can automatically generate flow volumes that increase downstream using the **GROWTH** tool (section 4.2.2.6). This option is then used in conjunction with the **INUNDATION** tool (section 4.2.2.7) to delineate inundation from flows that grow volumetrically downstream. The **GROWTH** tool has potential advantages: incorporating the growth of flows can create more realistic inundation zones higher in the drainage network (where growth occurs) and flow volumes and locations can be identified without needing to specify these constraints beforehand. This section provides guidance on selecting appropriate growth options as well as insight for interpreting patterns of growth. The parameters for this tool are described further in section 4.2.2.6). Section 2 outlines pathways for using the **GROWTH** tool.

Physical processes contributing to volumetric growth can differ between types of geomorphic terrain and can also vary spatially and temporally within terrain (for example, Reid and others, 2016). Debris-flow growth, for example, occurs in many settings, including steep forested slopes, alpine terrain, post-wildfire burned landscapes, breached glacial lakes, and volcano flanks (Hungr and others, 2005; Reid and others, 2016). Growth can result from erosion and entrainment of channel bed sediment (Takahashi, 1991; Hungr and others, 2005; Iverson and others, 2011), collapse of stream banks (for example, Johnson, 1970), debris contributions from nearby landslides (Hungr and others, 2005), rilling and surface erosion of adjacent hillslopes (Santi and others, 2008), and coalescence of multiple flows downstream of channel junctions (Coe and others, 2011a; Coe and others, 2011b). Some of these growth processes occur on upslope contributing areas whereas others are focused in stream channels. Moreover, debris flows may originate either from discrete landslides or from runoff processes that affect upslope areas or upstream channels. With surface-runoff generated flows, growth can occur from processes such as hillslope erosion or channel-bed entrainment. In contrast, growth of rock avalanches tends to be primarily from entrainment of overridden sediment (Hungr and Evans, 2004; Aaron and McDougall, 2019). Explicitly incorporating the wide assortment of growth processes into computational dynamic flow routing models can be difficult, although some models include sediment entrainment (McDougall and Hungr, 2005; Hungr and McDougall, 2009; Hussin and others, 2012; Iverson and Ouyang, 2015; Han and others, 2020; Zheng and others, 2021).

Instead of attempting to quantify the amount and extent of each individual growth process, Grfin Tools lumps the effects of any growth processes into power laws with empirically determined growth factors (or spatial growth rates). These growth factors are sometimes referred to basin lowering rates when scaled to upslope contributing area (Reid and others, 2016; Coe and others, 2021) or as bulking or yield rates when scaled to channel length (Hungr and others, 1984) or erosion. Growth factors based on upslope source area are in units of $L^3/L^2$, and growth factors based on channel length are in units of $L^3/L$, where $L$ is DEM units of length. In natural settings, growth may not be uniform along a flow path—flows can both erode and deposit as they travel, with growth occurring predominantly in upper, steeper parts of a basin (Benda and Cundy, 1990; Fannin and Wise, 2001; Theule and others, 2015). However, overall growth factors can be determined in areas of growth by comparing topography from before and after a flow event from either field mapping or lidar-derived or photogrammetrically derived DEMs (Reid and others, 2016; Coe and others, 2021). Growth factors can also be estimated using values previously obtained for similar terrain (Reid and others, 2016).

In Grfin Tools, growth factors are used in power laws and integrated over upslope contributing area and (or) upstream channel length to obtain flow volumes for various location in growth zones (refer to section 4.2.2.6.2 for more complete explanation). Users can select a particular method depending on the nature of the growth data available (for example, growth factors based on either upslope source area or upstream channel length) or the predominate physical processes occurring in the study area (for example, area-dependent growth processes like erosion or landsliding or length-dependent growth processes like bed entrainment or bank failure). It is also possible to combine multiple growth methods for any given area. In addition, growth can be limited to a maximum volume for a given setting.

Implementing volumetric growth is accomplished in two steps:

1. define the growth zones along an existing drainage network, and
2. calculate the flow volumes at each location along the growth zones.

These two steps are detailed in sections 3.6.2 and 3.6.3. The extent of spatial inundation from the volumetric growth of flows is an interplay between the location of the growth zones, the growth factors used in the area- and (or) length-dependent growth calculations, and any additional limitations on growth, such as a specified maximum volume.

The primary output files from the ***growth*** option include a raster image of the growth zones along the drainage network (<*DEMfilename*>*_grzone.tif*) and a shapefile containing volume components for each location in the growth zones (<*DEMfilename*>*_volumes.shp*). The contents of these files are further described in section 4.4.2.2.

## 3.6.2. Growth Zones

The first step in implementing flow growth is to define potential growth zones within the DEM. Growth zones, where volumetric growth potentially occurs, follow and depend on a drainage network. The ***growth*** option will automatically create a new drainage network using the default settings if a network has not been already created or previously saved (refer to section 3.4). At the downstream ends of each growth zone (defined as an AB point), inundation will continue propagating downstream into non-growth zones (refer to section 3.5). Typically, volumetric growth in flows occurs in the upper, steeper, and more confined parts of a drainage network (fig. 19). Each cell within a growth zone can have a different flow volume. Only cross-sectional inundation, $A$, is computed in growth zones—thus, all cells within growth zones are designated as A points in input and output files (sections 4.3.4 and 4.4.2.2). Planimetric inundation area is tracked only in non-growth zones. Methods for computing flow volumes in the growth zones are described in section 3.6.3.

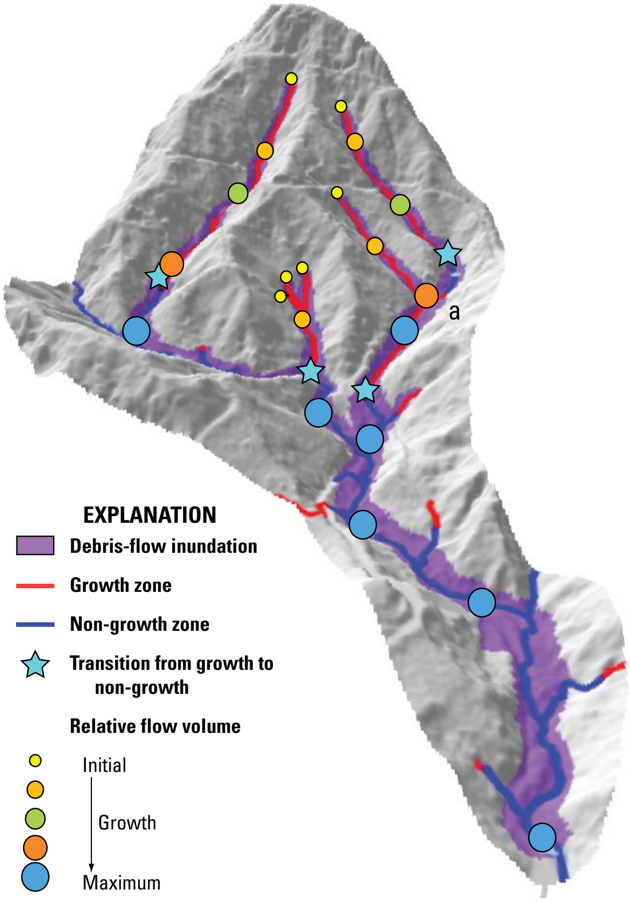


**Figure 19.** Example perspective view of topography showing a drainage network with volumetric growth and non-growth zones as well as debris-flow inundation computed using Grfin Tools. In growth zones, only cross-sectional inundation is computed (A points), and coalescence of flows can abruptly increase flow volumes downstream of tributary junctions (for example, location a). In this example, multiple growth zones can exist in each channel and relative flow volumes at select locations can be limited by a maximum volume. Downstream ends of growth zones are locations for the continuation of cross-sectional inundation and the initiation of planimetric inundation (AB points). Inundation downstream of growth zones matches the target planimetric areas (refer to fig. 11).

As many DEMs are clipped to a rectangular shape, typically there are partial drainage basins around the edges of DEMs—these are identified by TauDEM while using the **SETUP** tool. By default, Grfin Tools does not include any growth from partial basins and the effects of not including these partial basins can propagate into downstream basins within the DEM. Grfin Tools has an option to include growth in partial basins within the DEM (***include_partial***). However, even including partial basins may not fully reflect potential contributing volumes from outside the DEM, as outside source areas or channels are not included. This can lead to complications assessing growth from partial basins—some of these complications are illustrated in section 5.1.

Given that many physical processes and geomorphic settings potentially affect flow growth, Grfin Tools offers a suite of options for defining growth zones within drainage networks (table 4), as described below. At least one method is required for the ***growth_options*** section, although multiple methods may be used in combination to better target potential growth zones in different geomorphic settings. Combining options to obtain growth zones with multiple attributes is further described below. Grfin Tools includes methods that define continuous growth zones, leading to distinct transitions from growth in the proximal (upstream) areas to no growth in the distal (downstream) areas. Continuous growth zones do not have upstream non-growth zones in a given channel; however, multiple continuous growth zones may exist throughout a drainage basin. It also includes options that account for variations in local conditions; such conditions may result in multiple discontinuous growth zones interspersed with no-growth segments. This starting and stopping of growth along a drainage has been observed in different field settings (for example, Guthrie and others, 2010; Coe and others, 2021; Scheip and Wegmann, 2022).

**Table 4.** Methods for defining growth zones using Grfin Tools.

[Only one method is required, but these methods also may be used in any combinations. DEM, digital elevation model]

| Approach | Description | Always defines continuous zones?[1] | Input field |
|---|---|---|---|
| Stream slope | Local gradient of drainage | No | ***min_stream_slope*** |
| Curvature | Planform curvature from smoothed DEM | No | ***min_curvature_growth*** |
| Source-area ratio | Ratio of source area to total area | No | ***min_sourcearea_ratio*** |
| Stream order | Strahler order | Yes | ***max_stream_order*** |
| Contributing area | Area upslope of a location | Yes | ***max_contrib_area*** |
| Growth-zone raster | User-defined growth zones | Possible | ***growth_zone_raster*** |
| Growth-zone ratio[2] | Ratio of growth-zone length to upstream channel length | Possible | ***min_growthzone_ratio*** |

[1] Continuous growth zones do not have upstream non-growth zones.

[2] This approach can only be applied after at least one other growth-zone method has been applied.

Here we briefly describe each growth-zone approach and discuss some advantages and disadvantages of each approach, though many of these approaches can produce growth zones that are similar in appearance (fig. 20). The growth-zone ratio approach requires the prior application of other growth-zone approaches—its use is described in section 3.6.2.7.

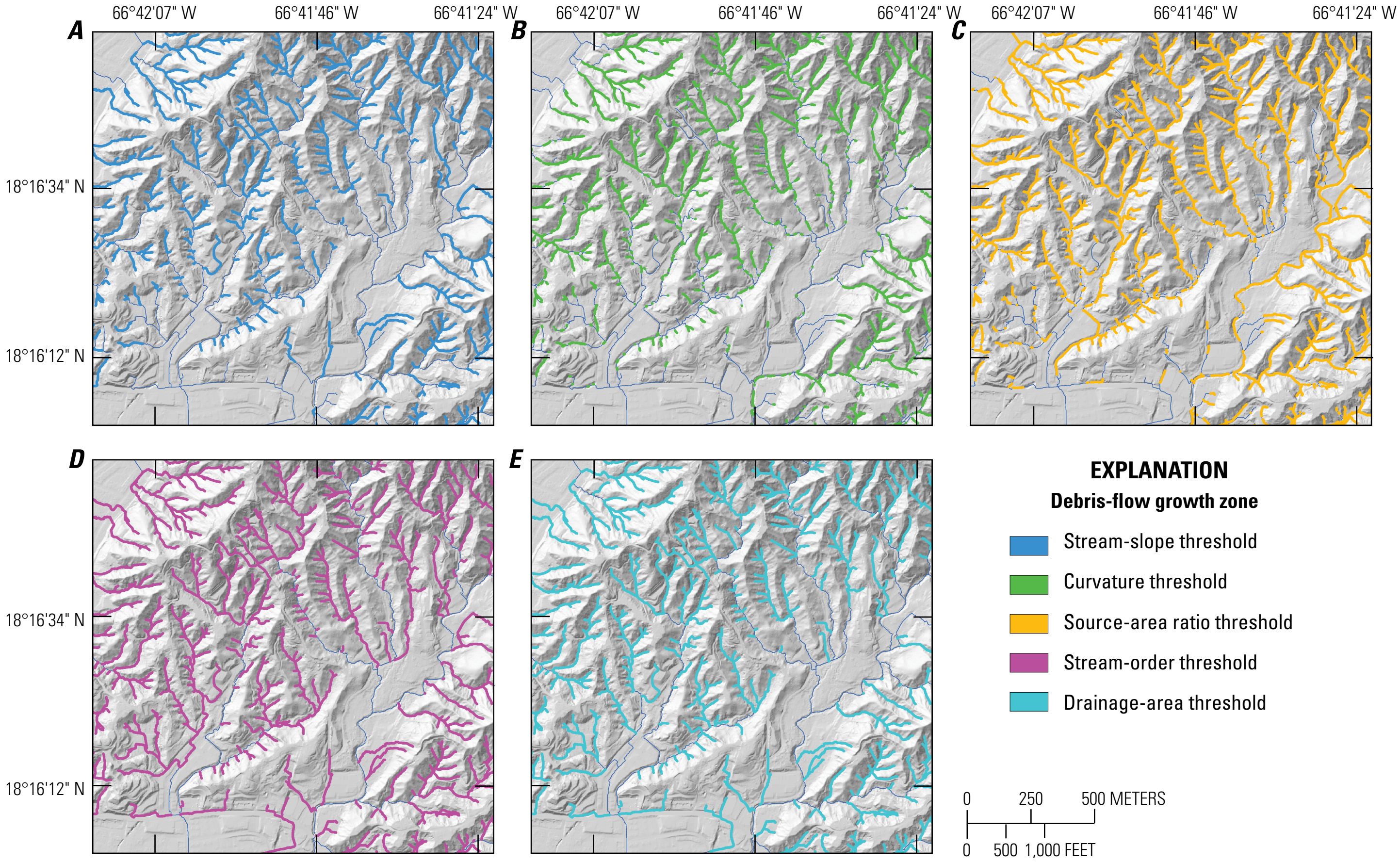


**Figure 20.** Maps showing potential debris-flow growth zones in part of Utuado, Puerto Rico, defined using different threshold options in the Grfin Tools **GROWTH** tool. *A*, Stream slope with default stream-segment method (***min_stream_slope*** set to "5"). *B*, Curvature method (***min_curvature_growth*** set to "0.02"). *C*, Source-area ratio method (***min_sourcearea_ratio*** set to "0.2"). *D*, Stream order method (***max_stream_order*** set to "3"). *E*, Upslope contributing drainage area method (***max_contrib_area*** set to "50000"). Parameter values are set by the user—values shown are for illustrative purposes. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

### 3.6.2.1. Stream Slope

The stream-slope method uses the local stream slope along the channel drainage network (refer to section 3.4) to define growth zones. Segments of the drainage network with stream slopes greater than a minimum threshold value (***min_stream_slope***) will be included in the growth zones (fig. 20*A*). Growth zones defined using a stream-slope threshold may start and stop along a drainage path. Stream slope is a dominant control on erosion and growth and generally provides a physically plausible control on flow growth and deposition with thresholds that are readily available (for example, Fannin and Wise, 2001; Guthrie and others, 2010; Reid and others, 2016; Coe and others, 2021), typically in the 3 to 10° range. Examples D, E and G (section 6) utilize the stream-slope method.

Local stream slope values depend on the stream length over which slope is computed. The default method in Grfin Tools uses slopes computed over stream segments between tributaries as performed by the StreamNet function in TauDEM (Tarboton and others, 2015). With this method, stream slopes are averaged over segments of potentially different lengths (fig. 21*A*). A stream-segment approach (***slope_method*** set to "segment") is common with models for stream sediment transport. If more detail in stream slope is desired (such as on locally steep or gentle stream slopes), Grfin Tools includes the option to average stream slopes over a fixed horizontal distance (***slope_method*** set to "downstream") instead of over segment lengths (fig. 21*B*). The default distance for computing stream slopes with the fixed-distance method is 50 m, but this value (***downstream_distance***) can be modified by the user.

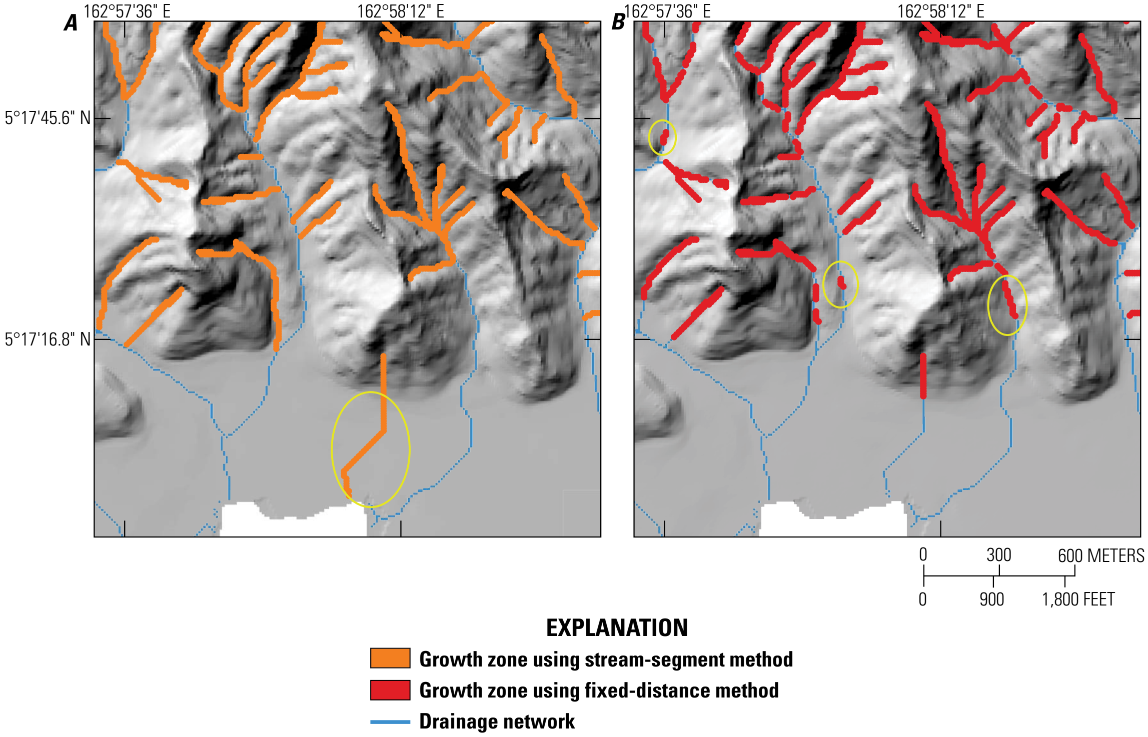


**Figure 21.** Maps showing potential drainage-network growth zones in part of Kosrae, Federated States of Micronesia, defined using two different methods for computing stream slopes in Grfin Tools; both methods use a minimum stream slope threshold of 5° (***min_stream_slope*** set to "5"). *A*, Default stream-segment method. *B*, Fixed-distance method. Circled areas show possible stream-slope growth zones that might exaggerate downstream inundation for each method. Refer to section 3.6.2.7 for ways to minimize these effects. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

Commonly, either the stream-segment or fixed-distance method using the same stream-slope threshold will yield similar growth zones. However, both methods have some deficiencies that can extend growth zones downstream, potentially leading to excessive growth and thereby exaggerated inundation. These effects can be particularly acute when using the area-growth method, as volumes computed within growth zones are a function of the entire upslope source area. Therefore, isolated growth zones downstream can create large flow volumes. For the stream-segment method, small, isolated growth zones are uncommon, but single-reach streams may produce average values that do not reflect locally steep or gentle sections, resulting in growth zones that extend across gentle fans or alluvial flats (fig. 21*A*). For the fixed-distance method, isolated downstream growth zones can be abundant and thereby may artificially increase flow volumes (fig. 21*B*). For both methods, many of these issues can be eliminated by combining multiple growth-zone methods (section 3.6.2.7).

#### 3.6.2.2. Curvature

The curvature method uses planform curvature (refer to section 3.4) greater than a minimum threshold (***min_curvature_growth***) to define growth zones (fig. 20*B*). In many settings, flow growth is strongly influenced by channel confinement (for example, Corominas, 1996) and topographic curvature provides a proxy for channel confinement. As local curvature values can vary over a drainage network, growth zones using this method may start and stop along a drainage path. This method can be used in combination with other options to eliminate modeled flows originating from relatively planar or convex slopes (refer to Brien and others, in press).

#### 3.6.2.3. Source-Area Ratio

The source-area ratio method defines growth zones based on the ratio of upslope source area to the total contributing area (source area/total area) at a growth-zone cell. Parts of the drainage network with source-area ratios greater than a minimum value (***min_sourcearea_ratio***) will be included in growth zones (fig. 20*C*). The method requires source areas to be defined (refer to section 3.2). In general, this ratio decreases downstream, as source areas tend to be more prevalent upstream. Thus, in downstream growth zones, the ratio of upslope source area to total contributing area is less. When used to define growth zones, this method implies that topographic areas with a smaller amount of source area are less likely to produce flow growth and areas with a larger amount of source area are more likely to aid growth. By combing this method with other growth-zone approaches, this option can screen out downstream areas where growth is unlikely (refer to example G, section 6.7 and Brien and others, in press). Examining the source-area ratio output file from a previous run (section 4.4.2.2.4) can help identify a reasonable threshold value. Ratios greater than 0.6 may define areas prone to growth and ratios less than 0.1 to 0.3 are unlikely to have significant debris-flow growth. Small values can be used in combination with other growth methods to limit the downstream extent of growth zones (example G, section 6.7).

#### 3.6.2.4. Stream Order

The stream-order method relies on the Strahler (1957) stream numbering system to define growth zones (fig. 20*D*). Segments of the drainage network with stream order less than a maximum threshold value (***max_stream_order***) will be included in growth zones. Strahler stream-order numbers start at the top of the drainage network with values of one for the initial stream segments (Strahler, 1957). Thus, this method targets drainages high in the stream network. This method is scale dependent, with larger basins typically including a greater number of streams. It defines continuous growth zones without upstream non-growth zones, allowing a clear distinction between proximal and distal areas. However, stream order may not perform well when using the same stream-order threshold across diverse types of terrain. This approach can also be combined with other methods to limit the downstream extent of growth zones using an appropriate stream-order threshold (example G, section 6.7).

#### 3.6.2.5. Contributing Area

The contributing-area method creates continuous growth zones (without upstream non-growth zones) using an upslope contributing-area threshold (fig. 20*E*). Here, growth zones are defined in drainage segments with contributing areas less than a maximum threshold value (***max_contrib_area***). This approach assumes that growth zones are located in the upper, smaller parts of a basin, but it does not account for local variations in topography, such as drainage density and basin shape. This method could be used in conjunction with slope-area thresholds that identity areas dominated by certain erosional processes, such as erosion by debris flows instead of water flows (Stock and Dietrich, 2003, 2006; Staley and others, 2014).

#### 3.6.2.6. Growth-Zone Raster

The growth-zone raster method (***growth_zone_raster***) requires a user-provided growth-zone raster (section 4.3.2). Such a raster can be utilized in two ways:

1. It can identify growth zones by itself based on criteria specified by the user. For example, it could delineate areas of readily entrainable sediment. Alternatively, it could be used to demarcate the growth-prone drainage upstream of a user-specified transition point or pour points in a drainage network.
2. It can be used in combination with other growth-zone methods to restrict growth zones. For example, a growth-zone raster could identify a particular drainage basin targeted for analysis within a DEM. Then, a combination of other selected growth-zone options with this raster would identify growth zones within the particular drainage. Example E (section 6.5) illustrates this option.

For each growth-zone method, variations in the maximum or minimum threshold can define different growth zones. For example, decreasing the stream slope threshold to include gentler slopes will allow growth zones to extend farther downstream (fig. 22). This can have a large effect on the extent of computed flow-inundation zones. Moreover, extending growth zones to gentler ground may increase the prevalence of discontinuous growth zones.

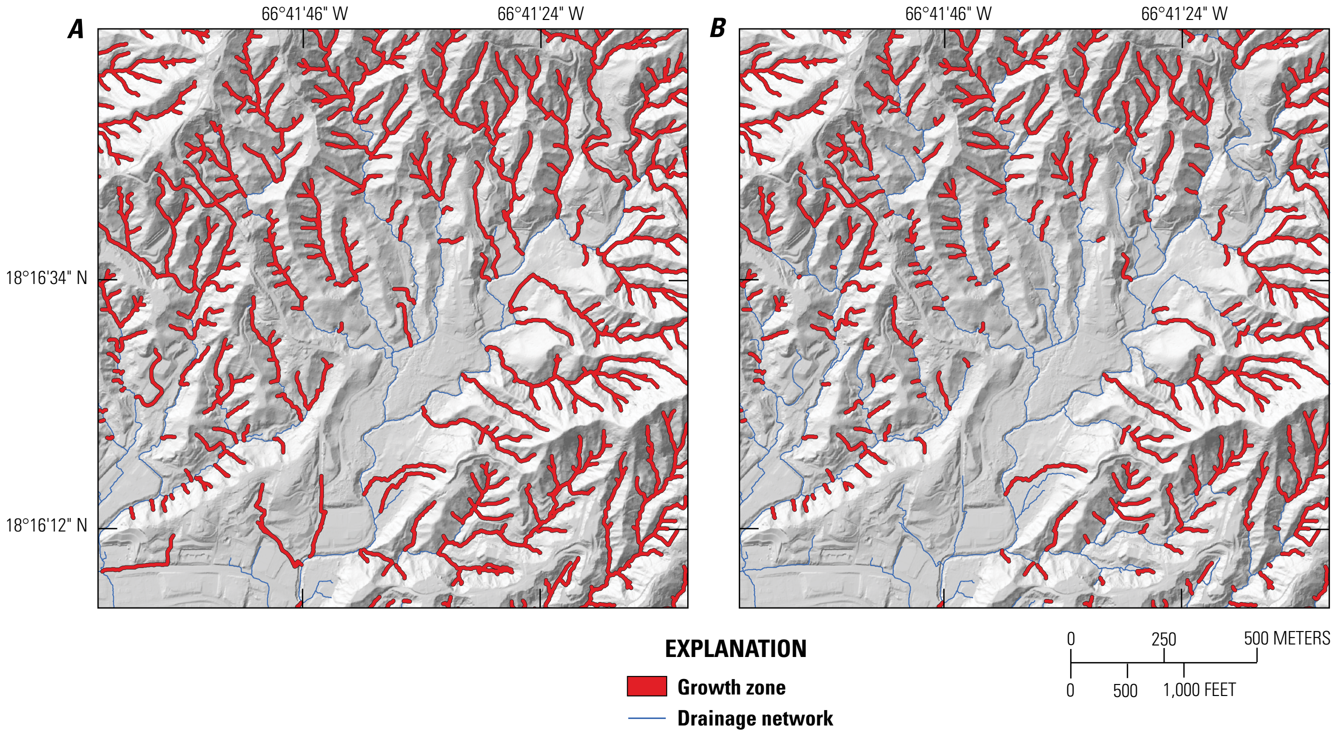


**Figure 22.** Maps showing potential drainage-network growth zones in part of Utuado, Puerto Rico, defined using the default stream-segment method and different stream-slope thresholds (using ***min_stream_slope***) in Grfin Tools. *A*, Lower stream-slope thresholds (here 5°) extend the growth zones into lower, flatter topography. *B*, Higher stream-slope thresholds (10°) limit the growth zones to upper, steeper topography. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

### 3.6.2.7. Combination of Growth-Zone Methods and Growth-Zone Ratio

Any of the growth-zone parameters described above can be combined in Grfin Tools to define growth zones for inundation. An additional option, ***min_growthzone_ratio*** (described below), can be used in conjunction with at least one of the other growth-zone options. The combined growth zones from multiple options must meet all of the selected parameters (using Boolean operator AND); thus, the resulting growth zones from multiple options typically will be less extensive than those from a single option. However, the use of multiple parameters can also lead to greater fragmentation of the growth zones. Small growth-zone fragments can strongly influence local inundation patterns.

Combining different growth-zone methods can mitigate the deficiencies of a single method. For example, with the stream-segment method, single-reach streams can create undesirable growth zones extending across flatter topography. These undesirable sections typically can be removed by adding a low threshold value of curvature (such as 0.001) as a secondary growth-zone method. A low curvature threshold removes more planar or divergent topography (such as on fans or alluvial flats) from the growth zones (fig. 23). This approach can sometimes be useful when using the stream-segment method.

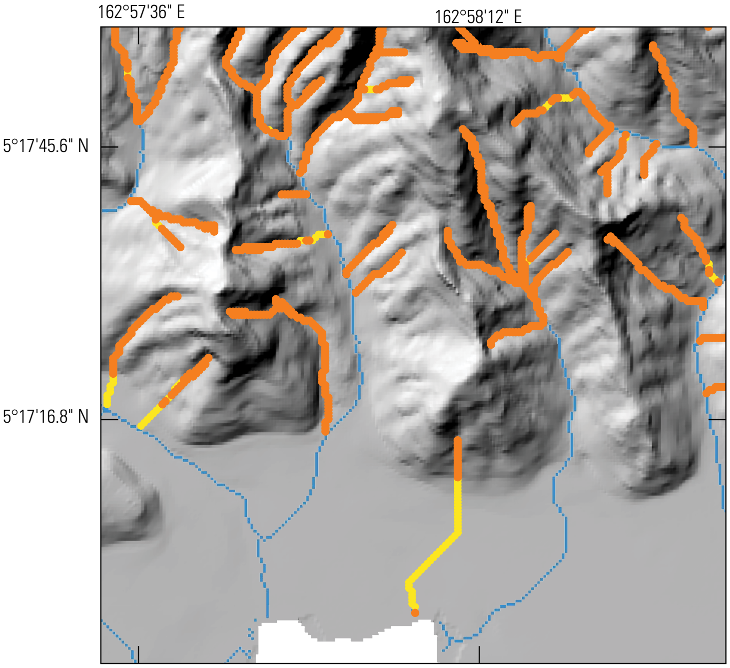


**Figure 23.** Map showing potential drainage-network growth zones in part of Kosrae, Federated States of Micronesia, defined using a combination of two thresholds in Grfin Tools: the default stream-segment method (***min_stream_slope*** set to “5”) and the minimum curvature method (***min_curvature_growth*** set to “0.001”). Single-reach stream segments in flat areas (having minimal curvature) are removed from the resulting growth zones. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

With the fixed-distance stream-slope method, small, discontinuous, and isolated growth-zone sections can be created in downstream sections of the drainage network. If the area-growth method is also being applied, adding a low threshold of source-area ratio (such as 0.1–0.3) as a secondary parameter can sometimes eliminate these isolated sections as growth zones (fig. 24). A low threshold of source-area ratio essentially screens out growth-zone segments that have little source area nearby compared to the entire upslope area. This approach can be effective when using the fixed-distance method with area growth, as illustrated in Example G (section 6.7).

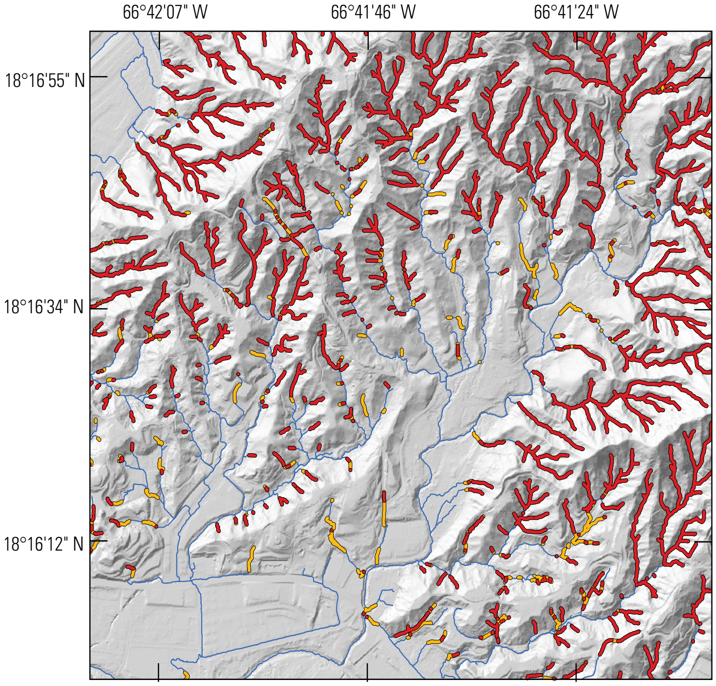


**Figure 24.** Map showing potential drainage-network growth zones in part of Utuado, Puerto Rico, defined using a combination of two thresholds in Grfin Tools: the fixed-distance stream-slope method (***min_stream_slope*** set to “5”) and the source-area ratio method (***min_sourcearea_ratio*** set to “0.3”). Small, disconnected downstream segments that meet the stream-slope threshold but not the source-area ratio threshold are removed from the growth zones. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

Another method for removing small, isolated growth zones is to use the growth-zone ratio option (***min_growthzone_ratio***)—this is applied after potential growth zones have been identified by at least one of the growth-zone methods described above. This feature utilizes the ratio of the upstream length of growth zones to the total upstream channel length at a growth-zone cell. Thus, higher growth-zone ratios indicate a greater spatial density of growth zones upstream, where growth might be likely to occur. Lower ratios indicate growth zones are sparse over the upstream network. The growth-zone ratio for each cell is computed after the growth zones are defined by other methods, resulting in values dependent on the previously determined growth zones. Applying a growth-zone ratio threshold will typically remove sparse, downstream growth-zone segments. Examining the growth-zone ratio output file (section 4.4.2.2.5) following a run can help identify a reasonable threshold for an area of interest; an appropriate value might differ between types of geomorphic terrain. However, a single minimum user-selected value will be applied to the entire domain under consideration. A low growth-zone ratio (such as <0.5) can be used to eliminate undesirable isolated growth-zone segments located far downstream from the areas with a greater density of growth zones. A high growth-zone ratio (for example, 0.9–0.95) will only retain growth-zone segments near other growth zones.

One possible use of the ***min_growthzone_ratio*** input field is illustrated in figure 25. Here, defining growth zones using the stream-segment method and a curvature threshold created some growth-zone fragments and these fragments produced isolated areas of inundation located downstream (fig. 25*A*). Growth in these downstream segments, such as those circled near the coast, may be unlikely and result in too much downstream inundation. Examining the growth-zone ratios output file, *<DEMfilename>_grzoneratio.tif* (generated using the ***min_growthzone_ratio*** input field), for this scenario (fig. 25*B*) indicates that the circled growth-zone fragments have a growth-zone ratio less than about 0.5. After applying a minimum threshold of 0.5, the resulting growth zones do not include the circled areas (fig. 25*C*) and this reduction removes the downstream, isolated areas of inundation. This low growth-zone ratio retains most of the other upstream growth-zone segments.

