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THE SCARP IDENTIFICATION AND CONTOUR CONNECTION METHOD (SICCM): A TOOL FOR USE IN SEMI-AUTOMATIC LANDSLIDE MAPPING

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See the digital publication folder for files. Geodatabase is Esri® version 10.1 format.
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Lutsinger.gdb

Feature classes:

- Areas_of_Interest
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1.0 REPORT SUMMARY

Landslides are a chronic problem, especially in places with moderate to steep slopes, wet climates, and/or relatively high seismic hazards. Landslides occur in both urban and rural settings and cause significant economic losses through infrastructure damage as well as indirect economic losses from road and building closures. The Pacific Northwest is particularly prone to landslides given its wet climate, weathered soils, steep terrain, and substantial seismicity.

Landslide inventory datasets help identify landslide-prone regions. Inventories are important to municipalities, transportation departments, and other agencies responsible for managing infrastructure and for public safety. Inventories are also a key component of more advanced susceptibility, hazard, and risk mapping. Given the utility of landslide inventory maps, accurate and timely maps are essential.

Fortunately, the accuracy of landslide mapping has dramatically improved with the increasing availability of lidar-based bare-earth digital elevation model (DEM) imagery. Lidar bare-earth DEMs capture important details of the topography below the tree canopy. To date, most detailed identification of landslides and attribution of a landslide inventory are based on lidar DEMs. Even with lidar base maps, the process of manually mapping of landslide deposits is a time-consuming process requiring expertise and judgment. The effort required to produce inventory maps limits mapping to smaller extents and can be a barrier to developing needed data in landslide-prone regions. Tools that help automate the process of visualizing and digitizing landslide features are therefore welcome.

This report describes a semi-automatic framework to improve the efficiency of landslide inventorying efforts by streamlining the mapping of landslide scarps and delineating deposits of deep-seated and translational landslides. The workflow uses a scarp identification and delineation tool (SI) and a landslide deposit delineation algorithm called the Contour Connection Method (CCM). Together, the tools, called SICCM, can quickly and consistently create an approximation of landslide scarps and deposits on lidar or other remote sensing bare earth DEM imagery. With varying levels of automation, SICCM can be used to rapidly generate scarp and landslide deposit feature class datasets. These provide preliminary maps of landslide extents to assist experienced landslide geologists in digitizing landslide inventories using protocols such as described in Oregon Department of Geology and Industries Special Paper 42 (SP-42), DOGAMI’s current standard process. SICCM is not a replacement of the detailed mapping procedures as outlined in SP-42; rather, SICCM results provide an alternative for mapping larger areas or an initial map that can be used as a precursor in the SP-42 process. Direct outputs from SICCM should not be used as an alternative to a landslide inventory, especially in cases where a detailed landslide inventory is required, such as for municipal planning departments. However, SICCM, when combined with experience of a qualified mapper, enables more rapid assessment of landslide risks and potential impacts over large spatial extents where broad planning decisions regarding infrastructure are needed.

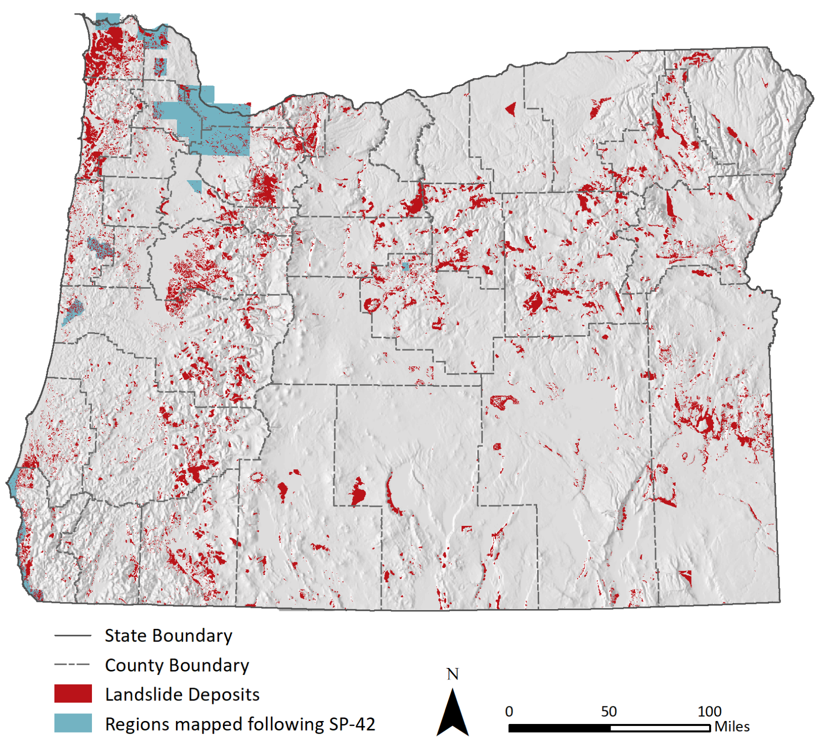
Three modes of the SICCM workflow with different levels of automation are demonstrated by both modeling and mapping landslides in the Lutsinger Creek watershed, Oregon. Observations regarding tool inputs and optional modeler interventions for improving accuracy are presented, demonstrating stages where SICCM modelers may apply expert judgment. For the Lutsinger Creek study area, SICCM achieved modeling results in reasonable agreement with manual mapping using the SP-42 protocol.

2.0 INTRODUCTION

Climate, geology, and topography combine to render portions of the landscape susceptible to landslides. Rainfall, earthquakes, and human activity are the primary triggers of landslides. Worldwide, landslides cause billions of dollars in property damage and thousands of deaths every year (Hong and others, 2007). In Oregon, landslides are a significant chronic natural hazard to the public, damaging residential homes and public infrastructure. Most of Oregon's landslide damage has been associated with severe winter rainstorms (Wang and others, 2002). For example, during the 1996-1997 storms, thousands of landslides occurred and caused losses exceeding $100 million in direct damage (Wang and others, 2002). Significant landslide damage is expected to occur during future earthquakes (OSSPAC, 2013). Great subduction zone earthquake events around the world have triggered thousands of landslides. As an example, over 3,400 landslides were found in Japan after the 2011 Tohoku earthquake (Wartman and others, 2013). Similar landslide counts and damages are expected in the Pacific Northwest during the next Cascadia Subduction Zone (CSZ) earthquake.

DOGAMI has produced a database of existing mapped landslides called the Statewide Landslide Information Database for Oregon (Burns and Watzig, 2014). The current database (release 3.4) has approximately 50,000 landslides (**Figure 1**). During the past decade, DOGAMI and others have mapped over 20,000 landslides with lidar (Burns, 2017).

Figure 1. Landslides are a significant chronic natural hazard in Oregon, as shown on this map of the Statewide Landslide Inventory for Oregon, version 3.4 (SLIDO-3.4). Landslide deposit areas are colored red; regions mapped following the DOGAMI Special Paper 42 inventory method (Burns and Madin, 2009) are blue. To date, approximately 4% of the moderate to very high landslide susceptibility areas of Oregon have been mapped following SP-42.



To reduce the risk from existing and future landslides in Oregon, a variety of mitigation and risk reduction measures are required, all of which begin with an accurate and complete assessment, or inventory, of existing landslides. Inventories are important for understanding factors influencing landslides, and locations of past landslides can be the best predictors of future landslide movements (Wieczorek, 1984). Primary uses of landslide inventory data are to provide data for landslide hazard and risk assessment, to investigate the distribution, types, and patterns of landslides, and to study landscape evolution (Guzzetti and others, 2012). These types of maps are used directly in risk reduction activities such as planning and designing for future development including buildings, roads, and utilities. For example, a recent study by Mahalingam and others (2015) in Oregon found nearly 30 percent of the lifeline highway routes in the Oregon Coast Range were exposed to high or very high landslide susceptibility. Burns and Mickelson (2016) developed a protocol for deep landslide susceptibility mapping because large, deep landslides tend to reactivate over time, and thus the locations of existing landslides are the highest hazard locations for future deep landslides. Landslide inventories are part of this protocol.

In general, a landslide inventory comprises a survey and database or map of existing landslides (Soeters and van Westen, 1996, p. 134; Schwab and others, 2005). Two types of landslide datasets are central to this report: Special Paper 42 (SP-42) landslide inventory and SICCM landslide map.

2.1 SP-42 Landslide Inventory Datasets

In the early 2000s, the availability of lidar-derived topographic imagery datasets significantly improved landslide inventory mapping to the degree that lidar imagery base maps became the basis for all new landslide inventories from DOGAMI (Burns, 2007). In 2009, DOGAMI published DOGAMI Special Paper 42, Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery (Burns and Madin, 2009), which outlines a method for manual landslide inventory mapping by experienced professionals.

An SP-42 landslide inventory is created by an experienced geologist who manually digitizes landslide deposits, head scarps, internal scarps, and flanks, then attributes features and adds metadata. Burns and Madin (2009) recommended the following steps when creating an SP-42 landslide inventory: 1) All previously identified landslides from geologic maps, landslide studies, and other local sources should be compiled. 2) The mapper should have experience identifying all types and ages of landslides within the area being studied. 3) Lidar data should be used to identify landslides and accurately locate the extents of previously mapped landslides. 4) An orthophoto of similar age to the lidar data should be used to minimize misidentification of man-made cuts and fills as landslides. 5) The mapper should use at least one set of historical stereo-pair aerial photographic imagery to locate landslides in the area being studied. 6) Nonspatial data should be collected at the time of the mapping so that a comprehensive database can be made. Nonspatial data include, for example, confidence of interpretation, movement class, and direction of movement. 7) A comprehensive review, including technical review of mapped landslides and field checks where possible, of spatial (map) and nonspatial attribute data should be developed and implemented.

2.2 SICCM Landslide Map Datasets

Authors Bunn, Leshchinsky, and Olsen at Oregon State University developed and produced the scarp identification [SI] and modified Contour Connection Method [CCM] tool known as SICCM. SICCM uses a set of Python scripts bundled together in an Esri® ArcGIS® toolbox to produce polygons approximating the locations and extents of landslide deposits in an efficient, semi-automatic framework. The output also produces approximated landslide head scarps represented as lines. Levels of automation, or modes, ranging from nearly fully automated to manual provide opportunities for analysis, interpretation, and modification by experienced practitioners. The output quality can vary significantly depending on the level of intervention and the terrain being mapped. SICCM was developed partially as an advancement to the Contour Connection Method (CCM) (Leshchinsky and others, 2015). The theory of Scarp Identification and Contour Connection Method (SICCM) is described in further detail by Bunn and others (2019). The sensitivity of the algorithm to changes in input parameters, and exploring how geology influences the resulting landslide inventory results, and how the results may be used to discern geologic features and trends are also described in detail. The development of SICCM and its relevance to several Oregon transportation networks, as well as discussion of a simple risk methodology for linear infrastructure is described by Leshchinsky and others (2019). CCM was developed to automate landslide deposit identification by quickly scanning large areas within a region and detecting topography suggestive of possible landslides on the basis of morphological features.

2.3 Automated Versus Manual Landslide Mapping Methodologies

Two methods of landslide inventory mapping are 1) manual, or digitizing landslide polygons "by hand" (e.g., SP-42) and 2) automated (e.g., SICCM). This section summarizes a representative sampling of existing landslide mapping methodologies. Creating manual landslide inventories can be a challenging task. Accuracy, time, cost, experience, effort, and scale can affect output. Hence, in recent decades, significant research has been oriented toward improving landslide mapping procedures by using automated workflows.

Schulz (2004) used lidar-derived digital elevation models (DEM) to manually identify landslides in highly vegetated and urban Seattle, Washington. Identification was aided by orthorectified aerial photographs and numerous additional lidar-derivatives, including hillshades of varying sun azimuth, ground slope, and a 2-m contour map. The different forms of data were then evaluated to locate morphological features of interest, including head scarps, hummocky terrain, and convex and concave slopes, from which landslides were identified. The method correctly identified the locations of recorded historic landslides, while also identifying many landslides that had previously gone unnoticed.

In 2009, Burns and Madin published DOGAMI SP-42, a methodology similar to that of Schulz (2004), for manual landslide inventorying, that included a framework for tabular data associated with the mapped features. The supporting data include landslide type, depth, and roughly 20 other attributes. DOGAMI SP-42 is the standard practice followed in Oregon for landslide inventory mapping and has been adopted and/or adapted by other states (Mickelson and others, 2017).

Despite the ability to achieve high-quality results, manual landslide mapping using lidar data is a time-consuming process that requires specialized training. For these reasons, research efforts have aimed to develop computer algorithms that can simulate human interpretation to improve speed and efficiency of the mapping process. Using lidar data from much of the area studied by Schulz (2004) in Seattle, Washington, and additional data for the Tualatin Mountains, near Portland, Oregon, Booth and others (2009) developed an inventorying method for deep landslides based on two-dimensional discrete Fourier transforms and two-dimensional continuous wavelet transforms performed on a lidar DEM. The purpose of both transforms was to determine topographic wavelengths representative of landslide features that could then be extracted from the DEM compared with wavelengths empirically determined to be representative of landslide features.

An alternative automatic mapping method using lidar data was presented by Van den Eeckhaut and others (2012). The area considered consisted of vegetated hills in the Flemish Ardennes of Belgium. Landslides were mapped through the segmentation and classification of a lidar DEM. Segmentation was performed by implementing image binarization algorithms to identify and group cells of similar texture and to locate abrupt changes in terrain. Segmented features were then classified as landslide scarps or bodies based on their ground roughness, slope, plan view curvature, and several other variables.

Leshchinsky and others (2015) introduced the Contour Connection Method (CCM), which uses the shape of topographic features to locate past landslides. The high resolution of most lidar-derived DEMs is typically unnecessary, making CCM less influenced by noise in the scan itself or by defects in the DEM. Alternative DEMs may be compatible (e.g., InSAR, SRTM) where the derived model is representative of bare-earth conditions; however, lower resolutions may inhibit the ability to map smaller features. CCM first identifies landslide scarps based on an upper slope threshold, and then moves downslope until a lower slope threshold is reached. Computational speed is improved by reducing high-resolution DEMs into a mesh of contours with regularly spaced nodes that are connected when acceptable slopes between nodes are achieved. After the algorithm has been implemented, information pertaining to the number of connections to each node and the slope of each connecting line can then be analyzed to reveal distinct signatures for the type of slide that has been mapped.

Although automated results are quick and reduce the subjectivity that can occur when different mappers manually trace landslides, the results are generally approximate and cannot be used for regulatory purposes.

Both manual and automated landslide mapping methods have positive and negative features. Therefore, combining automated and manual methods and optimizing the positive aspects of each is the best path forward at this time. In this report, a practitioner who creates a landslide inventory using the SP-42 method is called a *mapper* and a practitioner who runs the SICCM tool is called a *modeler*.

3.0 PURPOSE

The purpose of this report is to describe the procedure for landslide deposit modeling using the SICCM tool and to test SICCM results by overlaying SICCM-generated landslide scarps and polygons on manually digitized SP-42–style landslide polygons. DOGAMI staff provided feedback on the tool, reviewed the method, and helped produce this report in order to highlight how an automated method like SICCM may supplement an established, manual landslide inventory method like DOGAMI SP-42 to increase efficiency in landslide inventory mapping. The intention is to incorporate an accessible, open-source automated landslide mapping method into the existing DOGAMI landslide hazard map workflow, not replace existing DOGAMI protocols.

SICCM is unique among automated tools because it has been packaged into a simple-to-use, documented tool implemented in commonly available software and the tool has been tested by many modelers in numerous settings. A combined SICCM–SP-42 protocol can accelerate, increase the mapping confidence, and increase consistency for the overall mapping process. As previously stated, SP-42 landslide inventory has only been completed for a small portion of the state. Available funding has impeded the ability to map more of the state. Although SICCM does not influence attribute development and entry—the most time-consuming portion of SP-42—the time savings from SICCM when drawing features can decrease the total time expended and thus decrease cost.

Although this report demonstrates how to incorporate SICCM into the existing SP-42 protocol, the methods presented here do not imply an exclusive endorsement by DOGAMI. DOGAMI may incorporate other automated landslide mapping methods as accessibility increases, technology changes, and more research is performed. No effort was made to review or incorporate any other automated method available into the existing SP-42 landslide inventory method.

Partial financial support came from the Oregon Department of Transportation, research project SPR 786 (ODOT Research Section, Agreement No. 30530), and the U.S. Department of Agriculture, U.S. Forest Service, grant number 17-CS-11015600-008. Leshchinsky and others (2019) provide an overview of development of SICCM and its relevance to several Oregon transportation networks, as well as discussion of a simple risk methodology for linear infrastructure. ODOT is interested in this work because of the cost of and hazard from landslides to the transportation network in Oregon. ODOT is responsible for very long, extensive corridors throughout Oregon, including mountainous and coastal localities with known historical landslide movement. This study area was chosen with the consideration of linear road infrastructure (in this case, Highway 38) through the Coast Range. Landslide inventories within ODOT jurisdiction area help highlight areas with landslide hazard, and are useful for a variety of planning, maintenance, and construction projects.

4.0 METHODS AND TOOL IMPLEMENTATION

The protocol described in this paper was developed to use the SICCM tool in tandem with DOGAMI Special Paper 42. DOGAMI Special Paper 42 was designed to use high-resolution, remotely sensed digital elevation data to map landslides in Oregon.

The Contour Connection Method, developed by Leshchinsky and others (2015), was conceived in order to effectively use newly available remote-sensing datasets, such as lidar, for a known problem: a lack of landslide hazard maps. The primary purpose of development was to save time and effort of manual landslide inventory methods, by analyzing the geomorphological characteristics of the slope considering basic landslide mechanics. Many alternative approaches use machine learning algorithms or statistical analysis techniques. However, Leshchinsky and others (2015) pointed out that many machine learning or statistically based systems are computationally expensive, requiring specialist training for use of other tools or post-processing of data outputs.

CCM uses downslope terrain connectivity as its primary basis, with four adjustable parameters that can react to the topography of a study area. Much of the tool can be run with little or no modeler intervention or input. The tool uses elevation data to create landslide deposit polygons, based on the downslope connection between nodes on contours derived from the elevation data. CCM can be used across a wide variety of terrains, and for a wide variety of landslide types.

Additional work has been done to improve CCM since Leshchinsky and others (2015). A second set of tools has been added into the workflow. The Scarp Identification (SI) method adds head scarp lines as a feature class input in ArcGIS, in order to control the initiation points of the landslide deposit polygons mapped with CCM. This addition results in greater accuracy and precision in detecting landslide deposits, by focusing the CCM tool to run from particular areas identified as head scarps. The SI portion of the tool can be run using almost completely automated default parameters. Alternatively, some SI parameters can be adjusted so that the tool runs in semi-automated mode. A third option is to draw scarps manually for direct input into the CCM part of the tool. SICCM is described in further detail by Bunn and others (2019).

4.1 Overview

The fully automated, semi-automated, and manual landslide scarp identification (SI) modes described in this report work with a modification of the CCM developed by Leshchinsky and others (2015). The new approach, SICCM, uses scarp lines rather than user-defined slopes as input at the initiation of CCM. As a result, the new approach has two steps: 1) identifying scarp lines (SI), both head scarps and internal scarps, and 2) running CCM to map landslide deposit polygons downhill of each scarp line. The choice of mode is dictated by the desired results, the existence of nearby manual landslide inventories, and available time. As a reminder, text in the following sections refers to a person using the SICCM tool and method as the *modeler*, and a person with expertise in landslide identification and the capability of landslide deposit determination as the *mapper*.