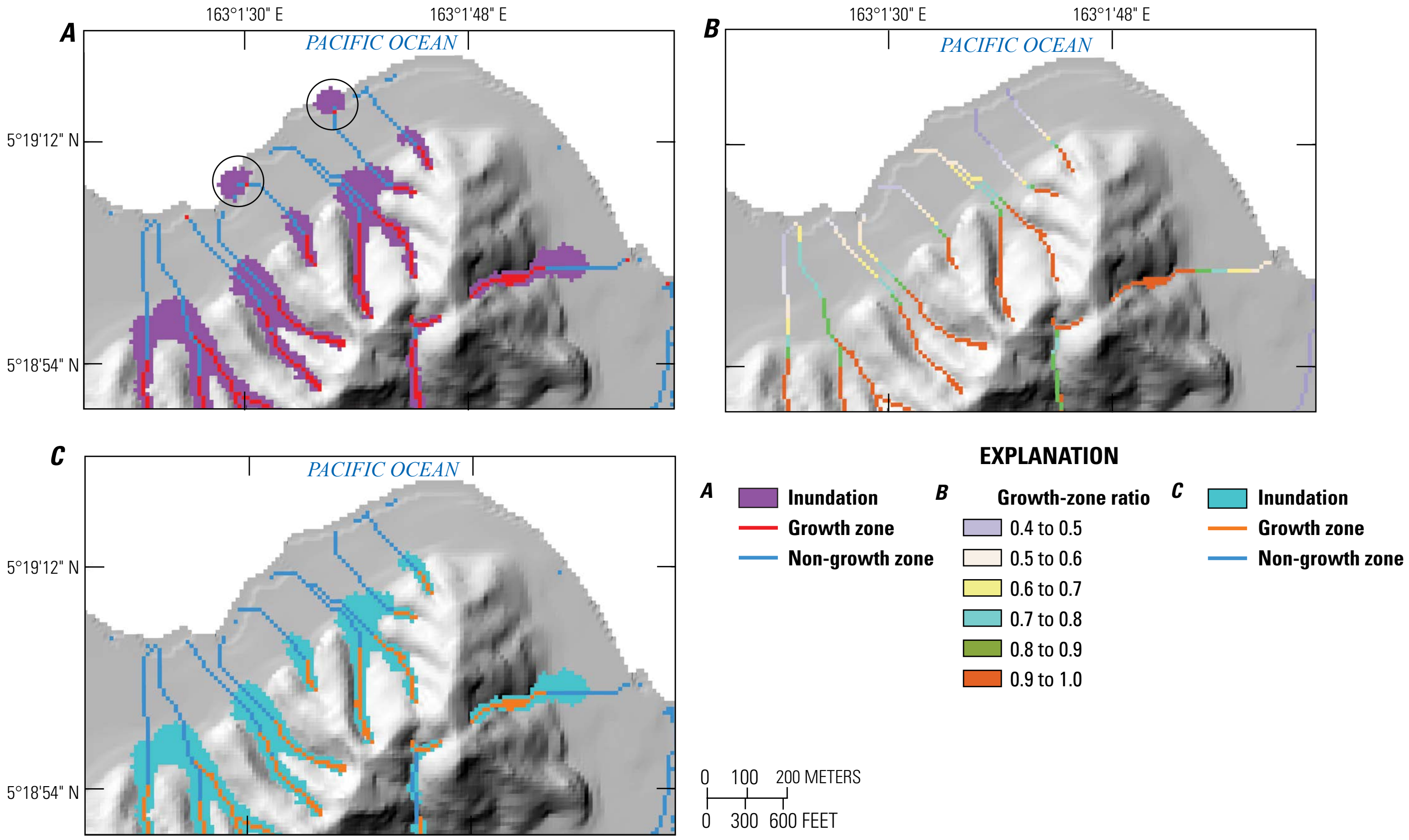


**Figure 25.** Maps showing potential drainage-network growth zones in part of Kosrae, Federated States of Micronesia, illustrating use of the ***min_growthzone_ratio*** option in Grfin Tools. *A*, Growth zones defined using the stream-segment method (***min_stream_slope*** set to "5") and a minimum curvature threshold (***min_curvature_growth*** set to "0.001") and resulting inundation areas. Note two small growth zones near the coast (circled) that lead to excess inundation. *B*, Growth-zone ratios showing values around 0.5 near the coast. *C*, Growth zones defined as in *A* with a minimum growth-zone ratio threshold of 0.5 to remove the small coastal segments. Here, excess inundation at the coast is excluded. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

### 3.6.3. Growth Volumes

After potential growth zones are defined (refer to section 3.6.2), the second step for the **GROWTH** tool is to compute flow volumes at each cell along the growth zones. Variable flow volumes along the growth zones provide the basis for computing inundation in these areas (section 3.5.3). In Grfin Tools, flow volumes from growth can be computed using two primary methods: integration of growth over upslope source area (area growth) and (or) over upstream channel length (length growth) in the growth zones. Only one method is required to compute flow volumes and using only one method provides the simplest forecasting model. However, area- and length-growth methods can also be combined in the ***growth_options***. In addition, volumes in the growth zones can be affected by two other user-specified constraints:

1. a maximum volume limit, $V_{\max}$, and (or)
2. point sources located upslope of growth zones, $V_{\mathrm{pt}}$ (section 4.3.3).

The choice of method(s) allows flexibility for a particular analysis, depending on available growth factors and the nature of the growth processes. Area growth and length growth obey the following power laws, similar to those presented in Reid and others (2016) with the addition of an exponent:

$$V_U = c_1 (U_{\mathrm{src}})^a \text{ , and} \tag{4}$$

$$V_L = c_2 (L_{\mathrm{gz}})^b \text{ ,} \tag{5}$$

where

$V_U$ is area-growth volume ($L^3$),
$V_L$ is length-growth volume ($L^3$),
$c_1$ is the area-growth factor ($L^3/L^2$),
$c_2$ is the length-growth factor ($L^3/L$),
$U_{\mathrm{src}}$ is upslope contributing source area ($L^2$),
$L_{\mathrm{gz}}$ is upstream channel length in growth zones ($L$),
$a$ is the area-growth exponent, and
$b$ is the length-growth exponent.

These growth functions allow linear or non-linear growth. $L$ is DEM unit of length.

Growth factors used in equations 4 and 5 account for overall volumetric growth in the growth zones (section 3.6.1). Examples of published debris-flow growth factors are shown in table 5 where both area- and length-growth factors were determined for two areas. Additionally, Reid and others (2016) summarized some other measured length-growth factors. Default values for the power-law exponents are set to one in Grfin Tools (section 4.2.2.6.2), creating linear functions and, thus, emphasizing the full effects of the growth factors in a conservative hazard assessment. Observations from some flow events indicate that growth may be reduced as the basin size increases accompanied by increasing total contributing areas, $U$, or total channel lengths, $L$ (for example, Scheip and Wegmann, 2022). In these situations, the exponents can be set between zero and one, resulting in non-linear growth functions.

**Table 5.** Ranges of area- and length-growth factors for two study areas in Oregon and Puerto Rico.

| Study area | Area-growth factor, $c_1$ (m$^3$/m$^2$) | Length-growth factor, $c_2$ (m$^3$/m) | Reference |
|---|---|---|---|
| Coast Range, Oregon | 0.12 to 0.2 | 11.4 to 24.2 | Reid and others (2016) |
| Utuado and Naranjito, Puerto Rico | 0.01 to 0.13 | 0.7 to 30.4 | Coe and others (2021) |

Total flow volume, $V_{\mathrm{T}}$, at a location in the growth zones with growth power laws integrated over upslope areas and upstream channel lengths is calculated using the following equation:

$$V_{\mathrm{T}} = \int c_1 (U_{\mathrm{src}})^a dU + \int c_2 (L_{\mathrm{gz}})^b dL + \int V_{\mathrm{pt}} dU \text{ ,} \tag{6}$$

where $V_{\mathrm{pt}}$ is volume at a user-specified point source (section 4.3.3). In a digital landscape, equation 6 becomes

$$V_{\mathrm{T}} = c_1 \sum\nolimits_{\mathrm{upslope}} (U_{\mathrm{src}})^a + c_2 \sum\nolimits_{\mathrm{upstream}} (L_{\mathrm{gz}})^b + \sum\nolimits_{\mathrm{upslope}} V_{\mathrm{pt}} \text{ ,} \tag{7}$$

where the summation is over DEM cells. The simplified equation is the sum of the various volume components:

$$V_{\mathrm{T}} = V_U + V_L + V_{\text{pt total}} \;, \tag{8}$$

where $V_{\text{pt total}}$ is the total volume from upslope point sources. With equation 8, volume is assumed to increase instantaneously at each cell and is not affected by any possible differences in growth process, such as disparities in mobilization timing between bed entrainment or landslide contributions. In Grfin Tools, $V_{\mathrm{T}}$ can be limited by a user-specified maximum volume, $V_{\max}$ (section 4.2.2.6.2).

Using volumes computed from growth coupled with the volume-area equations (eqs. 1, 2), Grfin Tools makes the following assumptions when computing flow with growth using the **INUNDATION** tool. Within growth zones, cross-sectional inundation, $A$, is a function of the computed flow volume at any cell along a drainage path and, thus, may vary. The start of non-growth zones, designated with AB points, occurs at the downstream end of growth zones where growth has ceased and volumes have reached a fixed value. With multiple growth zones along a drainage path, an AB point will be located at the downstream end of each growth zone, with potentially different fixed volumes at each AB point. Using the volume from the AB point immediately upstream, cross-sectional area, $A$, is then computed for cells in the non-growth zone downstream. In addition, planimetric inundation, $B$, is only computed and accumulated in non-growth zones downstream of the AB points (section 3.5.3). As upstream growth has already occurred, planimetric inundation downstream of these growth zones is best represented using $B$ values in equation 2 from a $B1$ distal-area approach. Given that volume-area coefficients appear similar for either $B0$ or $B1$ approaches, however, either could be utilized for inundation (section 3.5.2).

### 3.6.3.1. Area Growth

The use of area growth may be desirable if an area-dependent growth factor (in $L^3/L^2$) is available or the growth processes are primarily a function of upslope contributing source area (such as erosion, rilling, or widespread landsliding). Area growth relies on equation 4 to compute volumes along a growth zone. The upslope source area, $U_{\text{src}}$, can be designated using the **SOURCE** tool (section 3.2), or the entire upslope contributing area can be used as the source area if no specific source is identified.

An example of inundation using area growth is shown in figure 26. In general, increasing flow volumes with increasing source area create increasing inundation downstream. Area growth can also create abrupt discrete jumps in flow volumes where (1) tributary channels merge within a growth zone or (2) multiple disconnected growth zones are present along a drainage path. In the latter case, area growth uses the entire source area upslope of each growth zone, which can lead to large volume increases when growth zones restart downstream. Example D (section 6.4) further illustrates the uses of area growth.

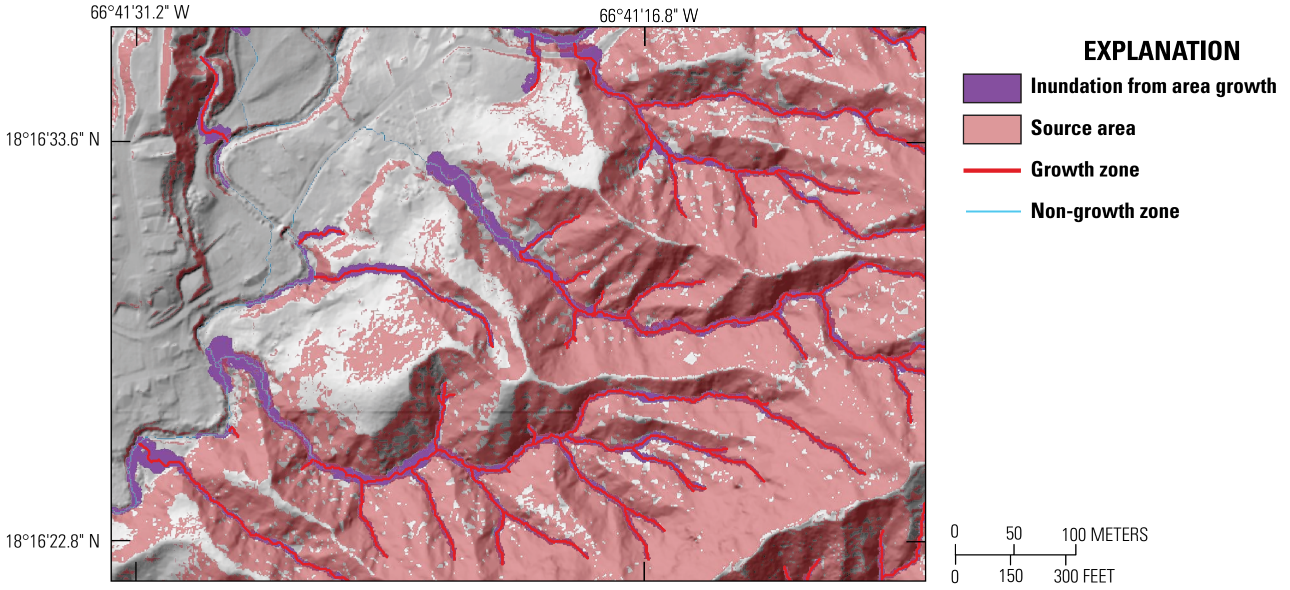


**Figure 26.** Map showing inundation in part of Utuado, Puerto Rico, calculated using an area-growth factor of 0.015 cubic meters per square meter (***area_growth_factor*** set to "0.015") in Grfin Tools. Drainage-network growth zones are defined by stream slopes ≥6°. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

### 3.6.3.2. Channel-Length Growth

The calculation of channel-length growth may be desirable if a length-dependent growth factor (in $L^3/L$) is available or if the dominate growth processes are primarily a function of upstream channel length (such as bed entrainment or channel bank failure). Length growth relies on equation 5 to compute volumes along a growth zone. The length of the upstream growth zones, $L_{gz}$, is defined by the growth-zone selection (section 3.6.2).

An example of inundation using length growth is shown in figure 27. Here, increasing flow volumes with increasing channel growth zones lead to more inundation downstream. Length growth can create abrupt discrete jumps in flow volumes where tributary channels merge within a growth zone, although they tend to be less dramatic than jumps using area growth. In contrast to area growth, length growth only uses the upstream length of the growth zones, so there is no large volume jump when disconnected growth zones start and stop. It is possible to obtain similar inundation zones using either area- or length-based growth factors (compare figs. 26 and 27). Example E (section 6.5) further illustrates the uses of length growth.

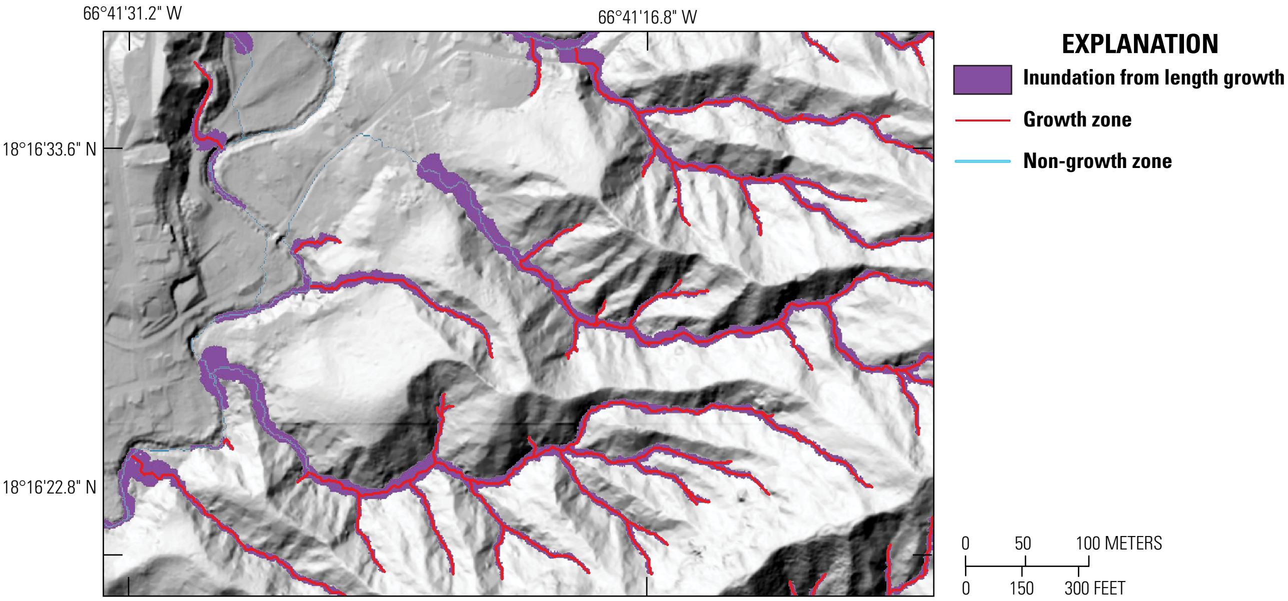


**Figure 27.** Map showing inundation in part of Utuado, Puerto Rico, calculated using a length-growth factor of 0.7 cubic meters per meter (***length_growth_factor*** set to “0.7”) in Grfin Tools. Drainage-network growth zones are defined by stream slopes ≥6°. Inundation area is similar to area-growth inundation shown in figure 26. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

### 3.6.3.3. Other Controls on Growth

In addition to area and length growth, Grfin Tools includes several options to increase or limit volumes computed using growth (section 4.2.2.6.2). Total volume, $V_T$, can be limited to a specified maximum, $V_{max}$. This feature ensures that growth does not continue unabated downstream and prevents unrealistically large flows. Example E (section 6.5) illustrates the uses of $V_{max}$.

For some scenarios, a known volume at a specified location could contribute to overall growth volumes. These point-source features might include a landslide or a check dam within a drainage where failure would increase the total volume, $V_T$. For these situations, Grfin Tools allows a user-specified series of point-source volumes (section 4.3.3). These point-source volumes, $V_{pt}$, have two effects: (1) they contribute to total volumes in any growth zones downslope of the point sources and, thus, can increase inundation area, and (2) inundation proceeds directly downslope of point sources, much as it does from initial point locations (section 4.3.4). The result is composite inundation from the growth zones and from the discrete source points. As shown in figure 28, using point sources for growth can increase the overall inundation as well as add inundation zones downslope from the point sources.

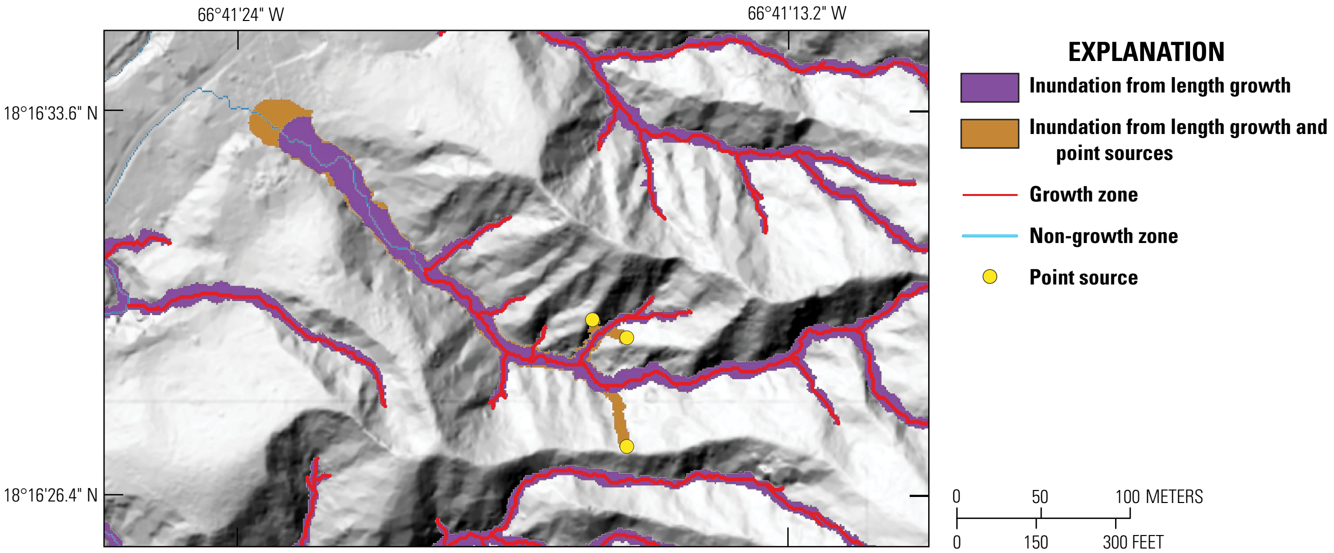


**Figure 28.** Map showing inundation in part of Utuado, Puerto Rico, calculated using a combination of three point sources (with specified volumes of 200 cubic meters) and a length-growth factor of 0.7 cubic meters per meter (***length_growth_factor*** set to "0.7") in Grfin Tools. Drainage-network growth zones are defined by stream slopes ≥6°. Inundation is expanded downslope of the three point sources compared to figures 26 and 27. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

# 4. Program Input and Output Files

This section describes the input files used by and output files generated by Grfin Tools. The types of input files required and output files generated depend on the tools and analyses being used. The sections discussing pathways and examples (sections 2 and 6) contain various practical applications and should be consulted when planning investigations using Grfin Tools. Further details underlying the basis for each of the tools can be found in section 3. Details of the latest software options and methods for running Grfin Tools can be found in the Grfin Tools software release (Cronkite-Ratcliff and others, 2025).

Regarding file naming and file path conventions, Grfin Tools uses the Windows operating system conventions for file- and directory-name lengths, allowable characters, and extensions. Forward slashes in a path name are allowed. Path names can be relative or absolute; relative path names are relative to the current working directory. Most output files follow the format <*DEMfilename*>_<*filedescription*>.<*extension*> where <*DEMfilename*> is the name of the DEM without its extension. In addition, many of the subdirectories that Grfin Tools creates have a prefix of <*DEMfilename*>. One output file that contains settings information is named <*Settingsfilename*>_<*description*>.<*extension*> where <*Settingsfile name*> is the name of the Settings file without its extension.

## 4.1. File Formats

In Grfin Tools, input and output files are constructed in the following formats:

1. GeoTIFF (.tif file extension). The DEM and other raster images associated with the DEM are georeferenced files in GeoTIFF format. All raster images must be in a projected coordinate reference system (such as UTM or State Plane), not a geographic (latitude and longitude) coordinate system. The contents of each raster image (such as a source raster image) must cover the same extent (dimensions), use the same resolution (cell size) and base length (distance) units, and be georeferenced in the same datum and projection as the original DEM. Elevations are assumed to be in the same units as the horizontal length units. This format is readily ingested into GIS software.

   Note that Grfin Tools can utilize length units of either meters or feet for DEM raster images; it will not accept other length units. All associated raster images must be in the same length units as the DEM. User input in the Settings file for any length-based parameters need to be in the same units as the DEM. Any default values that rely on length units are automatically converted to values consistent with the DEM base length units.

2. YAML (.yaml file extension). The primary Settings input file is in YAML (YAML Ain't Markup Language) format (refer to https://yaml.org). The YAML format provides a simple human-readable format for creating settings or configuration files and is readily parsed by many programming languages. YAML files are in plain text.

3. Comma-separated values (.csv file extension). Several input and output files use this format, which is readily viewable in spreadsheet or text editing software. Columns are in a designated order with values delimited by commas and the files should contain no header lines.

4. Text (.txt file extension). Several of the output files are produced using ASCII-character text without formatting, which is readable by many text editors.

5. Shapefile and associated files (.shp file extension, associated files have .prj, .dbf, and .shx extensions). Several output files use a shapefile format and associated files to allow ready viewing in a GIS. Information contained in the files enables examination of multiple attributes for each point or line segment in the shapefile. For example, *<DEMfilename>_volumes.shp* can be used to display different volume components as well as the total volumes at locations within growth zones.

## 4.2. Required Input Files

The input files needed for various applications are outlined in table 6. Two input files are required for all analyses: a DEM and a Settings file, which contains the options and parameters used in a Grfin Tools run. Additional input files are needed for select options (section 4.3). All input file names are specified by the user.

**Table 6.** Required and optional input files for Grfin Tools.

[Input field names, used in the required Settings file to designate other input files, are also listed. DEM, digital elevation model]

| File | Purpose | File format | Settings file input field |
|---|---|---|---|
| | | Required | |
| DEM | Defines topography | GeoTIFF | ***demfilename*** |
| Settings | Defines analysis options | YAML | NA |
| | | Optional | |
| Source raster | Defines source areas | GeoTIFF | ***source_raster*** |
| Growth zone raster | Defines growth zones | GeoTIFF | ***growth_zone_raster*** |
| Growth point sources | Identifies growth points | Comma delimited (csv) | ***point_source_volumes_file*** |
| Inundation starting points | Identifies starting volumes | Comma delimited (csv) | ***user_specified_volumes_file*** |
| Inundation cross sections | DEM for cross sections | GeoTIFF | ***xsec_demfilename*** |

### 4.2.1. DEM File (GeoTIFF format)

A DEM file covering the area of investigation is always required for a Grfin Tools analysis. This file should be in GeoTIFF format with a projected coordinate system (such as UTM or State Plane) for processing by the TauDEM software. **Note that geographic (latitude/longitude) projections of the DEM cannot be processed.** Topography controls the drainage network and flow directions and, therefore, it directs runout and inundation in Grfin Tools. In general, the DEM should include all areas of interest and any adjacent areas that might encompass potential source, runout, or inundation areas.

### 4.2.2. Settings File (YAML format)

The Settings file is always required and defines the types of analyses to be performed as well as the parameters, options, and other input files associated with those analyses. This section describes in detail the formatting and input field options in the Settings file (table 7). Each input field name is separated from its corresponding value by a colon and a space in a key–value pair on the same line. Input in text format does not have to be contained in quotes. For example, if the DEM file named "*BigCountry.tif*" is contained in a directory named "*inputdata*", defining the value of the ***demfilename*** input field can be achieved using the key–value pair `demfilename: inputdata/BigCountry.tif`.

**Table 7.** Required and optional sections and fields in the Grfin Tools Settings input file using a YAML format.

[Input field names are nested under sections and subsections; these are for entering values. Some sections are conditionally required depending on other options selected. Refer to the Grfin Tools software release (Cronkite-Ratcliff and others, 2025) for any revisions to these requirements]

| YAML input field name | Required? | Category |
|---|---|---|
| **setup:** | Required | Section heading |
| title: | Optional | Input field |
| demfilename: | Required | Input field |
| compute_taudem_grids: | Optional | Input field |
| dest_dir: | Required | Input field |
| num_procs: | Optional | Input field |
| **options**: | Required | Section heading |
| hl: | Required | Input field |
| growth: | Required | Input field |
| inundation: | Required | Input field |
| standalone_drainage_network: | Optional | Input field |
| **drainage_options:** | Optional | Section heading |
| compute_new_drainage: | Conditionally required* | Input field |
| dem_neighborhood: | Optional | Input field |
| min_curvature_drainage: | Optional | Input field |
| min_concav_area: | Optional | Input field |
| min_drainage_area: | Optional | Input field |
| **source:** | Optional | Section heading |
| source_raster: | Conditionally required* | Input field |
| min_source_value: | Optional | Input field |
| max_source_value: | Optional | Input field |
| min_curvature_source: | Optional | Input field |
| min_source_area: | Optional | Input field |
| **hl_options:** | Conditionally required * | Section heading |
| min_reach_angle: | Conditionally required* | Input field |
| **growth_options:** | Conditionally required* | Section heading |
| growth_zones: | Conditionally required* | Subsection heading |
| include_partial: | Optional | Input field |
| min_stream_slope: | Optional | Input field |
| slope_method: | Optional | Input field |
| downstream_distance: | Optional | Input field |
| max_stream_order: | Optional | Input field |
| max_contrib_area: | Optional | Input field |
| min_curvature_growth: | Optional | Input field |
| min_sourcearea_ratio: | Optional | Input field |
| growth_zone_raster: | Optional | Input field |
| min_growthzone_ratio: | Optional | Input field |
| growth_volumes: | Conditionally required* | Subsection heading |
| max_volume: | Optional | Input field |
| point_source_volumes_file: | Optional | Input field |
| area_growth: | Optional | Sub-subsection heading |
| area_growth_factor: | Conditionally required* | Input field |
| area_power: | Optional | Input field |
| length_growth: | Optional | Sub-subsection heading |
| length_growth_factor: | Conditionally required* | Input field |
| length_power: | Optional | Input field |
| **inundation_options**: | Optional | Section heading |
| flowtype: | Optional | Input field |
| xsec_alpha1: | Optional | Input field |
| plan_alpha2: | Optional | Input field |
| user_specified_volumes_file: | Optional | Input field |
| xsec_demfilename: | Optional | Input field |
| output_img: | Optional | Input field |
| hbar: | Optional | Input field |

*Field required if section or subsection selected.

The Settings file contains a hierarchical series of sections for different tools; each section or subsection contains fields for controlling program behavior. Section and subsection headings also end with a colon. Indentation in the Settings file controls the operational structure and must be preserved when creating YAML files for Grfin Tools. Subsections are indented under sections and field names are indented under either sections or subsections. **For consistency, all indentation in the Settings file consists of two spaces. Incorrect indentation will lead to errors!** In Grfin Tools the section, subsection, and field names are in lowercase, although the parameter values themselves can be in either uppercase or lowercase. Fields can be listed in any order within a section, although the order listed in table 7 aids organization of the input data. User comments can be added with a leading number symbol (#) and are ignored by Grfin Tools during processing. Editing one of the Settings files provided for the examples in section 6 is an easy method for following the required indentation nesting scheme. Also refer to the Grfin Tools software release (Cronkite-Ratcliff and others, 2025).

The Settings file contains input field sections for ***setup***, ***options***, ***source***, ***hl_options***, ***drainage_options***, ***growth_options***, and ***inundation_options***. The ***growth_options*** section has subsections for ***growth_zones*** and ***growth_volumes*** and sub-subsections for area growth and length growth (fig. 29). Although section and subsection names do not have any values associated with them in the Settings file, they must be listed for their nested subsections and fields to be used. Fields within a section or subsection allow the user to input values needed for a specific analysis. For example, `min_stream_slope: 5` specifies that the minimum stream slope parameter is set to a value of 5°.

```
setup:
  demfilename: data/exampleDEM
  dest_dir: output                    < directory and file name path

options:                              < section header, no input value
  hl: no                              < two-space indentation for parameter within a section
  growth: yes
  inundation: yes

growth_options:
  growth_zones:                       < two-space indentation for subsection header within a section
    min_stream_slope: 5               < four-space indentation for parameter within a subsection
  growth volumes:
    length_growth:
      growth_factor_length: 2.0
```

**Figure 29.** Annotated example text showing required sections and input fields for a minimal Settings input file including a mock digital elevation model (DEM) file named “*exampleDEM*” located in a directory named “*data*”. This example performs debris-flow inundation in Grfin Tools (note that the ***inundation_options*** section is not required in this case, as the default settings are sufficient). In this example, debris-flow growth occurs in drainage zones with stream slopes ≥5° and growth in volume is proportional to the length of the growth zones (2 cubic meters per meter). Input fields shown in table 7 that are not included here are either not computed or are computed using default settings. Primary output files are placed in the designated ***dest_dir*** directory; TauDEM files and drainage files are placed in subdirectories of the directory containing the DEM.

The ***setup*** and ***options*** sections are always required in the Settings file. The other sections are only used as needed for a specific analysis—as controlled by the ***options*** section. For example, if an *H*/*L* runout analysis is not selected in the ***options*** section (`hl: no`), then the ***hl_options*** section does not need to be included in the file. If present, it will be ignored. Similarly, optional fields do not need to be included in the file if they are not being used. This structure, combined with a variety of default settings in Grfin Tools, allows the use of sparse and simple Settings files for various situations (refer to section 6, “Examples of Applications”). Table 7 shows a complete list of all sections, subsections, and input field names, whereas figure 29 shows a sparse example Settings file for debris-flow inundation from growth zones with a specified length-growth factor.

#### 4.2.2.1. Setup (required)

The required ***setup*** section specifies the DEM name and path, ensures that the necessary TauDEM grids are or have been generated, and handles several file location and processing options. Specific input fields in the ***setup*** section (table 8) are described below.

**Table 8.** Input fields in the Grfin Tools ***setup*** section.

[NA, no default value (inactive if not required). Local directory is relative to command prompt window directory. File and directory names need to have lengths, characters, and extensions valid for the Windows operating system]

| YAML input field name | Required? | Data type | Possible values | Default value |
|---|---|---|---|---|
| ***setup*** | | | | |
| ***title*** | Optional | Text | -- | NA |
| ***demfilename*** | Required | GeoTIFF file name | -- | NA |
| ***compute_taudem_grids*** | Optional | Specified text | “yes”, “no”, “if_absent” | “if_absent” |
| ***dest_dir*** | Required | Directory name | -- | Local directory |
| ***num_procs*** | Optional | Integer | >0 | 1 |

##### ***title*** (optional)

*Field description*

The optional ***title*** input field allows a user-specified text description for a given Grfin Tools analysis. It can be left empty and has no effect on operations or processing. If this field is omitted, the title will be empty.

*Potential uses*

The designated title can be used as an identifier for documenting runs and managing analyses.

##### ***demfilename*** (required)

*Field description*

The required ***demfilename*** input field designates the name and location of the DEM file covering the area of interest in a Grfin Tools analysis. It must be a valid, existing GeoTIFF file. The ***demfilename*** field can have an associated absolute directory path or a path relative to the current directory. Without a path, the DEM must exist in the current directory (where the Settings file exists).

##### ***compute_taudem_grids*** (optional)

*Field description*

The optional ***compute_taudem_grids*** input field controls the creation of TauDEM grids using the DEM that are required for Grfin Tools operations. These five raster files (called grids in TauDEM) are generated and placed in the subdirectory *<DEMfilename>_taudem*:

- Pit-filled DEM (*<DEMfilename>_fel.tif*).
- D8 flow direction from the pit-filled DEM (*<DEMfilename>_felp.tif*).
- D8 slope (*<DEMfilename>_sd8.tif*).
- Flow accumulation from complete drainage basins (*<DEMfilename>_ad8.tif*).
- Flow accumulation from both complete and partial drainage basins in the DEM (*<DEMfilename>_ad8min.tif*). Partial drainage basins are typically located at the edges of a DEM.

The ***compute_taudem_grids*** field has three possible settings: “yes”, “no”, and “if_absent”. If “yes” is selected, then new versions of all five TauDEM grids are computed, regardless of whether they already exist. If “no” is selected, then all five TauDEM grids ***must already exist or an error will be returned***. If “if_absent” is selected, then all these files will be created if any of the five files do not already exist. The default option is “if_absent”. More information about the structure of these raster files can be found in the TauDEM documentation (Tarboton, 2005).