Modelers using SICCM should have a basic, working knowledge of GIS software and methods as well as an understanding of the fundamental aspects of geomorphological processes and landslide mechanics. This protocol also includes a description of the limitations of the output data obtained when following this method and a description of the workflow into the SP-42 landslide inventory procedure. Following this method results in a range of end products from a completely automatic generated dataset of SICCM mapped landslide topography to a file set of individually mapped landslides ready for SP-42 mapping. The modeler will need to decide which of the end products are appropriate for the area of interest and level of effort allocated.

The automation levels (**Table 1**) allow for a range of end products. At the lower effort, lesser accuracy end, are fully automated results. These results use the default settings of both the scarp identification (SI) portion and CCM. At the mid-range effort, and the recommended automation level, are semi-automated scarp identification results. Semi-automated results involve short, focused points of human interpretation throughout the fully automated procedure. At the highest effort, with the greatest accuracy, manually digitized head scarps are input to the CCM tool with the same adjusted parameters as the semi-automatic Scarp Identification Procedure input.

In remote areas where details about specific landslides may not be needed for a project and/or when time is very limited (for example, if a DEM were collected after an earthquake or a large storm event with an impending emergency situation), the fully automated method may be selected. For more conventional landslide mapping to be used in planning or risk assessments, semi-automatic or manual mode input to the CCM tool is suggested.

Table 1. Summary of Scarp Identification and Contour Connection Method (SICCM) model automation levels. Also see Table 5.

	SICCM Scarp Identification Automation Level		
	Fully Automated	**Semi-Automated**	**Manual**
Effort (time/resources) required	some (< 2 days)	more (< 1 week)	most (1-2 weeks)
Accuracy	least	better	best
Modifications based on modeler's judgement and additional data sources allowed?	no	yes (optional)	skip directly to CCM after manually digitizing scarps
Expertise level	novice/experienced practitioners	experienced landslide modelers	experienced landslide mappers
End products useful for…	quick, overview results	polygons editable to create landslide inventory	allows drawings of internal scarps, which improves performance on large, hummocky landslides
SICCM not appropriate for: falls, topples, spreads, and debris flows, or areas without a base map with resolution enough to identify scarps visually.	Results from all modes, with review and revision from a licensed geologist, appropriate for: • assisting in the manual landslide polygon mapping process • to support broad planning efforts that do not relate to zoning, development, or other authoritative decisions, such as understanding the relative scale of landslide hazards in a region • to provide data layers for teaching or research purposes		

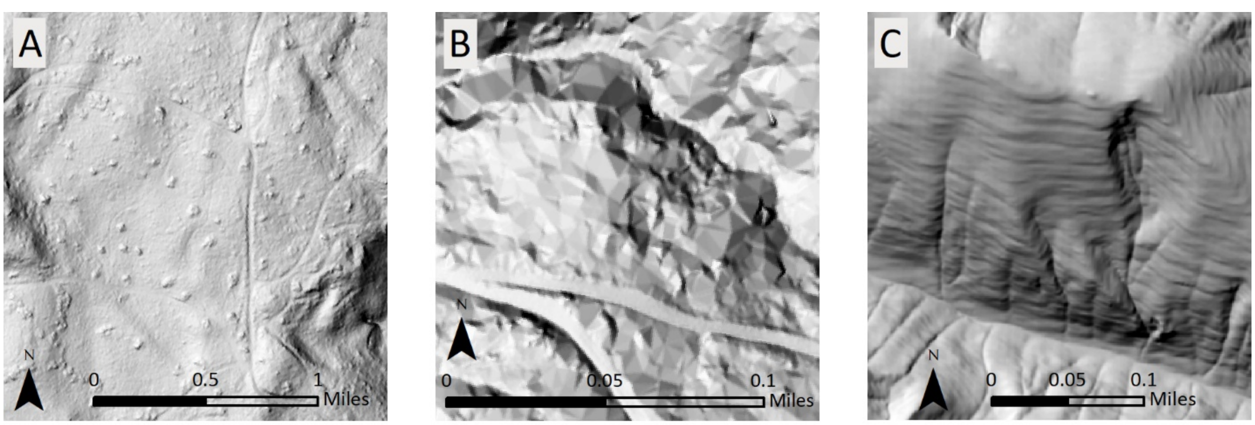
4.1.1 Landslide types not modeled by SICCM

Because SICCM identifies landslides on the basis of scarplike morphological features, the SICCM method requires a defined head scarp connected to, or in the immediate vicinity of, a landslide deposit. The SICCM method is intended to capture both rotational and translational landslides, and certain flow types, such as earth flows. Landslide types not modeled by the SICCM method include falls, topples, spreads, and debris flows, using the nomenclature of Cruden and Varnes (1996). The unifying features that exclude these movement types from identification by the model is the 1) lack of convex-up head scarp area, and 2) disconnection between the landslide initiation region (zone of rupture) and transported landslide debris portion downslope.

4.2 Base Data Selection and Preparation

Landslide mapping approaches presented in this report begin with a lidar DEM, but the DEM may be derived from other remotely sensed data. No DEM is automatically disqualified from being mapped using SICCM methodology, but the resolution and quality directly influence the size of landslide that can be mapped. The modeler must first look at a hillshade or other DEM-derived layer of their choice, such as a slope shade, and decide if landslides are visible. If landslides are not visible to the modeler, then it is also likely that the landslides are not likely to be identified by SICCM, but if the modeler can see landslides, the focus shifts to how confident the modeler is about the landslides. Confidence is commonly dictated by the quality of the DEM. Quality represents the uncertainty in the DEM caused by noise or artifacts caused by limitations in data or spatial interpolation. Noise may be the result of random error in sensor readings, limitations in reliably capturing the ground surface in dense vegetation, or errors in processing, such as inconsistent vegetation removal from lidar data. In general, with lidar imagery, noise is important only at small scales (less than 30-ft DEM cell size), where it can be difficult to distinguish between low vegetation and the ground surface, which are often aggregated into a single return. Spatial interpolation, such as the generation of a triangular irregular network (TIN) with lidar or commonly available contour-derived surfaces (**Figure 2**), can also produce unnatural planar artifacts in areas with sparse data resulting from heavy canopy coverage, other obstructions, or insufficient overlap between flight lines. Although these forms of noise may be present at the DEM's native resolution, it is assumed that when reduced to a working resolution, the noise will be muted. Nonetheless, if the scarp features exist at the same scale as the noise, then the working resolution will mute those features as well, meaning that there is a minimum size of landslides that may be mapped. Although it is important to understand this limitation, mapping at the DEM's native resolution will produce excess scarp lines and significant overprediction of deposit polygons.

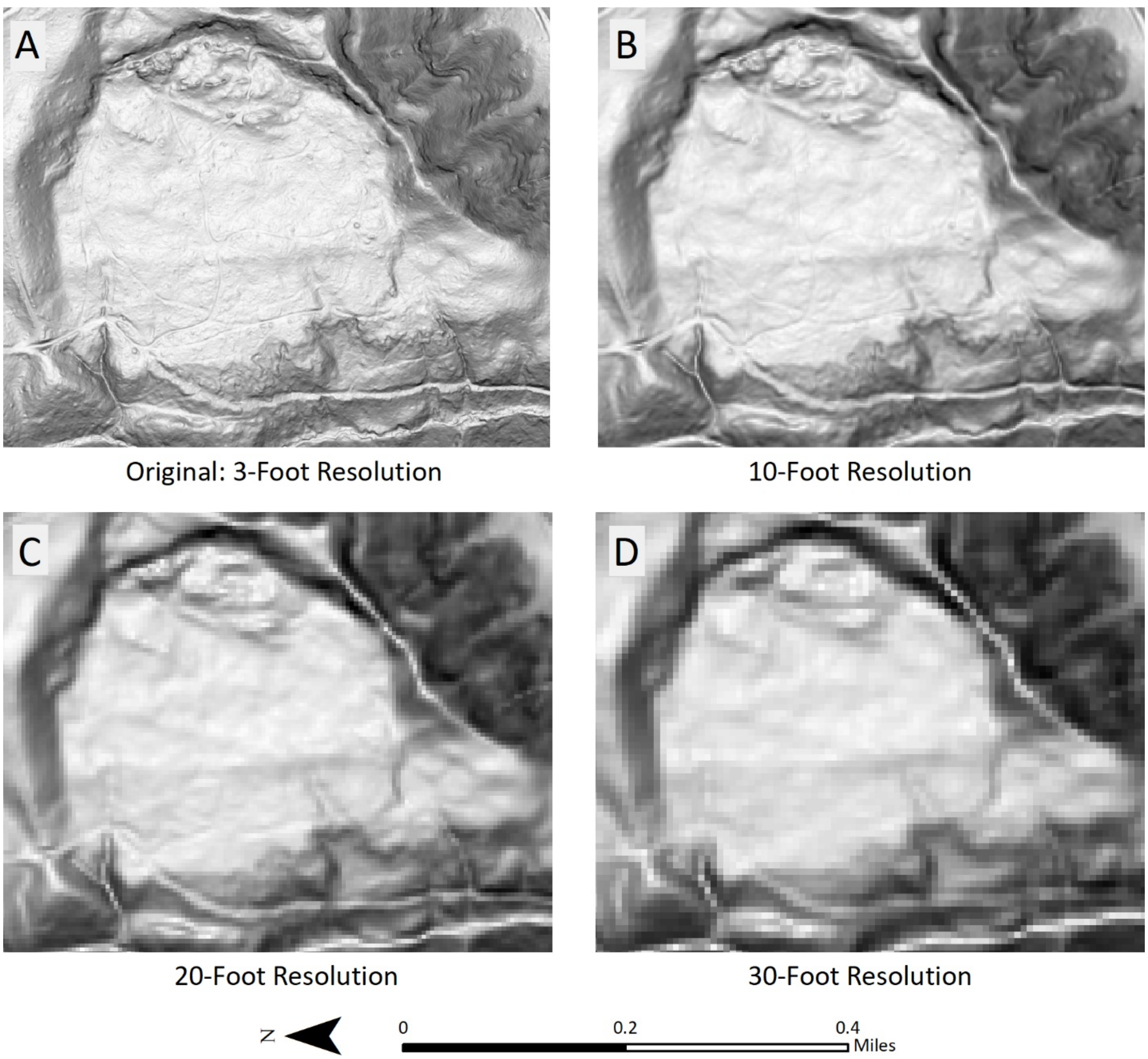
Figure 2. Examples of noise commonly present in lidar DEMs including (A) vegetation artifacts, (B) TIN interpolation artifacts, and (C) artifacts from spatial interpolation of contours. The scale at which noise exists can vary significantly depending on how a DEM was produced as well as properties of the source data.



In the SICCM workflow, selection of a working resolution is a qualitative endeavor. Testing has shown that resampling of 3-ft native resolution DEMs to a 20-ft working resolution can be reasonably effective.

Modelers and mappers interested in optimizing the working resolution for a specific dataset should resample their DEM to several different resolutions and compute slope from each resampled DEM. The optimal resolution is the smallest raster cell size that eliminates unwanted artifacts and anthropogenic features (e.g. roads and building foundations). This process is illustrated in **Figure 3**, where an originally 3-ft resolution DEM was resampled to 10-, 20-, and 30-ft resolutions using bilinear interpolation. Notice how artifacts are still present in the 10-ft hillshade, but not in the 20- and 30-ft hillshades. The 20-ft DEM is better for landslide mapping than is the 30-ft DEM because the 20-ft DEM has eliminated most of the artifacts while sacrificing less detail of the original DEM. In the SICCM Toolbox, Tool 3 provides an optional modification step to help review and resample the DEM resolution.

Figure 3. Hillshades computed from a lidar DEM of the Lutsinger Creek watershed and three resampled DEMs. The 20-ft resolution DEM is considered optimal because it eliminates artifacts (e.g., roads crossing the landslide, tree stumps, planar facets, etc.) while retaining much of the original detail in the DEM.



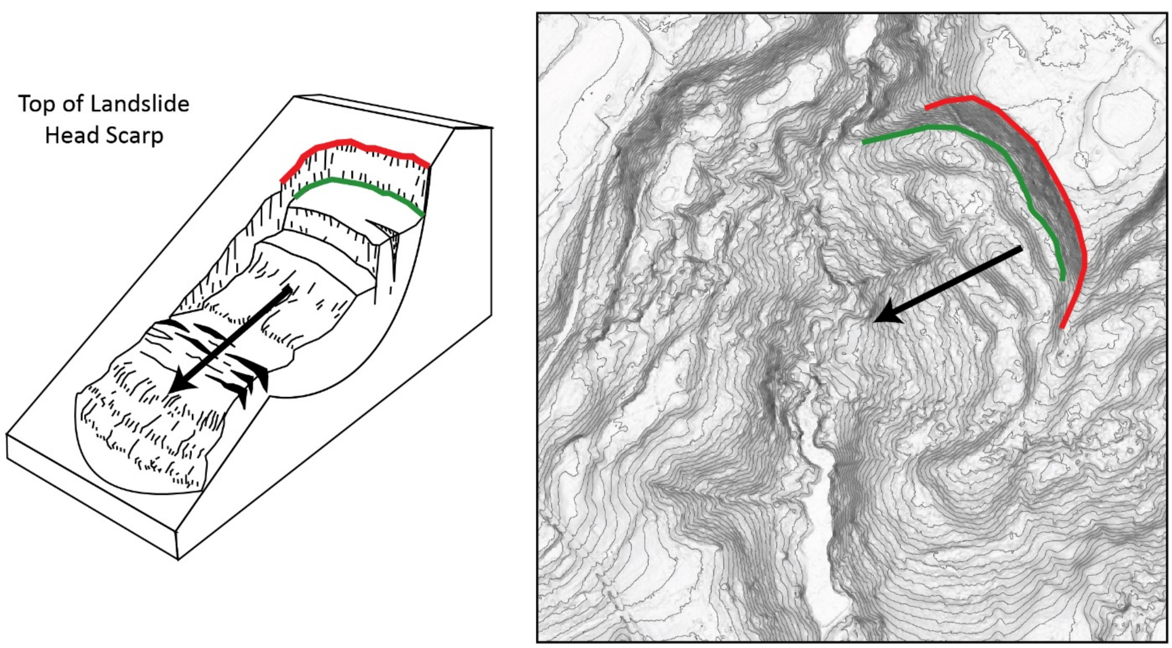
Although the 20-ft resolution works well for the example in **Figure 3** and serves as an excellent starting point for all lidar-derived DEMs prepared to OLC standards, mappers and modelers should understand that landslide scarps exist at all scales. If scarps at many scales are important to the work being performed, it is recommended that the SI procedure be completed at multiple resolutions and that all resulting scarp lines be merged before running CCM.

4.3 Modeling Scarps Using the Scarp Identification (SI) Procedure

A landslide scarp is the location of vertical displacement that marks the uppermost boundary of a landslide's extent. At the base of the ideal scarp, a hummock exists where displaced material has come to rest. Where the scarp and the hummock meet, there is a topographic trough where the terrain briefly curves upward. This trough may be well defined in low-gradient landslides with deposits present or may be subdued in high-gradient landslides where deposits have evacuated downslope. In the SICCM methodology, scarp lines may be defined as either the crest of the scarp or the upward curving trough (**Figure 4**).

This section discusses three modes for the scarp identification (SI) portion of SICCM: 1) manual (or expert), 2) semi-automated, and 3) fully automated. The first mode, manual mapping, is considered the most accurate yet most time-consuming approach. The semi-automated modeling requires less time than does the manual mode and, in some cases, less experience from the modeler or mapper, but allows for some modification. The fully automated mode runs with very little intervention by the modeler. The semi-automated and fully automated SI modes are discussed together in this paper because the fully automated mode is the same as the semi-automated mode if the modeler makes no optional modifications.

Figure 4. Acceptable locations for scarp lines used as input to CCM. SI fully automated or semi-automated mode scarp line locations are shown in green, while SP-42 scarp line locations are shown in red. SI manual mode scarp lines may be drawn in either location.



4.3.1 Manual scarp identification mode in SI

In manual mode, a mapper hand digitizes scarp lines on a native-resolution DEM, then begins using the SICCM Toolbox at Tool 11, bypassing much of the automated scarp identification process, and proceeding to CCM. The manual scarp identification method is the most time consuming of the three modes and may take almost as much time as drawing a polygon around the entire landslide deposit. However, it does result in the best CCM output dataset. The modeler will need to evaluate these advantages and disadvantages before deciding on which scarp line mode is the best for the situation.

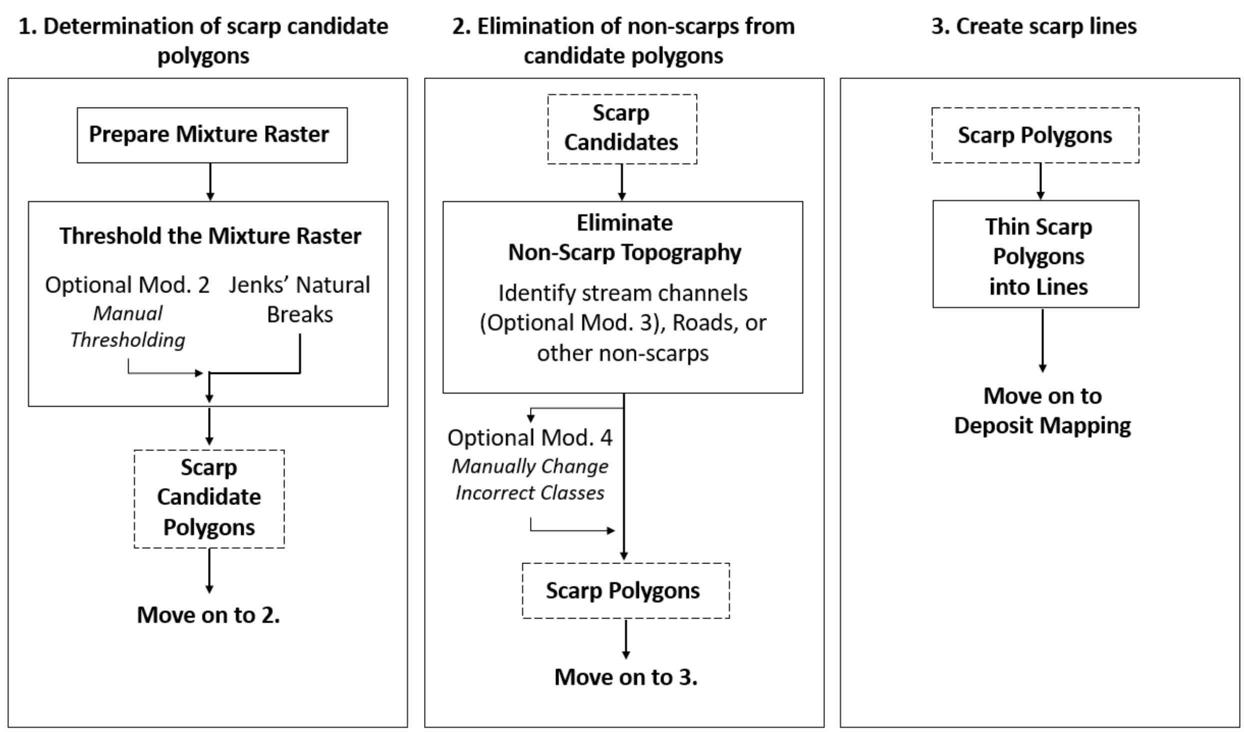
If using manual mode, a mapper has the choice of where to draw head scarp lines. As shown in **Figure 4**, there are two appropriate locations to draw scarp lines relative to scarp flanks. The first location is at scarp crests as described in the SP-42 protocol (red line in **Figure 4**); scarp crests may include only head scarps or both head scarps and internal scarps. The second location is at the upward curving portion of the trough for both head scarps and internal scarps (green line in **Figure 4**), which produces the most similar results to the semi-automated approaches.