*Potential uses*

Computing TauDEM grids can be computationally intensive and typically only needs to be performed once for a given DEM. Thus, the default “if_absent” option saves runtime by generating TauDEM grids only if they do not already exist. If this default option is desired, then the ***compute_taudem_grids*** option line is not needed in the Settings file. However, if a user wants new TauDEM grids to be generated (for example, a DEM with the same name was modified), then “yes” should be selected for this option.

#### ***dest_dir*** (required)

*Field description*

The required ***dest_dir*** input field indicates the directory (with or without an optional absolute or relative path) where the output files from a given run will be placed. If the user wants to utilize an existing directory, then the name (and path) must be a valid directory that already exists. If the directory designated by the ***dest_dir*** input field does not already exist, the program will attempt to create it.

*Potential uses*

Multiple Grfin Tools runs using a given DEM can become disorganized. The ***dest_dir*** field provides a method to manage output files from multiple runs. The complete output (for example, YAML settings, growth zones, runout zones, volumes, inundation areas, and so on) from a given run can be saved in a uniquely named output directory.

#### ***num_procs*** (optional)

*Field description*

The optional ***num_procs*** input field specifies the number of processes to be used for MPI-enabled TauDEM calls from Grfin Tools. MPI can parallelize computations. If not specified, the default is 1 and MPI will not be used. If specified, the number can range up to the maximum number of cores available on the system. If ***num_procs*** is greater than the total number of available cores, then the number of available cores will be used. If the number is less than 1, then only one process will be used.

*Potential uses*

As TauDEM routines can be computationally intensive (both during the initial **SETUP** and subsequent processing phases), utilizing more than one process can greatly reduce runtimes. Most modern computers have multiple cores that can be employed to speed computations. Many of the examples in section 6 use a ***num_procs*** of 8 to speed computations.

### 4.2.2.2. Analysis Options (required)

The required ***options*** section defines the tools being used in a given Grfin Tools run. The pathways and examples discussed in sections 2 and 6 provide further illustrations of these tools. If any option is set to “no”, then this specific analysis will not be performed. If all options are set to “no”, then Grfin Tools will execute the ***setup*** section and then quit. Specific fields for the ***options*** section (table 9) are described below. Each part identified in the ***options*** section has an associated section with its own associated parameters, as discussed below.

**Table 9.** Input fields in the Grfin Tools ***options*** section.

| YAML input field name | Required? | Data type | Possible values |
|---|---|---|---|
| ***options*** | | | |
| ***hl*** | Required | Specified text | yes/no |
| ***growth*** | Required | Specified text | yes/no |
| ***inundation*** | Required | Specified text | yes/no |
| ***standalone_drainage_network*** | Optional | Specified text | yes/no |

### ***hl*** (required)

*Field description*

The required ***hl*** input field controls the use of the **HL** tool to perform an *H*/*L* runout analysis. This field must be set to "yes" or "no". Note that this option requires a ***source*** section in the Settings file as well. Other *H*/*L* options are described in section 4.2.2.5.

### ***growth*** (required)

*Field description*

The required ***growth*** input field controls the use of the **GROWTH** tool to perform flow growth computations and determine spatial distribution of flow volumes. This field must be set to "yes" or "no". Other growth computation options are described in section 4.2.2.6.

### ***inundation*** (required)

*Field description*

The required ***inundation*** input field controls the use of the **INUNDATION** tool to perform a flow inundation analysis. This field must be set to "yes" or "no". An inundation analysis can be performed with or without the **GROWTH** tool. To perform an inundation analysis without growth computations, a file of user-specified volumes must be named in the ***inundation*** section (using the ***user_specified_volumes_file*** input field). Other inundation options are described in section 4.2.2.7.

### ***standalone_drainage_network*** (optional)

*Field description*

The optional ***standalone_drainage_network*** input field controls the use of the **DRAINAGE** tool to construct a standalone curvature-based drainage network, saved as *<DEMfilename>_stream.tif* in GeoTIFF format. This field must be set to "yes" or "no". Note that a drainage network will be constructed if the ***growth*** input field is set to "yes", even if the ***standalone_drainage_network*** field is omitted. This field provides the ability to generate a drainage network even if the ***growth*** input field is set to "no". If the ***standalone_drainage_network*** input field is set to "yes" but no ***drainage_options*** section exists, a drainage network will be created using the default options. Other drainage network options are described in section 4.2.2.3.

*Potential uses*

A standalone drainage network can be used for other topographic analyses (outside of Grfin Tools) or for closer inspection of the drainage network prior to further Grfin Tools runs. The locations of channel initiation in the drainage network can be modified using input fields described in section 4.2.2.3.

### 4.2.2.3. Drainage Network (optional)

The optional ***drainage_options*** section controls the use of the **DRAINAGE** tool to construct a curvature-based drainage network with specific, non-default parameters. Note that a drainage network will be constructed if the ***growth*** input field is set to "yes", activating the **GROWTH** tool. In this situation, the drainage network will be constructed using the default parameters if the ***drainage_options*** section is omitted. To prevent new drainage network files from being created in subsequent runs, set the ***compute_new_drainage*** input field to "no". Drainage network parameters can be modified from their default values within the ***drainage_options*** section (table 10); they are explained in section 3.4 and illustrated in example C (section 6.3) and example G (section 6.7).

**Table 10.** Input fields in the Grfin Tools ***drainage_options*** section.

[NA, not applicable; DEM, digital elevation model; m, meter (/m, reciprocal DEM length units); m$^2$, square meters]

| YAML input field name | Required? | Data type (Possible values) | Units | Default value[1] | Suggested range of values |
|---|---|---|---|---|---|
| ***drainage_options*** | | | | | |
| ***compute_new_drainage*** | Required | Text (yes/no) | NA | yes | -- |
| ***dem_neighborhood*** | Optional | Real number | DEM units | 10 m | 5–20 m |
| ***min_curvature_drainage*** | Optional | Real number | Reciprocal DEM units | 0.02/m | [2] 0.01–0.05/m |
| ***min_concav_area*** | Optional | Real number | Area using DEM units | 200 m$^2$ | 10–400 m$^2$ |
| ***min_drainage_area*** | Optional | Real number | Area using DEM units | 200 m$^2$ | 100–1,000 m$^2$ |

[1] Grfin Tools converts default values to English units in cases where the user-specified DEM file is in units of feet.

[2] Values for ***min_curvature_drainage*** are dependent on ***dem_neighborhood***: larger ***min_curvature_drainage*** values (0.1–0.5/m) may be selected in association with smaller ***dem_neighborhood*** values. The suggested range of values for ***min_curvature_drainage*** provided in this table are intended to work well with the default value for ***dem_neighborhood***.

### ***compute_new_drainage*** (required if ***drainage_options*** active)

*Field description*

The ***compute_new_drainage*** input field controls the creation of the drainage-related output files (refer to section 4.4.1.2) needed for the **GROWTH** tool or to create a standalone drainage network using non-default values. This input field is required to enter values in other input fields in the ***drainage_options*** section. This field must be set to "yes" or "no". If the ***compute_new_drainage*** input field is set to "yes", then new versions of the four drainage files described in section 4.4.1.2 are generated and placed in the <*DEMfilename*>*_drainage*/ subdirectory, regardless of whether they already exist. If the field is set to "no", then these drainage files must already exist in this subdirectory or an error will be returned.

*Potential uses*

Constructing drainage files can be computationally intensive and typically only needs to be performed once for a given DEM. A possible workflow involving the **GROWTH** tool is to initially run Grfin Tools for the DEM designated by the ***demfilename*** input field, examine the resulting drainage network and then, provided that no modifications are needed, ***compute_new_drainage*** can be set to "no" for all subsequent Grfin Tools runs. Note that the **GROWTH** tool creates some additional files that are placed in the drainage subdirectory with each run (refer to section 4.4.1.2).

### ***dem_neighborhood*** (optional)

*Field description*

The optional ***dem_neighborhood*** input field is used to specify the radius (in DEM length units) of a circular smoothing window surrounding each DEM cell to compute a local mean elevation for each DEM cell. The ***dem_neighborhood*** input field controls the degree of focal smoothing applied to the DEM file (designated using the ***demfilename*** input field) before planform curvature is computed to identify channel initiation locations. The default value is 10 m. For DEMs with a cell size larger than the ***dem_neighborhood*** value (either defined by default or user specified), no smoothing will occur. This value cannot be negative and is only used when a drainage network is computed.

*Potential uses*

Adjusting the smoothing window can retain or eliminate subtle features in the topography. For fine- to moderate-resolution DEMs (10 m), a smoothing window of 10 or 15 m works well in a variety of topographies. Windows smaller than 10 m will retain finer resolution details of the topography. This level of detail may be desirable in terrain with narrow, shallow stream channels or rilling (refer to example C, section 6.3). In addition, windows larger than 10 m can be selected if the DEM was previously smoothed using Grfin Tools or other software. Windows larger than 10 m will result in additional smoothing and may help to eliminate chronic problems with ridge-top roads (refer to example G, section 6.7.b). For lower resolution DEMs (>10 m), smoothing may not be necessary; Grfin Tools will use the cell size of the DEM for the smoothing window. Alternatively, if the ***dem_neighborhood*** input field is set to zero no smoothing is applied. Note that smoothing a DEM will change the minimum and maximum curvature values; thus, modifying ***dem_neighborhood*** may work well in combination with adjustments to the minimum curvature threshold (refer to example C, section 6.3).

### ***min_curvature_drainage*** (optional)

*Field description*

The optional ***min_curvature_drainage*** input field sets the minimum curvature threshold (in reciprocal DEM length units) to identify concavities in the DEM. The default value of 0.02/m is based on scaling factors and published curvature values used to define channel initiation (Pelletier, 2013; Mudd and others, 2019). This value cannot be negative and is only used when a drainage network is computed.

*Potential uses*

Values for ***min_curvature_drainage*** are dependent on the smoothing window set using the ***dem_neighborhood*** input field: suggested values for ***min_curvature_drainage*** range from 0.01 to 0.05/m for the default value of ***dem_neighborhood*** (10 m). Larger values (0.1–0.5/m) may be used with smaller smoothing windows. Viewing the planform curvature raster file (*<DEMfilename>_smooth.tif*) created from a smoothed DEM and calculating the maximum curvature is suggested before adjustments are made to ***min_curvature_drainage***.

### ***min_concav_area*** (optional)

*Field description*

The optional ***min_concav_area*** input field sets the minimum contiguous size of isolated concavities included in the contributing drainage area (***min_drainage_area***) used to define channel initiation. The default value is 200 m$^2$. This value cannot be negative and is only used when a drainage network is computed.

*Potential uses*

In settings where concavities in the topography are disconnected from the primary drainage network, increasing ***min_concav_area*** will eliminate isolated concavities smaller than the specified size. Decreasing ***min_concav_area*** will allow smaller isolated concavities to be included in the contributing area for identification of channel initiation, thus providing connectivity between these isolated concavities and the downstream channel network. Example C (section 6.3) illustrates a case where there are many small, isolated concavities (*<DEMfilename>_smoothplancurv.tif*). Suggested values for ***min_concav_area*** range from 10 to 400 m$^2$. This threshold only eliminates isolated concavities; if all concavities in the landscape are contiguous with the drainage network, ***min_concav_area*** will have no effect on the resulting drainage network.

### ***min_drainage_area*** (optional)

*Field description*

The optional ***min_drainage_area*** input field sets the minimum size of the contributing area used to define channel initiation, where the contributing area only includes concave areas. Concave areas are identified as areas with curvature greater than the minimum curvature threshold that are larger than the minimum concave area threshold. The default value for ***min_drainage_area*** is 200 m$^2$. This value cannot be negative and is only used when a drainage network is computed.

*Potential uses*

If the ***min_drainage_area*** threshold is used, suggested values are between 100 and 1,000 m$^2$.

### 4.2.2.4. Sources (required if certain other options are selected)

The ***source*** section is required if the **HL** tool is used or if a limited source area for ***area_growth*** in the ***growth_volumes*** section is desired to compute flow volumes for inundation. Otherwise, the ***source*** section is ignored. Note that if ***area_growth*** is selected in the Settings file but the ***source*** section is not included, then the entire DEM area will be treated as a potential source area. Various fields can filter or modify the original source raster file to create a new, more targeted source file (output named *<DEMfilename>_sourcearea.tif*) for analysis during a run. If no filters are selected, then all cells (except for NODATA cells) in the original file designated in the ***source_raster*** input field are used. The ***source*** section contains several specific input fields (table 11). For some fields, default values are applied if they are not defined.

**Table 11.** Input fields in the Grfin Tools ***source*** section.

[DEM, digital elevation model; NA, no default value (inactive if not used). File names need to have lengths, characters, and extensions valid for the Windows operating system]

| YAML input field name | Required? | Data type | Units | Default value | Values allowed |
|---|---|---|---|---|---|
| ***source*** | | | | | |
| ***source_raster*** | Required[1] | GeoTIFF file name | -- | -- | Can also be “slope” |
| ***min_source_value*** | Optional | Real number | Source raster units | NA | -- |
| ***max_source_value*** | Optional | Real number | Source raster units | NA | -- |
| ***min_curvature_source*** | Optional | Real number | Reciprocal DEM units | NA | -- |
| ***min_source_area*** | Optional | Real number | Area using DEM units | 1 | >0 |
| If ***source_raster*** is set to “slope”— | | | | | |
| ***min_source_value*** | Optional | Real number | Degrees | 0 | -- |
| ***max_source_value*** | Optional | Real number | Degrees | 90 | -- |

[1] Either a valid raster file name or the text “slope” is required.

## ***source_raster*** (required if ***source*** section is active)

*Field description*

The ***source_raster*** input field specifies either the word “slope” or designates the name and location of a raster file containing locations of potential landslide source areas which may be filtered using other ***source*** options. The file must be a valid, existing GeoTIFF file or an error will be returned. This field is required for other ***source*** options to be active. If the ***source_raster*** input field is set to the word “slope”, the raster file of ground surface slope in degrees generated by the **SETUP** tool will be used.

*Potential uses*

Typical ***source_raster*** files contain slope values, relative susceptibility categories, or factor-of-safety values from a landslide slope-stability analysis, or mapped landslide sources. These values can then be filtered to obtain more targeted source areas. Also refer to section 3.2 for more information on ways to use these files with the **SOURCE** tool.

## ***min_source_value*** (optional)

*Field description*

The optional ***min_source_value*** input field sets the minimum value of data from the ***source_raster*** file to include in a new targeted source area file. Values of ***min_source_value*** are in the same units used in the ***source_raster*** file and cannot be greater than ***max_source_value***. If ***source_raster*** is set to “slope”, then ***min_source_value*** must be in degrees ≥0° and ≤90°. If this field is omitted, there will be no minimum value.

*Potential uses*

This limiting value can provide a more targeted source area for analysis. For example, setting ***min_source_value*** to “30” when ***source_raster*** is set to “slope” will restrict source areas to those 30° or steeper, thereby filtering out gentle slopes. A similar approach can be used with source files containing susceptibility or factor-of-safety values.

## ***max_source_value*** (optional)

*Field description*

The optional ***max_source_value*** input field sets the maximum value of data from the ***source_raster*** file to include in a new targeted source area file. Values of ***max_source_value*** are in the same units used in the ***source_raster*** file and cannot be less than ***min_source_value***. If ***source_raster*** is set to “slope”, then ***max_source_value*** must be in degrees ≥0° and ≤90°. If this field is omitted, there will be no maximum value.

*Potential uses*

This limiting value can provide a more targeted source area for analysis. For example, setting ***max_source_value*** to 60° when ***source_raster*** is set to “slope” will restrict sources areas to those 60° or gentler, thereby filtering out steeper slopes. A similar approach can be used with source files containing factors of safety values or other indices of landslide susceptibility.

### ***min_curvature_source*** (optional)

*Field description*

The optional ***min_curvature_source*** input field sets the minimum value of smoothed planform curvature, generated from the smoothed DEM, to include in a new targeted source area file. Values of ***min_curvature_source*** are in reciprocal map units of the DEM file. Cells from a GeoTIFF file designated using the ***source_raster*** input field that also have curvature values greater than ***min_curvature_source*** in the *<DEMfilename>_smoothplancurv.tif* file will be included in the new targeted source area file. If this field is omitted, there will be no minimum value.

*Potential uses*

This limiting value can provide a more targeted source area for analysis. It can be used to distinguish source areas with some topographic curvature, such as hollows or swales, from more planar or divergent topography. Typical curvature values to identify source areas are greater than 0.01/m, although source areas in some types of terrain can be relatively planar (~0/m). The degree of smoothing applied to the DEM used to estimate planform curvature is defined using the ***dem_neighborhood*** input field (section 3.4).

### ***min_source_area*** (optional)

*Field description*

The optional ***min_source_area*** input field sets the minimum size of contiguous areas to include in a new targeted source area file. The smallest contiguous area will be in multiples of the DEM cell size. Values of ***min_source_area*** are in area units of the DEM and cannot be negative. If this field is omitted, it defaults to 0.

*Potential uses*

This limiting value can provide a more targeted source area for analysis. It can eliminate smaller, isolated source area cells that might be less likely to provide a landslide source (these will be smaller areas than the ***min_source_area*** value).

### 4.2.2.5. *H*/*L* Runout (required if **HL** tool is used)

The ***hl_options*** section is required if the **HL** tool is enabled by entering “yes” in the ***hl*** input field of the ***options*** section. If the ***hl*** input field is set to “no”, then this section will be ignored. This section also requires a ***source*** section in the Settings input file, as source information defines the starting locations for runout. The ***hl_options*** section contains one required input field (table 12).

**Table 12.** Input field in the Grfin Tools ***hl_options*** section.

[NA, no default value]

| YAML input field name | Required? | Data type | Units | Default value | Values allowed |
|---|---|---|---|---|---|
| ***hl_options*** | | | | | |
| ***min_reach_angle*** | Required | Number | Degrees | NA | 0°< value ≤45° |

### ***min_reach_angle*** (required if ***hl_options*** section is active)

*Field description*

The ***min_reach_angle*** input field sets the minimum value of angle of reach (or arctan ($H/L$)) in degrees to define runout areas from a specified source area. It is required if the ***hl_options*** section is used. This input field is restricted to values >0 and ≤45°.

*Potential uses*

This value controls the amount of runout area. Steeper angles of reach typically lead to less runout from a given source, as the steeper angle of reach affects less ground. Typical values range from 20 to 35°. Values greater than the source area slope commonly result in minimal runout. Refer to section 3.3.2 for more information.

### 4.2.2.6. Flow Growth (required if **GROWTH** tool is used)

The ***growth_options*** section is required if the **GROWTH** tool is enabled by entering “yes” in the ***growth*** input field of the ***options*** section. If the ***growth*** input field is set to “no”, then this section will be ignored. The ***growth_options*** section contains two required subsections: ***growth_zones*** and ***growth_volumes***. Input fields within the ***growth_zones*** subsection are used to identify parts of the drainage network where growth will occur (unless limited by a maximum volume, ***max_volume***). Input fields within the ***growth_volumes*** subsection are used to compute the flow volumes present at each drainage cell in the growth zones. Growth volumes can be further controlled by imposing an overall maximum volume (***max_volume***). Refer to section 3.6 for more information about growth zones and growth volumes. The ***growth_options*** section contains several specific input fields (table 13). For some fields, default values are applied if they are not defined.

**Table 13.** Input fields in the Grfin Tools ***growth_options*** section.

[csv, comma-separated values; DEM, digital elevation model; m, meter (/m, reciprocal DEM length units); NA, no default value (inactive if not used). File names need to have lengths, characters, and extensions valid for the Windows operating system]

| YAML input field name | Required? | Data type | Units | Default value | Values allowed |
|---|---|---|---|---|---|
| ***growth_options*** | | | | | |
| ***growth_zones*** | Required[1] | -- | -- | -- | -- |
| ***include_partial*** | Optional | Specified text | NA | no | yes/no |
| ***min_stream_slope*** | Optional | Real number | Degrees | 0 | 0°≤ value ≤90° |
| ***slope_method*** | Optional | Specified text | -- | "segment" | "segment" or "downstream" |
| ***downstream_distance*** | Optional | Real number | DEM units | 50 m | -- |
| ***max_stream_order*** | Optional | Integer | Non-dimensional | 999 | ≥0 |
| ***max_contrib_area*** | Optional | Real number | Area using DEM units | NA | ≥0 |
| ***min_curvature_growth*** | Optional | Real number | Reciprocal DEM units | −10/m | -- |
| ***min_sourcearea_ratio*** | Optional | Real number | Non-dimensional | 0 | 0≤ value ≤1 |
| ***growth_zone_raster*** | Optional | GeoTIFF file name | -- | NA | -- |
| ***min_growthzone_ratio*** | Optional | Real number | Non-dimensional | 0 | 0≤ value ≤1 |
| ***growth_volumes*** | Required[2] | -- | -- | -- | -- |
| ***max_volume*** | Optional | Real number | Volume using DEM units | NA | ≥0 |
| ***point_source_volumes_file*** | Optional | csv file name | -- | NA | -- |
| ***area_growth*** | Optional | -- | -- | -- | -- |
| ***area_growth_factor*** | Required | Real number | Volume/area using DEM units | yes | ≥0 |
| ***area_power*** | Optional | Real number | Non-dimensional | 1 | 0< value ≤1 |
| ***length_growth*** | Optional | -- | -- | -- | -- |
| ***length_growth_factor*** | Required | Real number | Volume/length using DEM units | yes | ≥0 |
| ***length_power*** | Optional | Real number | Non-dimensional | 1 | 0< value ≤1 |

[1] At least one of the following input fields is required: ***min_stream_slope***, ***max_stream_order***, ***max_contrib_area***, ***min_curvature_growth***, ***min_sourcearea_ratio***, or ***growth_zone_raster***.

[2] At least one ***growth_volumes*** option (point source, area growth, or length growth) is required. If ***area_growth*** or ***length_growth*** is selected then a corresponding growth factor is also required.

### 4.2.2.6.1. Growth Zones (required if **GROWTH** tool is used)

The ***growth_zones*** subsection is required if ***growth_options*** is used. As growth may be governed by diverse processes and, thus, correlated with multiple attributes, this subsection includes a variety of user-specified options to define zones of growth. At least one of the following input fields must be provided: ***min_stream_slope***, ***max_stream_order***, ***max_contrib_area***, ***min_curvature_growth***, ***min_sourcearea_ratio***, or ***growth_zone_raster***. Any combination of these six fields is permissible—the resulting growth zones are determined by the intersection (using the Boolean operator AND) of the chosen conditions, that is the growth zones must meet all the specified conditions. This intersection of options is designed to limit potential growth zones. Default values are out-of-range values that will not affect construction of growth zones. Note that some parameters will provide continuous growth zones without upstream non-growth zones (for example, ***max_stream_order*** and ***max_contrib_area***), whereas others can result in discontinuous growth zones separated by non-growth segments. If ***min_stream_slope*** is specified, two additional (optional) input fields, ***slope_method*** and ***downstream_distance***, can be provided to control how stream slope is calculated. After potential growth zones have been identified using one or more of these options, the zones can be further modified using the growth-zone ratio. This ratio can be used to eliminate isolated, downstream growth zones. The ***include_partial*** input field controls the extent of the growth zones but does not define them. Refer to section 3.6.2 for more information.

### ***include_partial*** *(optional)*

*Field description*

The optional ***include_partial*** input field allows the user to include or exclude partial drainage basins that are included in the DEM in the construction of growth zones. It can be set to “yes” or “no”. The default value is “no”.

*Potential uses*

Accurate portrayal of flow growth and inundation depends on assessing complete drainage basins (section 3.6.2). However, many analyses use rectangular DEMs that typically include partial basins on the edges. If ***include_partial*** is set to “no” (this is also the default value), any growth zones affected by partial basins will not be included in the growth analysis. This may reduce or remove growth and inundation in partial basins. The complete effects of these partial basins can be difficult to anticipate, as source areas and growth zones outside the partial basins are not included. Growth zones resulting from full or partial basins are identified in the raster file *<DEMfilename>_grzone.tif* (section 4.4.2.2.1). In many cases, partial basins have minimal effects on results of interest. Setting the input field to “yes” provides an analysis that includes growth zones affected by partial basins (refer to section 5.1).

### ***min_stream_slope*** *(optional)*

*Field description*

The ***min_stream_slope*** input field sets the minimum stream slope (in degrees) for a drainage network stream cell to be included in a growth zone. Stream cells with slopes greater than or equal to ***min_stream_slope*** will be included in the growth zones. The default value is 0, which will result in this field not influencing the growth zones. Two additional optional parameters can be used to control the calculation of stream slope: ***slope_method*** and ***downstream_distance***.

*Potential uses*

Many field observations document the stream slopes where growth, transport, and deposition have occurred during previous flow events. These observations can be readily used to define growth zones, where growth typically occurs in steeper stream segments. Values can vary significantly between different types of terrain; observations note growth commonly ceases in slopes from 3° to 10° (for example, Reid and others, 2016). This field can create discontinuous growth zones that start and stop, which may be appropriate for a given geomorphic setting.

### ***slope_method*** *(optional with **min_stream_slope**)*

*Field description*

The optional ***slope_method*** input field specifies the method for computing stream slope if the ***min_stream_slope*** option is used to define growth zones. This field can be set to either the word “segment” or the word “downstream”; the default value is “segment”. The “segment” option uses the stream-segment method from the StreamNet function of TauDEM (Tarboton and others, 2015) to determine overall slope along stream reaches between tributary junctions (links). The “downstream” option uses a fixed-distance method to compute stream slope over a specified horizontal distance measured along the drainage network.

*Potential uses*

Stream slope can be an important control on flow growth, but slopes can vary depending on the measuring scale. The “segment” option provides average slopes over a stream reach and smooths localized slope variations; this approach is commonly used for sediment transport modeling. The “segment” option reduces the occurrence of small, isolated, and discontinuous growth-zone sections defined by stream slope. A potential downside to this approach arises with single-reach streams, where the slope average over a segment may not reflect steep or gentle sections important for defining growth zones (refer to section 3.6.2). If more spatial granularity in delineating stream slopes is desired to capture locally steep or gentle sections, then the “downstream” option can be used. This option computes slope over a specified downstream horizontal distance. The default distance is 50 m, but the distance can be modified using the ***downstream_distance*** input field.

### ***downstream_distance*** *(optional if **slope_method** is set to “downstream”)*

*Field description*

The optional ***downstream_distance*** input field specifies the channel distance over which stream slope is computed. This parameter is only used if the ***slope_method*** input field is set to “downstream”. The default value is 50 m.

*Potential uses*

Larger values of ***downstream_distance*** smooth small changes in calculated stream slope and can help reduce problems with discontinuous growth zones defined by stream slope. For channel length-based growth methods, if stream slope is expected to control debris-flow growth and continuous growth zones are not desired, values of ***downstream_distance*** less than the default value could be applied. Suggested values are between 10 and 200 m.

### ***max_stream_order*** *(optional)*

*Field description*

The ***max_stream_order*** input field specifies the maximum Strahler stream order (refer to section 3.6.2) for a drainage network stream cell to be included in a growth zone. Stream cells with order numbers less than or equal to the ***max_stream_order*** will be included in the growth zones. The default value is 999, which will result in this field not influencing the growth zones. The value is an integer and must be at least 1.

*Potential uses*

Growth commonly occurs in the upper sections of a drainage network. For drainage networks that contain similarly sized basins, lower stream orders may correlate with growth zones. For terrain with variably sized basins, this approach may be less successful. This option can be used in combination with other growth zone fields to eliminate downstream growth zones in higher order streams. Using this field by itself will create continuous growth zones without upstream non-growth zones.

### ***max_contrib_area*** *(optional)*

*Field description*

The ***max_contrib_area*** input field sets the maximum upslope contributing area (in DEM area units) for a drainage network stream cell to be included in a growth zone. Stream cells having upslope contributing area smaller than or equal to ***max_contrib_area*** will be included in the growth zones. If a value is not provided, there will be no maximum by default.

*Potential uses*

Growth in specific types of terrain may only occur in smaller basins. This field can restrict growth by contributing area. For example, growth may be defined by slope-area relations, although, as with stream order, this approach may be less successful with variably sized basins. Using this field by itself will create continuous growth zones.

### ***min_curvature_growth*** *(optional)*

*Field description*

The ***min_curvature_growth*** input field sets the minimum planform curvature threshold (in reciprocal DEM length units) for a drainage network stream cell to be included in a growth zone. Stream cells with curvature greater than or equal to ***min_curvature_growth*** will be included in the resulting growth zones. The curvature raster generated from a smoothed DEM using the **DRAINAGE** tool is used (section 3.4) but a user can select any curvature threshold from this raster to delineate growth zones. The default value is −10/m, which will result in this field not influencing the growth zones.

*Potential uses*

Flows in more confined topography commonly grow more and travel farther than flows on more open slopes. This curvature field provides a proxy for confinement where larger values of curvature indicate more confinement. The ***min_curvature_growth*** option can be used to screen out small, planar downstream drainages that are unlikely to result in flow growth. This field can create discontinuous growth zones, which may be appropriate for certain geomorphic settings.

### ***min_sourcearea_ratio*** *(optional)*

*Field description*

The ***min_sourcearea_ratio*** input field sets the minimum value of the ratio between upslope source area and the entire upslope contributing area. This source-area ratio highlights locations where growth is more likely due a higher spatial density of potential source areas (section 3.6.2). Drainage network stream cells with ratios greater than or equal to ***min_sourcearea_ratio*** will be included in the resulting growth zones. The default value is 0, which will result in this field not influencing the growth zones. The value must be between 0 and 1, inclusive.

*Potential uses*

This field can be used to screen out parts of a drainage network with sparse potential sources, which have low source-area ratio values (such as 0.1 or 0.2). Alternatively, a high source-area ratio value can emphasize parts of the drainage network with abundant potential sources. Observations indicate that growth commonly occurs in areas with high source-area ratio values (>0.6) (Brien and others, in press). This field can create discontinuous growth zones, which may be appropriate for certain geomorphic settings.

### ***growth_zone_raster*** *(optional)*

*Field description*

The ***growth_zone_raster*** input field designates the name and location of a raster file containing the locations of growth zones. It must be a valid, existing file in GeoTIFF format.

*Potential uses*

This option can be used in several ways. Used alone it can define growth zones derived from other analyses—such zones might include the distribution of entrainable channel sediment for example. Used with other growth-zone fields, it can be used to restrict analysis to select basins of interest. This usage is demonstrated in example E (section 6.5). In addition, source zones computed by Grfin Tools can be modified outside of Grfin Tools (such as in a GIS) and then used in subsequent runs as a ***growth_zone_raster***; for example, this approach could be used to eliminate unrealistic, short, downstream growth-zone fragments.

### ***min_growthzone_ratio*** *(optional)*

*Field description*

The ***min_growthzone_ratio*** input field sets the minimum value of the computed ratio between upstream growth-zone lengths and the entire upstream channel length. The growth-zone ratio highlights locations where growth is more likely due a higher spatial density of identified upstream growth zones (section 3.6.2). To use this input field, some growth zones must be already identified using other growth-zone options and computed values are dependent on the previously computed growth zones. Previously computed growth-zone cells having ratios greater than or equal to ***min_growthzone_ratio*** will be included in the resulting growth zones; any growth zones where the growth-zone ratio is below the threshold will be removed. The default value is 0, which will result in this field not influencing the growth zones. The value must be between 0 and 1, inclusive.

*Potential uses*

This field can be used to screen out isolated, downstream growth-zone segments that may be unrealistic and thereby create excessive inundation. Moderate growth-zone ratio values (such as <0.5) may be sufficient to eliminate sparse downstream growth zones. Alternatively, a high growth-zone ratio value (such as 0.9 or 0.95) can restrict growth to channel segments where the upstream drainage is dominated by growth. Examining the growth-zone ratio output file (*<DEMfilename>_grzoneratio.tif*) can aid in selecting appropriate values for a specific type of terrain.

### 4.2.2.6.2. Growth Volumes (required if **GROWTH** tool is used)

The ***growth_volumes*** subsection is required if the ***growth_options*** section is used. For flow inundation with growth, flow volumes will be computed for each drainage-network stream cell in the growth zones (A points) and for the downstream cell of the growth zones that denotes the start of non-growth inundation (AB point) (refer to section 3.5.3). Flow volumes at a cell are derived from the combination of any of three potential growth sources: (1) from upslope contributing or partial contributing areas (***area_growth***), (2) from upstream channel length (***length_growth***), and (or) (3) from user-specified point sources (***point_source_volumes_file***). At least one of these three growth sources must be included if the ***growth_options*** section is used. An optional input field can control the maximum flow volume (***max_volume***). Section 3.6.3 provides more details and examples D through G (sections 6.4–6.7) illustrate some applications of the ***growth_volumes*** section.

### ***max_volume*** *(optional)*

*Field description*

The optional ***max_volume*** input field sets the maximum computed flow volume (in units of volume relative to the DEM length units). If not specified, there will be no maximum value. There is no default value. The value cannot be negative.

*Potential uses*

In many study areas, observed flows rarely exceed a maximum volume. This field restricts flow volume, even in designated growth zones, and tempers potential effects from aggregated growth over large basins. It prevents excessively large flows by capping the volume. Examples D, E and G (sections 6.4, 6.5, and 6.7) illustrate usage of the ***max_volume*** input field.

### ***point_source_volumes_file*** *(optional)*

*Field description*

The optional ***point_source_volumes_file*** input field designates the name and location of a file that contains the locations and volumes of point sources adding to growth. Units of volume are relative to the DEM length units. It must be a valid, existing file in comma-separated values (csv) format. Refer to section 4.3.3 for more information.

*Potential uses*

Growth in volume can result from a point source within the landscape—for example, a known landslide, a check dam, or other in-channel sediment accumulation. These locations and their volumes can be specified and flows downstream will incorporate these specified volumes.

### ***area_growth*** *(optional)*

*Field description*

The ***area_growth*** section is an optional sub-subsection of the ***growth_volume*** subsection. This sub-subsection uses upslope contributing areas to compute growth volumes (section 3.6.3). This section contains two input fields (***area_growth_factor*** and ***area_power***) that pertain to the area-growth equation (eq. 4, section 3.6.3). If the ***source*** section is included in the Settings file, the source raster created in the ***source*** section will be used for the area-growth computations. If the ***source*** section does not exist, the entire upslope area (except for any NODATA values) is used for volume computations (section 3.6.3). Examples D, F, and G (sections 6.4, 6.6, and 6.7) illustrate usage of the ***area_growth*** section.

### ***area_growth_factor*** *(required if **area_growth** is used)*

*Field description*

The ***area_growth_factor*** input field is used for computing area-growth volumes. It is a scalar growth factor (in units of volume per area relative to the DEM length units) applied to the upslope contributing source area, as shown in the area-growth equation (eq. 4, section 3.6.3). The value cannot be negative.

*Potential uses*

In terrain where growth in flow volume is dependent on upslope area, this controls the spatial rate of growth.

### ***area_power*** *(optional)*

*Field description*

The optional ***area_power*** input field defines the exponent applied to upslope source area used with area growth (eq. 4, section 3.6.3). The default value is 1. The value must be greater than zero and less than or equal to 1.