The first approach has the benefit of producing CCM results that include scarp flanks, and it may lead to improved performance in places where large depressions at the bases of scarps flanks prevent CCM from effectively moving downslope. The second approach simulates the placement of semi-automatically detected scarps, which is good for comparison, and generally leads to less landslide overprediction. In either approach, choosing to draw internal scarps, located within the landslide body, improves performance on large, hummocky landslides, where shallow slopes and closed basins may prevent the downslope movement of the CCM algorithm.

4.3.2 Fully automated and semi-automated scarp identification in SI

The fully automated and semi-automated scarp identification modes each require three steps: 1) determining scarp candidate polygons by segmenting the DEM, 2) eliminating non-scarp from scarp candidate polygons by classifying polygons, and 3) forming scarp line features from polygons classified as scarps (**Figure 5**; also see the full-page SICCM process guide on p. **52**). Strategically placed within these three steps are several points at which an experienced modeler may choose to manually influence the process. These points are called optional modifications. Each optional modification is meant as a brief stopping point (minutes to hours commonly) when the modeler or mapper may review the entire study area and make minor changes to numerical thresholds or the size of objects being mapped before moving to the next process. If the modeler chooses not to influence the results during the SI process, the SI method is "fully automated." If the modeler makes changes, the method is "semi-automated."

Figure 5. Overview of fully automated and semi-automated mode scarp line modeling procedure. Locations of optional modifications are labeled where a semi-automated approach is preferred for higher-quality results.



4.3.2.1 Scarp candidate polygon determination

4.3.2.1.1 Concavity-convexity mixture raster preparation

The first group of tasks illustrated in **Figure 5** comprises the determination of scarp candidate polygons. The first purpose of the process is to create the mixture raster. The mixture raster multiplies two DEM derivatives, slope (in degrees) and profile curvature, which results in cell values that represent the terrain's concavity or convexity, scaled by local slope. It exaggerates crests (convex topographical features) and troughs (concave topographical features).

4.3.2.1.2 Mixture concavity threshold setting

Once the mixture raster is created, the natural breaks (Jenks) classification method is used to assign each mixture raster pixel into one of three classes (**Figure 6**, top). There is no physical basis why the natural breaks classification is effective for this task, but this classification has consistently broken the mixture raster in appropriate places and is therefore considered useful. This performance is likely related to the commonly normal distribution of mixture raster values and the fact that the mixture threshold is not a very sensitive number. The class with the lowest valued pixels (e.g., Class 1 in **Figure 6**, top) represents areas of convexity in the terrain, which include scarp crests and ridgelines. The class with the highest valued pixels (e.g., Class 3 in **Figure 6**, top) represents areas of concavity in the terrain, which include troughs and stream channels. Pixels in the middle class tend to be flat with little curvature. The mixture threshold is the break between the class with the highest valued pixels and the other two classes.

Separating scarp crests from ridgelines is challenging due to their topographic similarities (**Figure 6**, bottom). Failure to separate scarps from ridgelines results in significant landslide overprediction. Because of this challenge, in the fully automated and semi-automated modes, scarp *troughs* are mapped instead. The values that represent scarp troughs in the mixture raster are found in the class with the highest valued pixels. Pixels within the highest-valued class, individual or clustered together, are then converted into polygons, called scarp candidate polygons. Each scarp candidate polygon represents an area that may be a scarp trough or a non-scarp, such as streams, roads, or other topography with concavity, as displayed in **Figure 6**, bottom. Separating scarp trough polygons from non-scarp trough polygons is discussed in Section **4.3.2.2**.

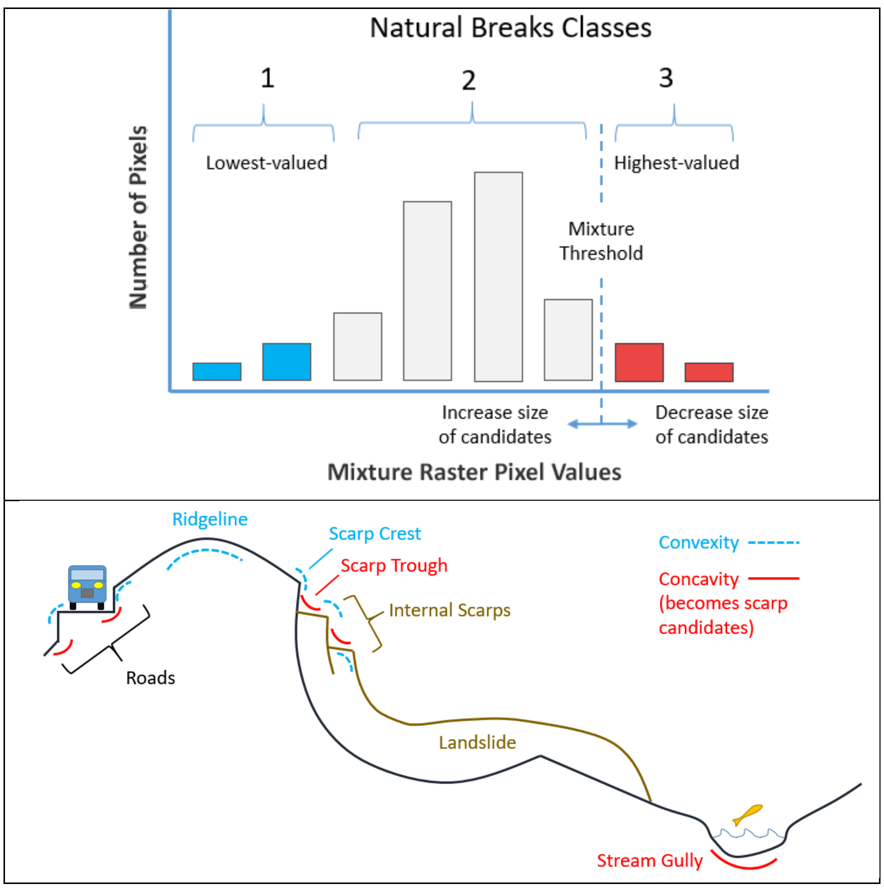


Figure 6. Relationship of mixture raster and mixture threshold to terrain features.

(top) Natural breaks (Jenks) histogram showing classes and mixture threshold point. The class with the highest valued pixels (Class 3, red) represents areas of concavity in the terrain, which include troughs and stream channels.

(bottom) Schematic illustrating concavity and convexity of different features in the terrain.

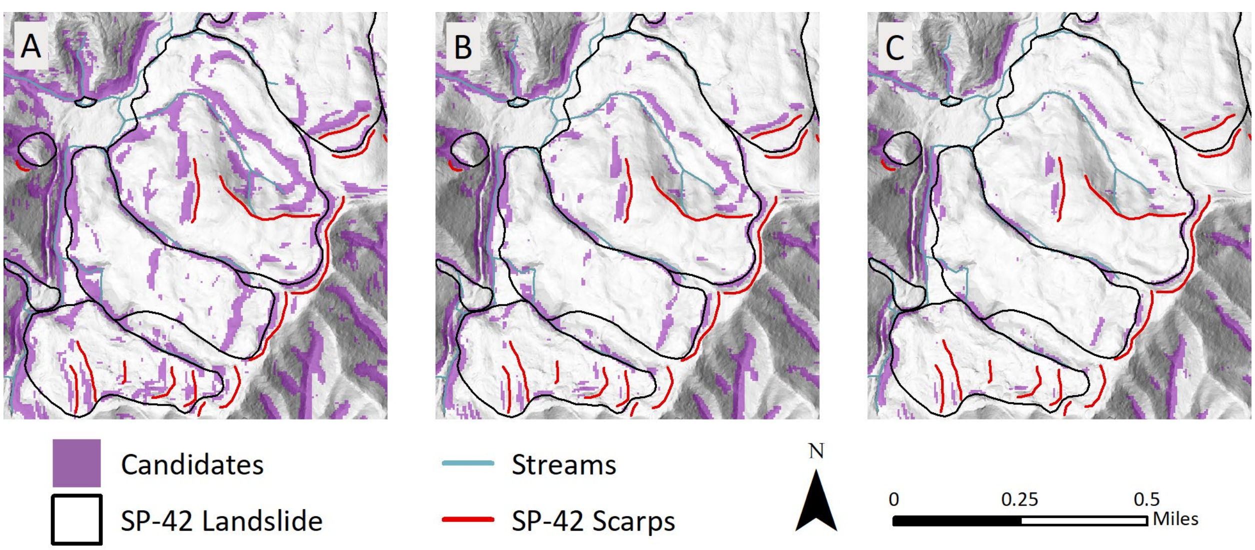
4.3.2.1.3 Optional Modification 2 – Adjust mixture threshold

Procedurally, thresholding should begin at the default mixture threshold defined by natural breaks. Although the default natural breaks classification is effective at identifying the mixture threshold, manual adjustments to the threshold value commonly lead to improved results. These adjustments include increasing or decreasing the threshold that divides the classes. Increasing the threshold decreases the size of candidate polygons and may eliminate some candidate polygons. Decreasing the threshold increases the size of candidate polygons; however, this may connect potential scarp polygons to non-scarp polygons. If these features become connected, results of the later classification step may worsen. There will never be a perfect value of the mixture threshold—if modifying the mixture threshold, the modeler must qualitatively identify which value might be best.

To determine how to adjust the threshold, the modeler should review candidate polygons overlain on the DEM. The modeler should have significant experience digitally mapping landslides, because the adjustments to the threshold are based on a visual review of the initial output of candidate scarp lines. If there are many candidate polygons that do not correspond to actual scarp lines, increase the threshold. If there are actual scarp lines missing or excluded from candidates, decrease the threshold.

Proper modification requires that the modeler understand the appearance of candidates and how the appearance is influenced by the threshold. **Figure 7** shows an example of what to look for during manual thresholding of the mixture raster. Good scarp lines rely on simple, continuous candidate polygons that are not over-connected. Over-connected polygons may link or conjoin scarp and non-scarp polygons together, which will result in the whole polygon being misclassified in a later step.

Figure 7. Three examples of mixture thresholds, using 20-foot cell size, and their effect on candidate scarp polygon formation (purple areas). SP-42 scarp lines (red) are shown for comparison. A) mixture threshold is too low, B) mixture threshold is appropriate, and C) threshold is too high. A hillshade raster underlies the polygons to aid in visualization.



4.3.2.2 Elimination of non-scarps from candidate polygons

Once candidate polygons have been produced, the task is to identify which polygons are scarp troughs. For this step, the modeler may choose to eliminate non-scarp features through a series of optional automated processes. Modelers who perform these tasks should have experience mapping landslide features, as interpretation is fundamental to obtaining good results. The outcome is that all candidates are assigned a label of scarp or non-scarp.

Scarp troughs, roads, and streams all have topography that causes them to be mapped as candidates (**Figure 6**, bottom). If most non-scarp trough topography is associated with streams or roads, then it is possible to eliminate these features using digitized road or stream layers. Modelers may also create their own stream layers using GIS flow accumulation models and a DEM of interest (4.3.2.2.1). Candidate polygons that intersect road or streamlines may simply be assigned a label of non-scarp.

4.3.2.2.1 Optional Modification 3 — Digitize stream channels

Through the SICCM Toolbox, it is possible to create a digital stream network to help classify candidate polygons. Relevant tools from the ArcGIS® Hydrology toolset have been grouped together into a single tool governed by the minimum accumulation area needed to define the starts of streams. By varying the accumulation area for streams, the modeler can determine the most effective digital stream network for correctly labeling candidates as scarp or non-scarp.

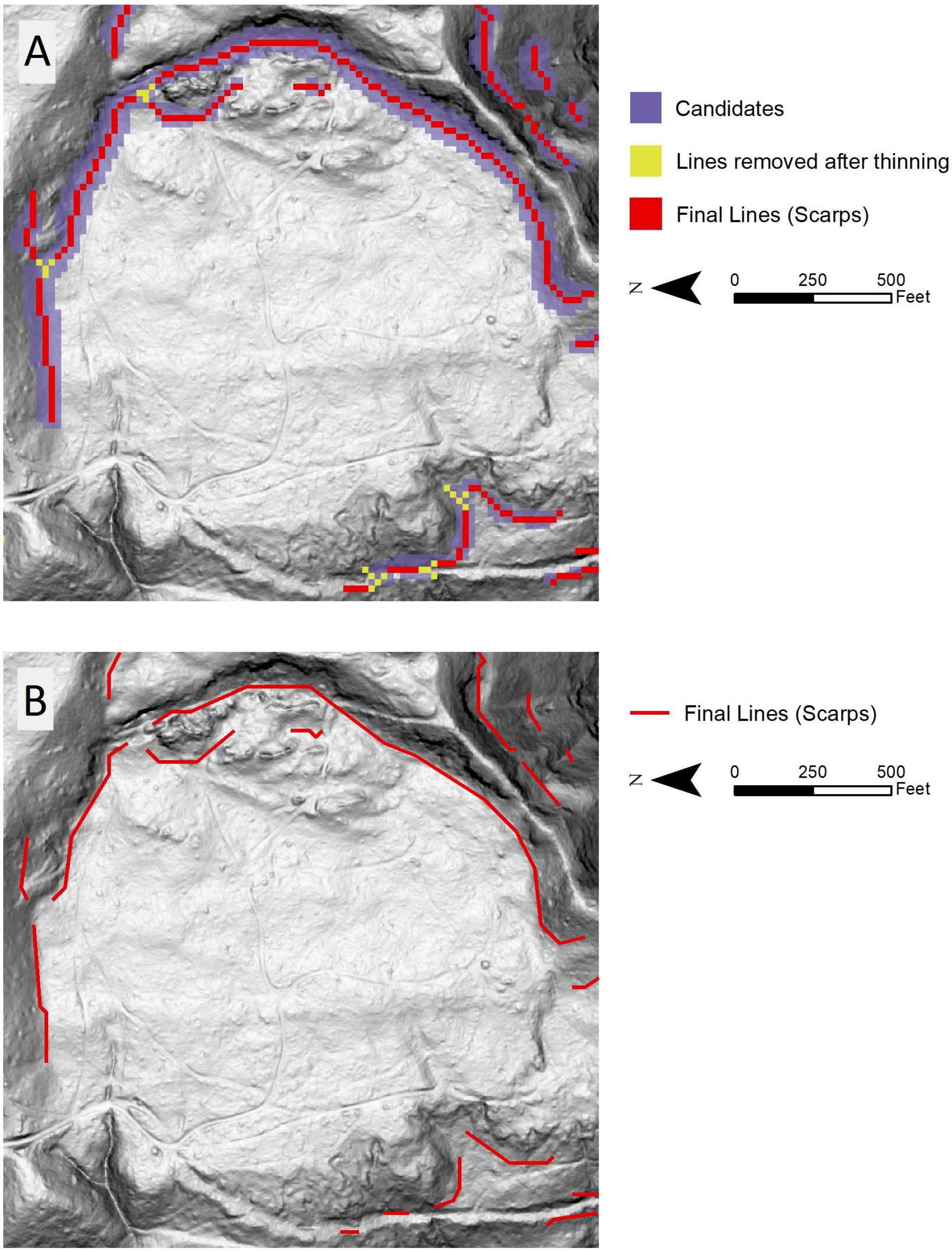
4.3.2.2.2 Optional Modification 4 — Reclassify scarp polygon candidates

After road and streamline intersections have been used to label candidates, the modeler may manually change the labeling of individual polygons. Because the labels—but not the spatial extents of the shapes—are changed, the process is limited to a simple binary decision by the modeler: landslide or not landslide.

4.3.2.3 Scarp line creation

After candidate polygons have been classified, the polygons identified as scarps are automatically thinned into a scarp line raster (**Figure 8**) and converted into polylines. Thinning is performed by removing outside pixels until a single line remains. Following thinning, the scarp polylines are attributed with elevations from the resampled DEM and are ready for input into CCM (see Section **4.4**). Thinning is performed to provide a vector input for the vector-based creation of connections.

Figure 8. Illustration of the thinning process from (A) rasterized polygon candidates to (B) final vectorized polylines. Purple candidate pixels are thinned into the red scarp lines during the thinning process. Yellow lines are removed in Tool 10 to prevent intersecting scarp lines. Process is displayed over a 3-foot cell size hillshade raster.



4.4 Modeling Landslide Deposits Using the Contour Connection Method (CCM)

4.4.1 Overview of the Contour Connection Method in SICCM

In the SICCM workflow, landslide deposits are modeled using an adaptation of the CCM algorithm (Leshchinsky and others, 2015). Required inputs include the scarp lines identified in Section **4.3** and the four CCM parameters listed in **Table 2**. Each CCM parameter has a physical meaning (**Figure 9**) and a role in dictating the shape of landslide deposits modeled by CCM.

Table 2. Definitions of the four CCM parameters used by the modified Contour Connection Method. Notation follows that of Leshchinsky and others (2015). Recommended values only apply to lidar-derived DEMs.

Parameter	Name	Definition	Recommended Values
Δactive	Active slope	Minimum gradient for active slide region	0.03, 0.05 (rise/run)
ΔEz	Contour interval	A fixed vertical distance between X-Y contour layers for a given range Z	10, 20, 30 feet
Ln	Nodal spacing	A fixed length between contour node assignments	10, 20, 30 feet
Bn	Branching parameter	A branching connection parameter	3, 5

The steps taken by CCM are as follows, and the outputs are illustrated in **Figure 10**.

1. A DEM is input in a raster format (Esri grid or TIFF). If the fully automated or semi-automated SI mode was used, use the DEM resampled to the working resolution, as it will minimize ill effects from noise. If scarps were drawn manually, use of the DEM in its native resolution is acceptable. The effect of noise on CCM is considerably smaller than on SI, and the difference between results using either DEM should be difficult, or even impossible, to notice.
2. A collection of scarp lines is input as polyline features.
3. Based on the dimensions of each individual scarp line, the algorithm draws a region of interest.
4. The DEM is clipped to the region of interest in order to reduce the amount of area analyzed for computational efficiency.
5. Elevation contours are generated at the modeler-specified contour interval.
6. Nodes are placed at the modeler-defined nodal spacing along each contour.
7. Nodes are connected to nodes on the adjacent downslope contour. The number of connections must be less than, or equal to, the modeler-specified branching parameter, and node connections may only be drawn if the slope exceeds the modeler-specified active slope. Consider that *n* represents the value of the branching parameter. If more than *n* connections exceed the active slope, then only the *n* connections having the steepest slopes are retained as part of a landslide deposit.
8. A polygon is drawn around the edges of the connected nodes. This polygon represents the possible extents of a landslide.

Figure 9. Visual representation of the four parameters used by the modified Contour Connection Method.

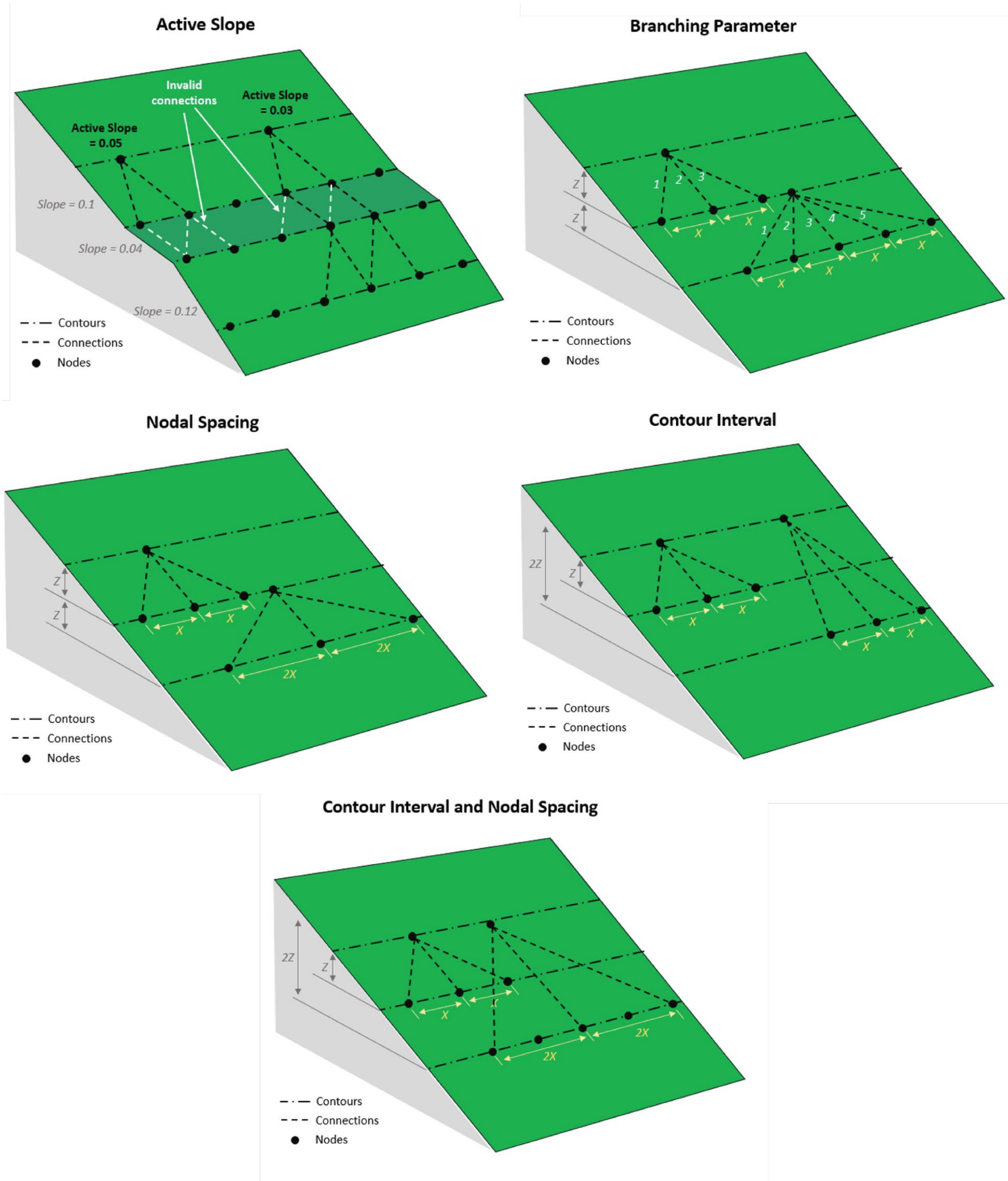
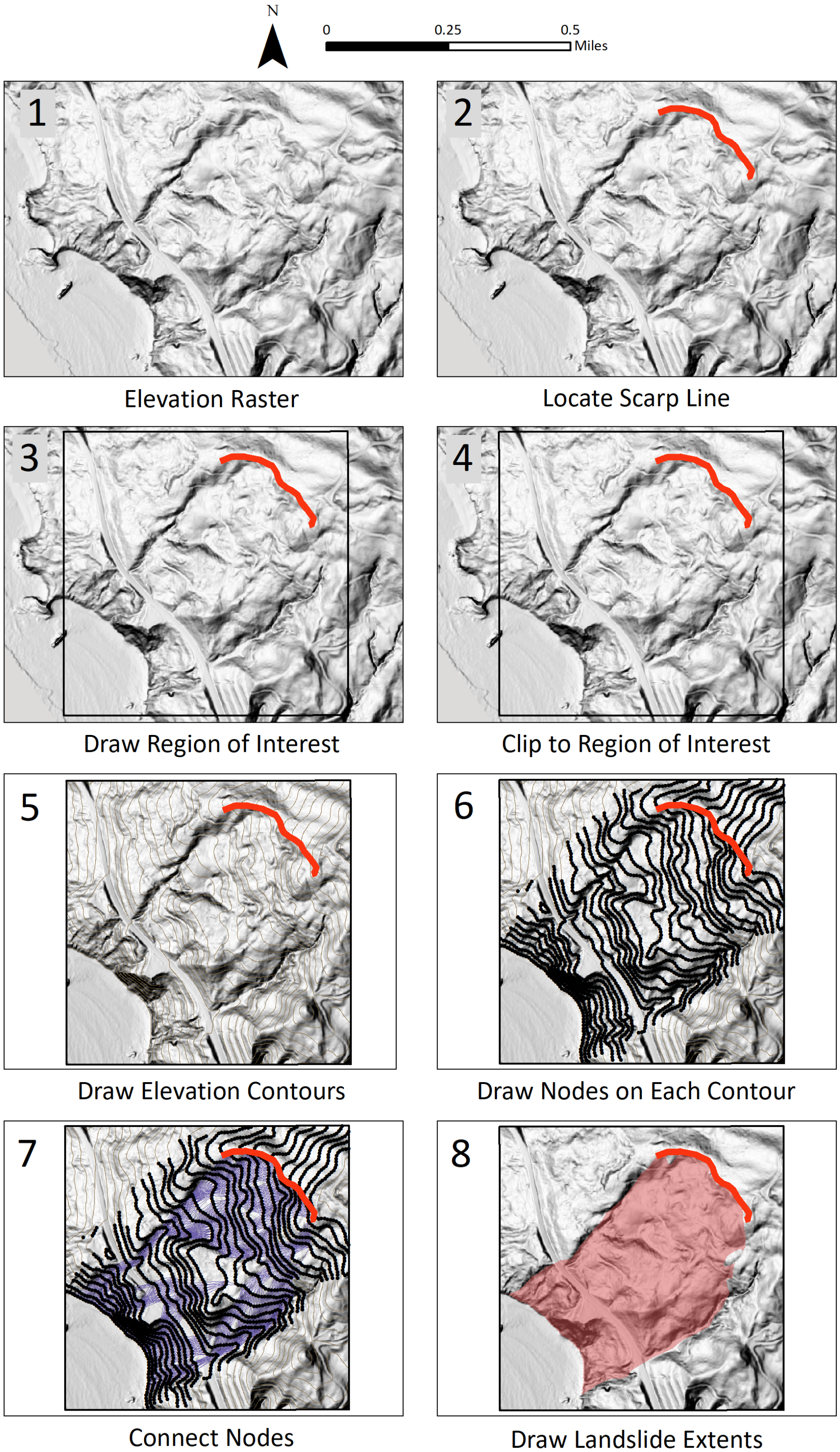


Figure 10. Operations of the modified Contour Connection Method. Process is displayed over a 3-ft cell size hillshade raster.



1. A DEM is input in a raster format (Esri grid or TIFF). To minimize ill effects from noise, it is recommended that the DEM has been resampled to the working resolution first.
2. A collection of scarp lines is input as a polyline shapefile.
3. Based on the dimensions of each individual scarp line, the algorithm draws a region of interest.
4. The DEM is clipped to the region of interest in order to reduce the amount of area analyzed for computational efficiency.
5. Elevation contours are generated at the modeler-specified contour interval.
6. Nodes are placed at the modeler-defined nodal spacing along each contour.
7. Nodes are connected to nodes on the adjacent downslope contour. The number of connections must be less than or equal to the modeler-specified branching parameter. Connections are drawn only if their slope exceeds the modeler-specified active slope.
8. A polygon is drawn around the edges of the connected nodes. This polygon represents the possible extents of a landslide.

CCM should first be run using the recommended (default) parameters (**Table 2**). The recommended CCM parameters are not perfect for all landslides but perform well on terrain with a variety of landslide types (e.g., the Oregon Coast Range). **Figure 9** provides guidance on how each CCM parameter affects the shape of landslide deposits that are modeled. After careful review of the results obtained with the recommended parameter values, experienced modelers can modify parameters in a trial and error approach to find the optimal parameters for the area of interest. Manually selecting appropriate CCM parameters requires understanding the relative influence of each CCM parameter. **Figure 11** shows examples of the effect of changing each CCM parameter from its default value.

4.4.2 CCM parameter: active slope

Active slope controls the termination of the contour connection process. The parameter is necessary to ensure that contour connections move downslope and that they do not traverse slopes adjacent to the landslides. However, setting the active slope parameter value too high may severely limit the ability to model a polygon. Landslides occurring in steep terrain will be better modeled using large active slopes, while landslides occurring in gradual terrain will be better modeled with small active slopes. In selecting an active slope, the modeler will want to choose a value that is steep enough to prevent connections from traversing hillslopes or crossing flat terrain, but shallow enough to allow connections to form over and around landslide hummocks (**Figure 9**). In **Figure 11**A, right image, the active slope was too steep, which resulted in the landslide on the right not being modeled to the full extent.

4.4.3 CCM parameter: branching parameter

The CCM branching parameter controls the number of connections that may originate at a given node. This functionality helps, along with nodal spacing, to dictate the extent to which deposits spread out as the process moves downslope (**Figure 9**). Larger branching parameters may be good for cases where the landslides being modeled are broad, low sloping, or hummocky, where connections need to flow around objects. Use of too large of a branching parameter can lead to overpredicted landslide regions (i.e., ridgelines such as shown in the center of **Figure 11**B, right image) as well as major increases in computation time. Recommended branching parameter values are between 2 and 5.

4.4.4 CCM parameter: nodal spacing

Nodal spacing is the distance between adjacent nodes on the same contour. Greater nodal spacing (**Figure 9**) will typically cause the shape of deposits to spread out and has a significant influence on the distance used to compute connection slope. As nodal spacing increases, there is an increase in the slope distance and no change in the slope rise. That is, with larger nodal spacing, the nodes placed on a given contour are farther from nodes on the next contour level, subsequently decreasing the calculated slope for connections. Small nodal spacing increases computation times as more connections must be made, but better discretizes the surface topography. Increasing nodal density (decreasing nodal spacing) has a result is similar to increasing the branching parameter but at the same time reducing computation time. In **Figure 11**C, increasing the nodal spacing has caused the deposits to spread out and cover more area; many holes caused by topographic obstacles have been filled in.

4.4.5 CCM parameter: Contour interval

Contour interval controls the downslope resolution of the contour connection procedure. Increasing the contour interval without changing nodal spacing tends to produce longer, thinner landslide deposits (**Figure 9**). Larger contour intervals can be useful for overcoming topographic obstacles that cause early termination, without producing major changes to results obtained using the recommended parameters. This behavior is illustrated in **Figure 11**D, which shows that using a greater contour interval results in filling many of the gaps left at lower contour interval. The figure also shows that connections are longer, and that network of connections is less dense.

4.4.6 Combined contour interval and node spacing

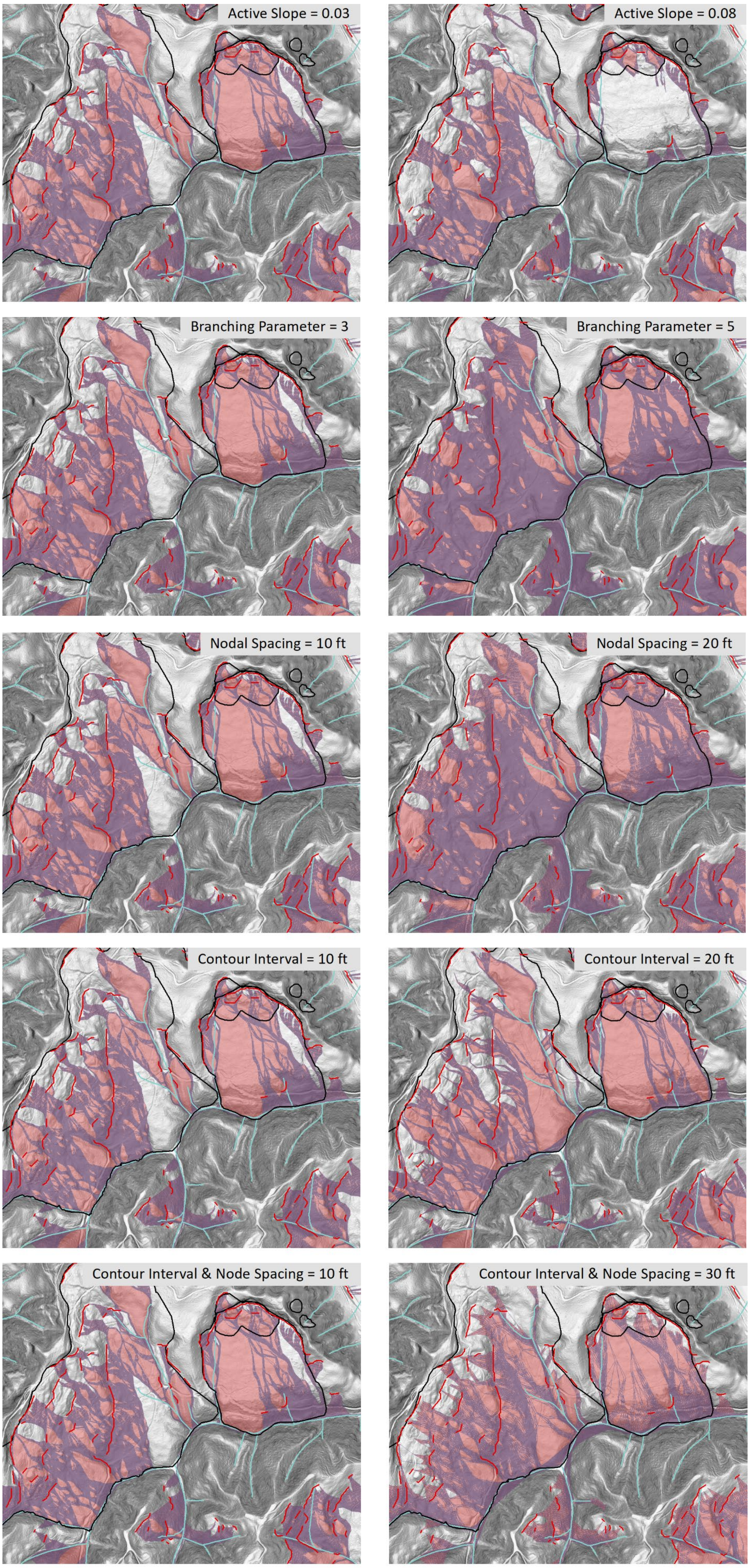
Increasing nodal spacing and contour interval together increases the scale of CCM outputs (**Figure 9**) and reduces the influence of the roughness of large hummocks that might prevent the algorithm from continuing down the slope. The results are generally similar to those obtained using the recommended parameters (**Figure 11**E) and can be used in situations where the modeler is limited by time, although there are downsides. The first downside of using higher contour interval and higher nodal spacing, and the main observation from **Figure 11**E, is that the network of connections becomes coarser, meaning that rounder landslide deposit features will become more angular. This change may result in outputs with less natural appearance. The second downside is that smaller landslides will be missed as nodes and connections are placed farther apart. **Table 3** provides the computation time and disk space used by each modified CCM trial in **Figure 11** and may be useful for deciding on contour interval and node spacing values. Although computing speed will vary among modelers depending on available hardware, the time presented in **Table 3** represents an accurate relative measure of the time cost behind each CCM parameter choice.

Table 3. Computation times for various modified Contour Connection Method parameter combinations. The area modeled was approximately 10 square kilometers with 120 input scarps and a DEM having 20-foot cell size. Computations were completed on an Intel Xeon 2400 MHz processer with 4 cores and 24 gigabytes of RAM. Performance will vary depending on the actual configuration used.

Report Figure	Active Slope	Branching Parameter	Nodal Spacing	Contour Interval	Computation Time (min:sec)	Memory (MB)
11A Left	0. 03	3	10	10	3:20	80
11B, Right	0. 03	5	10	10	10:10	290
11A, Right	0. 08	3	10	10	2:20	63
11C, Right	0. 03	3	20	10	2:20	47
11D, Right	0. 03	3	10	20	1:00	38
11E, Right	0. 03	3	30	30	0:40	18

Figure 11. Graphical effects of varying the four parameters used by the modified Contour Connection Method (CCM). Left column shows the same image, computed using the minimal recommended (default) CCM parameters: active slope of 0.03, branching parameter of 3, contour interval of 10 feet, and nodal spacing of 10 feet. Landslide extents predicted by the CCM algorithm are shown as slightly transparent red, and CCM connections are shown as purple lines (overlapping CCM extents and connections appear purple). Red lines indicate input scarps, and black lines represent manually digitized SP-42 deposit polygon extents; all results are visualized over a hillshade computed from the raw 3-foot DEM. Right images show the effects of modifying CCM parameters.

(left) **Result using recommended (default) parameters** (right) **Result using manually selected parameters**



A. **Effect of varying the active slope**. Active slope controls the termination of the contour connection process. The right image was modeled using an active slope of 0.08 instead of the default of 0.03. In the right image, the active slope was set too high, which resulted in the landslide on the right not being modeled to the full extent.

B. **Effect of varying the branching parameter.** The branching parameter controls the number of connections that may originate at a given node. The right image was modeled using a branching parameter of 5 instead of the default of 3. A branching parameter value that is set too high can lead to overpredicted regions, i.e., ridgelines such as shown in the center of the right image.

C. **Effect of varying nodal spacing.** Nodal spacing is the distance between adjacent nodes on the same contour. Greater nodal spacing will typically cause the shape of deposits to spread out and has a significant influence on the distance used to compute connection slope. The right image was modeled using a nodal spacing of 20 feet instead of the default of 10 feet.

D. **Effect of varying contour interval.** Contour interval controls the downslope resolution of the contour connection procedure. A larger contour interval can be useful for overcoming topographic obstacles that cause early termination, without producing major changes to results obtained using other recommended parameters. The right image was modeled using a contour interval of 20 feet instead of the default of 10 feet; using the larger contour interval filled many of the gaps left by using the smaller contour interval.

E. **Combined effect of varying contour interval and node spacing.** Increasing these together increases the scale of CCM outputs and reduces the influence of the roughness of large hummocks that might prevent the algorithm from moving downslope. The right image was modeled using a contour interval and node spacing of 30 feet instead of the default contour interval and node spacing of 10 feet.

5.0 SICCM LANDSLIDE MAPPING EXAMPLE: OREGON COAST RANGE

Having clear expectations of the purpose of SICCM outputs and knowing how to apply them in a landslide inventory workflow are essential for proper use. SICCM modeled output used as informative layer as an aid in drawing deposits has the potential to increase the speed and confidence of SP-42 inventory mapping.

To show how the three SICCM modes compare to each other and as an example of how the output of SICCM can be used to support an SP-42 inventory, DOGAMI staff modeled landslides in the Lutsinger watershed using the three SICCM modes:

- Fully automated head scarp lines and CCM
- Semi-automated head scarp lines and CCM
- Manually mapped head scarp lines and CCM

OLC lidar-derived 3-ft imagery was used as the initial DEM. The DEM was accessed via the DOGAMI Lidar Viewer: https://gis.dogami.oregon.gov/maps/lidarviewer/. The data are open-source. In addition, DOGAMI staff manually digitized landslide deposit polygons according to the SP-42 protocol, although for the purpose of this exercise the polygons were not fully attributed. The four landslide polygon datasets (FullyAutoExtents, ManualExtents, SemiAutoExtents, SP_42_Outlines) are included with this publication.