*Potential uses*

Some observations of growth indicate that flow volumes do not scale linearly with upslope area, rather they increase at a slower rate as contributing area increases. This exponent allows the effects of upslope source area to diminish with increasing area.

### ***length_growth*** *(optional)*

*Field description*

The ***length_growth*** section is an optional sub-subsection of the ***growth_volume*** subsection. This sub-subsection uses upstream channel lengths to compute growth volumes (section 3.6.3). This section contains two input fields (***length_growth_factor*** and ***length_power***) that pertain to the length-growth equation (eq. 5, section 3.6.3). Example E (section 6.5) illustrates usage of the ***length_growth*** section.

### ***length_growth_factor*** *(required if **length_growth** is used)*

*Field description*

The ***length_growth_factor*** input field is used for computing length-growth volumes. It is a scalar growth factor (in units of volume per length relative to the DEM length units) applied to the upstream channel length in growth zones, as shown in the length-growth equation (eq. 5, section 3.6.3). The value cannot be negative.

*Potential uses*

In settings where growth in flow volume is dependent on channel length, this controls the spatial rate of growth.

### ***length_power*** *(optional)*

*Field description*

The optional ***length_power*** input field defines the exponent applied to the upstream channel length in growth zones, $L_{gz}$ , used with length growth (eq. 5, section 3.6.3). The default value is 1. The value must be greater than zero and less than or equal to 1.

*Potential uses*

Some observations of growth indicate that flow volumes do not scale linearly with upstream channel length, rather they increase at a slower rate as length increases. This exponent allows the effects of upstream channel length area to diminish with increasing length.

### 4.2.2.7. Flow Inundation (optional)

The **INUNDATION** tool can be run (***inundation*** input field set to "yes") using default settings and so the ***inundation_options*** section may not be required. If the ***inundation*** input field is set to "no", then this section will be ignored. Flow inundation from growth can be calculated using the default settings listed in table 14, including a ***flowtype*** of debris flow, without the need to include the ***inundation_options*** section in the Settings file. For geophysical mass flow types other than debris flows, a specific ***flowtype*** needs to be entered in the ***inundation_options*** section (refer to section 3.5.3).

**Table 14.** Input fields in the Grfin Tools ***inundation_options*** section.

[csv, comma-separated values; NA, no default value (inactive if not used). File names need to have lengths, characters, and extensions valid for the Windows operating system]

| YAML input field name | Required? | Data type | Units | Default value | Values allowed |
|---|---|---|---|---|---|
| ***inundation_options*** | | | | | |
| ***flowtype*** | Optional | Specified text | -- | "debrisflow" | "debrisflow", "lahar", "rockavalanche", "custom" |
| ***xsec_alpha1*** | Optional | Real number | Non-dimensional | NA | >0 |
| ***plan_alpha2*** | Optional | Real number | Non-dimensional | NA | >0 |
| ***user_specified_volumes_file*** | Optional | csv file name | -- | NA | -- |
| ***xsec_demfilename*** | Optional | GeoTIFF file name | -- | setup: demfilename | -- |
| ***output.img*** | Optional | File name | -- | NA | -- |
| ***hbar*** | Optional | Specified text | yes/no | no | -- |

If the **GROWTH** tool is not enabled, then flow volumes and locations need to be specified in the ***user_specified_volumes_file*** designated in the ***inundation_options*** section. In this case, inundation proceeds from defined locations and follows the D8 flow direction paths determined in the ***setup*** section; a drainage network from the **DRAINAGE** tool is not required. The use of specified volume locations is described in section 3.5.3. The ***inundation_options*** section contains several specific input fields (table 14); all are optional.

### ***flowtype*** (optional)

*Field description*

The optional ***flowtype*** input field defines the type of flow and therefore the volume-area relations used for inundation (section 3.5.3). This field can be set to the words "debrisflow", "lahar", "rockavalanche", or "custom"; the default is "debrisflow". If "custom" is selected, then both the ***xsec_alpha1*** and ***plan_alpha2*** input fields are required.

*Potential uses*

Standard volume-area coefficients for ***flowtype*** ("debrisflow", "lahar", and "rockavalanche") are from Iverson and others (1998) and Griswold and Iverson (2008) (refer to table 2). One of these flow types should suit most applications. Entering "custom" in the ***flowtype*** input field may be necessary if event observations and accompanying statistics indicate significant differences from the standard fit coefficients in Iverson and others (1998) and Griswold and Iverson (2008).

### ***xsec_alpha1*** (required if ***flowtype*** is "custom")

*Field description*

If "custom" is entered in the ***flowtype*** input field, the ***xsec_alpha1*** input field sets the $\alpha_1$ coefficient in the volume-area equation for cross-sectional area (eq. 1, section 3.5.2). If used, then a value is also required in the ***plan_alpha2*** input field.

*Potential uses*

Custom values of $\alpha_1$ can modify the width and extent of flow inundation. This parameter should only be modified using numerous, precise observations of cross-sectional inundation for a range of events of interest; it is not intended to be used to calibrate flow inundation to a specific event.

### ***plan_alpha2*** (required if ***flowtype*** is "custom")

*Field description*

If "custom" is entered in the ***flowtype*** input field, the ***plan_alpha2*** input field sets the $\alpha_2$ coefficient in the volume-area equation for planimetric area (eq. 2, section 3.5.2). If used, then a value is also required in the ***xsec_alpha1*** input field.

*Potential uses*

Custom values of $\alpha_2$ control the planimetric extent of flow inundation. This field should only be modified using numerous, precise observations of planimetric inundation for a range of events of interest; it is not intended to be used to calibrate flow inundation to a specific event.

### ***user_specified_volumes_file*** (optional)

*Field description*

The optional ***user_specified_volumes_file*** input field designates the name and location of a file that contains the locations of starting points and volumes for flow inundation (section 4.3.4). Units of volume are relative to the DEM length units. It must be a valid, existing file in comma-separated values (csv) format. It is not required when the ***growth_options*** section is included. Note that if this input field is used in conjunction with the ***growth_options*** section, inundation from the starting points in this file will supersede any inundation from growth zones; volumes from growth will not be used.

*Potential uses*

This option provides the primary method to compute inundation from specified volumes and locations, rather than from growth zones. Inundation proceeds from the starting points and follows the D8 flow direction paths determined in the ***setup*** section; a drainage network defined using the **DRAINAGE** tool is not required. Specifying starting points and volumes is common with many flow inundation models, including Laharz (Schilling, 2014).

### ***xsec_demfilename*** (optional)

*Field description*

The optional ***xsec_demfilename*** input field designates the name and location of a file containing an alternative DEM to be used for constructing inundation cross sections. The ***xsec_demfilename*** DEM must be a valid, existing GeoTIFF file and its extent and resolution should match the original DEM. If this optional input field is not specified, the original DEM designated using the ***demfilename*** input field in the ***setup*** section is used for construction of cross sections.

*Potential uses*

The original DEM undergoes pit filling and the pit-filled DEM is used for the identification of flow directions and drainage networks, as described in section 3.1. Unless otherwise specified, the original, non-pit-filled DEM is then used for constructing cross sections. Alternatively, the ***xsec_demfilename*** input field allows a different DEM to be used to calculate cross-sectional areas. For example, in some cases using the pit-filled DEM may extend inundation laterally and better represent potential inundation effects. In other cases, where the original DEM was smoothed to remove disruptions such as roads (see section 6.7.b), the ***xsec_demfilename*** input field allows a non-smoothed DEM to be used for cross-section construction that better represents local topography.

### ***output_img*** (optional)

*Field description*

The optional ***output_img*** input field allows a user-specified name for the inundation output raster file, instead of the default name <*DEMfilename*>*_inundation.tif* (section 4.4.2.1.5). This file is saved in the output directory designated by the ***dest_dir*** input field.

*Potential uses*

Unique naming can be useful to distinguish between multiple runs using similar input files and (or) parameters.

### ***hbar*** (optional)

*Field description*

The optional ***hbar*** input field sets an additional constraint on the width of computed inundation cross sections. This input field can be set to the words “yes” or “no”. If ***hbar*** is set to “yes”, the minimum overall inundation height for all cross sections will be greater than or equal to the average inundation height for a given flow volume, such that overall height is $\geq \bar{h}$ . The default value is “no”.

*Potential uses*

This option has little effect on inundation in confined topography where cross sections can be readily constructed. However, in unconfined areas without distinct topographic barriers for constructing cross sections, this option holds the average inundation height to a fixed average height that is dependent on flow volume at a drainage cell and the volume-area relations selected (section 3.5.3). In unconfined areas, this results in a more uniform inundation width and a more tongue-like planimetric inundation portrayal. This option may be useful when less spreading and more downstream inundation is desired in unconfined areas. The total planimetric area of inundation is the same (within a small tolerance) with or without this option.

## 4.3. Optional Input Files

Additional input files are required for some optional features. Brief descriptions of these files are given below; use of these features is described further within the descriptions of specific fields in the Settings file in section 4.2.2. As noted in section 4.1, all optional input files in the GeoTIFF format need to have the same cell size and extent as the ***demfilename*** file. Most of these optional input file features are also illustrated by the examples (section 6).

### 4.3.1. Source Raster File (GeoTIFF format)

The user-provided source raster input file provides basic source-area information for *H*/*L* runout analyses or inundation analyses with restricted source-area growth (section 3.2.2). It is designated by the ***source_raster*** input field in the ***source*** section of the Settings file. It is only required if the **HL** tool is used. Note that if ***source_raster*** is set to “slope”, then no separate raster file is needed—Grfin Tools will compute slope from the DEM.

Source raster files typically contain either a series of values that define potential sources, such as factors of safety, or a series of zeros and ones, where non-zero values designate source areas. Source raster files can be filtered, for example, by minimum and maximum values, to delineate desired sources within the raster. Filtering is typical when using factors of safety or other susceptibility indices (section 3.2.2). Source zones are the inclusive range between filter minimum and maximum values (section 4.2.2.4). If no filters are implemented, then the entire source raster is used for analysis (excluding NODATA values). Examples A, D, and G (section 6) illustrate analyses using different source raster files.

### 4.3.2. Growth-Zone Raster File (GeoTIFF format)

The optional user-provided growth-zone raster input file specifies locations in the drainage network where volumetric growth may occur. It is designated by the ***growth_zone_raster*** input field in the ***growth_zones*** subsection of the Settings file. It is only needed for providing user-defined or modified growth zones. This raster file can be used alone or in combination with other ***growth_zones*** input fields to define potential growth zones (section 3.6.2). Cells in this raster with an exact value of 1 will be included in the growth zone; others will be ignored. An integer data type is recommended. A variation in example E (section 6.5) illustrates the use of a growth-zone raster file.

### 4.3.3. Growth Point Sources File (comma delimited text, csv format)

The optional user-provided growth point sources input file specifies locations and volumes of any point sources used for volumetric growth. It is designated by the ***point_source_volumes_file*** input field in the ***growth_volumes*** subsection of the Settings file. This file is only needed for providing user-specified point sources and volumes for growth. Volumes contained in this file are included in growth computations downslope or downstream from the point sources. The file must be in comma-separated values (csv) format with each line containing coordinate information and volume.

```
x location, y location, volume
```

Locations use the same coordinate system as the primary DEM designated by the ***demfilename*** input field. Volumes use the base units of the primary DEM. The file should not contain column headings.

### 4.3.4. Inundation Starting Points File (comma delimited text, csv format)

The optional inundation starting points input file specifies locations of starting points and volumes for flow inundation. It is designated by the ***user_specified_volumes_file*** input field in the ***inundation_options*** section of the Settings file. This file is needed if the **INUNDATION** tool is used without the **GROWTH** tool. Inundation proceeds from the starting points and follows the D8 flow direction paths (section 3.5.3). The file must be in comma-separated values (csv) format with each line containing coordinate information, volume, and an optional designator.

```
x location, y location, volume, designator
```

Locations use the same coordinate system as the primary DEM designated by the ***demfilename*** input field. Volumes use the base units of the primary DEM. The file should not contain column headings. Example B (section 6.2) illustrates the use of an inundation starting points file.

The designator column is optional. If no designator is specified or the fourth column is not used, the operational default for the designator is “AB”—this enables inundation in non-growth zones (section 3.5.3). This file is typically used without a designator column. If a designator is specified, it can be either “A” or “AB”, where “A” indicates that the flow volume will be used to compute only cross-sectional inundation and “AB” indicates that the flow volume will be used to compute both cross-sectional and planimetric inundation areas in the downstream non-growth zone. Note that the *<DEMfilename>_volumes.csv* file generated as output contains this complete information, including the designator column. Thus, this output file from a previous run can be used directly as input for a subsequent run by entering the previous output file name in the ***user_specified_volumes_file*** input field. This might be used, for example, to rerun scenarios without needing to recompute flow volumes in growth zones. It can also be used to calculate growth-based volumes in an initial run and then compute inundation in a subsequent run.

### 4.3.5. Inundation Cross-Section File (GeoTIFF format)

The optional inundation cross-section input provides an alternate DEM to construct inundation cross sections and thus delineate planimetric inundation areas. It is designated by the ***xsec_demfilename*** field in the ***inundation_options*** section of the Settings file. Flow directions and drainage networks are always derived from the primary DEM, but a separate DEM may better represent local topography. This DEM may have undergone pit filling or it may not be smoothed in order to honor local topography (where a smoothed DEM was used originally to create flow directions). The supplemental part of example G (section 6.7.b) illustrates the use of an inundation cross-section file.

## 4.4. Output Files

Grfin Tools produces various output files, depending on the options selected. Many of these output files are raster files in the same GeoTIFF format as the original DEM. These raster files can be visualized in GIS software. Other output files are in comma-separated values (csv) or text format and can be viewed in a variety of text editing software.

Most output raster files have a file naming convention using a prefix of *<DEMfilename>_*, where *<DEMfilename>* is the original DEM used for a given analysis. An exception is the output settings file, which uses the input Settings file name as a prefix.

Output files are placed in several directories and Grfin Tools creates subdirectories for select files (table 15). The primary output files are contained in the directory designated by the ***dest_dir*** input field in the ***setup*** section of the input Settings file (refer to section 4.2.2.1). Within the designated directory, Grfin Tools may create a subdirectory for growth-related files if the **GROWTH** tool is used. Basic TauDEM setup files and drainage files that can be used for subsequent runs are saved in specific subdirectories located in the same directory as the primary DEM. Output files are discussed below by directory and subdirectory.

**Table 15.** Directories and subdirectories containing Grfin Tools output files.

[The **GROWTH** tool invokes the **DRAINAGE** tool with default options if the **DRAINAGE** tool is not specified]

| Directory | Subdirectory | Contents |
|---|---|---|
| DEM directory | -- | DEM |
| -- | *<DEMfilename>_TauDEM/* | TauDEM files from **SETUP** and **HL** tools |
| -- | *<DEMfilename>_drainage/* | Drainage files from **DRAINAGE** tool |
| ***dest_dir*** directory | -- | Primary output files |
| -- | *<DEMfilename>_growth/* | Growth files from **GROWTH** tool |

## 4.4.1. Output Files in the DEM Directory

Ground-surface hydrology files created by TauDEM with the **SETUP** tool and drainage files created by the **DRAINAGE** tool are saved in two subdirectories within the primary DEM directory. These files can be utilized for multiple analyses of the same DEM and therefore do not need to be recreated unless topographic or drainage characteristics are modified between runs.

### 4.4.1.1. TauDEM Output Files

Files created by TauDEM with the **SETUP** tool are placed in the *<DEMfilename>_taudem/* subdirectory; this subdirectory is located within the directory containing the primary DEM (table 16). This subdirectory is created if it does not already exist. An additional TauDEM file is placed in this subdirectory if the **HL** tool is used (created by the TauDEM D-infinity flow direction tool). All files are utilized for internal Grfin Tools processing and may be applied to multiple runs. Details about the structure of these files can be found in the TauDEM documentation (Tarboton, 2005). Typically, a user will not need to view these output files.

**Table 16.** Output files created by a Grfin Tools call to TauDEM and placed in the *<DEMfilename>_taudem/* subdirectory within the directory containing the primary digital elevation model (DEM).

| File | Description | Tool used | File format |
|---|---|---|---|
| *<DEMfilename>_fel.tif* | DEM with pits removed | **SETUP** | GeoTIFF |
| *<DEMfilename>_felp.tif* | D8 flow direction grid | **SETUP** | GeoTIFF |
| *<DEMfilename>_ad8.tif* | D8 flow accumulation grid (NODATA values assigned where full contributing area is truncated) | **SETUP** | GeoTIFF |
| *<DEMfilename>_ad8min.tif* | D8 flow accumulation grid (includes partial basins) | **SETUP** | GeoTIFF |
| *<DEMfilename>_sd8.tif* | D8 slope grid (measured as drop over distance) | **SETUP** | GeoTIFF |
| *<DEMfilename>_felang.tif* | D-infinity flow direction grid | **HL** | GeoTIFF |

### 4.4.1.2. Drainage Output Files

Drainage output files are placed in the *<DEMfilename>_drainage/* subdirectory; this subdirectory is located in the same directory containing the primary DEM (table 17). This subdirectory is created if it does not already exist. Drainage files are generated using either the ***standalone_drainage_network*** input field or the **GROWTH** tool. The ***compute_new_drainage*** input field must be set to “yes” to create new drainage files with non-default parameters. Four of the files listed in table 17 are created by the **DRAINAGE** tool. Five other files in the *<DEMfilename>_drainage/* subdirectory (including multiple components of a shapefile) are created by the **GROWTH** tool. If a user wants to use drainage files created during a previous run (to save processing time), the ***compute_new_drainage*** field can be set to “no”.

**Table 17.** Drainage-related output files created by Grfin Tools and placed in the *<DEMfilename>_drainage/* subdirectory within the directory containing the primary digital elevation model (DEM).

[Shapefiles (.shp extension) have multiple associated files: .shx, .dbf, and .prj]

| File | Description | Tool used | File format |
|---|---|---|---|
| *<DEMfilename>_drain_settings.txt* | Settings for drainage network | **DRAINAGE** | Text |
| *<DEMfilename>_stream.tif* | Stream drainage network | **DRAINAGE** | GeoTIFF |
| *<DEMfilename>_smooth.tif* | Smoothed DEM | **DRAINAGE** | GeoTIFF |
| *<DEMfilename>_smoothplancurv.tif* | Planform curvature from smoothed DEM | **DRAINAGE** | GeoTIFF |
| *<DEMfilename>_stream.shp* | Stream drainage network with attributes | **GROWTH** | Shapefile (.shp) and 3 associated files |
| *<DEMfilename>_slpdeg.tif* | Stream slope in degrees | **GROWTH** | GeoTIFF |

##### 4.4.1.2.1. Drainage Settings Summary File (text format)

A drainage settings summary file named <*DEMfilename*>*_drain_settings.txt* is created if new drainage files are saved. This will occur if the ***growth*** input field is set to "yes" unless the ***compute_new_drainage*** input field is set to "no". This file is also generated if the ***standalone_drainage_network*** input field and the ***compute_new_drainage*** input fields are both set to "yes". The file contains a text summary of the drainage network parameter values selected by the user, as well as any default fields implemented in the drainage network construction.

##### 4.4.1.2.2. Stream Drainage Network File (GeoTIFF format)

A stream drainage network file named <*DEMfilename*>*_stream.tif* file is created if a new drainage network is constructed. This file contains the stream drainage paths, starting with channel heads defined by the curvature-based drainage network method (section 3.4). Drainage-network stream cells have a value of one, other cells in the raster have a value of zero.

##### 4.4.1.2.3. Smoothed DEM File (GeoTIFF format)

A smoothed DEM file named <*DEMfilename*>*_smooth.tif* is created if a new drainage network is constructed using the **DRAINAGE** or **GROWTH** tool. This file contains a smoothed version of the DEM using a smoothing window defined by the ***dem_neighborhood*** input field in the ***drainage_options*** section (refer to section 4.2.2.3). The smoothed DEM is used to define the drainage network; it can also be used to reduce undesirable drainage patterns caused by roads (section 5.2).

##### 4.4.1.2.4. Smoothed Planform Curvature File (GeoTIFF format)

A planform curvature file named <*DEMfilename*>*_smoothplancurv.tif* is created from the smoothed DEM file if a new drainage network is constructed. This file contains computed planform curvature values for each DEM cell (section 3.4). These curvature values are used for drainage network delineation; they are also used if a curvature threshold is set for the **SOURCE** tool (section 3.2) or **GROWTH** tool (section 3.6.2).

##### 4.4.1.2.5. Stream Drainage Network Shapefiles (shapefile format and associated files)

A series of stream drainage network shapefiles named <*DEMfilename*>*_stream…* with extensions .dbf, .prj, .shp, and .shx are created if the **GROWTH** tool is used. These files can be used to view a vector shapefile of the stream network in a GIS. The attribute table for this shapefile contains 16 attributes for each stream segment, including segment length, Strahler stream order, and stream segment slope; refer to Tarboton and others (2015) description of the StreamNet function for details.

##### 4.4.1.2.6. Stream Slope File (GeoTIFF format)

A stream slope file named <*DEMfilename*>*_slpdeg.tif* is created when the **GROWTH** tool is used. This file contains stream slope (in degrees) along the drainage network defined over either a stream segment or a fixed horizontal distance, as specified by the ***slope_method*** field in the ***growth_options*** section (refer to section 4.2.2.6.1).

### 4.4.2. Output Files in the Primary Output Directory

Grfin Tools output files that are specific to an individual run, and not used for multiple runs, are placed in the directory designated by the ***dest_dir*** input field. When using the **GROWTH** tool, a subdirectory named "<*DEMfilename*>*_growth/*" is created in this designated directory to contain output files related to flow growth.

#### 4.4.2.1. Primary Output Files

The primary output files (table 18) containing source areas, *H*/*L* runout distances and reach angles, and flow inundation areas are saved in the directory designated by the ***dest_dir*** input field along with text files containing summary information and an inundation log. The contents of these files are described in more detail below.

**Table 18.** Primary output files created by Grfin Tools and placed in the designated ***dest_dir*** directory.

[Specific files saved depend on options selected]

| File | Description | Tool used | File format |
|---|---|---|---|
| *<Settingsfilename>_settings.txt* | Summary information for a run | All tools | Text |
| *<DEMfilename>_sourcearea.tif* | Source areas | **SOURCE** | GeoTIFF |
| *<DEMfilename>_hlrunoutdistance.tif* | *H*/*L* runout distances from source areas | **HL** | GeoTIFF |
| *<DEMfilename>_hlreachangle.tif* | *H*/*L* reach angles to source areas (in degrees) | **HL** | GeoTIFF |
| *<DEMfilename>_inundation.tif* or user-specified file name | Flow inundation areas | **INUNDATION** | GeoTIFF |
| *<DEMfilename>_inundation_log.txt* | Log from inundation computations | **INUNDATION** | Text |

#### 4.4.2.1.1. Settings Summary File (text format)

A settings summary file named "*<Settingsfilename>_settings.txt*" is created with each Grfin Tools run and contains a text summary of the options used in the analysis, the input field values selected by the user, and the default parameters implemented. Values set by default are designated with an asterisk (*). This file also contains the Grfin Tools version number and total runtime. It is recommended that a user examine this text file to ensure that the desired settings were implemented in a given run.

#### 4.4.2.1.2. Source-Area File (GeoTIFF format)

A source-area file named "*<DEMfilename>_sourcearea.tif*" is created if the **SOURCE** tool is used. This file contains the filtered source areas derived from the file designated using the ***source_raster*** input field (section 4.2.2.4). Source cells have a value of one in this raster; other cells contain values of zero.

#### 4.4.2.1.3. *H*/*L* Runout Distance File (GeoTIFF format)

An *H*/*L* runout distance file named "*<DEMfilename>_hlrunoutdistance.tif*" is created if the **HL** tool is used. This file contains runout distances at each cell along a flow path, with the highest angle of reach from the source areas (section 3.2) as defined in the ***source*** section. Any positive values in this raster delineate areas affected by *H*/*L* runout. This file is equivalent to the TauDEM output file created with the "*Output_Path_Distance_Grid*" parameter when using the D-Infinity Avalanche Runout tool (Tarboton, 2005). Positive values in this raster file are distances in DEM length units; areas with no runout have NODATA values in their cells. The smallest possible runout distance is the length of a DEM cell. Note that displaying all positive values in this raster file will portray overall runout.

#### 4.4.2.1.4. *H*/*L* Runout Reach Angle File (GeoTIFF format)

An *H*/*L* runout angle of reach file named "*<DEMfilename>_hlreachangle.tif*" is created if the **HL** tool is used. This file contains the angles of reach for each runout cell along a flow path, extending back to the source areas (section 3.2) as defined in the ***source*** section. Reach angles contained in this file are greater than or equal to the threshold set by the ***min_reach_angle*** input field. This file is equivalent to the TauDEM output file created with the "*Output_Runout_Zone_Grid*" parameter when using the D-Infinity Avalanche Runout tool (Tarboton, 2005). Positive values in this raster file are angles of reach in degrees; areas with no runout have NODATA values in their cells. Note that as with the *<DEMfilename>_hlrunoutdistance.tif* raster file, displaying all positive values in this raster file will portray overall runout.

#### 4.4.2.1.5. Flow Inundation File (GeoTIFF format)

A flow inundation file named "*<DEMfilename>_inundation.tif*" is created if the **INUNDATION** tool is used. This file identifies the areas affected by flow inundation (section 3.5.3), using non-zero integer values. Inundated cells can have four different values, depending on whether inundation is from a growth or non-growth zone and whether inundation is influenced by cross sections that encounter a DEM boundary or NODATA cells. This latter condition might result in situations where the target planimetric area is not achieved, as inundation is halted at the DEM boundary or NODATA area. Integer values in this file are as follows:

| | |
|---|---|
| 10 | inundation in a growth zone, |
| 20 | inundation in a non-growth zone, |
| −10 | inundation in a growth zone from cross sections that encounter a DEM boundary or NODATA cells, and |
| −20 | inundation in a non-growth zone from cross sections that encounter a DEM boundary or NODATA cells. |

These inundation designations can be used for more detailed examination of a run. Cells with no inundation have a value of zero. Note that displaying all non-zero values in this raster file will portray overall runout.

#### 4.4.2.1.6. Flow Inundation Log File (text format)

A flow inundation log file named "*<DEMfilename>_inundation_log.txt*" is created if the **INUNDATION** tool is used; this file records special conditions that arise while computing inundation cross sections (section 3.5.3). Messages in this log file can result from cross sections encountering a DEM boundary or NODATA cells, or from inundation being halted when reaching the DEM boundary or NODATA area. These situations may result in the target planimetric area not being achieved. Messages in this log file are to be expected for cross sections adjacent to DEM boundaries and NODATA areas. Messages are denoted by

```
       id,   init_x,   init_y,              message,     at_x,     at_y,
```

where

| | |
|---|---|
| `id` | designates the A or AB point number, |
| `init_x` and `y` | are coordinates in the DEM framework of the initial A or AB point associated with the message, |
| `message` | is text that describes the situation being logged, and |
| `at_x` and `y` | are the coordinates of the initial point of the cross section where the message condition occurred. |

### 4.4.2.2. Growth Output Files

If the **GROWTH** tool is used, the *<DEMfilename>_growth/* subdirectory is created in the output directory designated by the ***dest_dir*** input field. Growth-related output files are placed in this subdirectory (table 19).

**Table 19.** Growth-related output files created by Grfin Tools and placed in the *<DEMfilename>_growth/* subdirectory within the designated ***dest_dir*** directory.

| File | Description | Tool(s) used | File format |
|---|---|---|---|
| *<DEMfilename>_grzone.tif* | Growth zones in drainage network | **GROWTH** | GeoTIFF |
| *<DEMfilename>_volumes.shp* | Volume components | **GROWTH** | Shapefile .shp and associated files |
| *<DEMfilename>_volumes.csv* | List of total volumes | **GROWTH** | Comma delimited (csv) |
| *<DEMfilename>_scrarearatio.tif* | Source-area ratios | **GROWTH** and **SOURCE** | GeoTIFF |
| *<DEMfilename>_grzoneratio.tif* | Growth-zone ratios | **GROWTH** | GeoTIFF |

#### 4.4.2.2.1. Growth-Zone File (GeoTIFF format)

A growth-zone file named "*<DEMfilename>_grzone.tif*" is created if the **GROWTH** tool is used. This file identifies segments of the drainage network that are growth zones for a given run, specified by positive integer values. Cell values of one indicate growth zones within complete drainage basins, whereas values of two indicate growth zones affected by drainage from partial basins in the DEM. Cells not included in a growth zone have a value of zero. Although partial drainage basins are excluded by default, they can be included by setting the ***include_partial*** input field to "yes" (section 4.2.2.6.1). If partial drainage basins are included, this file provides some insight into the potential effects of growth zones from partial basins.

#### 4.4.2.2.2. Volumes Shapefiles (shapefile format and associated files)

A series of volumes shapefiles named "*<DEMfilename>_volumes…*" with extensions.dbf, .prj, .shp, and .shx are created if the **GROWTH** tool is used. These files can be used to view to view a vector shapefile of points along the growth zones in a GIS. The attribute table for this shapefile contains seven attributes for each point:

| | |
|---|---|
| VolPtSrc | volume component from point sources, |
| VolArea | volume component from area growth, |
| VolLen | volume component from length growth, |
| VolInitSrc | volume component from initial source, |
| VolTotal | total volume from all components, |

| | |
|---|---|
| VolType | designator of "A" or "AB", as used for cross-sectional area (A) or both cross-sectional and planimetric area (AB) computations, and |
| AtMaxVol | indicator of whether total volume equals maximum volume (if this constraint was selected). |

Units of volume are relative to the DEM length units. Total volume includes volumes from point sources, area growth, length growth, and (or) initial volume components, if multiple growth options are used.

#### 4.4.2.2.3. Volumes List File (comma delimited text, csv format)

A volumes list file named "*<DEMfilename>_volumes.csv*" is created if the **GROWTH** tool is used. This file contains total flow volumes computed in the growth zones (as in the volumes shapefile). The file is in comma-separated values (csv) format with each line containing information for a point.

```
x location, y location, volume, designator
```

Units of volume are relative to the DEM length units. The designator is either "A" or "AB", where "A" indicates that the flow volume was used to only compute cross-sectional area (in a growth zone) and "AB" indicates that the volume was used to compute both cross-sectional and planimetric areas downstream in non-growth zones. Locations with "AB" are at the downstream ends of growth zones; typically, most locations in this file have values of "A", as every cell in the growth zones has a value. The "AB" locations in this file can be used as starting points for downstream flow inundation without re-computing growth volumes (section 4.2.2.4). Also, this file can be used directly as an input file in the ***user_specified_volumes_file*** input field for a subsequent run, if desired.

#### 4.4.2.2.4. Source-Area Ratio File (GeoTIFF format)

A source-area ratio file named "*<DEMfilename>_srcarearatio.tif*" file is created if both the **SOURCE** and **GROWTH** tools are used. This file contains values for the ratio of upslope source area to total upslope contributing area (sections 3.6.2).

#### 4.4.2.2.5. Growth-Zone Ratio File (GeoTIFF format)

A growth-zone ratio file named "*<DEMfilename>_grzoneratio.tif*" is created if the ***min_growthzone_ratio*** input field is set to "yes". This file contains values for the ratio of upstream channel length contained in growth zones to the total upstream channel length (section 3.6.2), based on previously defined growth zones.

# 5. Handling Special Conditions

Here we discuss approaches to handling several conditions that may affect delineation of flow inundation over large areas using Grfin Tools:

- Partial drainage basins
- Roads
- Water bodies
- Lengthy runtimes

The first three conditions can affect flow directions and resulting drainage networks and thereby affect inundation and runout. With the **HL** and **INUNDATION** tools, flow directions in the DEM control the flow paths; any local deviations of flow direction away from the natural channel will affect the delineation of flow inundation. With the **GROWTH** tool, the constructed drainage network controls the identification of growth zones and computation of growth volumes using upslope area- or channel-length-based methods (section 3.6.3). In the following sections, we offer suggestions for handling partial drainage basins incompletely encompassing drainage areas, reducing the effects of road-related artifacts disrupting drainage paths, removing spurious effects from large water bodies on inundation and runout patterns, and improving runtimes.

## 5.1. Partial Drainage Basins

To accurately compute both $H/L$ runout and flow inundation using Grfin Tools, all potential source areas and growth zones within the selected DEM domain must be included. For small basins, clipping the DEM to the complete basin drainage area may be sufficient to encompass all elements affecting runout and inundation (although inundation may extend outside a small basin).

In most cases, however, a rectangular DEM domain is used for analysis—these rectangular domains almost always include partial drainage basins around their margins and exclude headwaters of adjacent basins. Partial basins are identified by TauDEM with the **SETUP** tool (section 3.1). When assessing *H*/*L* runout or flow inundation from starting points, a user should be able to determine visually whether the DEM extent sufficiently spans the area of expected runout or inundation.

In contrast, the effects of partial drainage basins on delineating flow inundation using volumetric growth can be more subtle and difficult to discern. In this case, calculating growth with the **GROWTH** tool relies on a drainage network to define growth zones. By default, Grfin Tools does not include growth zones in any partial drainage basins as the zones are potentially incomplete. This can provide a coherent analysis of complete drainage basins within the DEM domain. However, upstream partial basins can affect downstream inundation in two ways: (1) partial basins within the DEM domain are not included in growth zones and, moreover, can also affect downstream growth zones, which potentially underestimates growth; and (2) partial basins may indicate the possibility of growth zones or sources completely outside the DEM domain and these potential effects will not be included.

Excluding partial basins from the analysis domain excludes any potential growth zones in these partial basins from inundation. Furthermore, a downstream channel connected to an upstream partial upstream basin (on the edge of the DEM) will not have growth zones (fig. 30*A*). Growth zones can be computed for partial basins by setting the ***include_partial*** input field in the ***growth_options*** section to “yes” (refer to section 4.2.2.6.1). With this setting, any partial basins will be included for identifying potential growth zones, as well as for enabling potential growth zones in downstream channels affected by the upstream partial basin drainages (fig. 30*B*). This can significantly increase potential growth. Comparing the growth-zone raster files (*<DEMfilename>_grzone.tif*) produced with each setting can show the extent of growth zones associated with partial basins. In this raster, values of 1 indicate growth zones not affected by partial basins, whereas values of 2 designate zones affected by partial basins.

The second potential effect of partial basins is that tributaries entering from outside the DEM domain may add flow volumes to those drainages within the basin. This effect might be partially mitigated if the outside tributary encounters a drainage that has already reached its maximum flow volume, thus reducing its influence on inundation within the DEM domain. Ultimately, it can be difficult to determine the influence of areas outside the DEM on flow growth without comparing growth zones and inundation results with and without areas outside of original DEM domain.

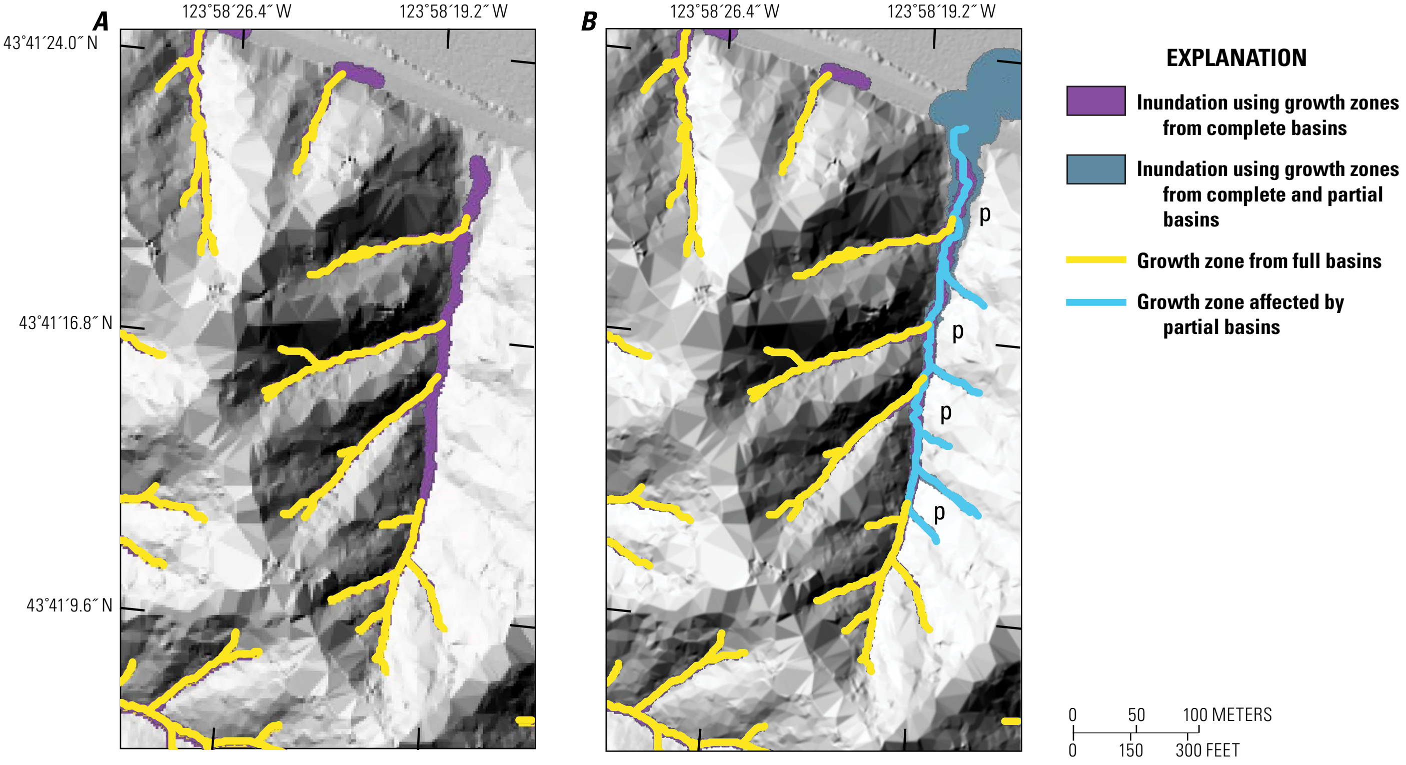


**Figure 30.** Maps showing inundation in part of the Coast Range, Oregon, calculated in Grfin Tools using growth zones from complete drainage basins (*A*) and growth zones from both complete and partial basins (*B*) within a digital elevation model (DEM). The DEM extent truncates basins along the right edge, creating partial drainage basins and excluding headwaters (section 3.6.2). These upstream partial basins (p) can also affect downstream growth zones in the larger streams. In this example, including growth zones from both complete and partial basins in the analysis increases downstream inundation. Hillshade from lidar-derived 3-foot-resolution DEM (Oregon Department of Geology and Mineral Industries, 2009).

## 5.2. Reduction of Road-Related Drainage Artifacts

In many types of terrain, flow directions in a DEM can be affected by roads crossing hillslopes and laterally intersecting natural drainage networks. For channel detection algorithms used to construct drainage networks, some roads can intercept and divert surface hydrologic flow, thereby obscuring natural channels. This is a scale-dependent process, so using high-resolution lidar-derived DEMs can result in detecting smaller roads on hillslopes. Moreover, wide multi-lane roads may have strong effects on flow directions. Flow in actual topography, however, may not actually proceed down the roads but instead be routed under roads via culverts or bridges into downslope natural channels or across roads due to inertial effects—though observations also indicate that some flows do travel down roads, especially where culverts are blocked. Grfin Tools drainage networks, used for delineating inundation from flows that grow, follow D8 flow directions defined by the DEM and do not bifurcate. In cases where actual flows might follow roads, cross roads, or follow both paths, users should decide which paths to use. Multiple scenarios with different drainage networks can be compared to assess changes in inundation patterns.

The default values for constructing drainage networks in Grfin Tools (section 3.4) typically eliminate road-related artifacts when identifying the initiation locations of channels in the upper part of the drainage network. However, downstream parts of the network may still have severe and unacceptable artifacts caused by roads diverting flow. In this case, it is possible to use a smoothed DEM to create a drainage network that reduces the effects of road diversions and instead follows natural drainages. The original DEM can be selected using the ***xsec_demfilename*** input field in the ***inundation_options*** section (refer to section 4.2.2.7) to represent the original topography when constructing cross sections and computing inundation. Alternatively, the DEM can be filtered using other software before the file is used in Grfin Tools. Brien and others (in press) used this process for performing inundation analysis over large areas in Puerto Rico.

Grfin Tools can remove some road related artifacts using the following multi-step method:

1. Create a smoothed DEM using the **DRAINAGE** tool. Enter “yes” in the ***standalone_drainage_network*** input field in the ***options*** section (refer to section 4.2.2.2) and set the radius of a smoothing window using the ***dem_neighborhood*** input field. For high-resolution (<10-m cell size) DEMs with road-related drainage problems, a 10–20-m smoothing window is suggested. Note that larger smoothing windows (typically >10 m) may also subdue some natural features in the topography, eliminate some inundation near-channel initiation in topographic hollows, and reduce the locational accuracy of the generated network. The drainage network constructed from the smoothed DEM can be placed in a new directory to better manage output files. Selecting an appropriate smoothing window may require some minor adjustments.

2. Run Grfin Tools using the smoothed DEM. Enter the file name of the smoothed DEM in the ***demfilename*** input field in the ***setup*** section (refer to section 4.2.2.1). In addition, specify the original DEM in the ***xsec_demfilename*** input field in the ***inundation_options*** section (refer to section 4.2.2.7) for constructing inundation cross sections and computing planimetric areas. The ***dem_neighborhood*** input field in the ***drainage_options*** section (refer to section 4.2.2.3) should be set to one, as DEM smoothing has already been applied. Using the original DEM for estimation of planimetric and cross-sectional areas will minimize issues related to loss of locational accuracy.

A complete step-by-step description of the process outlined above is presented in the supplement to example G (section 6.7.b). This procedure provides a semi-automated method to reduce the effects of some road-related artifacts, but it is not a full replacement for the creation of hydrologically correct DEMs or the application of stream-burning techniques (for example, Lindsay, 2016).

## 5.3. Water Bodies

Inundation can overwhelm water flowing in smaller streams, but this is unlikely to affect the accuracy of inundation delineated using Grfin Tools. However, large water bodies, such as lakes, reservoirs, oceans, and large rivers, are common in many types of terrain and they may enhance the mobility of rapidly moving geophysical flows that impact and hydroplane under water (for example, Mohrig and others, 1998; De Blasio and others, 2004). The planimetric volume-area relations used in Grfin Tools (section 3.5.2) are based on subaerial observations that do not account for substantial changes in mobility induced by interaction with large water bodies. In addition, $H/L$ runout may be impeded by water in coastal areas and similar settings. Although runout or inundation under water is possible, the extent of runout or flow inundation delineated by Grfin Tools into or across large water bodies is likely inaccurate. Two approaches are possible for removing spurious inundation and runout into water bodies—either masking out inundation that extends into water after analysis or preventing this inundation from being delineated in the first place.

As inundation and runout is controlled by flow paths, different conditions in the DEM can affect a drainage network constructed flowing into or near large water bodies. Grfin Tools performs differently depending on how water bodies are accounted for in DEMs:

1. For a DEM that contains water-surface elevation data for a large water body (common with reservoirs, wetlands, and large rivers), some elevations may vary slightly and this can lead to the construction of a wandering, unrealistic drainage network or spurious flow directions across the mostly flat surface of the water body. Although these flow network paths are not representative of actual flow directions across the water surface, computed inundation will proceed along these paths. Runout will also follow computed flow directions. Wandering flow directions can be observed in example E (section 6.5), where inundation follows a path into the Umpqua River. In this situation, we suggest that any inundation into the large water bodies be masked out of any map product, as the extent of inundation likely will be erroneous.

2. For a DEM that contains a hybrid of subaerial topography and bathymetric data for a large water body, flow paths may realistically follow the hybrid terrain, but the planimetric inundation areas may be erroneous due to differences between subaerial and subaqueous mobility. Again, subaqueous inundation may be unrealistic and thus need to be masked out of any map product.

3. For a DEM that contains NODATA values for a large water body (sometimes present with oceans), then no drainage paths will be created within the NODATA area, and the water body boundary acts essentially as a boundary of the DEM. Here, delineation of inundation will not occur in the NODATA area (section 3.5.3); cross sections that extend into the NODATA area are noted in the flow inundation log file (section 4.4.2.1.6). This process might result in inundation that does not achieve the target planimetric area derived from the volume-area relations, as inundation is halted at the NODATA boundary. Nevertheless, an advantage of this approach is that no inundation into water is delineated. Assigning NODATA values to a large water body can also increase computational efficiency (section 5.4).

## 5.4. Lengthy Runtimes

Although computing inundation and runout with Grfin Tools is typically very computationally efficient with short runtimes, some components of a Grfin Tools run can lead to longer runtimes. Methods to reduce lengthy runtimes include (1) avoiding re-computing large raster files in the ***setup*** and ***drainage_options*** sections and (2) assigning NODATA values to areas in a DEM that are outside the area of interest.

Commonly, using the **SETUP** tool to produce a pit-filled DEM as well as flow direction and flow accumulation raster files using TauDEM takes the majority of runtime. Fortunately, these raster files only need to be computed once for a given DEM. Assigning more computer processes available for TauDEM calls (using the ***num_procs*** input field in the ***setup*** section) can also reduce runtime. In subsequent runs using the same DEM and the default setting of “if_absent” for the ***compute_taudem_grids*** input field (section 4.2.2.1), these raster files will only be re-generated if any files are missing, thus saving substantial runtime. These TauDEM raster files are located in the <*DEMfilename*>*_taudem/* subdirectory of the DEM directory.

Creating a drainage network to identify growth zones can also take significant runtime. If the files associated with a given drainage network have already been created (located in <*DEMfilename*>*_drainage/* subdirectory of the primary DEM directory), then entering “no” in the ***compute_new_drainage*** input field in the ***drainage_options*** (section 4.2.2.3) can reduce runtimes.

In some cases, assigning NODATA values to parts of a DEM outside the areas of interest can also reduce overall runtimes. However, runout and inundation may travel onto flatter ground or beyond the mouths of small drainage basins, so be careful to not eliminate potential inundation areas downslope and downstream of potential source areas.

Runtimes for the **SETUP** tool can be severely affected by large flat areas or large bodies of water in the original DEM. Determining flow directions in flat areas typically requires an iterative, time-intensive approach (for example, Pan and others, 2012). In particular, the presence of large water bodies, such as oceans, lakes, and reservoirs where DEM processing has produced constant elevations will adversely affect the runtimes needed to compute flow directions. These water bodies can be identified in GIS software as large, contiguous areas with slopes of zero. One way to greatly improve **SETUP** tool runtimes in these situations is to set all elevation values in these large water bodies to the NODATA value of the DEM using a masking process in GIS software. Masking could be done using areas of zero slope or areas with very similar elevations (such as oceans with elevations near zero). Flow directions will not be computed in NODATA areas. In addition, having NODATA values in these large water bodies serves to rationally halt inundation at the water boundaries (refer to section 5.3).

# 6. Examples of Applications

This section contains a series of examples demonstrating specific usage pathways, as outlined in section 2 of this document and summarized in table 20. These examples are an ideal way to learn to use Grfin Tools and explore its products.

**Table 20.** Example applications of Grfin Tools.

[DEM, digital elevation model; *H*/*L*, height-to-length ratio; m, meter; ft, foot]

| Example | Description | Location | DEM resolution |
|---|---|---|---|
| A | *H*/*L* runout from landslide sources only; no inundation | Kosrae, Federated States of Micronesia | 10 m |
| B | Lahar inundation from user-specified point sources and volumes | Lassen Peak, California | 1 m |
| C | Standalone drainage network | San Bernardino, California | 1 m |
| D | Debris-flow inundation using growth factors based on upslope source area | Utuado, Puerto Rico | 1 m |
| E | Debris-flow inundation using growth factors based on stream length | Umpqua River, Oregon | 3 ft |
| F | Debris-flow inundation using multiple growth components based on field or remote measurements | Naranjito, Puerto Rico | 1 m |
| G | Landslide susceptibility map using a combination of tools and scenarios | Utuado, Puerto Rico | 1 m |

All examples are available in self-contained packages, including an appropriate DEM, input Settings files for a base case and variations, and any needed ancillary input files. Detailed instructions on how to download, configure, and run Grfin Tools are contained in the Grfin Tools software release available online at https://doi.org/10.5066/P9NVKFE2 (Cronkite-Ratcliff and others, 2025).

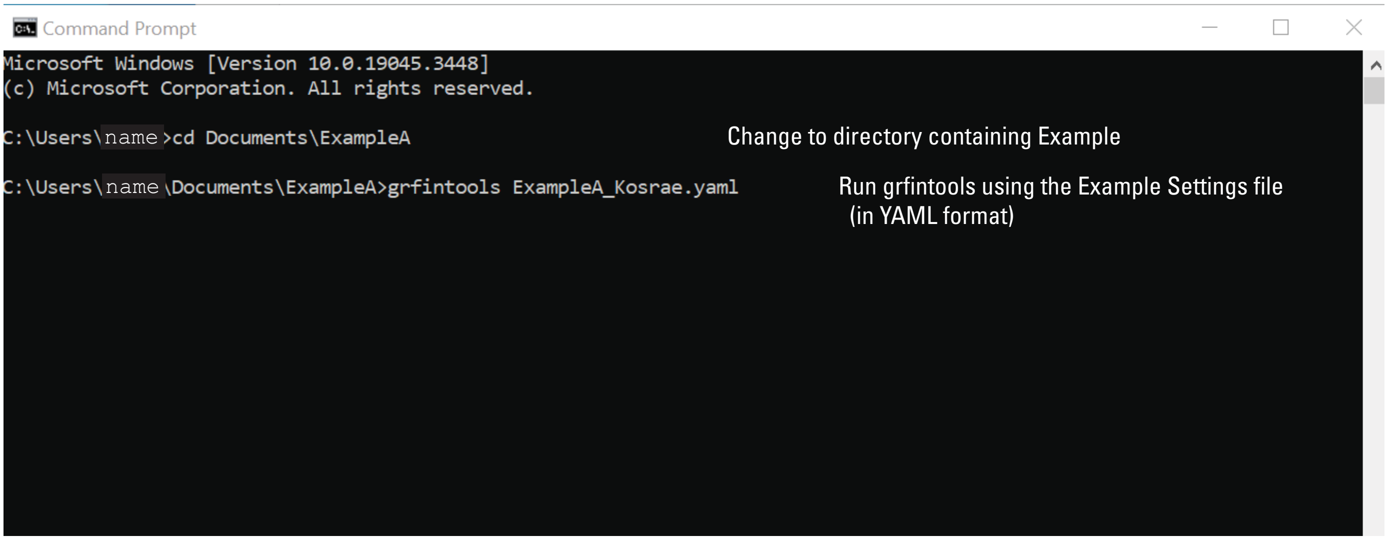
Each example is explained in a detailed description below, with sections containing:

- an overview of the example,
- a brief description of the background and physical setting,
- highlighted input files and options,
- output products generated, and
- and a discussion of the output results.

The discussion for each example explains the variations and portrays their effects in multiple figures.

## Running an example

An easy approach to running an example is to download a specific example package into a user directory that is accessible to the installed Grfin Tools on the user's computer (such as the *Documents/* directory). Open a command prompt window and change directories to the directory name containing the example by typing “cd” and then the location of the example directory (in fig. 31 this is *Documents/ExampleA*). Type “grfintools <*ExampleName*>.yaml” and press the Enter key, then the run should proceed with information scrolling into the command prompt window. These commands using “ExampleA” in place of “<*ExampleName*>” are illustrated in figure 31.



```
Microsoft Windows [Version 10.0.19045.3448]
(c) Microsoft Corporation. All rights reserved.

C:\Users\name>cd Documents\ExampleA

C:\Users\name\Documents\ExampleA>grfintools ExampleA_Kosrae.yaml
```

Change to directory containing Example

Run grfintools using the Example Settings file (in YAML format)

**Figure 31.** Annotated screen capture of command prompt window illustrating commands to change directories to the *ExampleA/* directory and then start a Grfin Tools run using the example A Settings file.

Spatial raster files generated by example runs are in GeoTIFF format and can be readily visualized in any GIS software. More description of various output files and their locations can be found in section 4.4 and table 15 of this document. Primary output files are located in the directory designated by ***dest_dir*** input field in the Settings file of a given example. Drainage-related output files are located *<DEMfilename>_drainage/* subdirectory within the DEM directory. Growth zone output files are in the *<DEMfilename>_growth/* subdirectory within the output directory. Note that the output raster files for inundation (default name: *<DEMfilename>_inundation.tif*), runout angle of reach (*<DEMfilename>_hlreachangle.tif*), and runout distance (*<DEMfilename>_hlrunoutdistance.tif*) contain additional non-zero information for use in more advanced analyses (section 4.4.2.1). For example, this information might indicate whether inundation is from a growth zone or the runout distances from source cells. For purposes of viewing an entire inundation or runout zone in GIS software, this extra information can be ignored: all non-zero values in these raster files can be used to portray the entire inundation or runout zones.

## 6.1. Example A. *H/L* Runout from Source Areas Only; No Inundation (Kosrae)

### Overview

Example A illustrates how the **HL** tool can be used to delineate areas of potential runout from upslope landslide source areas. The area of runout is identified using an angle of reach threshold (defined using the ***min_reach_angle*** input field in the ***hl_options*** section) starting from potential landslide source areas that have slopes equal to or greater than a specified topographic slope value (identified using the **SOURCE** tool). These thresholds and parameters are specified in the Settings input files. The underlying basis for the **HL** tool is discussed in section 3.3. In this example, the **DRAINAGE**, **GROWTH**, and **INUNDATION** tools are not used. This example demonstrates the first pathway shown in figure 2 (section 2.2).

### Background and Physical Setting

The main island of Kosrae in the Federated States of Micronesia has steep, dissected, and jungle-covered terrain adjacent to flat coastal aprons. On other islands in the Federated States of Micronesia, such as in the States of Chuuk and Pohnpei, landslides triggered by tropical storms on similar hillslopes have traveled onto and across flatter, more populated areas (Harp and Savage, 1997; Harp and others, 2004; Harp and others, 2009).

### Input Files and Options

Each run of the base case or the variations requires the DEM file and a Settings file, which are provided in the example A package. The base case for this example uses the following input files and options:

- 10-m DEM of part of Kosrae, Federated States of Micronesia (*Kosrae_clip.tif*), located in the *DEM_dataA/* directory.
- Settings file (*ExampleA_Kosrae.yaml*; fig. 32) containing parameters, with the following options:

- In the ***options*** section, ***hl*** is set to “yes” to enable the **HL** tool. The other input fields are set to “no”.
- In the ***source*** section, ***source_raster*** is set to “slope” and ***min_source_value*** is set to “30”. The raster file of ground surface slope generated by the **SETUP** tool will be used to delineate source areas having topographic slopes greater than or equal to 30°.
- In the ***hl_options*** section, ***min_reach_angle*** is set to “25”. *H*/*L* runout zones are defined by angles of reach greater than or equal to 25°.

```
setup:
  title: Example A base case: H/L runout (Kosrae)
  # Uses small clip of Kosrae, Fed. States of Micronesia (10-m DEM)
  demfilename: DEM_dataA/Kosrae_clip.tif
  # Change num_procs if desired, default is 1.
  num_procs: 8
  dest_dir: output_ExampleA

options:
  inundation: no
  growth: no
  hl: yes

source:
  source_raster: slope
  min_source_value: 30

hl_options:
  min_reach_angle: 25
```

**Figure 32.** Text from the Settings file for the base case of example A (*ExampleA_Kosrae.yaml*) for a landslide runout analysis using the Grfin Tools **HL** tool. Variations a through c use separate Settings files. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

The Settings files for the variations use the following options:

- *Variation a.*—In the ***source*** section, ***min_source_value*** is set to “40” to limit the source area by increasing the minimum slope angle to 40° (Settings file *ExampleA_Kosrae_variation_a.yaml*).
- *Variation b.*—In the ***source*** section, ***min_source_area*** is set to “1000” to remove isolated source areas smaller than 1,000 m$^2$ (Settings file *ExampleA_Kosrae_variation_b.yaml*).
- *Variation c.*—In the ***hl_options*** section, ***min_reach_angle*** is set to “20” to reduce the minimum angle of reach to 20° and potentially lengthen runout to affect more ground (Settings file *ExampleA_Kosrae_variation_c.yaml*).

Each Settings file designates a different output directory using the ***dest_dir*** input field to separate the outputs from each run. The discussion below covers the base case and these variations individually, but most options can also be combined in one run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the base case and variations; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—*output_ExampleA/* for the base case. Variations are placed in separate output directories. Primary results of immediate interest are contained in the following files:

- Text file summarizing the settings (*ExampleA_Kosrae_settings.txt*).
- GeoTIFF of the spatial extent of potential landslide source areas (*Kosrae_clip_sourcearea.tif*); this may differ for each variation.
- GeoTIFF of the spatial extent and length of landslide runout (*Kosrae_clip_hlrunout_distance.tif*). Note that the entire spatial extent of runout can be visualized by using all non-zero values in this file.

## Discussion of Output Results

### Base case

This example uses potential landside source areas (contained in *Kosrae_clip_sorucearea.tif*) to generate *H*/*L* runout areas (contained in *Kosrae_clip_hlrunout_distance.tif*) downslope of these source areas. Here, source areas are defined by slopes greater than or equal to 30° (fig. 33*A*). *H*/*L* runout areas are defined by angles of reach greater than or equal to 25° (fig. 33*B*). Runout from each specified source cell then follows a downslope flow path until the overall angle from the source cell becomes less than the specified 25° minimum angle of reach. Runout then halts. This procedure is performed for all source cells and amalgamated into a runout zone. Refer to section 3.3 for more details.

In this case, runout areas extend downslope from source areas in steeper topography and onto the coastal flats (fig. 33*C*). Runout extends from each individual source cell; therefore, runout zones from individual upslope source cells can affect downslope source cells, as illustrated in parts *A* and *B* of figure 33.

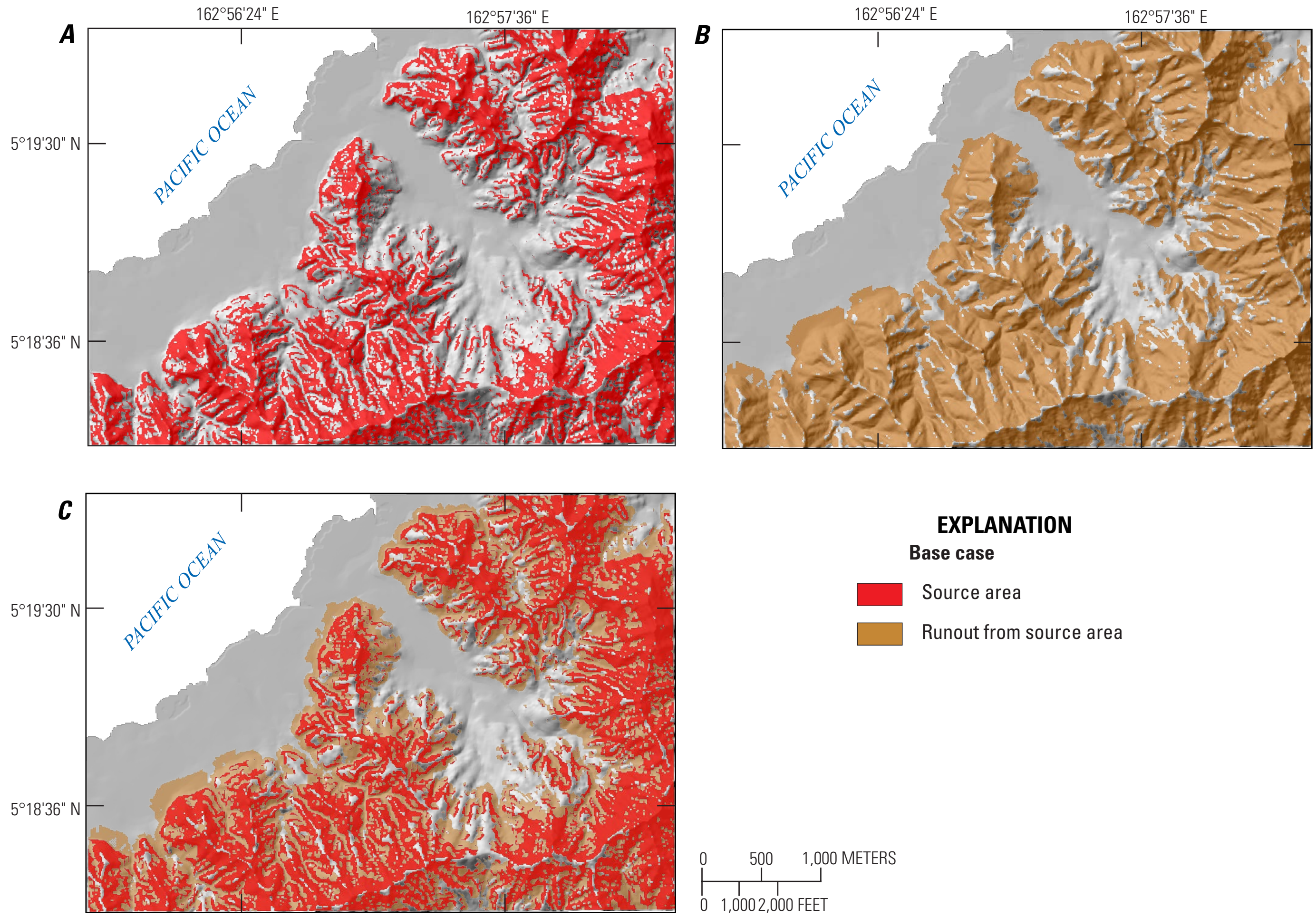


**Figure 33.** Maps showing landslide source areas and runout in part of Kosrae, Federated States of Micronesia, illustrating results from the base case of example A. Source areas restricted to slope values ≥30° and angle of reach for runout is ≥25°. *A*, Potential landslide source areas in steeper terrain. *B*, Landslide runout zones from source areas in *A*. *C*, Combination of source areas and runout zones with source areas overlying runout. Topography has steeper hillslopes adjacent to flatter coastal plain. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

### Variation a

Variation a illustrates increasing the minimum slope threshold of potential landslide source areas to ≥40° (using the ***min_ source_value*** input field) to restrict source areas to steeper slopes (fig. 34). Even with restricted source areas, most of the runout areas are similar to those in the base case. This occurs because source areas at higher elevations (included in both cases) with the same angle of reach essentially extend over the same runout areas (fig. 34). Where steeper source areas are not present upslope, runout is more limited compared to the base-case runout. Nevertheless, the overall pattern of runout in this variation is markedly similar to the base case.

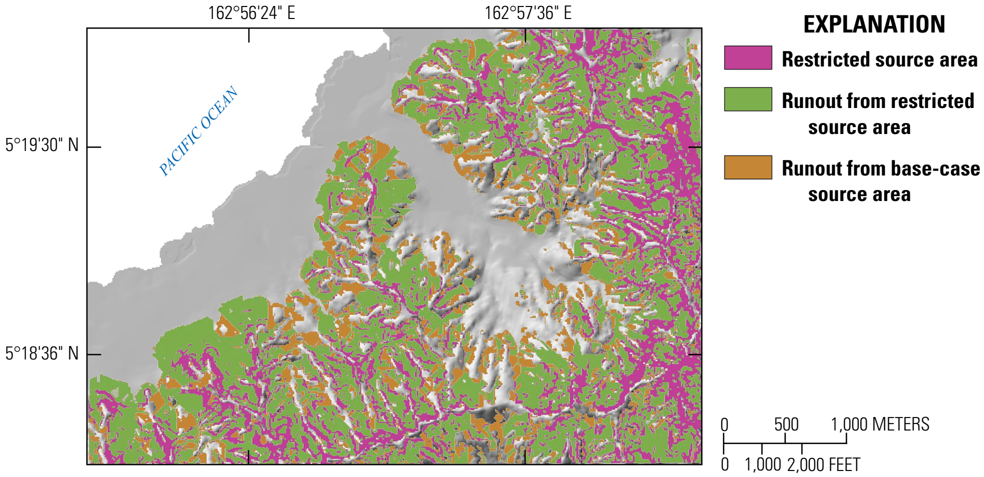


**Figure 34.** Map showing landslide source areas and runout in part of Kosrae, Federated States of Micronesia, illustrating results from variation a of example A. Source areas restricted to slope values ≥40° and angle of reach for runout is ≥25°. Runout from the base case is also shown for comparison. Runout is more extensive in the base case. Topography has steeper hillslopes adjacent to flatter coastal plain. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

### Variation b

Variation b illustrates setting a minimum size for source areas of 1,000 m$^2$ (using the ***min_source_area*** input field) to modify *H*/*L* runout results (fig. 35). This option eliminates smaller, isolated source areas of only a few DEM cells, and uses only contiguous cells above a minimum coverage area. Source areas smaller than 1,000 m$^2$ (encompassing between 1 and 9 contiguous DEM cells, given 10-m DEM cells) are not included as runout sources. The elimination of isolated source areas in this example has minimal overall effect compared to the base case, but this may be important in specific locations.

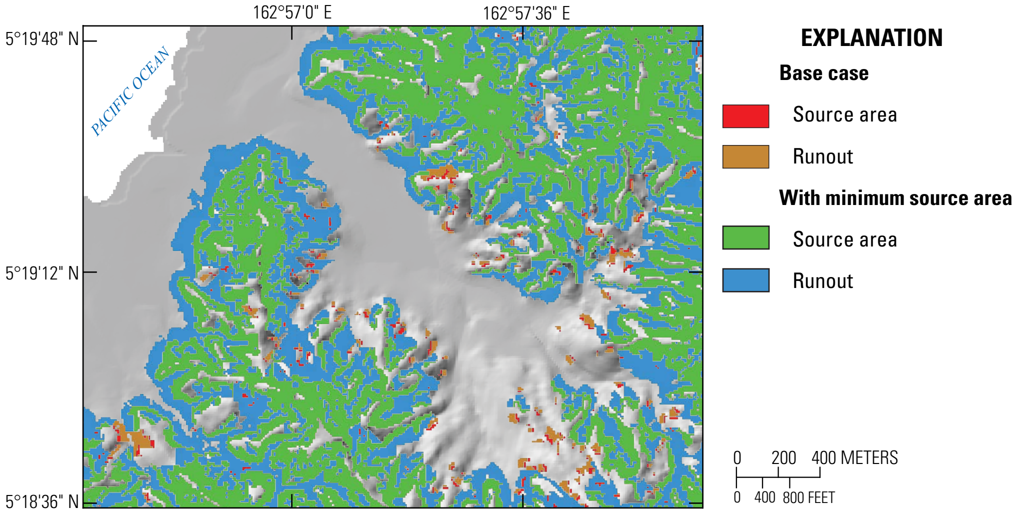


**Figure 35.** Map showing landslide source areas and runout in part of Kosrae, Federated States of Micronesia, illustrating results from variation b of example A. Isolated source areas smaller than 1,000 m$^2$ are eliminated. Source areas restricted to slope values ≥30° and angle of reach for runout is ≥25°. Source areas and runout from the base case are also shown for comparison. Runout is very similar to the base case. The area shown is a slight zoom in on part of the area shown in figure 34. Topography has steeper hillslopes adjacent to flatter coastal plain. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

### Variation c

Variation c illustrates decreasing the minimum angle of reach from 25° to 20° (using the ***min_angle_reach*** input field) to change the *H*/*L* runout area (fig. 36). Lower angles of reach typically lead to larger and longer runout zones (more examples of this behavior are presented in the section 3.3). In this variation, the landslide source areas remain the same as in the base case. The additional runout is notable in flatter terrain downslope of higher elevation topography. However, extra runout beyond the base case does not occur everywhere, as runout depends on upslope topography.

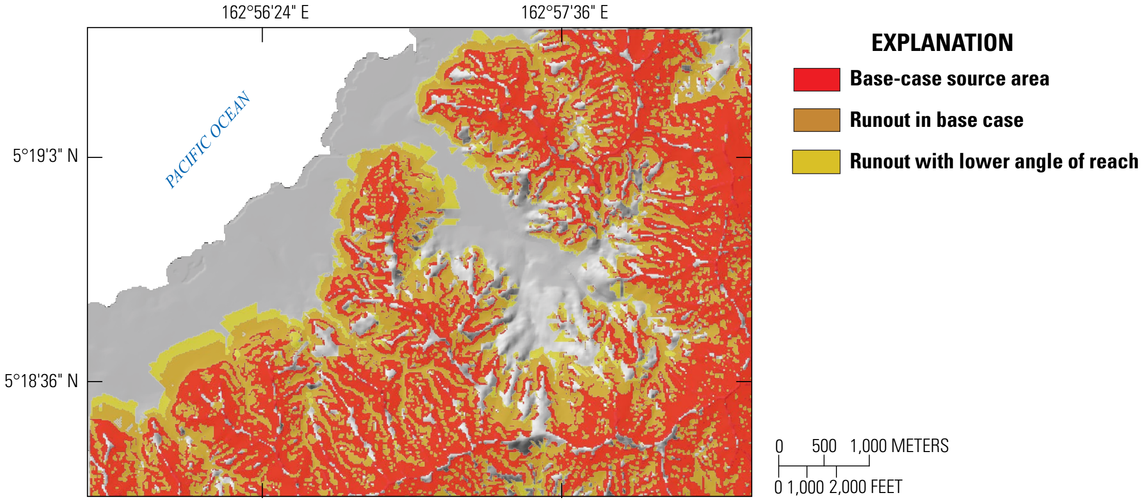


**Figure 36.** Map showing landslide source areas and runout in part of Kosrae, Federated States of Micronesia, illustrating results from variation c of example A. Source areas restricted to slope values ≥30° and angle of reach for runout is ≥20°. Landslide runout is more extensive than the base case; base-case runout also shown for comparison. Topography has steeper hillslopes adjacent to flatter coastal plain. Hillshade from 10-meter-resolution merged digital elevation model (U.S. Geological Survey, 2013a, b).