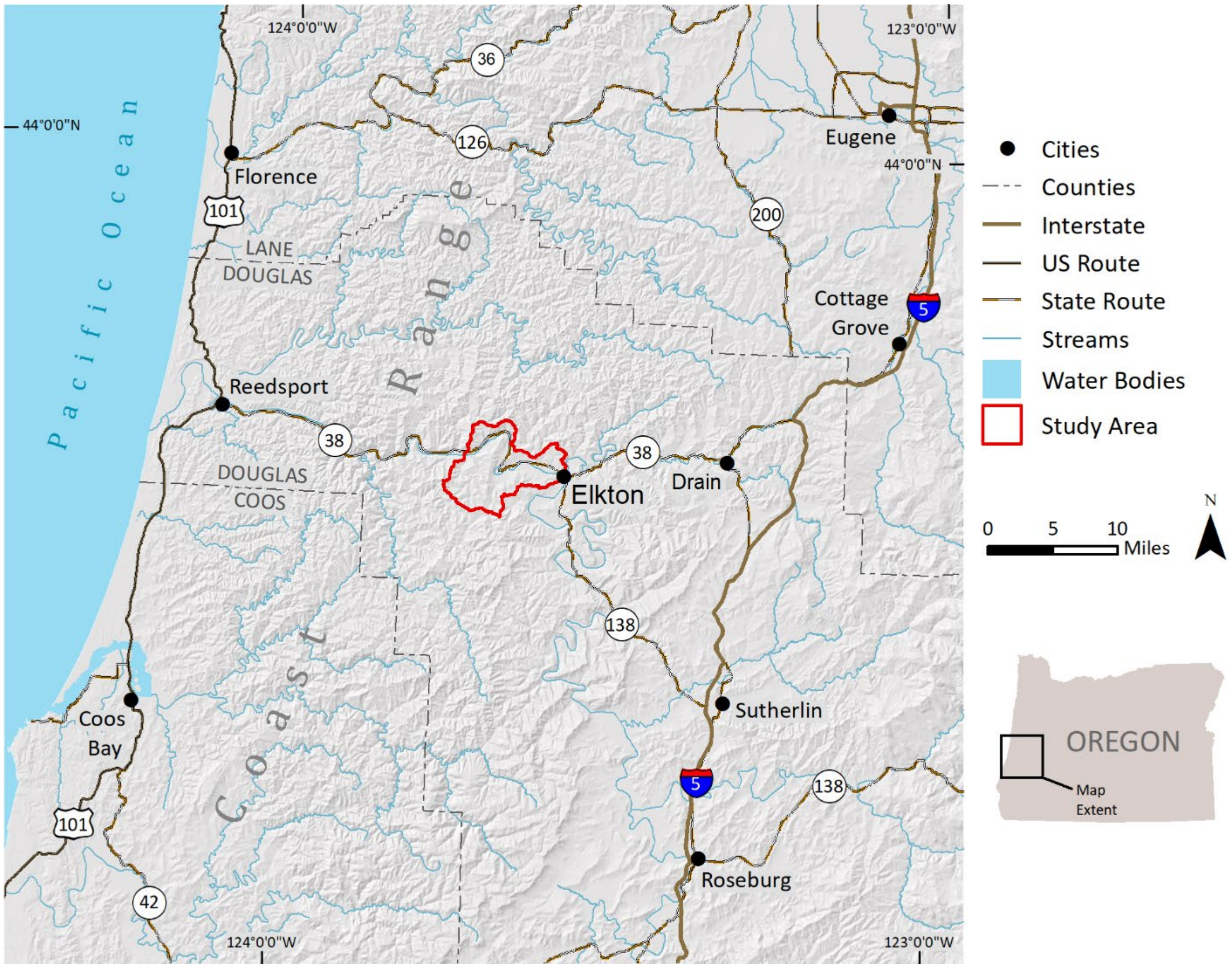
Although SICCM modeling and SP-42 mapping were completed for the entire watershed, four areas of interest (AOIs labeled A, B, C, D), each approximately 4 km^2 and representative of the greater watershed area and the central Oregon Coast Range, were selected within the watershed to provide specific locations for comparing results from the three modes. Depending on the needs of the modeler, different levels of automation may be appropriate (also see **Table 1**). After presenting the results from the study area, limitations of the model and how best to incorporate SICCM landslide deposits into SP-42 mapping method will be discussed.

5.1 Study area

The Lutsinger Creek watershed area was chosen because its topographic variability captures both a variety of landslide types and a high density of landslide deposits, while the regularity of its geologic setting (Niem and others, 1989; Wells and others, 2000) limits the complexity of our analysis.

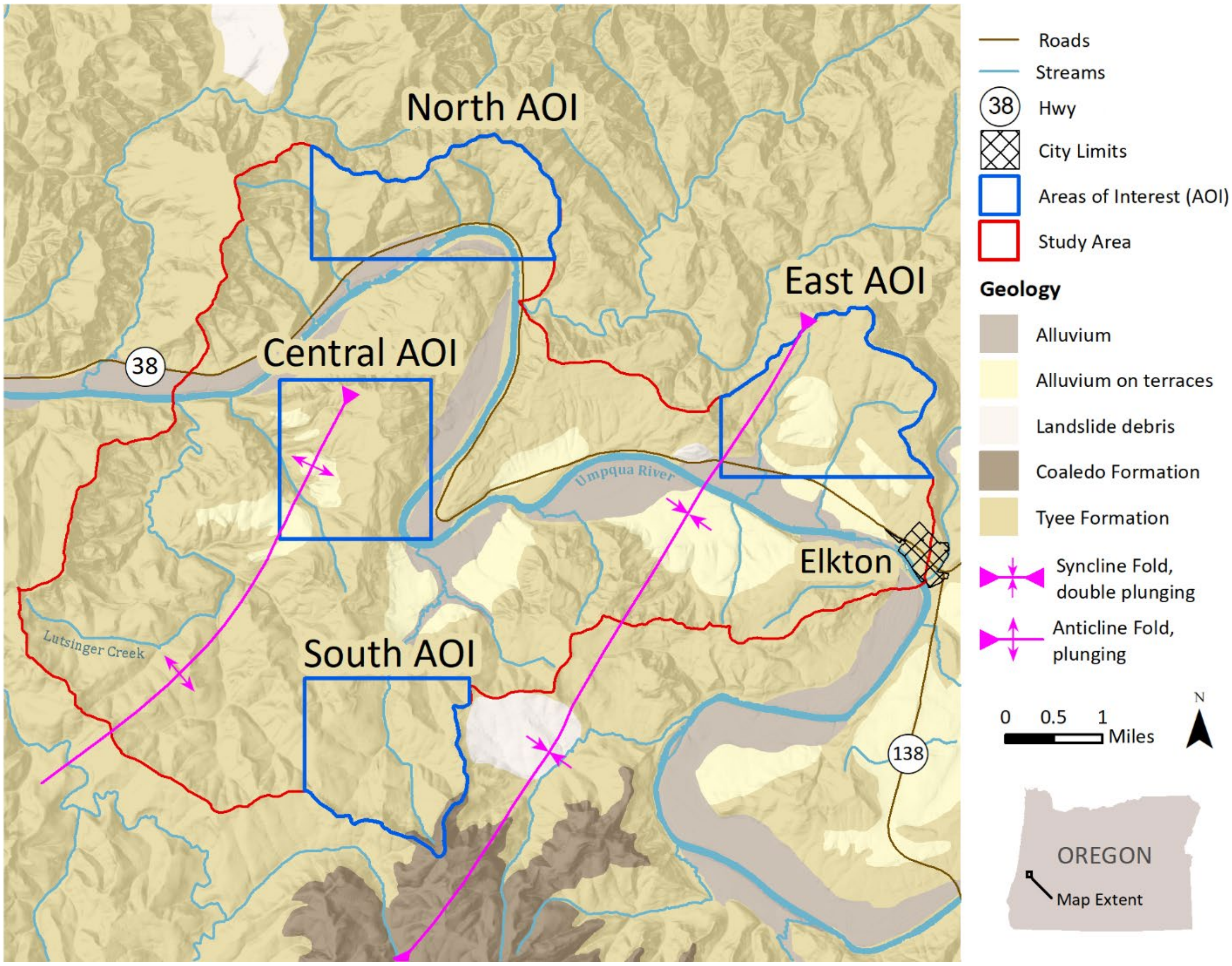
The Lutsinger Creek watershed, located in the Oregon Coast Range, is a hydrologic unit code (HUC) 12 watershed of approximately 100 km^2 area (Seaber and others, 1987). It straddles the Umpqua River and the town of Elkton (**Figure 12** and **Figure 13**). This area was selected as a sample area to demonstrate the tool, because of the area's moderate size and relatively uniform geology, and because DOGAMI had created an SP-42 landslide inventory in nearby watersheds. The nearby SP-42 landslide inventories indicated that there was adequate diversity and abundance of landslides and landslide types locally, making it an ideal sample area.

Figure 12. Regional study area. Note highway through study area.



The geology in the study area consists primarily of the Tyee Formation from the mid-Eocene. The Tyee Formation consists of well-indurated, thick to very thick beds of micaceous and arkosic turbidite sandstone beds and rhythmically interbedded thin graded sandstone and siltstone (Niem and others, 1989; Wells and others, 2000). There are one anticline and one syncline, both of which trend to the southwest (Niem and others, 1989; **Figure 13**). North of the Umpqua River, the Tyee sandstone dips between 9 to 12 degrees toward the southwest. In the central portion of the study area, the geology is folded by an anticline with its hinge defining the ridgeline. On the east of the ridge, the limb of the syncline dips 9 degrees southeast and on the west of the ridge, it dips 10 degrees to the southwest. These details are important to a landslide study, because underlying geologic structures can contribute and control landslide density and orientation. In particular, slopes aligned with structure dip angles (dip-slopes) are prone to landslides (Highland, 2004).

Figure 13. Geologic map of the study area (Niem and Niem, 1989) from Oregon Geologic Data Compilation (OGDC) 6.0 (Smith and Roe, 2015).



5.2 Results

Maps showing output from the three modes for the four areas of interest are shown on Plate 1.

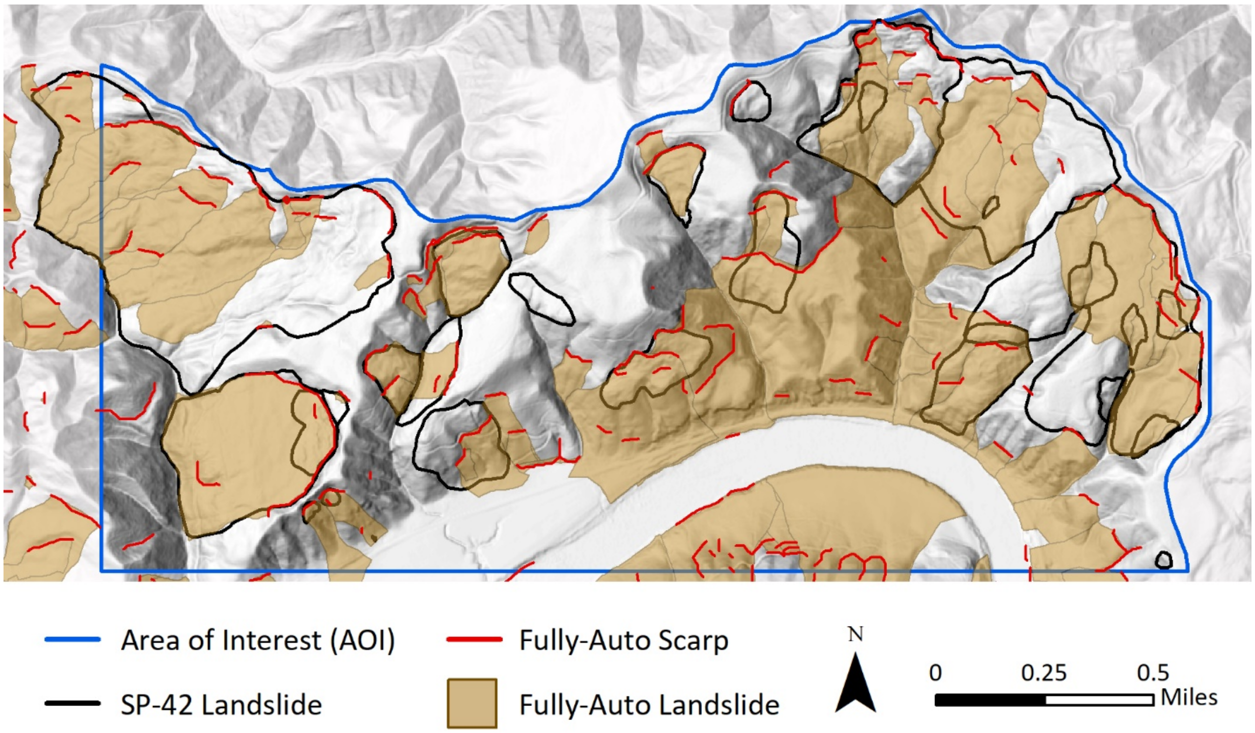
5.2.1 Fully automated mode results

The SI model output was derived from default model parameters, without any optional modification by the modeler. These results were created in less than two days, with the majority of time spent in computation time. The automatically generated scarp lines were input into CCM using the recommended (default) CCM parameters.

The fully automated model provides the quickest output and requires no modification by the modeler. Fully automated model output is moderately comparable to SP-42 deposits, but overall the fit is variable (**Figure 14**). However, the SP-42 deposits were created by modifying the fully automated SICCM results, or by making new polygons based on expert analysis of the topography after review of the fully automated model results: a direct comparison does not test the value of the SICCM results.

For the mapper, the SICCM model output polygons draw attention to and build confidence in features that have the potential of being associated with landslides. This automation level can be used to inform the mapper’s determination as to whether or not landslides are located in the areas indicated by the output polygons, and to what extent. The output dataset should increase the speed of decision-making and possibly the confidence of the mapper by focusing attention on specific locations within a mapping area.

Figure 14. Area A-North with fully automated model outputs (light brown polygons) and SP-42 deposit polygons (black outlines) displayed over a 3-foot cell size hillshade raster. The large landslide in the SW portion was one where the SICCM-generated polygon matched well enough to the mapper-interpreted landslide extent that the SICCM output could be used as an SP-42 compliant deposit polygon, saving time and effort.



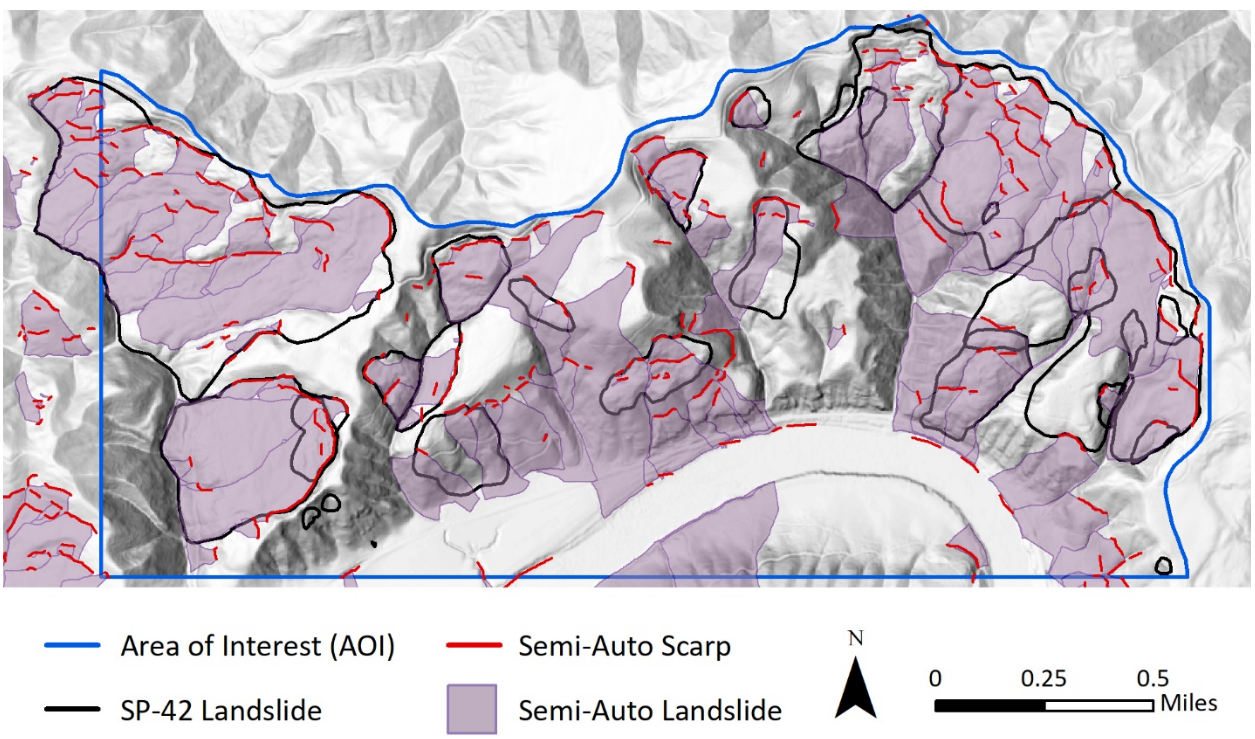
Results from this model were variable. In area D-East, the output polygons did not assist the mapper in creating the SP-42 deposits (Plate 1). This is likely due to the subdued topographic expression and lack of continuous scarp features. However, in area A-North (**Figure 14**), one landslide was close enough that the mapper was able to use the auto detected SICCM polygon and modify it to an SP-42 compliant deposit. Areas B-Central and C-South (Plate 1) contained many cases where the mapper used the SICCM output data to inform the creation of SP-42 deposits. This demonstrates that the output polygons are highlighting areas that have a higher potential of being landslide deposits. As can also be seen in **Figure 14**, the orange polygons underproject the extents of some landslide deposits. However, if the modeler uses this as an "indicator" data layer, the areas to focus on are properly highlighted and serve to expedite the landslide identification process. Recalling that the SICCM model output is not intended to replicate an SP-42 inventory, but to provide an additional data layer to be used for the inventory, the fully automated SI mode has some utility.

5.2.2 Semi-automated mode results

The procedure to create scarps was performed with all optional modifications described in Section 4.3. Resulting scarp lines were then input to the CCM tool. CCM parameters were analyzed considering the results from the first run of CCM tool and subsequently adjusted to improve the mapping of the landslide deposits. As is discussed in Section 4.4, changing the CCM's nodal spacing, contour spacing, and active slope parameters alter the extents and area covered by the CCM tool outputs. Changing CCM parameters is straightforward, allowing the modeler to review initial results, adjust CCM parameters, and run the CCM tool again. The CCM parameters were modified twice; hence, the tool ran three times. Total processing time for this method took 3-4 days and was primarily spent running the CCM tool (between one to several hours, each run) and included approximately a half day of modeler involvement.

The semi-automated mode generated scarps and CCM outputs cover more of the SP-42 deposits, when compared to the fully automated mode results (Figure 15). Because these outputs provide much more than an indicator of the potential presence of landslide terrain, they can be used as a digitization template for the mapper. In some cases, the polygons could be traced and reshaped, providing a higher level of efficiency in the creation of landslide polygons.

Figure 15. Area A-North with semi-automated head scarp lines and deposit polygon outputs (purple polygons) and SP-42 deposit (red outlines) displayed over a 3-foot cell size hillshade raster.