## 6.2. Example B. Inundation from User-Specified Point Sources and Volumes (Lassen Peak)

### Overview

Example B illustrates how the **INUNDATION** tool can be used to define lahar flow inundation starting from user-specified point sources with predefined volumes. In addition, it illustrates the use of lahar flow relations, rather than debris-flow relations, by examining potential lahars that could affect drainage from Lassen Peak volcano, California. These lahar flow relations are specified in the Settings file. This approach applies user-specified point-source locations (for example, from inventories or hazard assessments) and volumes (for example, measured after events or modeled in other software) (designated using the ***user_specified_volumes_file*** input field), which is common in many other flow-inundation approaches, including Laharz (Iverson and others, 1998; Schilling, 1998, 2014) and DFLOWZ (Berti and Simoni, 2007). The underlying basis for the **INUNDATION** tool is discussed in section 3.5. In this example, the **SOURCE**, **HL**, **DRAINAGE**, and **GROWTH** tools are not used. This example demonstrates the third pathway shown in figure 2 (section 2.2).

This example uses both a relatively small ($1\times10^7$ m$^3$) and a large ($9\times10^7$ m$^3$) initial source volume and the same starting locations as those analyzed with Laharz (Schilling, 2014) by Robinson and Clynne (2012). Here, we illustrate how initial volume size can control the overall width of the inundation zone as well as how changing valley width can lead to fluctuating inundation width as flows transit from broad floodplains into narrow canyons.

## Background and Physical Setting

Lassen Peak is one of the southernmost volcanoes in the Cascade Range volcanic arc. The 1915 eruption of Lassen Peak produced significant lahars that traveled northward along Hat Creek (Day and Allen, 1925) and downstream into Lost Creek despite lacking the conditions typical for generating lahars (high relief, steep slopes, and persistent snowfields) (Robinson and Clynne, 2012).

In previous work, Robinson and Clynne (2012) used field relationships to estimate lahar volumes from the May 1915 Lassen Peak eruption on the order of $15 \times 10^6$ $m^3$. They then used Laharz (Schilling, 1998) to define potential lahar inundation along the headwaters of Manzanita and Hat Creeks using a variety of source volumes ranging from $1 \times 10^6$ $m^3$ to $9 \times 10^7$ $m^3$. Maps of these inundation zones can be viewed in Robinson and Clynne (2012).

## Input Files and Options

Each run of the scenarios requires the DEM file, a Settings file, and a user-specified volumes file specific to the scenario. Files for both the small- and large-volume scenarios are provided in the example B package. The scenarios use the following input files and options:

- 10-m DEM of Lassen Peak volcano and surrounding area (*Lassen.tif*) located in the *DEM_dataB/* directory.
- One of two separate files containing locations of starting points and associated volumes for the small-volume and large-volume runs (*Lassen_pts_1e7.csv* and *Lassen_pts_9e7.csv*, respectively) in comma-separated values (csv) format. These files are located in the *DEM_dataB/* directory and used as user-specified volumes files.
- One of two separate Settings files (*ExampleB_Lassen_small_volume.yaml* [fig. 37] and *ExampleB_Lassen_large_volume.yaml*) containing parameters used in the small-volume and large-volume runs, respectively, with the following options:
  - In the ***options*** section, ***inundation*** is set to “yes” to enable the **INUNDATION** tool. The other input fields in this section are set to “no”.
  - In the ***inundation_options*** section—
    - ***flowtype*** is set to “lahar” to use lahar volume-area inundation relations.
    - ***user_specified_volumes_file*** is set to one of two separate files “*DEM_dataB/Lassen_pts_1e7.csv*” or “*DEM_dataB/Lassen_pts_9e7.csv*”.

Each Settings file designates a different output directory using the ***dest_dir*** input field to separate the outputs from each run. Note that if multiple volumes are assigned to the same *xy* location pair in the same user-specified volumes file, the inundation from the largest volume flow will overwrite inundation from any smaller flows.

```
setup:
  title: Example B - inundation from points (Lassen Peak, CA, USA)
  # Small volume starting points
  demfilename: DEM_dataB/Lassen.tif
  num_procs: 8
  dest_dir: output_ExampleB_small_volume

options:
  inundation: yes
  growth: no
  hl: no

inundation_options:
  flowtype: lahar
  user_specified_volumes_file: DEM_dataB/Lassen_pts_1e7.csv
```

**Figure 37.** Text from the Settings file for the small-volume scenario of example B (*ExampleB_Lassen_small_volume.yaml*) for a lahar flow-inundation analysis using the Grfin Tools **INUNDATION** tool. A separate Settings file is provided for the large-volume scenario (*ExampleB_Lassen_large_volume.yaml*). The number sign (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the small- and large-volume scenarios; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—either *output_ExampleB_small_volume/* or *output_ExampleB_large_volume/*, depending on the scenario selected. Primary results of immediate interest are contained in the following files:

- Text files summarizing the settings for each scenario (*ExampleB_Lassen_small_volume_settings.txt* or *ExampleB_Lassen_large_volume_settings.txt*).
- GeoTIFFs of the spatial extents of flow inundation (*ExampleB_Lassen_small_volume_inundation.tif* or *ExampleB_Lassen_large_volume_inundation.tif*). Note that the entire spatial extent of runout can be visualized by using all non-zero values in these files.

## Discussion of Output Results

Comparing the output flow inundation for the small-volume ($1\times10^7$ $m^3$) and large-volume ($9\times10^7$ $m^3$) lahar scenarios illustrates the greater inundation produced by the larger starting volume (fig. 38). This larger initial volume results in both wider inundation extents along the flow path of the lahar and a near-doubling of downstream inundation length in both the Manzanita and Hat Creek drainages. For Manzanita Creek, the upstream lahar inundation width is narrow and gradually widens downstream as the stream channel transitions from a lava flow downstream of the volcano flank into a broad valley. In the large-volume lahar scenario the Manzanita Creek inundation zone widens as the floodplain width increases and narrows again as the drainage enters an incised gorge. Note that the small volume is an order-of-magnitude larger than the smallest volume used by Robinson and Clynne (2012). These results highlight the capability of Grfin Tools to handle complex changes in along-valley floodplain geometry without creating spikey map-view inundation artifacts.

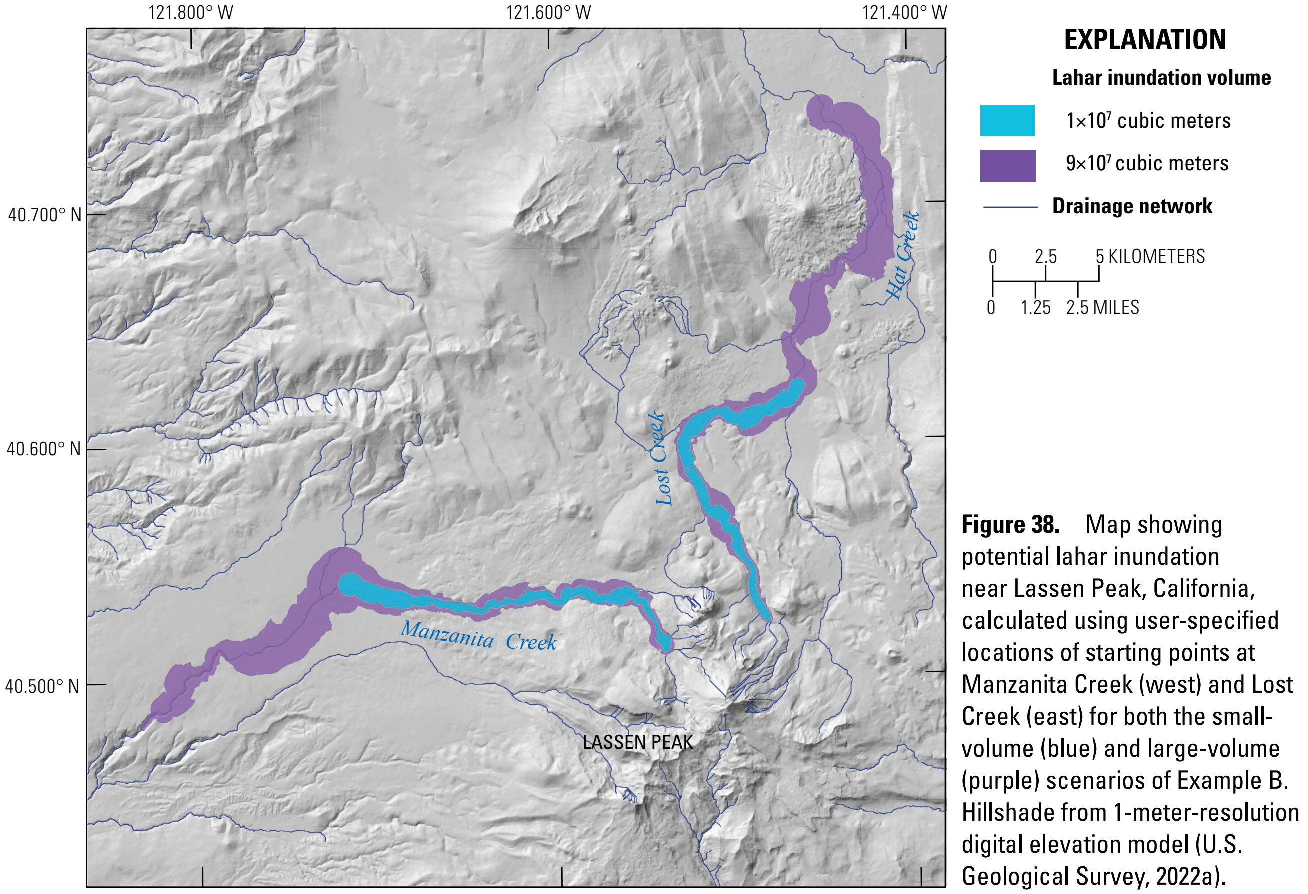


**Figure 38.** Map showing potential lahar inundation near Lassen Peak, California, calculated using user-specified locations of starting points at Manzanita Creek (west) and Lost Creek (east) for both the small-volume (blue) and large-volume (purple) scenarios of Example B. Hillshade from 1-meter-resolution digital elevation model (U.S. Geological Survey, 2022a).

## 6.3. Example C. Standalone Drainage Network (San Bernardino)

### Overview

Example C illustrates how the **DRAINAGE** tool can be used to create a drainage network and how to customize the ***drainage_options*** parameters, if desired. The ***standalone_drainage_network*** option (in the ***drainage_options*** section) has several potential uses, including:

1. Visualizing and assessing a drainage network before using the **GROWTH** and **INUNDATION** tools.
2. Creating a drainage network for use outside of Grfin Tools.

In this example, the **SOURCE**, **HL**, **GROWTH**, and **INUNDATION** tools are not used. This example demonstrates the fourth pathway shown in figure 2 (section 2.2).

### Background and Physical Setting

The Transverse Ranges in San Bernardino County, California, have steep, highly dissected terrain dominated by rills and gullies. In this terrain, the default settings for the **DRAINAGE** tool do not adequately portray the upstream initiation of the drainage network. Debris flows are common in this landscape, triggered by rainstorms or snowmelt and exacerbated by wildfires (Morton and others, 2008; Rengers and others, 2021).

### Input Files and Options

Each run of the base case or the variations requires the DEM file and a Settings file, which are provided in the example C package. The base case for this example uses the following input files and options:

- 1-m DEM of drainage basins in part of the Transverse Ranges, San Bernardino County, California (*San_Bernardino_clip.tif*), located in the *DEM_dataC/* directory.
- Settings file (*ExampleC_SanBern.yaml*) containing parameters, with the following options:
    - In the ***options*** section, ***standalone_drainage_network*** is set to “yes” to enable the **DRAINAGE** tool. The other input fields in this section are set to “no”.
    - The base case uses the default settings, so there is no ***drainage_options*** section.

The Settings files for the variations modify the ***drainage_options*** section using the following options:

- *Variation a.*—In the ***drainage_options*** section, ***min_curvature_drainage*** is set to “0.01” to decrease the minimum curvature threshold to 0.01/m and allow channel initiation locations to be identified higher in the drainage basins (Settings file *ExampleC_SanBern_variation_a.yaml*).
- *Variation b.*—For step 1, in addition to the ***min_curvature_drainage*** setting from variation a (0.01), in the ***drainage_options*** section ***dem_neighborhood*** is set to “2” to decrease the size of the smoothing window for the DEM to 2 m and retain finer scale features in the topography. For step 2, ***min_concav_area*** is set to “400” to increase the minimum size of isolated concave areas to 400 m$^2$ and ***min_drainage_area*** is set to “50” to decrease the contributing drainage-area threshold used to define channel initiation to 50 m$^2$ (Settings file *ExampleC_SanBern_variation_b.yaml*; fig. 39).

To fine-tune the location of channel initiation higher in the drainage basin than shown with variation a, multiple drainage parameters must be modified to avoid undesirable artifacts. Such artifacts can result from topographic concavities on hillslopes or ridgetop roads rather than from channelized topography.

Note that drainage network output files are saved to the DEM data directory *DEM_dataC/San_Bernardino_clip_drainage/*. Running Grfin Tools for each variation will overwrite the drainage network output files from previous runs. If desired, the files may be retained by renaming the files or renaming the output drainage directory after each run.

```
setup:
  title: Example C - drainage only, variation b (San Bernardino, CA)
  demfilename: DEM_dataC/San_Bernardino_clip.tif
  dest_dir: output_ExampleC

options:
  inundation: no
  growth: no
  hl: no
  standalone_drainage_network: yes

drainage_options:
  compute_new_drainage: yes
  dem_neighborhood: 2          # decrease from default value (10 m)
  min_curvature_drainage: 0.01 # decrease from default value (0.02/m)
  min_concav_area: 400         # increase from default value (200 m2)
  min_drainage_area: 50        # decrease from default value (200 m2)
```

**Figure 39.** Text from the Settings file for variation b, step 2, of Example C (*ExampleC_SanBern_variation_b.yaml*) for creating a standalone drainage network using the Grfin Tools **DRAINAGE** tool. Separate Settings files are provided for the base case and variation a. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the base case and variations; specific file contents are described in section 4.4. For this example, only a summary file of settings (*output_ExampleC*) is placed in the output directory designated by the ***dest_dir*** input field and all other files are placed in the *DEM_dataC/San_Bernardino_clip_drainage/* subdirectory. Primary results of immediate interest are contained in the following files:

- Text file summarizing the settings (*ExampleC_SanBern_drain_settings.txt*).
- GeoTIFF of the drainage network (*San_Bernardino_clip_stream.tif*).
- GeoTIFF of the planform curvature from the smoothed DEM (*San_Bernardino_clip_smoothplancurv.tif*).

## Discussion of Output Results

### Base case

The base case (*ExampleC_SanBern.yaml*) generates a drainage network using default drainage network parameters. This network could be used with the **GROWTH** and **INUNDATION** tools or as a standalone product. However, the generated network does not extend to the uppermost part of the drainage network, as is visible in a hillshade image of the topography (fig. 40*A*). Capturing the upstream extent of the drainage network may be important in some landscapes or for some user needs. One of the primary controls limiting the upstream extent is the planform curvature of the topography, which is visible in the planform curvature from the smoothed DEM (*DEM_dataC/San_Bernardino_clip_drainage/San_Bernardino_clip_smoothplancurv.tif*), shown in part *B* of figure 40. Here, the primary segments of the drainage network that were not included in the drainage network generated with default settings (fig. 40*A*) have a planform curvature between 0.01 and 0.02/m, less than the default ***min_curvature_drainage*** threshold of 0.02/m (dark brown areas in fig. 40*B*). The settings in variation a generate the more extensive drainage network shown in part *C* of figure 40.

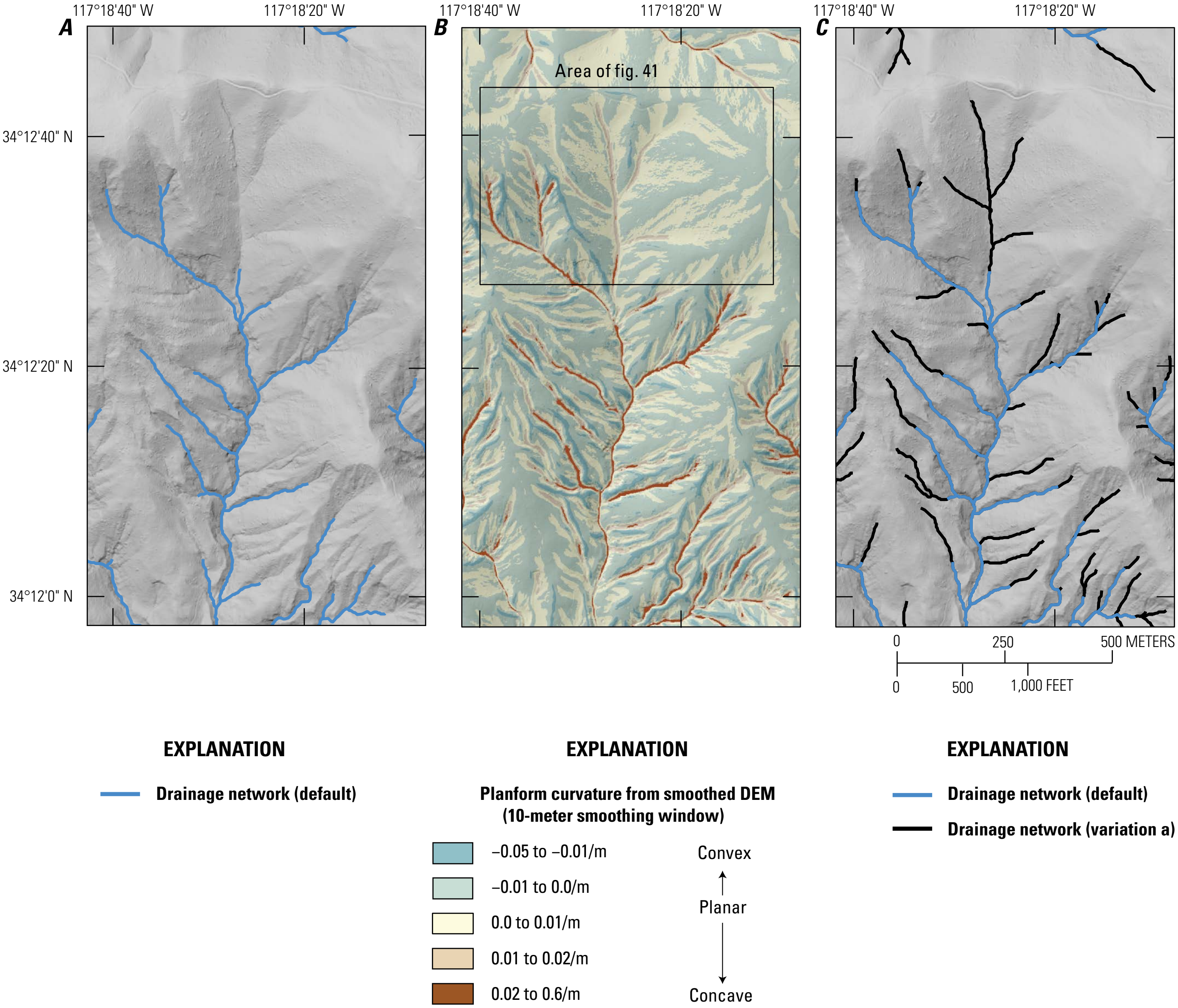


**Figure 40.** Maps showing drainage networks and planform curvature in part of the Transverse Ranges, San Bernardino County, California, illustrating results from variation a of example C. *A*, Drainage network generated from the base case, using the default settings. *B*, Planform curvature (*San_Bernardino_clip_smoothplancurv.tif*) from a digital elevation model (DEM) smoothed using a 10-meter window (default setting). *C*, Drainage network generated from the base case (default settings) (blue only) compared with variation a (blue and black combined); variation a uses a lower curvature threshold. Stream raster files (*San_Bernardino_clip_stream.tif*) were converted to lines in geographic information system software. m, meter (/m, reciprocal DEM length units). Hillshade–slopeshade combination from lidar-derived 1-m-resolution DEM (U.S. Geological Survey, 2022b).

## Variation a

Variation a uses a modified curvature threshold to create the revised drainage network shown in part *C* of figure 40 (combined blue and black lines). The results illustrate the effects of decreasing the curvature threshold (***min_curvature_drainage***) to 0.01/m. This modification incorporates all areas where planform curvature is greater than 0.01/m (combined light and dark brown areas in fig. 40*B*). The inclusion of these slightly less concave parts of the topography moves the location of channel initiation higher in the drainage basin.

### Variation b

Variation b uses additional modifications to the parameters in the ***drainage_options*** section (refer to section 4.2.2.3.) to produce a drainage network that captures finer details of curvature in the topography. These modifications identify less well-defined topographic concavities that may represent channels, gullies, or previous landslide scars. To capture this finer scale topography, the smoothing window for the DEM (***dem_neighborhood***) is decreased from 10 to 2 m and the resulting planform curvature shows more detail (fig. 41). The results of variation b are illustrated in two steps, to demonstrate the independent influence of drainage parameter modifications.

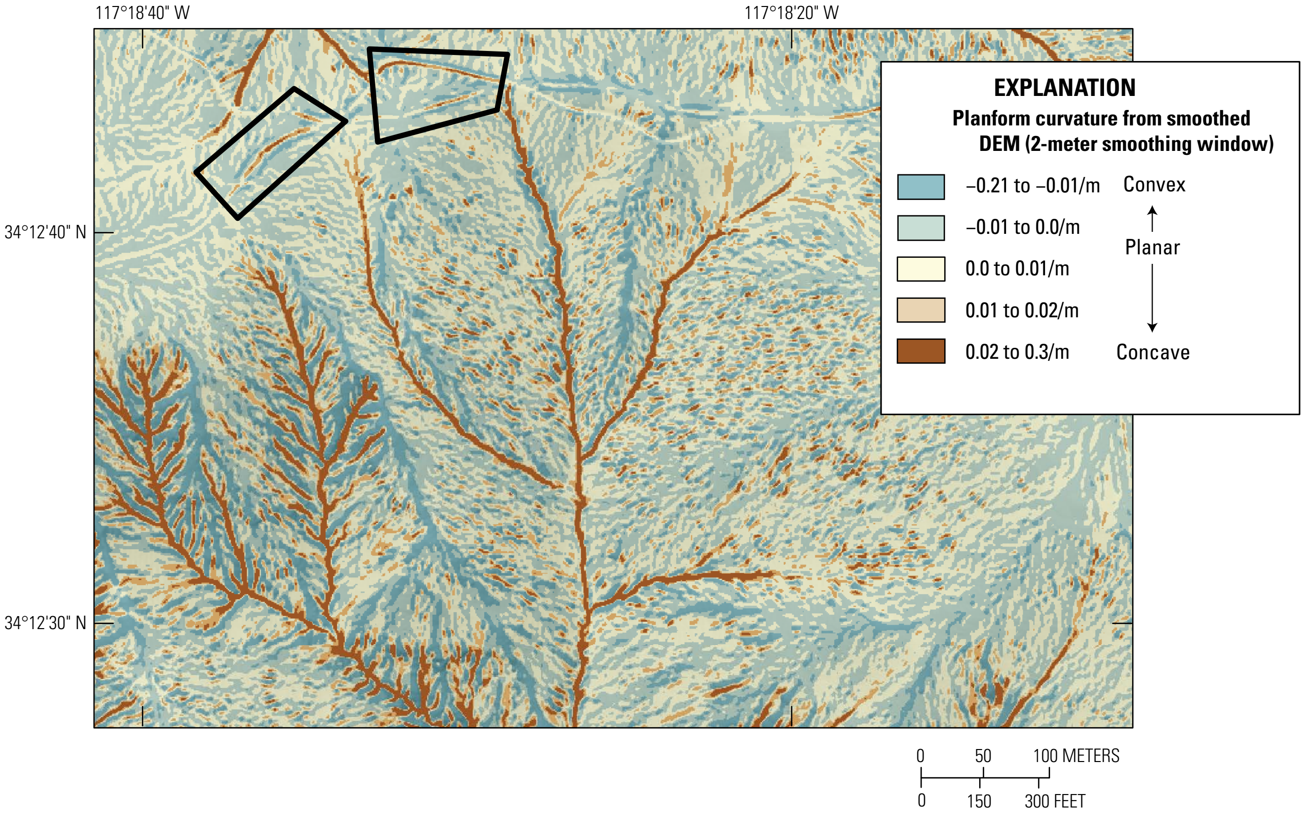


**Figure 41.** Map showing planform curvature in part of the Transverse Ranges, San Bernardino County, California, comparing results from default settings, variation a, and variation b variation b, step 1, of example C (*San_Bernardino_clip_smoothplancurv.tif*). The digital elevation model (DEM) was smoothed using a 2-meter window. Area of map shown in part *B* of figure 40. The smaller smoothing window used here retains finer scale topography compared to the default smoothing window. Black polygons in the upper left outline areas where concave areas adjacent to roads are not representative of natural terrain. m, meter (/m, reciprocal DEM length units). Hillshade–slopeshade combination from lidar-derived 1-m-resolution DEM (U.S. Geological Survey, 2022b).

The drainage networks and planform curvature resulting from variation b are shown in figure 42. In step 1, the size of the DEM smoothing window is decreased and other parameters from variation a are retained (default parameters, except for a decreased minimum curvature threshold) (fig. 42*A*, *B*). These modifications capture finer details, but also produce some undesired effects, such as the inclusion of isolated concave areas that are disconnected from the drainage network. Areas smaller than the default minimum size of isolated concave areas (200 $m^2$) are not included, but larger areas, including some concave areas adjacent to a ridgetop road (black polygons in fig. 41) contribute to the area used to define channel initiation. In addition, the results do not capture concave areas of the topography smaller than the default minimum size of the contributing areas used to define channel initiation (200 $m^2$).

In step 2, two additional parameters are modified from their default values to eliminate isolated concavities smaller than 400 $m^2$ (***min_concav_area***) and decrease the contributing-area threshold to 50 $m^2$ to better define channel initiation locations (***min_drainage_area***) (fig. 42*C*). The resulting drainage network does not include the road-related artifacts in step 1, and it captures additional smaller scale topographic features. This drainage network could be used outside of Grfin Tools or for flow growth and inundation within Grfin Tools, where the growth and inundation zones will start higher in the drainage basin than inundation results using default parameters or with variation a.

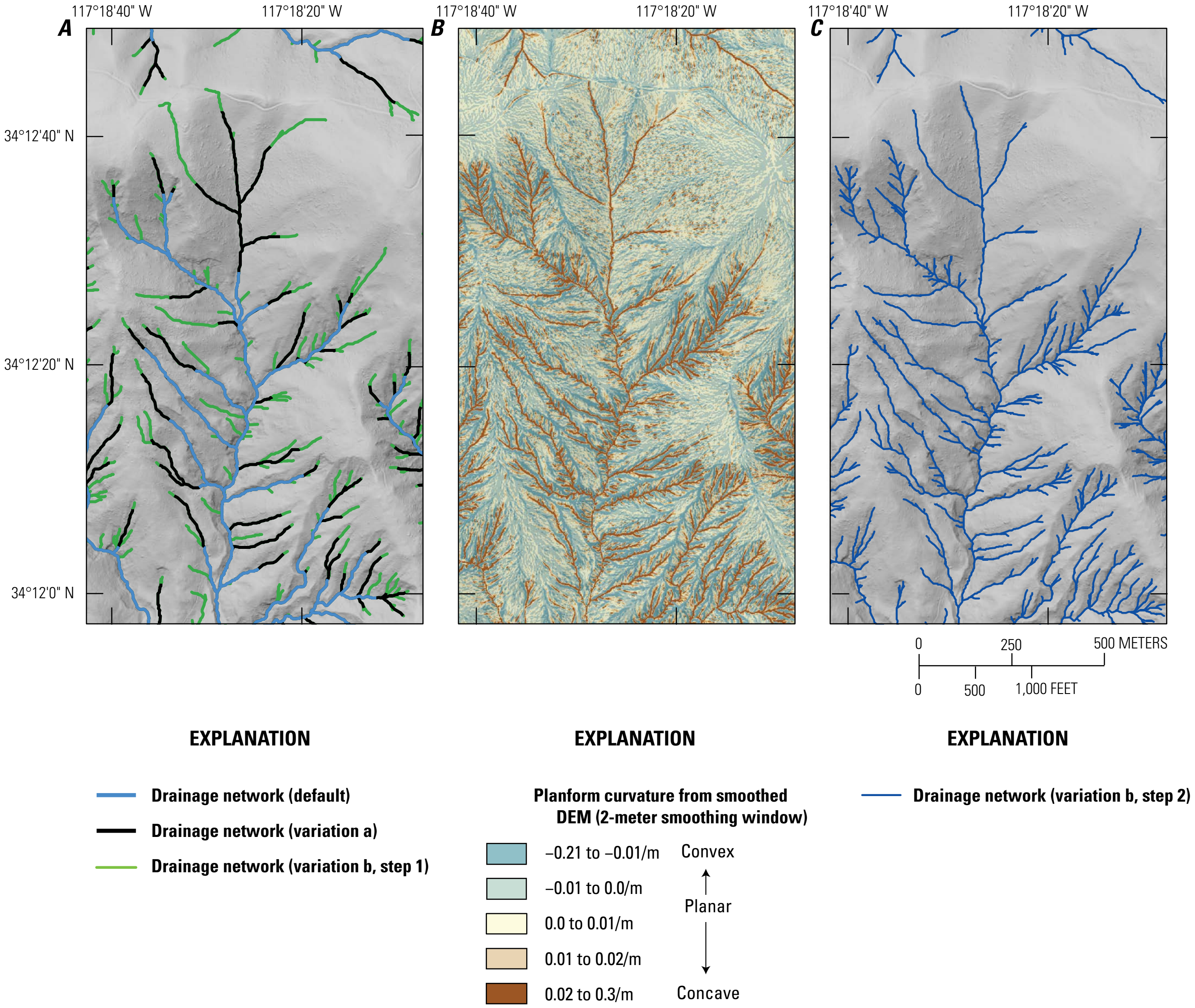


**Figure 42.** Maps showing drainage networks and planform curvature in part of the Transverse Ranges, San Bernardino County, California, comparing results from default settings, variation a, and variation b of example C. *A*, Drainage networks generated from the base case (default settings) (blue only); variation a (blue and black combined); and variation b, step 1 (blue, black, and green combined). *B*, Planform curvature (*San_Bernardino_clip_smoothplancurv.tif*) from a digital elevation model (DEM) smoothed using a 2-meter window. *C*, Drainage network generated from variation b, step 2. Stream raster files (*San_Bernardino_clip_stream.tif*) were converted to lines in geographic information system software. m, meter (/m, reciprocal DEM length units). Hillshade–slopeshade combination from lidar-derived 1-m-resolution DEM (U.S. Geological Survey, 2022b).

## 6.4. Example D. Inundation with Growth Factors Based on Upslope Source Area (Puerto Rico)

### Overview

Example D illustrates how the **INUNDATION** and **GROWTH** tools can be used to delineate debris-flow inundation where changes in upslope source area control the growth of flow volumes. This area-growth approach to generating flow volumes could be used in terrain where growth in flow volume results predominantly from shallow landsliding, rilling, or other processes that might deliver sediment rapidly from hillslopes to channels. In this approach, debris-flow growth only occurs in defined growth zones within the drainage network (created by the **DRAINAGE** tool using default options). Within growth zones, flow volumes increase in a cumulative manner downstream proportional to upslope source area (identified using the **SOURCE** tool) using a power-law growth relation (eq. 4 in section 3.6.3). This equation contains two parameters—an area-growth factor (***area_growth_factor***) and an area-growth exponent (***area_power***) used where flow volumes do not scale linearly with increasing upslope source area. In this example, the **HL** tool is not used. This example demonstrates the second pathway shown in figure 2 (section 2.2).

### Background and Physical Setting

The municipality of Utuado in the central mountainous part of Puerto Rico suffered the highest spatial frequency of debris flows in Puerto Rico resulting from Hurricane Maria in 2017 (Bessette-Kirton and others, 2019; Hughes and Schulz, 2020). The largest of these debris flows commonly nucleated from multiple shallow landslides and grew as they traveled downstream (Coe and others, 2021). Because the observed debris-flows nucleated from shallow landslides during the Hurricane, this study area is well-suited for testing how changes in growth parameters affect calculations of debris-flow growth and inundation.

### Input Files and Options:

Each run of the base case or the variations requires the DEM file and a Settings file, which are provided in the example D package. The base case for this example uses the following input files and options:

- 1-m DEM of drainage basins in part of Utuado, Puerto Rico (*Utuado_floodplain.tif*), located in the *DEM_dataD/* directory.
- Settings file (*ExampleD_Utuado.yaml*; fig. 43) containing parameters, with the following options:
  - In the ***options*** section, ***growth*** and ***inundation*** are set to “yes” to enable the **GROWTH** and **INUNDATION** tools. ***hl*** is set to “no”. The **GROWTH** tool automatically creates a drainage network using the **DRAINAGE** tool with default options.
  - In the ***source*** section—
    - ***source_raster*** is set to “slope”.
    - ***min_source_value*** is set to “30” and ***max_source_value*** is set to “60” to identify upslope source areas with topographic slopes greater than or equal to 30° and less than or equal to 60°.
    - ***min_source_area*** is set to “50” to set the minimum size of source areas to 50 $m^2$.
  - In the ***growth_options*** section—
    - In the ***growth_zones*** subsection, ***min_stream_slope*** is set to “5” to set the minimum stream slope for growth zones to 5°.
    - In the ***growth_volumes*** subsection—
    - ***max_volume*** is set to “3000” to limit the maximum flow volume to 3,000 $m^3$.
    - In the ***area_growth*** sub-subsection, ***area_growth_factor*** is set to “0.1” and ***area_power*** is set to “1” to set the area-growth factor to 0.1 $m^3/m^2$ and the area-growth exponent to 1 resulting in a linear form of the area-growth relation (eq. 4).
  - The default ***inundation_options*** settings are used.

```
setup:
  title: Example D - inundation with area growth (Utuado, Puerto Rico)
  demfilename: DEM_dataD/Utuado_floodplain.tif
  num_procs: 8
  dest_dir: output_ExampleD

options:
  inundation: yes
  growth: yes
  hl: no

source:
  source_raster: slope
  min_source_value: 30
  max_source_value: 60
  min_source_area: 50

growth_options:
  growth_zones:
    min_stream_slope: 5
  growth_volumes:
    max_volume: 3000
    area_growth:
      area_growth_factor: 0.1
      area_power: 1

inundation_options:
  # Default options used
```

**Figure 43.** Text from the Settings file for the base case of example D (*ExampleD_Utuado.yaml*) for an area-growth approach to delineating debris-flow inundation using the Grfin Tools **SOURCE**, **GROWTH**, and **INUNDATION** tools. Variations a through c use separate Settings files. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

The Settings files for the variations use the following options:

- *Variation a.*—In the ***area_growth*** sub-subsection, ***area_growth_factor*** is set to “0.01” and the ***area_power*** input field is set to “1” (Settings file *ExampleD_Utuado_variation_a.yaml*).
- *Variation b.*—In the ***area_growth*** sub-subsection, ***area_growth_factor*** is set to “0.1” and ***area_power*** is set to “0.66” (Settings file *ExampleD_Utuado_variation_b.yaml*).
- *Variation c.*—In the ***area_growth*** sub-subsection, ***area_growth_factor*** is set to “0.1” and ***area_power*** is set to “0.33” (Settings file *ExampleD_Utuado_variation_c.yaml*).

Each Settings file designates a different output directory using the ***dest_dir*** input field to separate the outputs for each run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the base case and variations; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—*output_ExampleD/* for the base case. Variations are placed in separate output directories. Primary results of immediate interest are contained in the following files:

- Text file summarizing the settings (*ExampleD_Utuado_settings.txt*).
- GeoTIFF of the spatial extent of debris-flow inundation (*Utuado_floodplain_inundation.tif*). Note that the entire spatial extent of inundation can be visualized by using all non-zero values in this file.

- GeoTIFF (*Utuado_floodplain_stream.tif*) and shapefile (*Utuado_floodplain_stream.shp*) of the drainage network located in the *DEM_dataD*/*Utuado_floodplain_drainage*/ subdirectory.
- GeoTIFF of growth zones within the drainage network (*Utuado_floodplain_grzone.tif*) located in the *Utuado_floodplain_growth*/ subdirectory of the designated output directory.

## Discussion of Output Results

This example estimates debris-flow inundation (contained in *Utuado_floodplain_inundation.tif*) using source-area growth with variations depending on the growth options selected. The drainage network, growth zones, and source areas for all variations are shown in part *A* of figure 44. Source areas are identified by topographic slopes between 30° and 60° with a minimum area of 50 $m^2$ and growth zones are defined by stream slopes greater than or equal to 5°. Downstream of growth zones (where no growth occurs), inundation transpires using the greatest volume attained in the adjacent upstream growth zone (refer to section 3.6) to a maximum of 3000 $m^3$. The resulting pattern of inundation is controlled by the interplay of options defining the location of the growth zones and the overall rate of growth downstream.

### Base Case and Variation a

The base case uses an area-growth factor of 0.1 $m^3/m^2$ and an area-growth exponent of 1 (1 is the default value) resulting in linear growth with upslope source area. Part *B* of figure 44 shows how a 10-fold reduction of the area-growth factor (variation a) reduces both the width along the inundation zone as well as the total inundation area. Modifying the area-growth factor can affect whether certain sections of low-lying neighborhoods are inundated.

### Variations b and c

Part *C* of figure 44 shows how modifying the area-growth exponent affects downstream inundation. Here, the flow volumes increase nonlinearly as a function of upslope source area, as other researchers (for example, Scheip and Wegmann, 2022) have noted that debris-flow growth can vary nonlinearly with increasing contributing area. The base case and variations b and c use an area-growth factor of 0.1 $m^3/m^2$ and have the same source areas. Relatively minor reductions in the area-growth exponent, resulting in nonlinear growth with upslope source area, yield a greater influence on the degree of both cross-sectional and planimetric inundation than the order-of-magnitude reduction in the area-growth factor shown in part *B* of figure 44. For example, a one-third reduction in area power to 0.66 (variation b) produces substantially narrower inundation zones across the study area than the base case, and a reduction in inundation length and area comparable to the 10-fold reduction in the area-growth factor in variation a. This occurs because reductions in the area-growth exponent progressively reduce the effects of area growth as upslope source area increases. Reducing the area-growth exponent even further, to 0.33 (variation c), greatly reduces inundation areas even though the growth factor and source area remain constant.

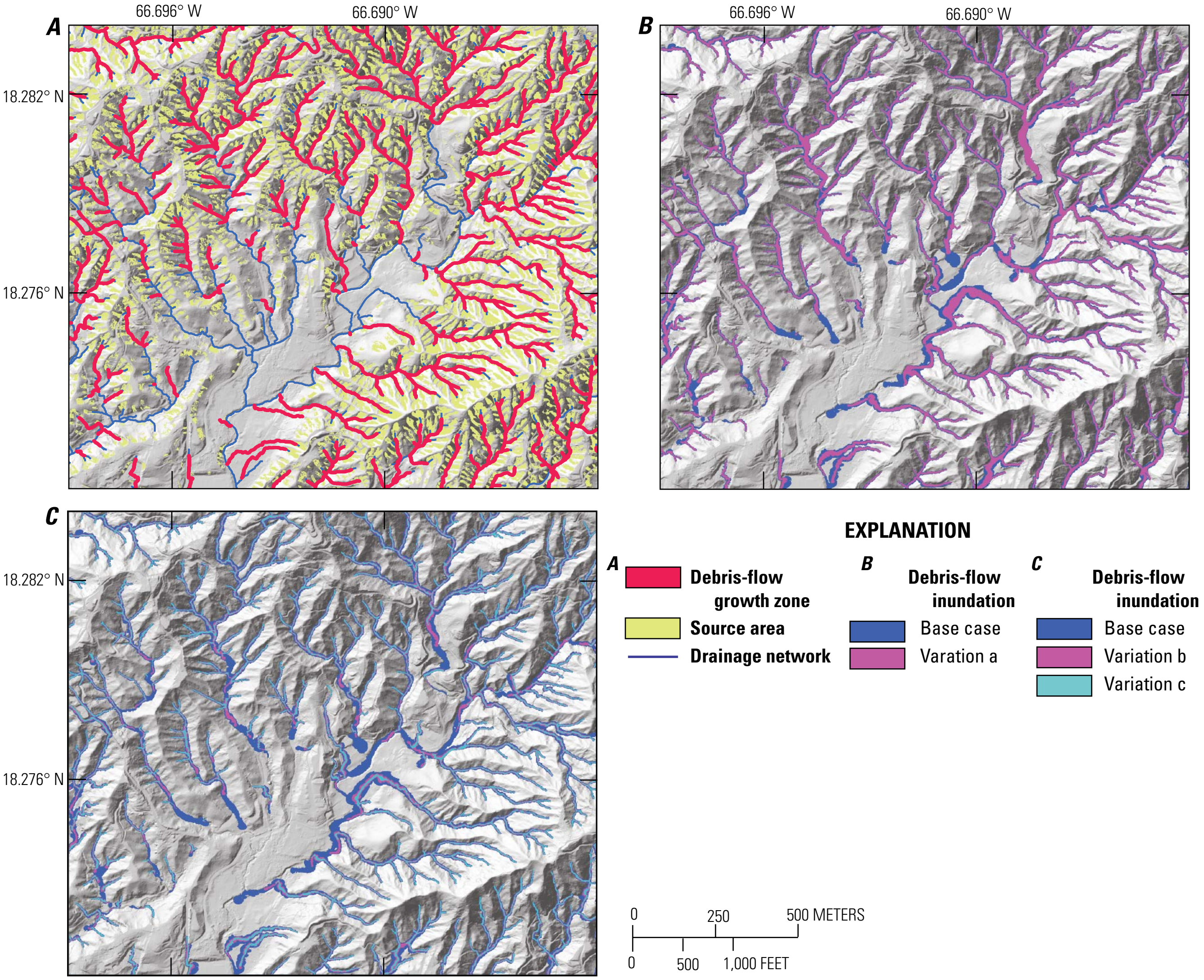


**Figure 44.** Maps of debris-flow inundation from area growth in part of Utuado, Puerto Rico, illustrating results from the base case and variations of example D. Growth only occurs from upslope source areas contributing to the growth zones; the area-growth factor and exponent in the area-growth equation (eq. 4) change the amount of volumetric growth and ultimately the inundation area. *A*, Drainage network, debris-flow growth zones, and debris-flow source areas for all variations. *B*, Debris-flow inundation comparing two growth factors with linear growth: the base case (factor is 0.1 and exponent is 1) and variation a (factor is 0.01 and exponent is 1). *C*, Debris-flow inundation comparing one linear and two nonlinear growth factors: the base case (linear), variation b (factor is 0.1 and exponent is 0.66), and variation c (factor is 0.1 and exponent is 0.33). Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

## 6.5. Example E. Inundation using Growth Factors Based on Stream Length (Oregon)

### Overview

Example E illustrates how the **INUNDATION** and **GROWTH** tools can be used to delineate debris-flow inundation where changes in upstream channel length in growth zones control the resulting flow volumes. This length-growth approach to generating flow volumes could be used in terrain where growth in flow volume results predominantly from entrainment of streambed sediment, stream-channel bank failures, or other processes of growth that scale with stream-channel length within growth zones. In this approach, debris-flow growth only occurs in defined growth zones within the drainage network (delineated using the **DRAINAGE** tool with default options). Within growth zones, flow volumes increase in a cumulative manner downstream proportional to upstream channel length using a length-growth relation (eq. 5 in section 3.6.3). This equation contains two parameters—a length-growth factor (***length_growth_factor***) and an optional length-growth exponent (***length_power***) used where flow volumes do not scale linearly with increasing upstream channel length. In this example, **SOURCE** and **HL** tools are not used. This example demonstrates the second pathway shown in figure 2 (section 2.2).

### Background and Physical Setting

The Coast Range in western Oregon has relatively steep and highly dissected terrain that includes several small drainage basins adjacent to the Umpqua River. In the Coast Range, debris flows triggered by rainstorms commonly originate from discrete shallow landslides and then grow downstream by entrainment of sediment and by coalescence of multiple debris flows from different origins (for example, Benda and Cundy, 1990; Montgomery and others, 1997; May and Gresswell, 2004; Montgomery and others, 2009; Coe and others, 2011a; Coe and others, 2011b). In this example, growth zones are defined as parts of the drainage network with stream slopes greater than or equal to 5° and a base case (smallest) length-growth factor of 33 $ft^3/ft$ (~3 $m^3/m$).

This example is similar to the results presented in figure 12 of Reid and others (2016), which also includes length-growth factors measured for Oregon and other regions worldwide, as well as a summary of stream-channel slopes where debris-flow growth likely occurs.

### Input Files and Options

Each run of the base case or the variations requires the DEM file and a Settings file. Variation c also requires an additional raster file. All files are provided in the example E package. The base case for this example uses the following input files and options:

- 3-ft DEM of drainage basins in part of the Coast Range, Oregon (*UmpquaTribs.tif*), located in the *DEM_dataE/* directory. This example illustrates automated use of DEMs having English units of length.
- Settings file (*ExampleE_Umpqua.yaml*; fig. 45) containing parameters, with the following options:
    - In the ***options*** section, ***growth*** and ***inundation*** are set to “yes” to enable the **GROWTH** and **INUNDATION** tools. ***hl*** is set to “no”. The **GROWTH** tool automatically creates a drainage network using the **DRAINAGE** tool with default options.
    - In the ***growth_options*** section—
        - In the ***growth_zones*** subsection, ***min_stream_slope*** is set to “5” to set the minimum stream slope for growth zones to 5°.
        - In the ***growth_volumes*** subsection and the ***length_growth*** sub-subsection, ***length_growth_factor*** is set to “33.0” to set the length-growth factor to 33.0 $ft^3/ft$ in the length-growth equation (eq. 5).

```
setup:
  title: Example E - inundation with channel-length growth (Umpqua River, Oregon)
  # Example similar to presentation in Reid et al. (2016).
  # Uses small Umpqua tributary area (3 ft. DEM).
  demfilename: DEM_dataE/UmpquaTribs.tif
  num_procs: 8
  dest_dir: output_ExampleE

options:
  inundation: yes
  growth: yes
  hl: no

growth_options:
  growth_zones:
    min_stream_slope: 5
  growth_volumes:
    length_growth:
    length_growth_factor: 33.0

inundation_options:
  # Default options used
```

**Figure 45.** Text from the Settings file for the base case of example E (*ExampleE_Umpqua.yaml*) for a length-growth approach to delineating debris-flow inundation using the Grfin Tools **GROWTH** and **INUNDATION** tools. Variations a through c are contained in separate Settings files in the *ExampleE/* directory. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

The variations use the following input files and (or) options:

- *Variation a.*—Settings file (*ExampleE_Umpqua_variation_a.yaml*) with the following option:
  - In the ***length_growth*** sub-subsection, ***length_growth_factor*** is to “110” to increase the length-growth factor to 110 $ft^3/ft$.
- *Variation b.*—Settings file (*ExampleE_Umpqua_variation_b.yaml*) with the following option:
  - In the ***growth_volumes*** subsection, ***max_volume*** is set to “113000” to limit the maximum flow volume to 113,000 $ft^3$.
- *Variation c.*— Settings file (*ExampleE_Umpqua_variation_c.yaml*) with the following option:
  - In the ***growth_zones*** subsection, ***growth_zone_raster*** is set to “*DEM_dataE/Umpqua_2basins.tif*” that delineates the extent of drainage basins of interest and restricts computed growth zones to that extent.

Each Settings file designates a different output directory using the ***dest_dir*** input field to separate the outputs for each run. The discussion below covers the base case and these variations individually, but most options can also be combined in one run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the base case and variations; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—*output_ExampleE* for the base case. Variations are placed in separate output directories. Primary results of immediate interest are contained in the following files:

- Text file summarizing the settings (*ExampleE_Umpqua_settings.txt*).
- GeoTIFF of the spatial extent of debris-flow inundation (*UmpquaTribs_inundation.tif*). Note that the entire spatial extent of inundation can be visualized by using all non-zero values in this file.
- GeoTIFF (*UmpquaTribs_stream.tif*) and shapefile (*UmpquaTribs_stream.shp*) of the drainage network located in the *DEM_dataE/UmpquaTribs_drainage/* subdirectory.
- GeoTIFF of growth zones within the drainage network (*UmpquaTribs_grzones.tif*) located in the *UmpquaTribs_growth/* subdirectory of the designated output directory.

## Discussion of Output Results

### Base case

The base case estimates debris-flow inundation (contained in *UmpquaTribs_inundation.tif)* using a length-growth factor of 33 $ft^3/ft$ (~3 $m^3/m$), as shown in figure 46. Growth zones are defined by stream slopes greater than or equal to 5°. Downstream of growth zones (where no growth occurs), inundation transpires using the greatest volume attained in the adjacent upstream growth zone (refer to section 3.6). The resulting pattern of inundation is controlled by the interplay of options defining the location of the growth zones and the overall rate of volumetric growth downstream. As expected, the largest inundation areas (and volumes from length growth) are downstream in the largest drainages. Smaller volumes of inundation occur in smaller channels in the upper parts of the basins and in small basins draining into the Umpqua River to the north.

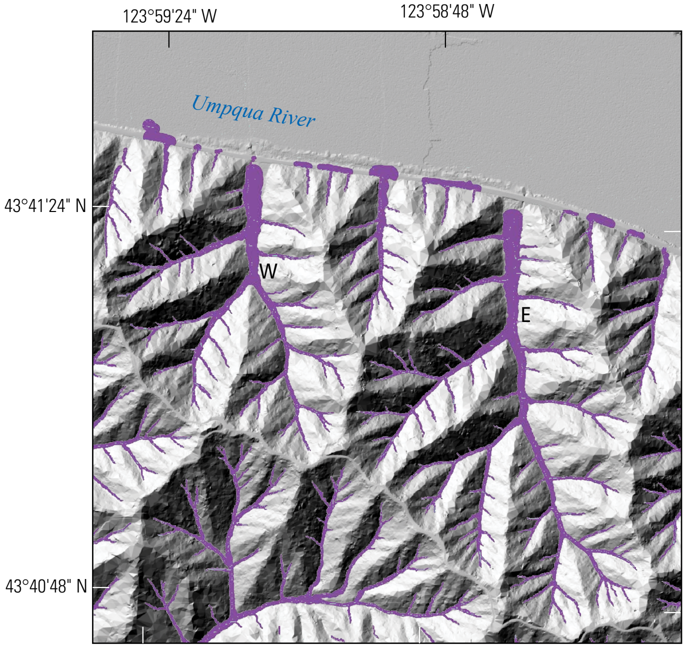


**Figure 46.** Map showing debris-flow inundation from channel length-growth in part of the Coast Range, Oregon, illustrating results from the base case of example E. The length-growth factor in the length-growth equation (eq. 5) is 33 cubic feet per foot (~3 cubic meters per meter). The map area contains small tributaries to the Umpqua River. Basins of interest: W, west; E, east. Hillshade from lidar-derived 3-foot-resolution digital elevation model (Oregon Department of Geology and Mineral Industries, 2009).

### Variation a

Variation a illustrates the effects of an increased length-growth factor with the same growth zones (stream slope ≥5°). The larger length-growth factor of 110 $ft^3/ft$ (~10 $m^3/m$) creates longer and slightly wider inundation zones than the base case, as shown in figure 47. This result is similar to the largest inundation zone shown in figure 12 of Reid and others (2016). This example also shows potential issues as the drainage network encounters roads and large bodies of water (such as the Umpqua River to the north).

In the western basin (labeled W in fig. 47), the drainage network flows north into the Umpqua River. Inundation follows this path, creating an inundation zone in the river itself. This zone is unlikely to represent the precise limits of inundation, as the flow directions in the river are incorrect. Moreover, debris flows into and under water exhibit different inundation characteristics than the volume-area relations used in Grfin Tools. Suggestions for masking an inundation zone along a water body edge are provided in section 5.3.

In contrast, in the eastern basin (labeled E in fig. 47) inundation proceeds to the east along the large road that is parallel to the river's edge. Drainage networks are often heavily influenced by roads. Debris-flow inundation might follow roads and, thus, an inundation zone such as that portrayed may be useful. However, if the debris flow is likely to flow into the river (either through an engineered structure under the road or by traveling directly across the road), then the drainage network would need to be modified to reflect this change. Suggestions for modifying a drainage network with roads are provided in section 5.2.

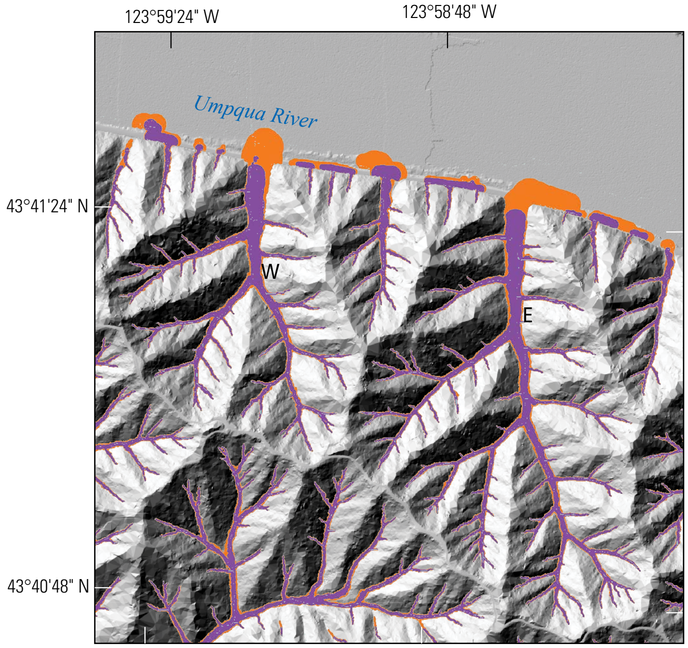


**Figure 47.** Map showing debris-flow inundation from channel length-growth in part of the Coast Range, Oregon, illustrating results from variation a of example E. The length-growth factor in the length-growth equation (eq. 5) is 110 cubic feet per foot (ft$^3$/ft) (~10 cubic meters per meter). Thin lines extending into the Umpqua River are parts of the delineated drainage network. Base-case inundation (length-growth factor of 33 ft$^3$/ft) shown overlaying variation a for comparison. Basins of interest: W, west; E, east. Hillshade from lidar-derived 3-foot-resolution digital elevation model (Oregon Department of Geology and Mineral Industries, 2009).

### Variation b

Variation b demonstrates using a maximum flow volume to constrain inundation. Here, a maximum volume of 113,000 ft$^3$ (3,200 m$^3$) limits the growth and inundation of larger flows downstream in both the west and east basins (fig. 48). Smaller flows in the upper basins have the same inundation as the base case. A maximum volume limit can be useful to minimize inundation from unrealistically large flows.

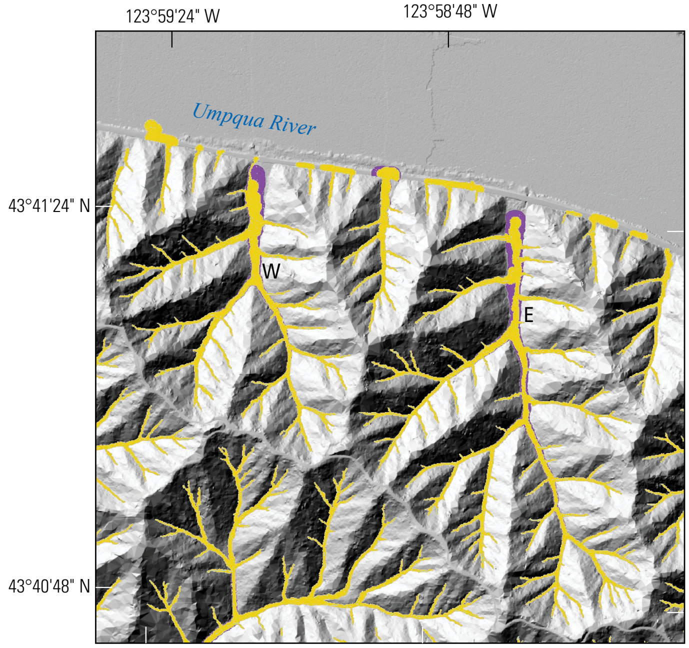


**Figure 48.** Map showing debris-flow inundation from channel length-growth in part of the Coast Range, Oregon, illustrating results from variation b of example E. The maximum (max) flow volume is limited to 113,000 cubic feet (~3,200 cubic meters). Base-case inundation (no volume limit) shown underlying variation b for comparison. Basins of interest: W, west; E, east. Hillshade from lidar-derived 3-foot-resolution digital elevation model (Oregon Department of Geology and Mineral Industries, 2009).

### Variation c

Variation c illustrates the application of a raster file containing user-defined growth-zones to restrict volume growth to specific areas. Here, we use a raster file that only delineates the stream network of the two basins shown in figure 12 of Reid and others (2016), instead of the entire DEM (fig. 49). This provides debris-flow inundation for the two drainage basins of interest (west and east). The resulting growth zones are within the growth zones raster defined above and in areas where stream slopes are greater than or equal to 5°. Results using this combination are the same as the base case in the two basins, but with no inundation computed elsewhere.

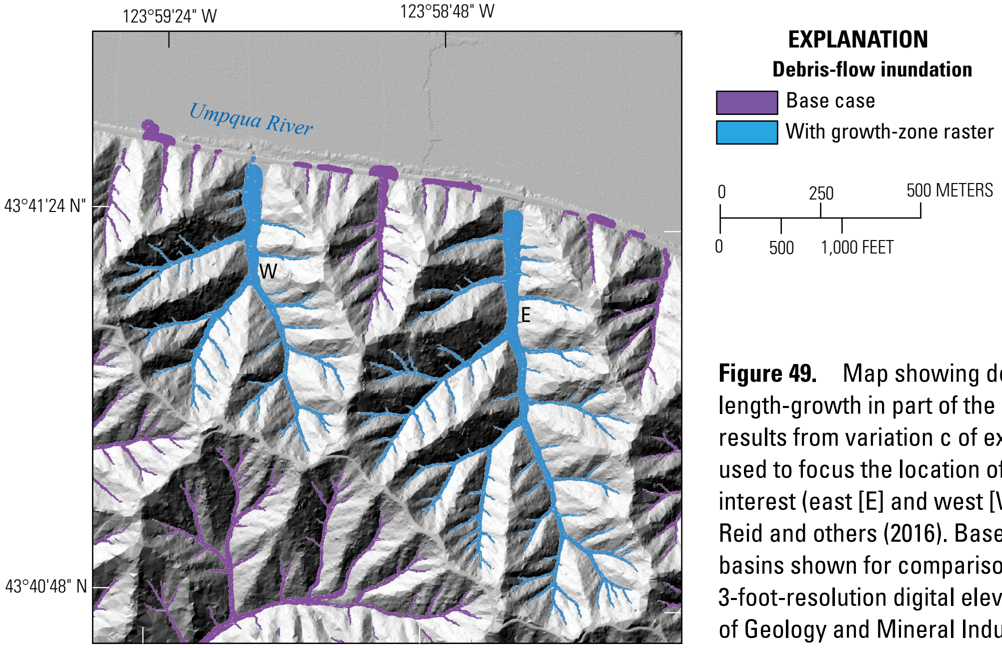


**Figure 49.** Map showing debris-flow inundation from channel length-growth in part of the Coast Range, Oregon, illustrating results from variation c of example E. A growth zone raster is used to focus the location of growth zones to two basins of interest (east [E] and west [W]) that are shown in figure 12 of Reid and others (2016). Base-case inundation outside the two basins shown for comparison. Hillshade from lidar-derived 3-foot-resolution digital elevation model (Oregon Department of Geology and Mineral Industries, 2009).

## 6.6. Example F. Inundation using Multiple Growth Components Based on Field or Remote Measurements (Puerto Rico)

### Overview

Example F illustrates how the **INUNDATION** and **GROWTH** tools can be used to estimate debris-flow inundation if detailed pre- or post-event information regarding landslide source areas and (or) growth factors is available. Here, growth volume parameters are estimated from a combination of known landslide source areas (identified using the **SOURCE** tool) and debris-flow growth from entrainment along a flow path (by calculating length growth). In this example, the **HL** tool is not used. This example demonstrates the second pathway shown in figure 2 (section 2.2).

This multiple component approach for defining flow volumes from known source areas can be applied when post-event information provides details representative of future events. If post-event estimates of growth are not available, this method could be used in a back analysis to estimate appropriate growth factors for a given event. Either estimated (from back analysis) or measured growth factors can then be used to forecast specific future events. In this example, multiple growth components are used: area growth (for the landslide sources) and length growth (for channel entrainment). Growth factors were obtained from detailed measurements of a previous debris-flow event.

### Background and Physical Setting

The municipality of Naranjito in Puerto Rico is a similar setting to Utuado, as described in Example D. This area has long-runout debris flows with known locations of landslide source areas and estimated growth factors from Hurricane Maria, based on pre- and post-event lidar (Coe and others, 2021). This area encompasses the informally named “Twenty Headed” drainage basin, where approximately twenty separate landslides supplied material to a single debris flow. The contributing volume from landslide source areas in this basin was 2,530±20 $m^3$ and the length-growth factor from channel-sediment entrainment was estimated as 0.7±0.1 $m^3/m$ (Coe and others, 2021).

### Input Files and Options

Running this example requires a DEM file, a Settings file, and two additional raster files, which are provided in the example F package. It uses the following input files and options:

- 1-m DEM of the Twenty Headed drainage basin and neighboring areas (*twentyhd.tif*), located in the *DEM_dataF/* directory.

- Separate raster file containing known locations of Hurricane Maria landslide source areas (*twentyhd_lssource.tif*) located in the *DEM_dataF/* directory and used as a landslide source raster file.
- Separate raster file delineating the extent of the drainage basin of interest (*twentyhd_basin.tif*) located in the *DEM_dataF/* directory and used as a growth-zone raster file.
- Settings file (*ExampleF_Naranjito.yaml*; fig. 50) containing parameters, with the following options:
    - In the ***options*** section, ***growth*** and ***inundation*** are set to “yes” to enable the **GROWTH** and **INUNDATION** tools. ***hl*** is set to “no”.
    - In the ***source*** section—
        - ***source_raster*** is set to “*DEM_dataF/twentyhd_lssource.tif*”.
        - ***min_source_value*** is set to “1” to limit sources in the source raster file to a targeted area.
    - In the ***growth_options*** section—
        - In the ***growth_zones*** subsection—
            - ***growth_zone_raster*** is set to “*DEM_dataF/twentyhd_basin.tif*”.
            - ***min_stream_slope*** is set to “8” to set the minimum stream slope for growth zones to 8°.
        - In the ***growth_volumes*** subsection—
            - In the ***area_growth*** sub-subsection, ***area_growth_factor*** is set to “1” to set the area-growth factor to 1 $m^3/m^2$ in the area-growth equation (eq. 4).
            - In the length_growth sub-subsection, length_growth_factor is set to “0.7” to set the area-growth factor to 0.7 m3/m in the length-growth equation (eq. 5).

```
setup:
  title: Example F - multiple components (Naranjito, Puerto Rico)
  # uses landslide source areas and estimated length-growth factors
  # from Twenty Headed drainage, Coe and others 2021
  demfilename: DEM_dataF/twentyhd.tif
  dest_dir: output_ExampleF

options:
  inundation: yes
  growth: yes
  hl: no

source:
  source_raster: DEM_dataF/twentyhd_lssource.tif
  min_source_value: 1

growth_options:
  growth_zones:
    min_stream_slope: 8
    growth_zone_raster: DEM_dataF/twentyhd_basin.tif
  growth_volumes:
    area_growth:
      area_growth_factor: 1
    length_growth:
      length_growth_factor: 0.7

inundation_options:
  # Default options used
```

**Figure 50.** Text from the Settings file for example F (*ExampleF_Naranjito.yaml*) for a multiple component analysis of debris-flow growth and inundation with locations of known landslides using the Grfin Tools **GROWTH** and **INUNDATION** tools. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

## Output Products

A variety of output files are generated; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—*output_ExampleF*. Primary results of immediate interest are contained in these files:

- Text file summarizing the settings (*ExampleF_Naranjito_settings.txt*).
- GeoTIFF of the spatial extent of debris-flow inundation (*ExampleF_Naranjito_inundation.tif*). Note that the entire spatial extent of inundation can be visualized by using all non-zero values in this file.
- Shapefile of the drainage network (*twentyhd_stream.shp*) located in the *DEM_dataF/twentyhd_drainage/* subdirectory.
- GeoTIFF of growth zones within the drainage network (*twentyhd_grzone.tif*) located in the *output_ExampleF/twentyhd_growth/* subdirectory.

## Discussion of Output Results

This example portrays debris-flow inundation (*twentyhd_inundation.tif)*, where volumes are derived from a combination of area growth (from the source raster) and length growth. The area-growth factor (1.0 $m^3/m^2$), representing contributions form landslide sources, is calculated from the contributing volume of landslides divided by the landslide source area. The length-growth factor is 0.7 $m^3/m$, based on Coe and others (2021). The minimum source value is set to one for this case to include all non-zero areas of the input source raster. This example also illustrates the application of a raster file containing user-defined growth-zones to restrict volume growth to specific areas. Here, we use a raster file that delineates a single drainage basin. Growth zones are defined as stream segments within a single drainage basin with stream slopes greater than or equal to 8°. The resulting inundation area, the extent of mapped landslide-affected areas, and observed debris-flow inundation are shown in figure 51. Note that the intermediate runout zone between landslide source areas and channelized inundation is not estimated. This non-channelized runout zone could be delineated with the **HL** tool (refer to example A, section 6.1). Simulated debris-flow inundation extends beyond the drainage basin; however, the downstream extent of actual inundation could not be precisely determined owing to reworking of deposits by subsequent flood waters (Coe and others, 2021).

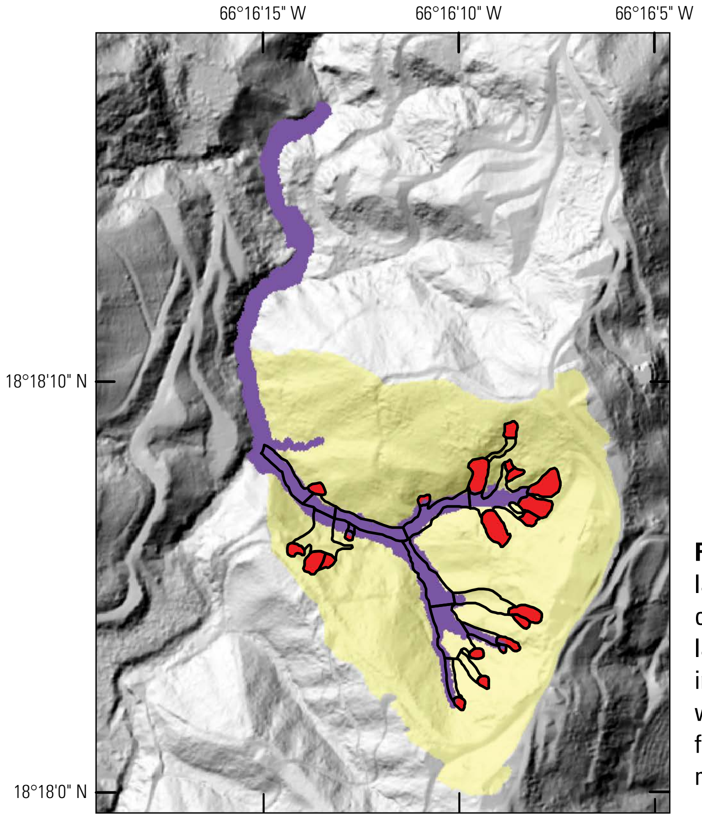


**Figure 51.** Map showing observed minimum extent of landslide-affected areas (black outline; from Coe and others, 2021), estimated debris-flow inundation, mapped landslide source areas, and extent of the drainage basin in part of Naranjito, Puerto Rico, derived using Grfin Tools with multiple growth components, for example F. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

## 6.7.a. Example G. Landslide Susceptibility Map using a Combination of Tools and Scenarios (Puerto Rico)

### Overview

Example G illustrates how the **DRAINAGE**, **SOURCE**, **HL**, **GROWTH**, and **INUNDATION** tools can be used to create landslide susceptibility maps. These tools are used to create a drainage network and differentiate mobility zones: (1) the ***drainage_options*** section is used to run the **DRAINAGE** tool initially and then disable it for subsequent runs to save runtime, (2) the **SOURCE** tool is used to identify potential landslide source areas, (3) the **HL** tool is used to compute non-channelized runout in open-slope topography, and (4) the **GROWTH** and **INUNDATION** tools are used to compute inundation from debris flows that grow as they travel down drainage channels. This example also demonstrates the use of landslide susceptibility modeling performed outside of Grfin Tools to define the source areas susceptible to shallow landslides. Here, potential landslide source areas are identified by a user-selected range of factors of safety from an analysis conducted using TRIGRS (Baum and others, 2024). Overall, this example is relatively complex and demonstrates how different tools and options can be combined to perform a more detailed analysis. This example demonstrates both the first and second pathways shown in figure 2 (section 2.2).