When using the SICCM tool, the practitioner must review and edit the output polygons for false positives, i.e., areas mapped incorrectly as landslide deposits. In the Lutsinger Creek watershed, false positives occurred where 1) steep stream channels and 2) very steep to near vertical bedrock outcrops were marked as scarp lines in semi-automated mode. Steep stream channels or gullies, due to the steep sides of incised channels and concavity of the slope transition to the streambed, have a similar topographic signature that can be mis-identified as landslide scarp candidates. During the classification step of the scarp identification procedure, elimination of non-scarp candidates (the optional modification described in Section **4.3.2.2.1**) deals with the false identification of channels or gullies by overlapping a digital stream feature class with the scarp candidates and deleting the scarp candidates that intersect. Bedrock outcrops can sometimes form cliffs or near vertical surfaces that display similar topographic signatures to landslide head scarps. Hummocky topographic features within a landslide deposit or on landslide toes are not easily deleted en masse. An example of a bedrock outcrop identified as a scarp candidate can be seen along the south border of the C-South (Plate 1), where the semi-automated method falsely identified a scarp line from which CCM created a landslide deposit.

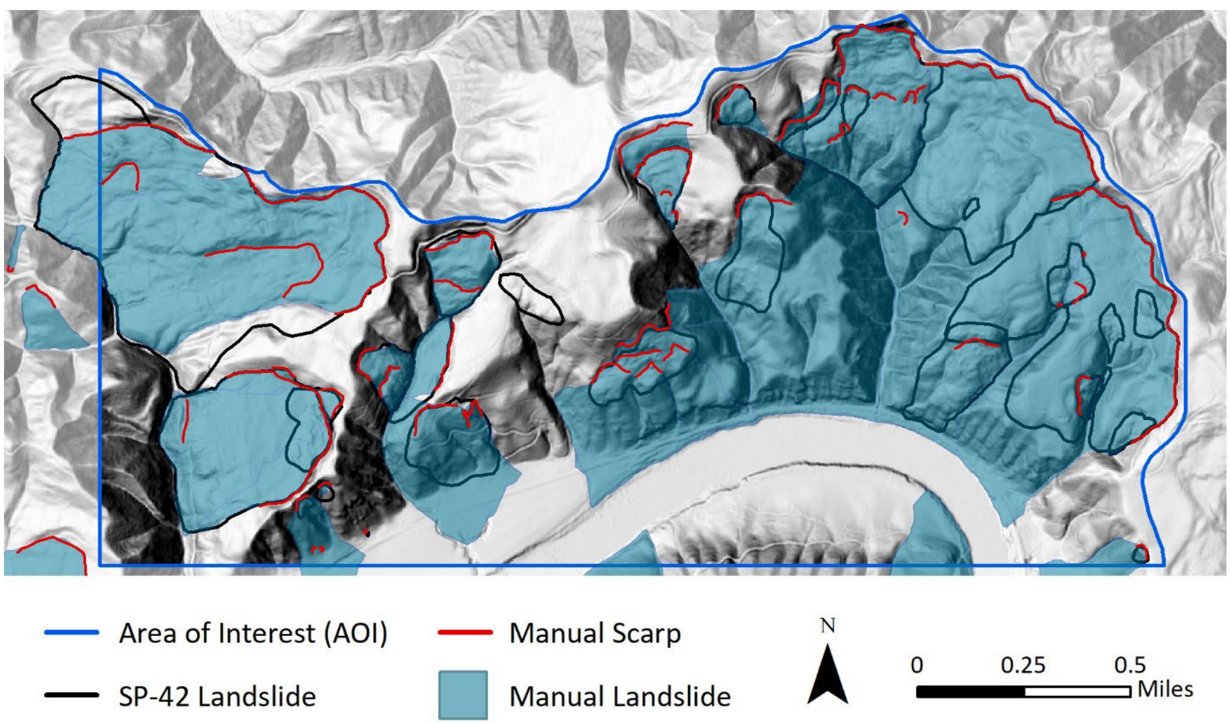
5.2.3 Manual mode results

Scarp lines were interpreted and manually digitized by an experienced DOGAMI mapper following a modified SP-42 method (Burns and Madin, 2009). Specifically, the scarps were drawn at the top of the landslide deposit instead of at the top of the head scarp as outlined in SP-42. Scarp digitization required approximately 4 days. The scarp lines were then input to CCM. The CCM model was run using the same modified parameters as those used for semi-automated mode scarp line input in this example area.

The SI manual mode CCM outputs generally span larger areas and, in some cases, extend farther downslope than do the SP-42 deposits (**Figure 16**). Also, because both the manual scarp lines and the SP-42 landslide deposits were created from a similar interpretation process, the majority of scarp lines overlapped with landslide deposits. As a result, CCM model output extents are equivalent to SP-42 polygons at the top of the deposit. In some cases, with minor reshaping this output can be used for creating SP-42 landslide deposits. However, the time spent manually drawing the scarp lines and running the SICCM tool may take longer than simply drawing the entire landslide deposit.

In the D-East area (Plate 1), the manual mode output included the most large, subdued dipslope landslides. However, the landslide terrain does not trigger the termination of the CCM active slope parameter, and deposits are routinely mapped down to the canyon floor.

Figure 16. Area A-North with manually drawn scarps and associated CCM deposit polygons (blue polygons) and SP-42 deposit polygons (red outlines) displayed over a 3-foot cell size hillshade raster.

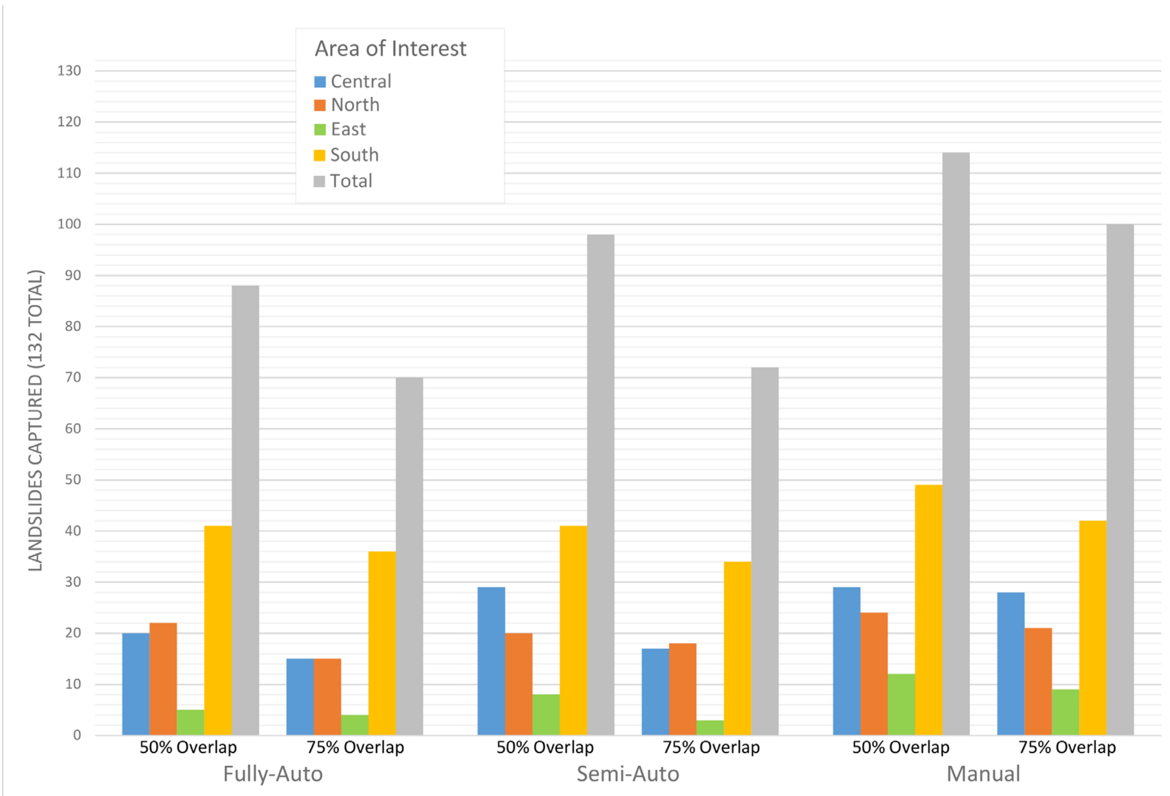


5.2.4 Statistical comparison of outputs

To obtain a quantitative measure of the accuracy of the three SICCM modes, fully automated, semi-automated, and manual mode outputs were compared to the 132 mapped SP-42 deposit polygons from the four AOIs by using Spatial Statistics tools in ArcMap 10. 4. Two metrics were examined: 1) overlap of SICCM output polygons to SP-42 polygons by at least 50% or at least 75% as a measure of capture, and 2) total percentage of overlap and non-overlap as a measure of overprediction.

In this first case, the measure of capture was based on the area of each SP-42 landslide that was also mapped by a SICCM model output. Two area thresholds were used to define overlap, 50% and 75%, with the goal of expressing a range in performance (Figure 17). In other words, if the SICCM output covered at least 50%, or at least 75%, of an SP-42 deposit polygon, that SP-42 deposit polygon was counted as captured.

Figure 17. Landslides captured by SICCM fully automated, semi-automated, and manual automation levels in the Lutsinger watershed areas of interest (Central, North, East, South). There are a total of 132 SP-42 landslide deposit polygons in all four areas of interest (Central: 31; North: 28; East: 16; South: 57). If a SICCM output polygon overlapped at least 50% or at least 75% of an SP-42 deposit polygon, the SP-42 deposit polygon was counted as captured. For example, in the Central AOI, the semi-automated mode captured with 50% or greater overlap 29 of 31 landslides. The Total column (gray color) is the sum of the four AOIs, not the percentage overlap across the entire watershed.



The fully automated mode had the greatest range of performance but was comparable to the semi-automated results (Figure 17). The semi-automated method captured more than two-thirds of the number of landslides (98 of the 132) when the 50% overlap threshold was used but did not achieve as much when the 75% threshold was used.

The manual method was substantially better at identifying greater than 75% of the landslide deposit area. This metric is telling for the usefulness of tracing SICCM modeled polygons and using them without considerable post-model revisions. This metric also highlights that the semi-automated method captures approximately half of landslide deposits modeled at a strict 75% cover agreement to the SP-42 manually mapped deposits. Given these metrics, SICCM could be a substantial time saver.

Although this analysis provides a measure of landslide areas that were correctly identified using the SICCM tool, it does not account for false positive or overprojected SICCM output. To examine false positive results, the percentage of each AOI covered by SICCM polygons that is not covered by SP-42 landslide polygons was calculated (**Table 4**).

Table 4. Percentage of areas falsely identified as landslides by SICCM in the Lutsinger Creek study area. Results are based on areas modeled as polygons by SICCM but not mapped as SP-42 polygons.

	Percentage of Area Falsely Identified as Landslides by SICCM		
Lutsinger Creek Watershed Area of Interest	Fully Automated Mode	Semi-Automated Mode	Manual Mode
Central	0%	9%	14%
North	1%	21%	20%
South	7%	12%	16%
East	0%	3%	11%
Total	2%	11%	15%

In the Lutsinger Creek AOIs, the areas of false positives increase with increasing automation level (**Table 4**). In the case of manual scarp digitization, the scarp lines are commonly longer and more connected than in either automated mode. This allows for more coverage during CCM model generation of deposit areas; meaning, it is likely for larger continuous areas to be included in the deposit polygons. In part, overprojection can be due to “stranded” landslide topography, which occurs when streams or rivers (in this case, the Umpqua River) incise existing landslides, leaving the hummocky deposits high above the modern flood plain and erasing the toe area.

An example of this can be seen in the North area in Plate 1; there is a significant slope break at the toe of several very large, old landslide deposits, above the Umpqua River near the apex of the river bend. A possible interpretation for this slope break is that the Umpqua River base level has lowered and the river’s geographic position has changed during its evolution.

Overall, the false-positive modeled area ranges from 0% to 21%, which translates to additional time spent by a reviewer deciding if an area modeled by SICCM is or is not a landslide. If the impact is significant, it may be an indication that the scarp lines generated by the semi-automated mode need further editing, or that the CCM parameters should be adjusted in each of the modes.

The Lutsinger watershed provides just one example of SICCM results, but it does illustrate some of the advantages and limitations of the SICCM method; a summary is provided in **Table 5**. Bunn and others (2019) discuss results for other areas of Oregon, as well as model sensitivities.

Table 5. Summary of advantages and disadvantages of SICCM automation levels, and SP-42 method, with time and effort considered. The information and estimates in this table were developed for the Lutsinger Creek watershed, which is approximately 100 km^2.

	SICCM Scarp Identification Mode	Advantages	Disadvantages	Amount of Time Needed to Generate and Process Results
Decreasing automation ↓	Fully automated	○ Minimal time input to produce model results ○ No landslide mapping expertise required to produce initial results ○ Can map a large region	○ False negatives and false positives common ○ Very noisy modeled results; very long and very short scarp candidates produce erroneous polygons ○ Requires considerable post-mapping editing	○ Less than 2 days to produce model results, regardless of region of interest (< 1 day of modeler time and < 1 day processing) ○ Time spent by an experienced mapper post-processing data and mapping deposits varies widely, from one week to several weeks; strongly dependent on size of area and desired precision
	Semi-automated	○ Minimal to moderate time input to produce initial results ○ Low input effort ○ Moderate control over scarp lines and candidates ○ Can map a large region	○ False-positives prevalent ○ False-negatives common ○ Moderate post-processing editing needed	○ Less than one week by experienced modeler; varies moderately by size of region of interest (~1 day modeler time and 2–4 days processing)
	Manual	○ High precision ○ Guides CCM outputs ○ Very few to no false negatives or positives ○ Low post-processing effort	○ Time intensive ○ Effort intensive ○ Requires skill and experience ○ Scale-dependent ○ Not reasonable for very large areas	○ One to two weeks by experienced modeler, varies greatly by size of region of interest (3-4 days modeler time and < 1 day processing)
	Special Paper 42 method (Burns and Madin, 2009)	○ High precision and accuracy ○ High resolution lidar-based DEM allows high-resolution landslide mapping ○ Variety of end users can immediately use maps	○ Very time intensive ○ Very effort intensive ○ Full time efforts by experienced modeler ○ Scale-dependent	○ Many weeks to months, very dependent on size of map area ○ About 60–65 hours per 100 km^2 for an individual to map landslide polygons (excluding SP-42 standard attributes, and scarp and flank polygons; Burns, 2007)

6.0 SICCM WORKFLOW WITH DOGAMI SPECIAL PAPER 42

The SP-42 landslide inventory mapping method, the standard at DOGAMI, is resource intensive. Commonly, individual landslide polygons may have well over 200 vertices. If an inventory has 200 to 1,000 landslides in a particular study area, 40,000 to 200,000 digital vertices must be created by the landslide mapper. The primary advantage of this method, however, is the high level of precision, confidence, and consistency in the identification of landslides, which is paramount to the accuracy of landslide inventory maps. With the automated scripts of SICCM, it is possible to model hundreds of square kilometers of terrain rapidly, given adequate quality elevation data. However, incorporating SICCM methods with traditional, expertise-based SP-42 landslide inventorying requires planning. Considerations include available time and landslide mapping experience, as well as the intended purpose of the product. There are benefits and costs, in hours spent, to making ideal scarp candidates and having fewer false positive landslide deposits in the CCM outputs, versus spending less time revising scarps, resulting in more falsely mapped landslide polygons. If accuracy and precision are of highest need, then extra time at the outset may be worthwhile.

An ideal option, or the "best value" option for use with SP-42, may be to generate landslide scarps using the semi-automated scarp line identification mode, with thoughtful changes to optional modification parameters, and then manually revise the generated scarp line candidates. These revisions can include deleting erroneous scarps, extending small scarps that partially delineate scarps, or adding scarp lines that the mapper deems were missed by automatic scarp generation. Initial polygons can then modeled by continuing with the CCM portion of the tool. Time is saved in the generation of the input data to CCM, and revisions after deposits are generated in CCM can achieve acceptable precision and accuracy.

After outputs from the CCM tool have been generated, post-processing revisions are necessary. The method of post-processing will be strongly influenced by the accuracy of the modeled polygons. For mapping completed by DOGAMI, the output would undergo scrutiny equal to that given to SP-42 deposit polygons; therefore it is necessary to have landslide deposit boundaries as accurate as possible.

The output of SICCM is a polygon feature class, with each polygon initiated from a unique scarp line. If multiple scarp lines are clustered together, the result is multiple polygons in close proximity, possibly overlapping. The mapper can then either keep the landslide polygons as individual polygons or merge or dissolve individual polygons, creating broad landslide terrain features, instead of individual landslide deposits. Each of these methods has benefits in the workflow of mapping landslide deposit polygons.

- Keeping individual landslide polygons allows individual landslide polygons to be kept as mapped landslide deposit features. If a modeled polygon closely aligns with an interpreted landslide deposit, this is the best strategy.
- Dissolving the boundaries between touching or overlapping polygons creates a single, larger polygon. Benefits for this strategy include ease of reshaping one landslide polygon boundary, versus many.

Modeled polygons can be used as a data layer that can be toggled on and off, to aid in landslide identification and interpretation. The polygons can then be used for tracing, reshaping, and/or retaining as mapped landslide deposits.

The options for incorporating modeled deposit polygons into the final landslide inventory include 1) reshaping model polygons using GIS reshape, cut, and merge editing tools, 2) tracing modeled deposits and altering as needed, or 3) redrawing polygons using modeled deposit results as temporary layer for visual inspection. A combination of these methods may work best, depending on how closely the modeled results agree with deposit bounds as interpreted by the mapper.

For the Lutsinger Creek study area (see Section 5.0), the best method for post-processing modeled polygon deposits included a combination of tracing the modeled polygons in a new layer, revising as the mapper saw fit, and redrawing polygons entirely, while toggling modeled deposit data layer on and off, to visualize and consider landslide deposit boundaries.

7.0 CONCLUSIONS

Existing landslides are the best guide to identifying landslide hazard zones, because future landslides tend to occur where landslides have happened. Landslide inventory maps help identify existing landslides, which, in turn, can be used for hazard maps and for understanding an area's landslide hazard.

The method of creating landslide inventories described in DOGAMI Special Paper 42 (SP-42) is based on the use of lidar-derived, bare-earth digital elevation model imagery to assist experienced geologists in mapping landslide deposits, head scarps and flanks, and internal scarps. These features are attributed and combined to create an SP-42 landslide inventory. A landslide inventory that strictly follows the SP-42 protocol is considered of sufficient quality to be used within the context of policy and regulatory purposes in the state of Oregon. In Oregon the public practice of geology must be performed by a licensed geologist or certified engineering geologist as regulated by the Oregon State Board of Geologist Examiners.

The SP-42 landslide inventory mapping method is accepted as the standard at DOGAMI, but the process is labor intensive and time consuming. The amount of effort to produce an inventory can be a barrier to developing needed data in landslide-prone regions. Accelerating the process of landslide mapping would enable more economical landslide inventories, larger study area extents, serial mapping with future lidar imagery collection, and the possibility of increased effort in other aspects of a project.

The Scarp Identification and Contour Connection Method (SICCM) uses a set of Python scripts packaged in an ArcGIS toolbox to provide an efficient, semi-automatic framework to quickly scan large areas within a region and detect morphological features that indicate possible landslides. Because SICCM identifies landslides on the basis of scarplike morphological features, the SICCM method requires a defined head scarp connected to, or in the immediate vicinity of, a landslide deposit. Falls, topples, spreads, and debris flows, following the nomenclature of Cruden and Varnes (1996), cannot be mapped with SICCM. SICCM requires elevation base data, Esri ArcGIS software with Spatial Analyst® extension, and a practitioner with knowledge and experience identifying landslides in remotely sensed imagery. Levels of automation offer opportunities during tool use for practitioners to analyze interim outputs and adjust parameters. SICCM creates approximated landslide head scarps, represented as lines, that are then used in creating polygons that approximate the locations and extents of landslide deposits.