This combined approach builds on example D (section 6.4), source-area growth, with the addition of potential landslide sources determined from outside of Grfin Tools, more complex growth zones, and *H*/*L* runout zones. The two scenarios in this example use different landslide source areas, debris-flow growth zones, growth factors, and maximum volumes. A separate supplemental example (section 6.7.b) related to this example demonstrates a multi-step method to identify flow directions that follow natural channels in situations where the drainage network is disrupted by road infrastructure (also refer to section 5.2).

### Background and Physical Setting

The physical setting and location for this example, in Utuado, Puerto Rico, is described in example D (section 6.4). Example G uses the parameters from two selected inundation scenarios described in Brien and others (in press). For potential landslide source areas in the two scenarios, factor-of-safety thresholds of 0.87 and 0.97 are selected to identify 75 and 90 percent, respectively (Baum and others, 2024), of mapped headscarp points from landslides triggered by Hurricane Maria (Hughes and others, 2019). These areas identify the source areas for both open-slope runout estimates and debris-flow inundation with area-growth-derived volumes.

### Input Files and Options

Each run requires the DEM file, a Settings file, and an additional source raster file. Files for both scenarios are provided in the example G package. Both scenarios use the following input files:

- 1-m lidar-derived DEM (*Utuado_clip.tif*), located in the *DEM_dataG/* directory.
- Separate raster file containing factor-of-safety values created outside of Grfin Tools to define source areas susceptible to shallow landsliding (*UtuadoTRIGRS_clip.tif*) located in the *DEM_dataG/* directory and used as a source raster file.
- The very high susceptibility scenario uses Settings file *ExampleG_Utuado_VeryHighSuscept.yaml*, and the high susceptibility scenario uses settings file *ExampleG_Utuado_HighSuscept.yaml*.
    - In the ***options*** section for both scenarios, ***inundation***, ***growth***, and ***hl*** are set to “yes” to enable the **INUNDATION**, **GROWTH**, and **HL** tools.
    - In the ***drainage_options*** section, ***compute_new_drainage*** is set to “yes” for the very high susceptibility scenario to generate a new drainage network and “no” for the high susceptibility scenario to reuse the same drainage network.
    - In the ***source*** section for both scenarios—
        - ***source_raster*** is set to “*DEM_dataG/UtuadoTRIGRS_clip.tif*”.
    - In the ***growth_options*** section for both scenarios—
        - In the ***growth_zones*** subsection—
            - ***include_partial*** is set to “yes” to include partial drainage basins.
            - ***slope_method*** is set to “downstream” with a default horizontal distance of 50 m along the drainage network.

- In the ***inundation_options*** section, ***output_img*** is set to "*Utuado_inundation_VeryHighSuscept.tif*" for the very high susceptibility scenario and "*Utuado_inundation_HighSuscept.tif*" for the high susceptibility scenario to specify the output file name of the estimated inundation area raster file.

Table 21 lists specific parameter values for all other input fields used in both scenarios.

**Table 21.** Input parameters for very high and high-susceptibility scenarios of example G.

[To define different potential landslide source areas for the two scenarios, different ***max_source_value*** thresholds are applied to the same source raster file (*UtuadoTRIGRS_clip.tif*) containing factor-of-safety values. m, meter (/m, reciprocal digital elevation model units); $m^2$, square meter; $m^3$, cubic meter]

| YAML input field name | Units | Very high | High |
|---|---|---|---|
| ***source*** | | | |
| ***max_source_value*** | Dimensionless | 0.87 | 0.97 |
| ***hl_options*** | | | |
| ***min_reach_angle*** | Degrees | 25 | 20 |
| ***growth_options*** | | | |
| ***growth_zones*** | | | |
| ***max_stream_order*** | Dimensionless | 3 | 4 |
| ***min_stream_slope*** | Degrees | 8 | 5 |
| ***min_sourcearea_ratio*** | Dimensionless | 0.2 | 0.2 |
| ***min_curvature_growth*** | 1/m | 0.02 | 0.02 |
| ***growth_volumes*** | | | |
| ***max_volume*** | $m^3$ | 1,000 | 5,000 |
| ***area_growth*** | | | |
| ***area_growth_factor*** | $m^3/m^2$ | 0.01 | 0.1 |

Running both scenarios creates output that covers a large area using the same input DEM and corresponding drainage network. To create the necessary drainage network and associated files, the initial run will require ***compute_new_drainage*** set to "yes". Subsequent runs can avoid unnecessary computational effort by setting ***compute_new_drainage*** to "no". Therefore, the very high susceptibility scenario should be run using the Settings file, *ExampleG_Utuado_VeryHighSuscept.yaml* (fig. 52), before the high-susceptibility scenario is run using the Settings file, *ExampleG_Utuado_HighSuscept.yaml,* to generate the necessary drainage files.

```
Setup:
  title: Example G – complete susceptibility map –
     source, H/L, growth, inundation (Utuado, Puerto Rico),
     very high susceptibility scenario
  # inundation parameters are equivalent to
  # scenario B-1K in Brien and others (in press)
  demfilename: DEM_dataG/UtuadoClip.tif
  num_procs: 8
  dest_dir: output_ExampleG_VeryHighSuscept

options:
  inundation: yes
  growth: yes
  hl: yes

drainage_options:
  compute_new_drainage: yes

source:
  source_raster: DEM_dataG/UtuadoTRIGRS_clip.tif
  max_source_value: 0.87

hl_options:
  min_reach_angle: 25

growth_options:
  growth_zones:
    include_partial: yes
    min_stream_slope: 8
    slope_method: downstream
    max_stream_order: 3
    min_curvature_growth: 0.02
    min_sourcearea_ratio: 0.2
  growth_volumes:
    max_volume: 1000
    area_growth:
      area_growth_factor: 0.01

inundation_options:
  output_img: Utuado_inundation_VeryHighSuscept.tif
```

**Figure 52.** Text from the Settings file for the very high susceptibility scenario of Example G (*ExampleG_Utuado_VeryHighSuscept.yaml*) to create components for a susceptibility map using the Grfin Tools **SOURCE**, **HL**, **GROWTH**, and **INUNDATION** tools. A separate Settings file is provided for the high-susceptibility scenario (*ExampleG_Utuado_HighSuscept.yaml*). The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin Tools run.

## Output Products

A variety of output files are generated by Grfin Tools runs of the very high and high-susceptibility scenarios; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—either *output_ExampleG_HighSuscept/* or *output_ExampleG_VeryHighSuscept/*, depending on the scenario. Primary results of immediate interest are contained in the following files:

- Text files summarizing the settings for each scenario (*output_ExampleG_VeryHighSuscept/ExampleG_Utuado_VeryHighSuscept_settings.txt* or *output_ExampleG_HighSuscept/ExampleG_Utuado_HighSuscept_settings.txt*).
- GeoTIFFs of the spatial extent of potential landslide source areas for each scenario (*output_ExampleG_VeryHighSuscept/Utuado_clip_sourcearea.tif* or *output_ExampleG_HighSuscept/Utuado_clip_sourcearea.tif*).
- GeoTIFFs of the spatial extent and length of landslide runout for each scenario (*output_ExampleG_VeryHighSuscept/Utuado_clip_hlrunoutdistance.tif* or *output_ExampleG_HighSuscept/Utuado_clip_hlrunoutdistance.tif)*. Note that the entire spatial extent of runout can be visualized by using all non-zero values in these files.
- GeoTIFFs of the spatial extent of debris-flow inundation for each scenario (*output_ExampleG_VeryHighSuscept/Utuado_inundation_VeryHighSuscept.tif* or *output_ExampleG_HighSuscept/Utuado_inundation_HighSuscept.tif*). Note that the entire spatial extent of inundation can be visualized by using all non-zero values in these files.

Some secondary files, used for visualization of specific components, include:

- Shapefile of the drainage network (*Utuado_clip_stream.shp*) located in the *DEM_dataG/Utuado_clip_drainage/* subdirectory.
- GeoTIFF of growth zones within the drainage network (*Utuado_clip_grzones.tif*) located in the *Utuado_clip_growth/* subdirectory of the designated output directory.

## Discussion of Output Results

The very high and high-susceptibility scenarios in this example illustrate using a combination of tools to generate landslide susceptibility maps (Baum and others, 2024; Brien and others, in press). The high-susceptibility scenario encompasses a larger area of susceptibility for source areas, landslide runout, and inundation with growth than the very high susceptibility scenario. The high-susceptibility scenario also uses a higher threshold for factor of safety, a lower reach angle, more generous estimation of growth zones, a higher growth factor, and a larger maximum volume.

The selection of growth zone parameters was based on detailed assessment of 124 landslide runout zones from Hurricane Maria (Brien and others, in press). In both scenarios, locations of debris-flow growth were defined with a combination of four options—stream slope, Strahler stream order, source-area ratio, and planform curvature. Stream slope was calculated over a downstream horizontal distance of 50 m. The primary criteria for growth zones—stream slope and stream order—are different in the two scenarios, whereas secondary criteria—source-area ratio and planform curvature threshold—are held constant. These secondary criteria alleviate some problematic discontinuous growth zones. Such problems are identified by downstream artifacts where large volumes are assigned in short, steep growth zones of the stream channel, located far downstream from confined, highly susceptible upstream areas. These artifacts result in unrealistic, and commonly discontinuous, inundation zones. The secondary growth zone criteria successfully eliminate downstream inundation zones where inundation area is disproportional to the immediately adjacent contributing source areas, and do not affect growth zones in the highly susceptible upstream areas.

Our susceptibility portrayal combines the output from both scenarios. Figure 53 shows the results for a small zoomed-in area of the DEM, where individual components can be viewed in detail:

- potential source areas (parts *A*, *E*, *I*) (from *Utuado_clip_sourcearea.tif* for each scenario),
- landslide runout (parts *B*, *F*, *J*) (from *Utuado_clip_hlrunoutdistance.tif* for each scenario),
- debris-flow inundation (parts *C*, *G*, *K*) (from *Utuado_inundation_VeryHighSuscept.tif* and *Utuado_inundation_HighSuscept.tif*), and
- combined source areas, landslide runout, and debris-flow inundation susceptibility zones (parts *D*, *H*, *L*).

In the images showing combined susceptibility zones (figs. 53*D*, *H*, *L* and 54), debris-flow inundation areas overlie all other zones and may conceal underlying source and landslide runout zones; non-channelized landslide runout zones underlie all other layers in the map. Figure 54 shows a larger area with the combined results.

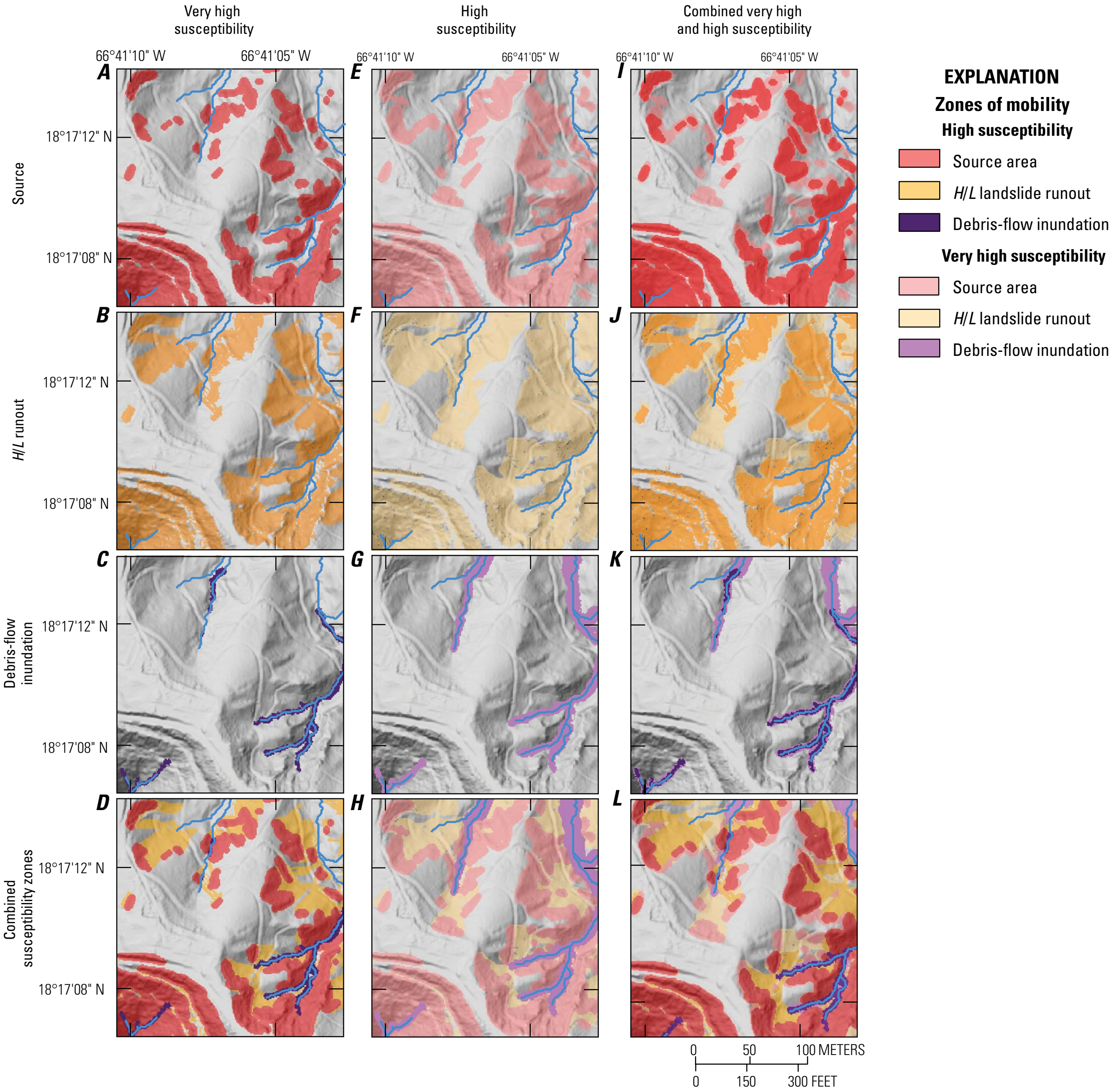


**Figure 53.** Maps showing zones of mobility from both scenarios of Example G. *A*, Potential source area for very high susceptibility scenario. *B*, Height-to-length (*H*/*L*) landslide runout zones for very high susceptibility scenario. *C*, Debris-flow inundation for very high susceptibility scenario. *D*, Combination of potential source area, *H*/*L* landslide runout, and debris-flow inundation for very high susceptibility scenario. *E*, Potential source area for high-susceptibility scenario. *F*, *H*/*L* landslide runout zones for high-susceptibility scenario. *G*, Debris-flow inundation for high-susceptibility scenario. *H*, Combination of potential source area, *H*/*L* landslide runout, and debris-flow inundation for high-susceptibility scenario. *I*, Potential source area for very high and high-susceptibility scenario. *J*, *H*/*L* landslide runout zones for very high and high-susceptibility scenario. *K*, Debris-flow inundation for very high and high-susceptibility scenario. *L*, Combination of potential source area, *H*/*L* landslide runout, and debris-flow inundation for very high and high-susceptibility scenario. Area of map shown in figure 54. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

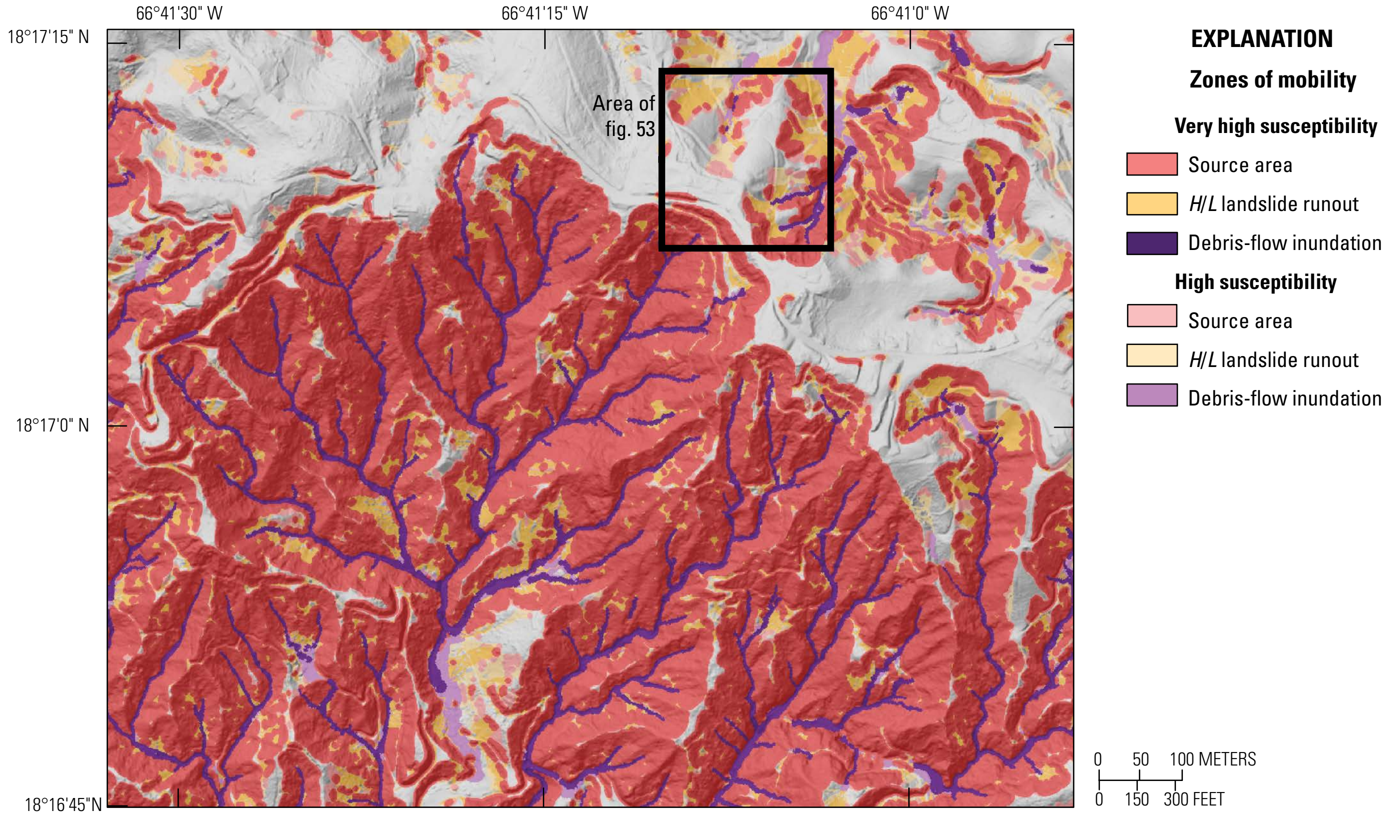


**Figure 54.** Map showing the combined zones of mobility (potential source area, *H*/*L* landslide runout, and debris-flow inundation) for the very high and high-susceptibility scenarios of Example G. Hillshade from lidar-derived 1-meter-resolution digital elevation model (U.S. Geological Survey, 2018).

## 6.7.b. Example G. Supplemental Technique—Road Removal (Puerto Rico)

This supplement to example G demonstrates the reduction of road-related artifacts near channel-initiation locations and downstream of channel initiation (following section 5.2). This supplement builds on example G, which used the default window of 10 m to smooth the DEM for creating the drainage network (fig. 55, purple lines). However, due to the prevalence of ridgetop roads, some minor road-related problems near channel initiation are present. Examples of these problems are apparent in the northwestern (black box, fig. 55) and north-central parts of figure 55. To remove these additional artifacts when identifying channel initiation locations, this supplement uses a DEM smoothing window (***dem_neighborhood***) of 15 m before applying the curvature thresholds used to define channel initiation (refer to section 3.4). The resulting revised drainage network from this first step eliminates road-related issues at channel initiation (fig. 55, orange lines), but downstream problems with roads are still present. In the final step of this supplement, the smoothed DEM is also used to derive flow directions, thereby eliminating unrealistic diversions of flow direction where the drainage network intersects roads downstream of channel initiation (fig. 55, blue lines). The multiple steps and associated Settings files for road removal are described in more detail below.

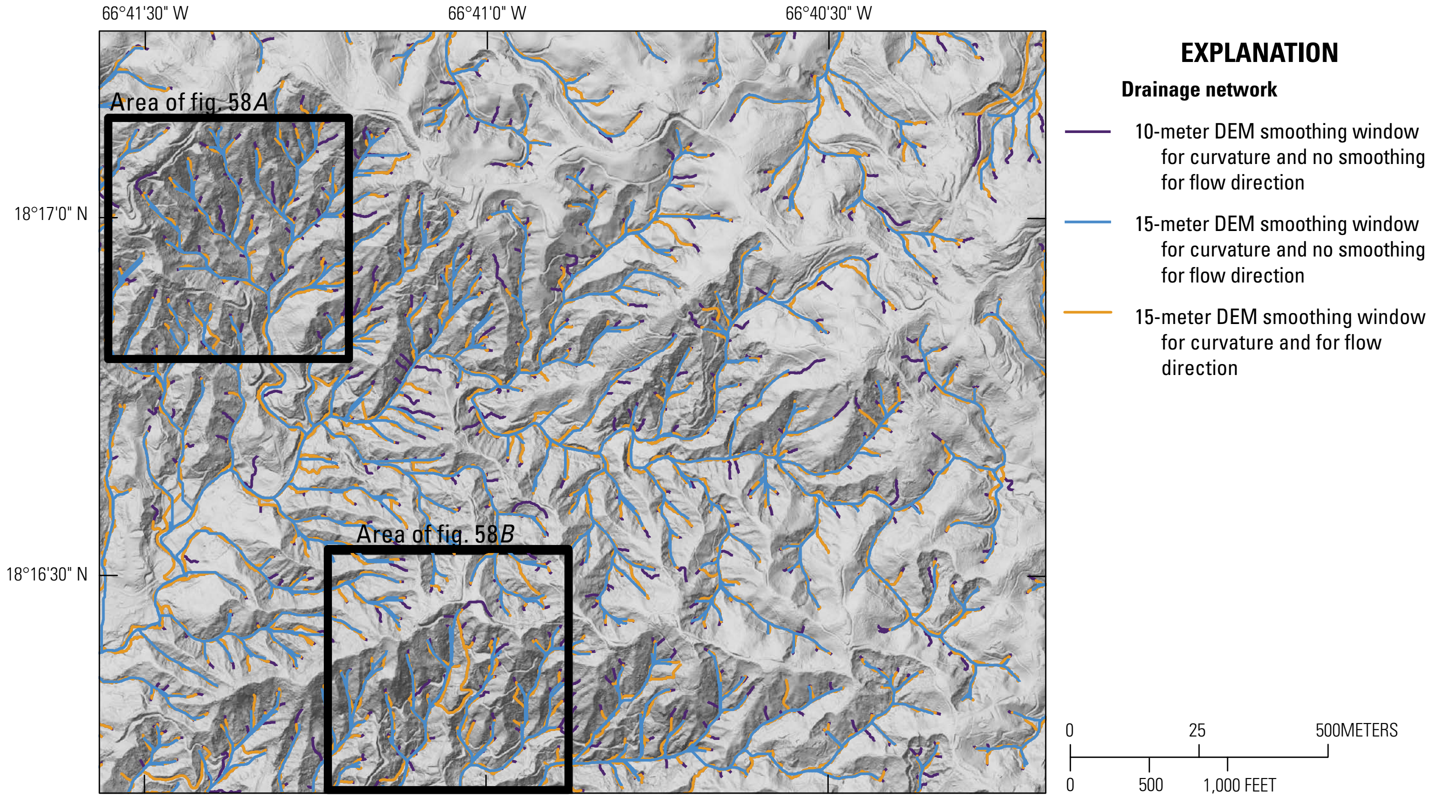


**Figure 55.** Map showing delineated drainage networks in Utuado, Puerto Rico, for example G, comparing different smoothing windows used to remove road-related artifacts. Output shapefiles used for this visualization are *DEM_dataG/Utuado_clip_drainage/Utuado_clip_stream.shp*, *DEM_dataG_smoothed/Utuado_clip_drainage/Utuado_clip_stream.shp*, and *DEM_dataG_smoothed/Utuado_clipsmooth15_drainage/Utuado_clipsmooth15_stream.shp*. Hillshade from lidar-derived 1-meter-resolution digital elevation model (DEM) (U.S. Geological Survey, 2018).

## Input Files and Options

The process to reduce road-related artifacts involves several steps. This requires running Grfin Tools two times with Settings files specific to each run and a DEM. All files are provided in the example G package.

Step 1 is to run Grfin Tools to delineate a drainage network only. Step 1 uses using the following input files and options:

- 1-m lidar-derived DEM from example G (*Utuado_clip.tif*), located in the *DEM_dataG_smoothed/* directory.
- Settings file (*ExampleG_Supp_Utuado_drainageonly.yaml*; fig. 56), with the following options:
  - In the ***options*** section, ***standalone_drainage_network*** is set to “yes” to generate a standalone drainage network. ***inundation***, ***growth***, and ***hl*** are set to “no”.
  - In the ***drainage_options*** section, ***dem_neighborhood*** is set to “15” to set the smoothing window to 15 m.

```
setup:
  title: Example G - Supplement, create stand-alone drainage for flow directions in
inundation
  # high susceptibility scenario with removal of road artifacts
  # 15 m smoothing window
  # Step 1 in Special conditions for road-related drainage artifacts
  demfilename: DEM_dataG_smoothed/Utuado_clip.tif
  num_procs: 8
  dest_dir: DEM_dataG_smoothed

options:
  inundation: no
  growth: no
  hl: no
  standalone_drainage_network: yes

drainage_options:
  compute_new_drainage: yes
  dem_neighborhood: 15
```

**Figure 56.** Text from the Settings file for step 1 of the supplement to example G (*ExampleG_Supp_Utuado_drainageonly.yaml*), showing necessary options to create a new drainage network from a smoothed digital elevation model (DEM) in Grfin Tools. The smoothing window is 15 m. The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin run.

Step 2 is to copy *Utuado_clipsmooth.tif* from the DEM_dataG_smoothed/Utuado_clip_drainage/ directory, rename it *Utuado_clipsmooth15.tif,* and place it in the *DEM_dataG_smoothed/* directory in order to use the smoothed DEM output from step 1 for downstream flow directions in step 3.

Step 3 is to run Grfin Tools using the smoothed DEM created in step 1 for flow directions and the original example G DEM for cross-sectional inundation. Most of the settings for this run are from the high-susceptibility scenario in example G. Step 3 uses the following input files and options:

- 1-m smoothed lidar-derived DEM (*Utuado_clipsmooth15.tif*), located in the *DEM_dataG_smoothed/* directory.
- Settings file (*ExampleG_Supp_Utuado_HighSuscept_roadsremoved.yaml*; fig. 57) of parameters, with the following options modified from the high-susceptibility scenario in example G:
  - In the ***setup*** section, ***demfilename*** is set to “*DEM_dataG_smoothed/Utuado_clipsmooth15.tif*” to use the smoothed DEM from step 1 and ***dest_dir*** is set to “*output_ExampleG_Supp_HighSuscept_roadsremoved*”.
  - In the ***options*** section, ***hl*** is set to “no” to disable the **HL** tool.
  - In the ***drainage_options*** section—
    - ***compute_new_drainage*** is set to “yes” to generate a new drainage network.
    - ***dem_neighborhood*** is set to “1” to set the smoothing window to the original DEM resolution of 1 m.
  - In the ***inundation_options*** section—
    - ***output_img*** is set to “*Utuado_inundation_HighSuscept_roadsremoved.tif*” to specify the output file name of the estimated inundation area raster file.
    - ***xsec_demfilename*** is set to “*DEM_dataG_smoothed/Utuado_clip.tif*” to use the original unsmoothed DEM for cross-sectional and planimetric areas.

```
# this is an excerpt showing pertinent modifications
# from ExampleG_Supp_Utuado_HighSuscept.yaml

setup:
  demfilename: DEM_dataG_smoothed/Utuado_clipsmooth15.tif
  dest_dir: output_ExampleG_Supp_HighSuscept_roadsremoved

drainage_options:
  compute_new_drainage: yes
  dem_neighborhood: 1

source:
  source_raster: DEM_dataG_smoothed/UtuadoTRIGRS_clip.tif
  max_source_value: 0.97

inundation_options:
  xsec_demfilename: DEM_dataG_smoothed/Utuado_clip.tif
  output_img: Utuado_inundation_HighSuscept_roadsremoved.tif
```

**Figure 57.** Excerpt of text from the Settings file for step 3 of the supplement to Example G (*ExampleG_Supp_Utuado_HighSuscept_roadsremoved.yaml*), showing necessary modification from the Settings file for the high-susceptibility scenario in example G (*ExampleG_Utuado_HighSuscept.yaml*). The number symbol (#) denotes a comment line—these lines can be used to add notes that do not affect a Grfin run.

## Output Products

A variety of output files are generated by the Grfin Tools runs in steps 1 and 3; specific file contents are described in section 4.4. Primary output files are placed in the directory designated by the ***dest_dir*** input field—*output_ExampleG_Supp_HighSuscept_roadsremoved*. Primary results of immediate interest are contained in the following files:

- Text file summarizing the settings (*ExampleG_Utuado_Supp_HighSuscept_roadsremoved_settings.txt*).
- GeoTIFF of the spatial extent of debris-flow inundation (*Utuado_inundation_HighSuscept_roadsremoved.tif*). Note that the entire spatial extent of inundation can be visualized by using all non-zero values in this file.
- Shapefile of the drainage network (*Utuado_clipsmooth15_stream.shp*) located in the *DEM_dataG_smoothed/Utuado_clipsmooth15_drainage/* subdirectory.

## Discussion of Output Results

Figure 58 shows two variations of estimated debris-flow inundation in the high-susceptibility scenario derived from channel networks using the following:

1. the original DEM smoothed with a 10-m window used to identify channel initiation based on curvature (example G). Downstream flow directions are derived from the original DEM, and
2. the DEM smoothed with 15-m window to identify channel initiation based on curvature. In this case, downstream flow directions are derived from the smoothed DEM (supplement to example G).

In the supplement, flow directions, growth zones, and growth volumes are derived from the smoothed DEM, but the original topography is used for estimation of cross-sectional and planimetric inundation areas. This supplement alleviates unrealistic road artifacts; for example, brown inundation zones following roads between natural channels are eliminated (fig. 58, red circled areas). Although this approach can sometimes over-smooth topography and eliminate smaller scale topographic features (fig. 58, purple circled areas), we successfully applied a similar technique in Puerto Rico (Brien and others, in press). For this supplement, the smoothed DEM provides an estimation of flow paths for debris-flow inundation representative of natural channels, not disrupted by diversions at road crossings. The original DEM, which maintains the original topography and associated location of the channel thalweg is used for estimating areas of potential inundation.

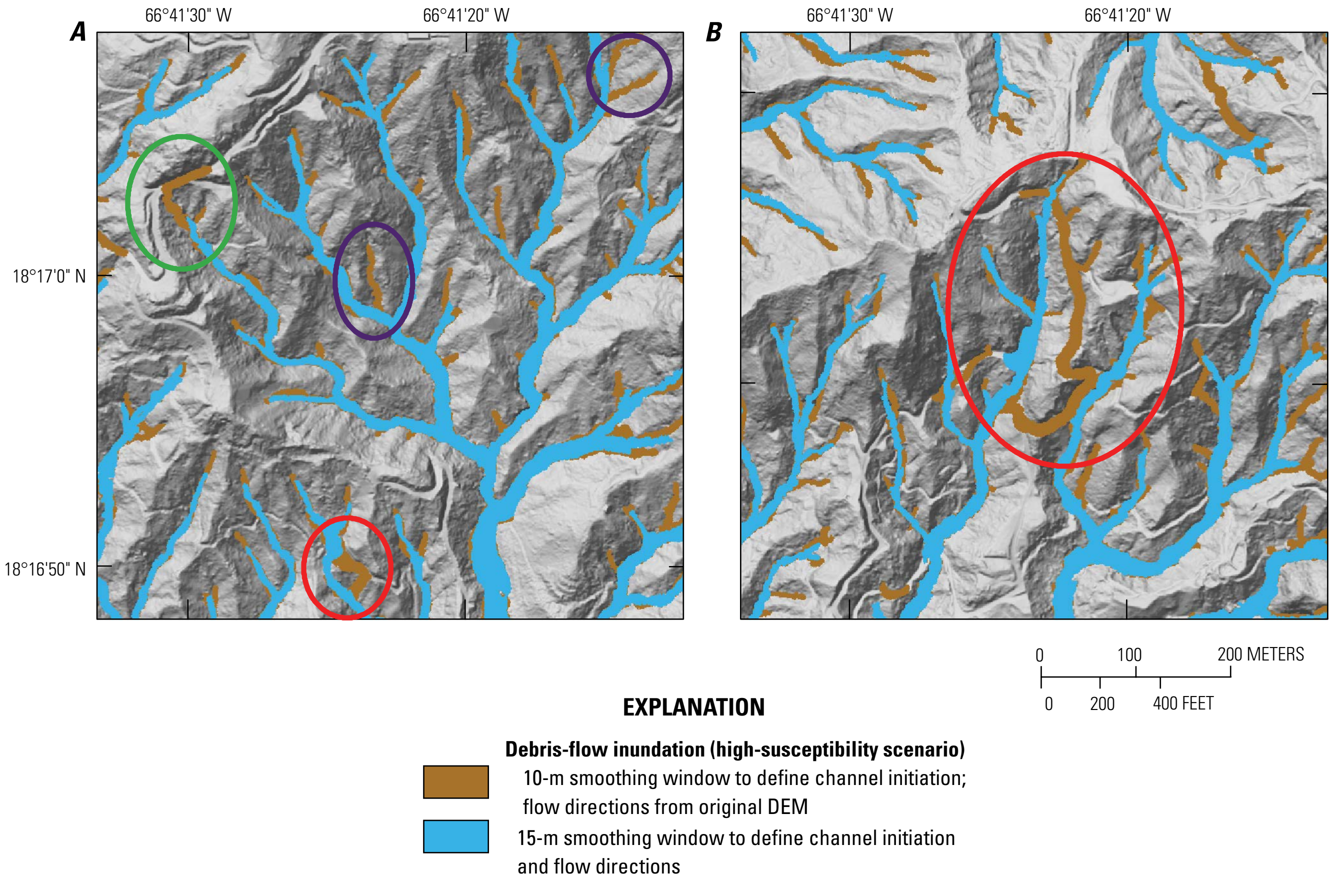


**Figure 58.** Maps showing computed debris-flow inundation in part of Utuado, Puerto Rico, illustrating results from the supplement to the high-susceptibility scenario in example G. Brown area is computed using the original digital elevation model (DEM) for flow directions and a DEM smoothed with a 10-meter (m) window to identify channel initiation based on curvature. Blue area is computed using the DEM smoothed with a 15-m window to identify both channel initiation and downstream flow directions. Circled areas highlight (1) improvements in channel initiation location with larger smoothing window (green), (2) improvements to flow directions (red), and (3) loss of finer scale details (purple). Hillshade from lidar-derived 1-m-resolution DEM (U.S. Geological Survey, 2018).

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