The SICCM process is intended to automate the discovery of landslide-like features at watershed to regional scales. SICCM can expedite landslide inventory mapping, but the SICCM process does not replace a geologist trained in landslide mapping. SICCM results, if used for the public practice of geology, should be carefully reviewed and edited by a licensed geologist or by a certified engineering geologist. Applications such as developing inventory maps for authoritative decisions in planning, zoning, and development restrictions require detailed review such that the resulting inventory is of quality equal to a SP-42 landslide inventory. However, SICCM results may be used to provide preliminary landslide information for nonregulatory purposes. Some examples of nonregulatory uses include maps that 1) assist in the manual landslide mapping process, 2) support broad planning efforts that do not relate to zoning, development, or other authoritative decisions, such as understanding the relative scale of landslide hazards in a region, (3) provide data layers for teaching or research purposes, and (4) support rapid response situations, such as after a regional earthquake, an intense precipitation event, or a wildfire. The fully automated SICCM model would be a good choice in this situation. It can provide timely information to help broad planning of impacts on infrastructure or supplement manual mapping of deposits. However, it must be noted that a landslide inventory map without proper review will contain errors and would not be appropriate as a regulatory planning tool.

SICCM can support the SP-42 landslide inventory process and may significantly decrease the time and effort required to create a robust landslide inventory by facilitating landslide identification. Applying the SICCM tool to an example area, the Lutsinger Creek watershed, showed the benefits and drawbacks of the three SICCM automation levels (**Table 5**). At the scale of this study area, about 100 km^2, the semi-automated scarp identification automation level plus the CCM tool, with several runs, provided the most useful landslide polygon outputs for SP-42 inventory work. The generated polygons had fairly good agreement with SP-42 mapped polygons and showed that SICCM output could be used as a starting point for SP-42 mapping. However, mappers must weigh the benefit of the output against the time needed for detailed revision of the generated scarp candidates. The ability to decide where in the process the most hours and effort will be best spent allows landslide mappers the flexibility to adapt the landslide identification and mapping process to their needs, study area, and type of landslides.

8.0 GLOSSARY

Active slope (CCM) – an input to the CCM Algorithm that that dictates the minimum connection slope that may be mapped before the process terminates.

Branching parameter (CCM) – an input to the CCM Algorithm that regulates the amount that landslide extents may spread transverse to the downslope direction.

CCM algorithm – an updated version of the Contour Connection Method of Leshchinsky and others (2015) that uses inputted landslide scarp lines to draw the extents of landslide deposits.

Classification – the act of assigning labels to scarp candidates. Labels may be either non-landslide scarp or landslide scarp.

Connection (CCM) – a straight three-dimensional line that connects nodes on adjacent contours.

Contour interval (CCM) – the vertical distance between adjacent contours drawn by the CCM algorithm.

Descriptive variables – single values used to describe a scarp candidate polygon. These variables may be geometric, such as perimeter or area, or topographic, such as statistical measures of elevation derivatives corresponding to the polygon (e.g., mean, standard deviations, etc.).

Elevation derivative – a raster computed through manipulation of a digital elevation model. Examples include slope, profile curvature, planform curvature, hillshade, and mixture.

Mapper – the person mapping landslides, with adequate experience and expertise to correctly recognize and map landslides.

Mixture raster – the raster used to emphasize landslide scarps during segmentation. Mathematically, the product of slope and profile curvature rasters.

Mixture threshold – the value of the mixture raster used to separate scarp candidates from all other terrain.

Modeler – the person running the SICCM model, who may not have landslide mapping experience, and thus may run SICCM but cannot verify the model outputs.

Nodes (CCM) – three-dimensional points located at equal spacing on contour lines that are connected by the CCM algorithm.

Node spacing (CCM) – the distance along a contour between that dictates the spacing on nodes.

Optional modification – a break in the procedure that gives the modeler an opportunity to interpret interim results and to adjust them manually and iteratively.

Practitioner – the person performing modeling and/or mapping.

Scarp candidate – a shape that represents the extents of features having topography similar to landslide scarps. Computationally, a polygon that encompasses mixture raster values exceeding the mixture threshold.

Segmentation – the act of breaking down a raster into smaller objects that may be classified. Segmentation is the process of determining which terrain will become scarp candidate polygons.

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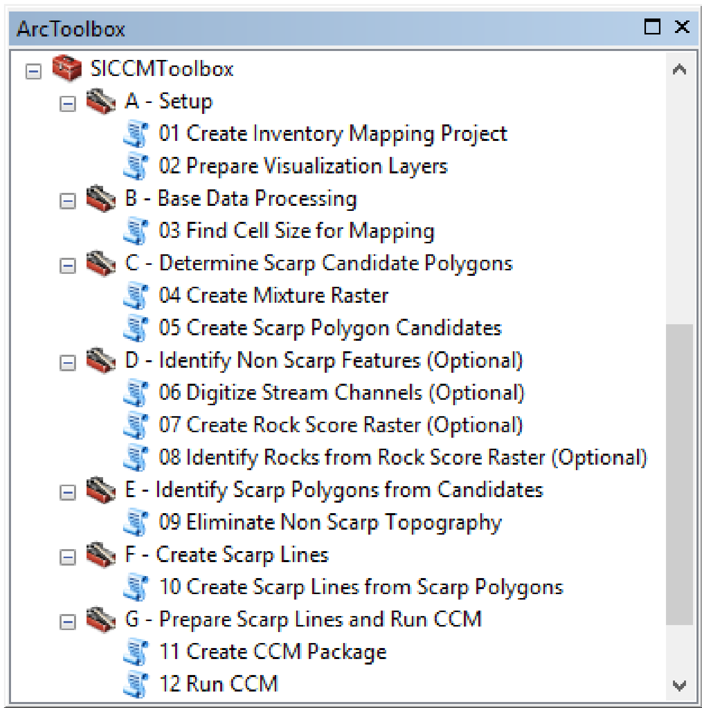
APPENDIX A-HOW TO USE THE SICCM TOOL

Toolbox Layout

Figure A-1. SICCM Toolbox ArcGIS toolset. Screenshots of each tool are provided at the end of this appendix.



Prerequisites

This appendix shows step-by-step instructions for performing semi-automated landslide deposit modeling using the SICCM procedure. Prior to getting started, it is important that you understand the following:

- The procedure requires that you have a basic understanding of Esri® ArcMap® and have Esri ArcGIS™ 10.3, or greater, installed on your computer. You will also need to install the SICCM Toolbox for ArcGIS (available as part of this digital publication) and the CCM application before starting work (CCM is available from http://geotech.forestry.oregonstate.edu/CCM.html).
- In its most basic form, the method inputs a digital elevation model raster (DEM) and outputs polygons representing the extents of landslide deposits. Along the way, there are opportunities for you to introduce other files, such as road and stream features, to potentially improve results.

- The DEM must be in a projected coordinate system and may not use a latitude/longitude (geographic) system. Tools in the SICCM toolbox are not designed to compensate for discrepancies between horizontal and vertical units, and the use of degrees in a geographic coordinate system will cause the tools to crash. If you find that the chosen DEM uses a geographic coordinate system, then you must project the raster into a projected coordinate system before attempting to use the toolbox. Numerous projected coordinate systems exist, and if you are not familiar with which to use for the area of interest, it is recommended that you identify the appropriate Universal Transverse Mercator (UTM) zone and use that.
- You should identify a location on your local computer with enough available memory to store SICCM outputs. A typical U.S. Geological Survey quadrangle (~50 square miles) will require up to 2 gigabytes of space for the Inventory Mapping Project geodatabase, and up to 5 gigabytes of space for each CCM Package. Modelers who have no prior experience with SICCM are recommended to have at least 15 gigabytes of available space.
- Each tool in the SICCM toolbox comes with built-in documentation. The documentation may be accessed by clicking the **Show Help >>** button located at the bottom right corner of a tool's interface.
- There are a large number of optional inputs associated with operation of the SICCM toolbox. As an aid, all optional inputs and default parameters have been summarized in Table A1.
- In an effort to maintain organization and reproducibility, output file names are automatically selected by each SICCM tool based on input parameters. The output file naming conventions are provided in Table A2.
- The SICCM toolbox has been tested thoroughly, but there is still the possibility you may encounter errors. If you encounter any error messages, please contact Dr. Ben Leshchinsky, Oregon State University, ben.leshchinsky@oregonstate.edu, with a description of the problem and a copy of the message. Any reported errors will assist in the development of SICCM tools and are greatly appreciated.

Default Tool Inputs and Output File Naming Conventions

Table A-1. Default tool inputs for the Scarp Identification and Contour Connection Method (SICCM).

Tool Name	Optional Parameter	Default Value	How to Input Default
03 Find Cell Size for Mapping	Test Cell Size 1	3 times the cell size of the Input DEM (Raw DEM)	Leave blank
03 Find Cell Size for Mapping	Test Cell Size 2	6 times the cell size of the Input DEM	Leave blank
03 Find Cell Size for Mapping	Test Cell Size 3	9 times the cell size of the Input DEM	Leave blank
04 Create Mixture Raster	Selected Cell Size	The default value of Test Cell Size 2: 6 times the value of the Input DEM	Leave blank
05 Create Scarp Polygon Candidates	Mixture Raster Value used as Threshold	The class break between the second and third classes of the mixture raster when classified into three groups using natural breaks (Jenks)	Leave blank
06 Digitize Stream Channels	First Stream Accumulated Area	1 acre	Input space is pre-populated
06 Digitize Stream Channels	Second Stream Accumulated Area	3 acres	Input space is pre-populated
06 Digitize Stream Channels	Third Stream Accumulated Area	5 acres	Input space is pre-populated
07 Create Rock Score Raster	Cell Size used to Subtract from Input DEM	Twice the cell size of the Input DEM	Leave blank
08 Identify Rocks from Rock Score Raster	Rock Score Threshold	50	Leave blank
09 Eliminate Non Scarp Topography	Input Non Scarps	At a minimum, the 5-acre stream channel layer; the modeler must select the layer as an input to the tool	The modeler must select the 5-acre layer from the dropdown menu
10 Create Scarp Lines from Scarp Polygons	Thinning Cell Size	The same cell size used in Tool 04	Leave blank
11 Create CCM Package	Output Folder	The current Inventory Mapping Project folder	Leave blank
12 Run CCM	Number of Nodes used to Cutoff Tails	Tails are not removed	Leave blank
12 Run CCM	Number of Contours to skip during Cutoff	3	Leave blank - applies only when the Number of Nodes used to Cutoff Tails is filled in

Table A-2. Output file naming conventions for the Scarp Identification and Contour Connection Method (SICCM).

Tool Name	Output	Output Name	Variable Parts	Location Saved
01 Create Inventory Mapping Project	Inventory Mapping Project Folder	Specified by Name of Inventory Mapping Project input		Specified by Location to Save Inventory Mapping Project input
01 Create Inventory Mapping Project	Inventory Mapping Project Geodatabase	Same as Inventory Mapping Project name		Inventory Mapping Project Folder
02 Prepare Visualization Layers	Copy of Input DEM	Raw DEM		Inventory Mapping Project Geodatabase
02 Prepare Visualization Layers	Hillshade Raster	Hillshade		Inventory Mapping Project Geodatabase
02 Prepare Visualization Layers	Slope Raster	Slope		Inventory Mapping Project Geodatabase
03 Find Cell Size for Mapping	Test Slope 1	TestSlope[1]	[1] Cell size	Inventory Mapping Project Geodatabase
03 Find Cell Size for Mapping	Test Slope 2	TestSlope[2]	[2] Cell size	Inventory Mapping Project Geodatabase
03 Find Cell Size for Mapping	Test Slope 3	TestSlope[3]	[3] Cell size	Inventory Mapping Project Geodatabase
04 Create Mixture Raster	Mixture Raster	Mix_CS[1]	[1] Cell size of the mixture raster	Inventory Mapping Project Geodatabase
04 Create Mixture Raster	Resampled DEM	RS_Elev[2]	[2] Cell size of the resampled DEM	Inventory Mapping Project Geodatabase
05 Create Scarp Polygon Candidates	Candidate Polygons	Cand_CS[1]_MT[2]	[1] Cell size of the mixture raster used to define candidate polygons, and [2] the mixture threshold value (If natural breaks (Jenks) were used, [2] becomes "NB")	Inventory Mapping Project Geodatabase
06 Digitize Stream Channels	First Stream Channel Layer	Channels[1]	[1] First stream accumulated area with units	Inventory Mapping Project Geodatabase
06 Digitize Stream Channels	Second Stream Channel Layer	Channels[2]	[2] Second stream accumulated area with units	Inventory Mapping Project Geodatabase
06 Digitize Stream Channels	Third Stream Channel Layer	Channels[3]	[3] Third stream accumulated area with units	Inventory Mapping Project Geodatabase
06 Digitize Stream Channels	Flow Accumulation Raster	FlowAcc		Inventory Mapping Project Geodatabase
07 Create Rock Score Raster	Rock Score Raster	RockScore_[1]	[1] Cell size of the rock score raster	Inventory Mapping Project Geodatabase
08 Identify Rocks from Rock Score Raster	Rock Outcrop Polygons	Rocks_Sc[1]	[1] Rock score threshold used to define outcrops	Inventory Mapping Project Geodatabase
09 Eliminate Non Scarp Topography	None			
10 Create Scarp Lines from Scarp Polygons	Scarp Polylines	Scarps_CS[1]_MT[2]	Same notation as for the candidate polygons used to produce scarp lines	Inventory Mapping Project Geodatabase
11 Create CCM Package	CCM Package Folder	[3]_Package_CS[1]_MT[2]	[1] and [2] are the same as the scarps included in the package, and [3] reflects whether the scarps are of Manual, Semi-Automated, or Automated origin	May be selected by modeler but, by default, in the Inventory Mapping Project Folder
11 Create CCM Package	CCM Package Geodatabase			CCM Package Folder
11 Create CCM Package	Geotiff Copy of DEM	CCM_DEM.tif		CCM Package Folder
11 Create CCM Package	3D Scarp Polyline Shapefile	CCM_scarps.shp		CCM Package Folder
12 Run CCM	CCM Folder	CI[1]_NS[2]_AS[3]_BP[5]	[1] contour interval, [2] nodal spacing, [3] active slope, and [4] branch parameter used in CCM run	CCM Package Folder
12 Run CCM	Deposit Extents	CI[1]_NS[2]_AS[3]_BP[5]	Same as for the CCM Folder	CCM Package Geodatabase

Tool Instructions

This appendix is color coded. The key to each color is provided below:

Blue = File Name
Purple = Tool Variable Name
Orange = ArcGIS Operation
Red = Process/Tool Name

Having understood the previous sections, you are ready to begin work. Modelers who have already digitized scarp lines should skip directly to part G - Prepare Scarp Lines and Run CCM (Tools 11 and 12).

A - Setup (Tools 01 and 02)

Open ArcGIS.

Open the ArcToolbox, and map the location of the SICCMToolbox toolbox.

Run 01 Create Inventory Mapping Project. Save the project to an appropriate folder with a relevant project name. The project name should not have spaces; instead, use underscores, for example "My_Project".

Open ArcGIS Map Document Properties and set the **Default Geodatabase** to the geodatabase in your newly created inventory mapping project folder. If you fail to update the **Default Geodatabase**, output files will be sent and stored in the ArcGIS default geodatabase located at within the "ArcGIS" folder of "My Documents" on your computer.

Optionally, run 02 Prepare Visualization Layers with your raw DEM as the **Input DEM**. The tool outputs a hillshade raster and a formatted slope and elevation (DEM) combination, which are meant to be used as base maps for the rest of the analysis. It is recommended that you use the default layer, slope, because it is not biased by the choice of sun angle used for hillshade computations (Burns and Madin, 2009). The outputs will be saved to your inventory mapping project geodatabase.

B - Base Data Processing (Tool 03)

Run tool 03 Find Cell Size for Mapping with the raw DEM as the **Input DEM**, or move on to tool 04 Create Mixture Raster (part C) and use the default cell size. Operation of Tool 03 constitutes **Optional Modification 1**, which is the first opportunity for you to interject judgement and customize your results.

Optional Modification 1

During the first attempt at Tool 03, leave the optional test cell sizes empty. Review the output slope rasters and determine a good cell size (see Section 4.2 of the main report). If necessary, run the tool again with different cell sizes (Table A-3) and repeat this step.

Table A-3. Recommended inputs for Tool 03 Find Cell Size for Mapping when performing Optional Modification 1.

Tool Attempt	Test Cell Size 1	Test Cell Size 2	Test Cell Size 3
1 (Default Values)	3 × Original Cell Size	6 × Original Cell Size	9 × Original Cell Size
2 (If Necessary)	11 × Original Cell Size	13 × Original Cell Size	15 × Original Cell Size

C - Determine Scarp Candidate Polygons (Tools 04 and 05)

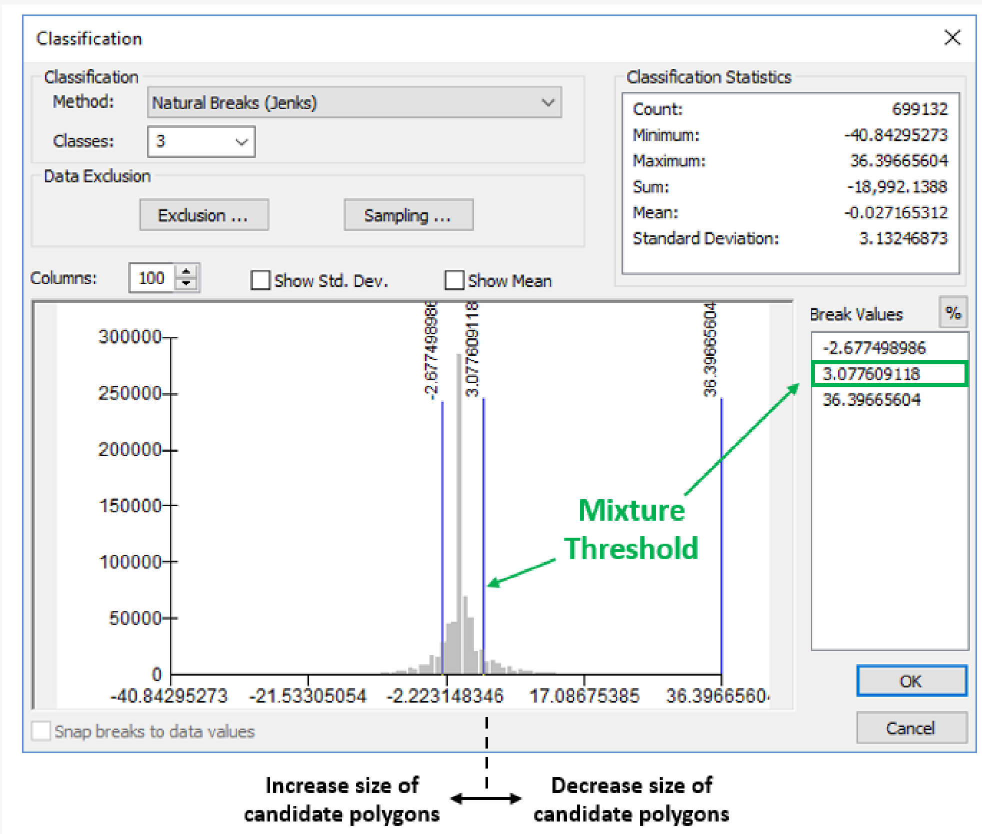
Run 04 Create Mixture Raster with the raw DEM as the **Input DEM**. Use the cell size that you determined with Tool 03 as the **Selected Cell Size**, or leave the cell size blank to use the default value. In this case, the default cell size is 3 times the cell size of the **Input DEM**. The mixture raster and a copy of the **Input DEM** resampled to the **Selected Cell Size** (Resampled DEM) will be saved to the project geodatabase. The mixture raster will be automatically displayed as three classes defined by natural breaks.

If desired, perform Optional Modification 2 by inspecting the mixture raster.

Optional Modification 2

Adjust the mixture threshold according to Section 4.3.2.1.3 of the report, and select a value that best includes most potential scarps.

Figure A-2. Identification of the mixture threshold within the ArcGIS classification window.



Run 05 Create Candidates with the desired **Input Mixture Raster**. If you performed **Optional Modification 2**, specify the mixture threshold for the **Mixture Raster Value used as Threshold**.

D - Identify Non Scarp Features (Optional; Tools 06, 07, and 08)

The tools used during the non scarp features identification process are optional because they present methods to identify stream channels and rock outcroppings, which may be identified by other means. If you have access to more advanced methods for identifying, or have already identified, either of these features, then you are welcome to use a different approach. Although this step is optional, you should skip directly to tool 09 only if you have a stream channel layer, at a minimum. Use of Tool 09 without at least a stream channel layer will most likely lead to poor results.

Run 06 Digitize Stream Channels with the Resampled DEM (produced by Tool 04) as the **Input DEM** and the DEM's linear unit (found under its Layer Properties) as the **DEM Linear Unit**. For the first run, leave the optional cell sizes with default values (1, 3, 5).

Tool 06 may used with or without modeler interpretation. To bypass modeler interpretation, remove the 1- and 3-acre stream channel layers from the map and retain the 5-acre layer. Modeler interpretation is highly recommended and is performed through **Optional Modification 3.**

Optional Modification 3

Review the output stream channels, using the diagram in the tool's help for guidance, and select the best stream channels layer. If the diagram cannot be satisfied by the first three stream channels, run Tool 06 again with different values (Table A4). Different values change the area included in the flow accumulation area; higher numbers include larger drainage areas; smaller values include smaller areas.

Table A-4. Recommended inputs for tool 06 (Digitize Stream Channels) when performing Optional Modification 3.

Tool Attempt	Accumulated Area 1	Accumulated Area 2	Accumulated Area 1
1 (Default Values)	1 acre	3 acres	5 acres
2 (If Necessary)	7 acres	10 acres	15 acres

If the terrain appears to have rock outcrops, run 07 Create Rock Score with the Resampled DEM as the **Input DEM**. Leave the **Cell Size used to Subtract from Input DEM** empty for the first run. If the resulting rock score raster does not appear to highlight outcrops (observed on the basemap layer), then try another **Cell Size**.

If Tool 07 has been performed, run 08 Identify Rock Outcrops from Rock Score with the desired **Input Rock Score Raster** and save the **Output Rock Outcrop Polygons** to your working folder. Leave the **Rock Score Threshold** blank, unless you are comfortable recognizing rock outcrops on the basemap layer. If you are comfortable, locate some rocks and identify their rock score raster value using the Identify cursor. The minimum observed rock score raster value may be used as the **Rock Score Threshold**.

After using Tools 06 through 08, determine if a road polyline layer is available for the map area. If so, inspect the layer against the basemap to determine if it is accurate. Inaccurate, or poorly drawn, road polylines should not be used.

E – Identify Scarp Polygons from Candidates (Tool 09)

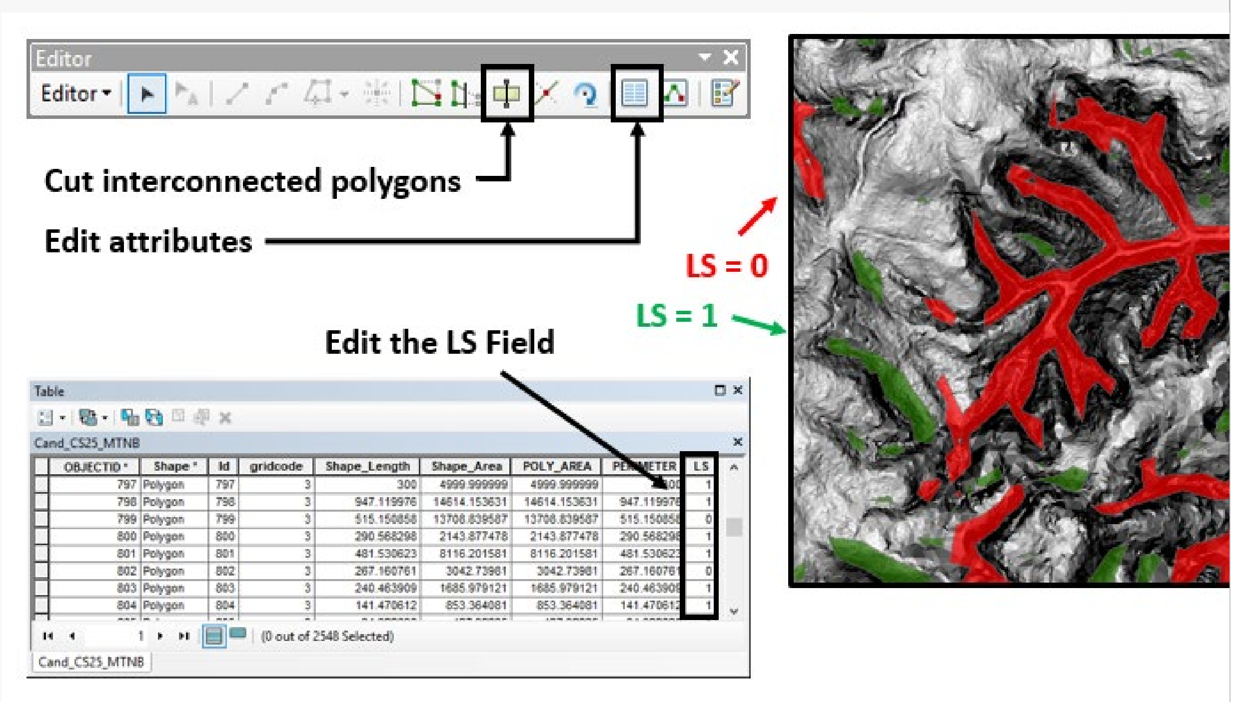
Run 09 Eliminate Non Scarp Topography with the candidate polygons created by Tool 05 as the **Input Candidates**. **Input Non Scarps** may be rock outcrop polygons, stream channels, or road polylines, and all available layers may be input together. In the case where poor-quality layers must be used as non scarps (not recommended), a **Search Distance** may be used to eliminate candidates within a certain distance of the non scarps. Tool 09 does not produce any outputs, but it does edit the "LS" field of the candidate polygons. Features with an "LS" value of 1 following Tool 09 are now called scarp polygons.

Perform **Optional Modification 4** to eliminate by inspection or reconsider classified candidates.

Optional Modification 4

See Section 4.3.2.2.2 for more information. Consider reclassifying the candidates in the attribute table manually. Additionally, the cut polygon tool can allow a partial inclusion or exclusion of a candidate into candidates.

Figure A-3. Locations of tools and attributes used to perform Optional Modification 4.



F - Create Scarp Lines (Tool 10)

Run 10 Create Scarp Lines from Scarp Polygons with the classified candidates as **Input Candidates**. The **Thinning Cell Size** is optional and gives you a chance to make scarps with more, or less, detailed appearance. By default, the **Thinning Cell Size** is set to that of your Resampled DEM. The output scarp lines will be saved to your project geodatabase. The thinned line provides a vector input for the vector-based analysis of CCM. Generally, a smoother scarp polyline is desired as it provides a more direct path for connections to proceed to downslope contours.

G - Prepare Scarp Lines and Run CCM (Tools 11 and 12)

Use tool 11 Create CCM Package to assign elevations to scarp lines and to create a CCM Package. The CCM Package is a directory used to organize any number of CCM outputs produced for a single set of scarp lines. **Input Scarp Lines** should be either the output of tool 10 or manually drawn scarp lines. The recommended **Input DEM** is the Resampled DEM (see boxed note, below). The **Method Used to Produce Scarps** is used to name the CCM Package folder and does not have any effect on physical results. You should select the appropriate method from the dropdown menu. Should you want to create multiple sets of scarps with the same settings, but perform different levels of modification, you may specify the **Output Folder** to distinguish between results.

Raw versus Resampled DEMs

The choice of the Resampled DEM, rather than the Raw DEM, as an input for tools 06 and 11 is based on significant improvements to computation time. You will find that the Raw DEM produces stream channels and scarp lines with a more natural appearance, but that these features may take roughly 30 times longer than their equivalents made using the Resampled DEM. Experienced modelers are welcome to input the Raw DEM at their own discretion.

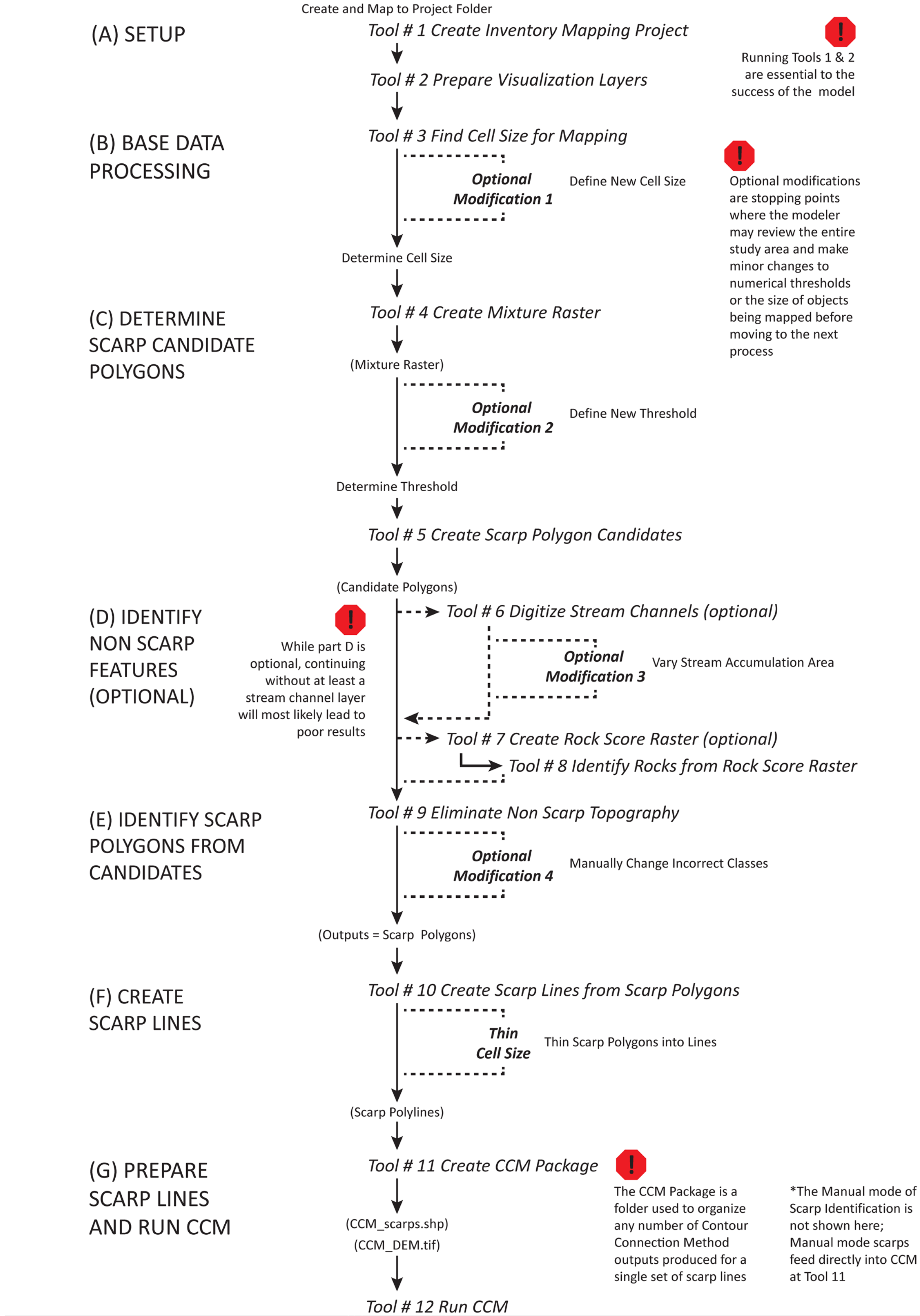
- Run CCM to Map Landslide Deposits Using Standalone GUI

    1. Save the Map Document, exit ArcMap, and open the CCM Flow GUI application.
    2. Create a New Model with the CCM_DEM.tif from the CCM Package as the **Input DEM**, the desired CCM_scarps.shp from the desired CCM Package as the **Input Scarp**, and the appropriate CCM Package folder as the **Output Folder**. Fill out the remaining required inputs based on criteria described in Section 4.4. Options on the right side of the New Model window may be adjusted to control what is outputted by the model. Click Add to Queue.
    3. Check that the model has been added to the queue, then click Run Queue. The tool will run for several minutes, depending on the number of scarps and the input parameters.
    4. Once the application has finished, the output prompt will say “Done with…” At this point, go back to ArcMap and open the Map Document. Add the CCM results to the map and inspect results. If necessary, create another CCM model.

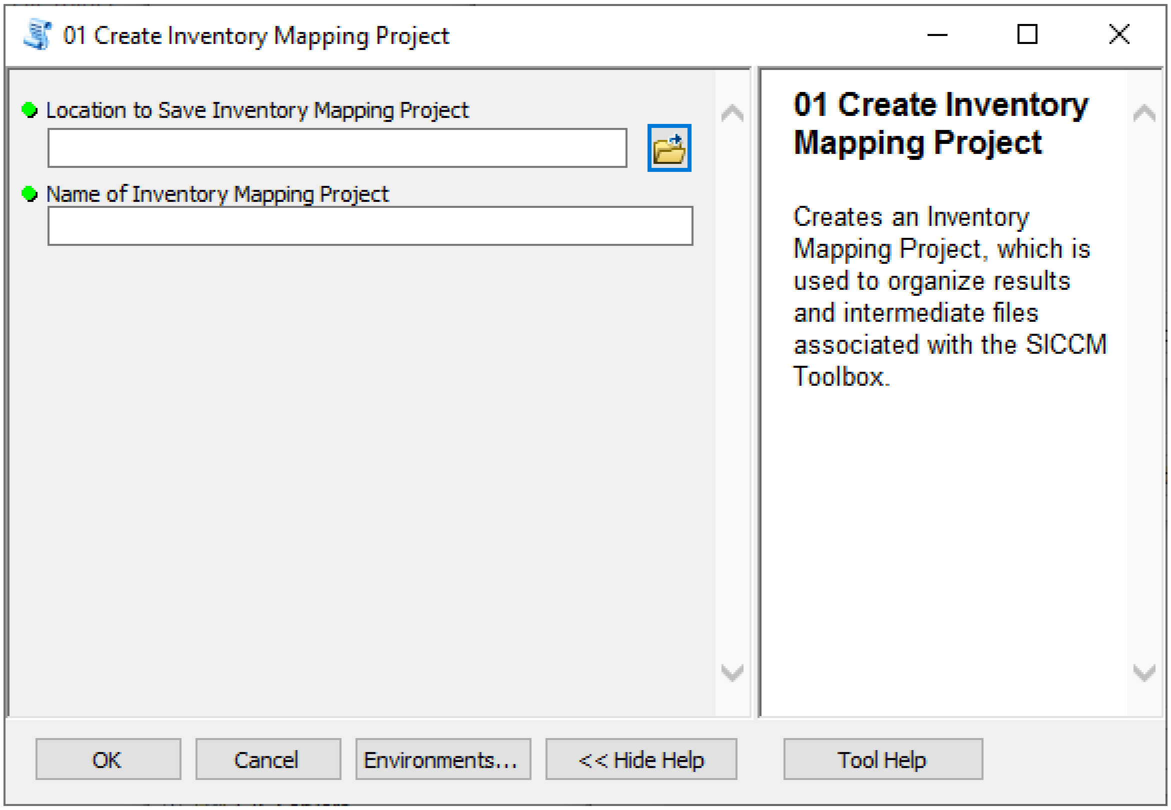
- Run CCM to Map Landslide Deposits within ArcMap

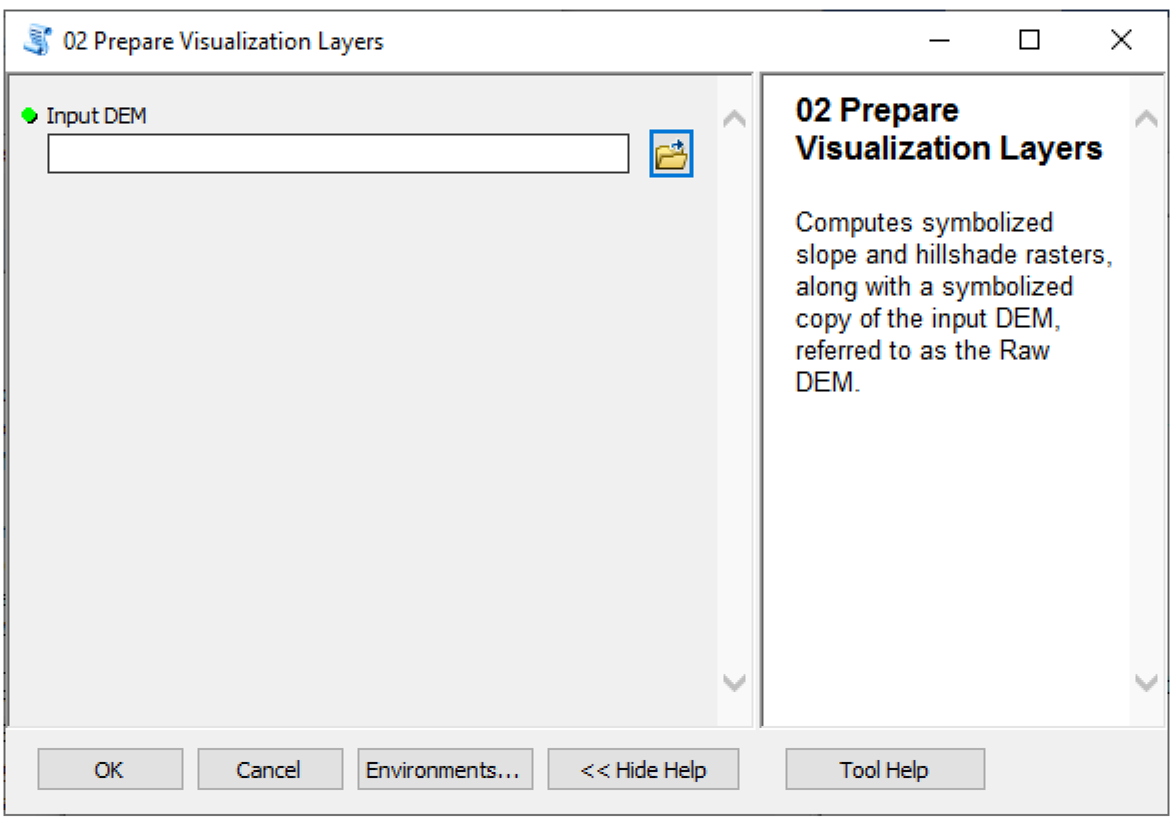
1. Make sure that you have the CCM Flow CLI (command line interface; available from http://geotech.forestry.oregonstate.edu/CCM.html) application installed on your computer.
2. Run tool 12 Run CCM with the desired **CCM Package** and CCM parameters (contour interval, node spacing, active slope, and branch parameter). If you choose to remove tails, fill in the **Number of Nodes used to Cutoff Tails** and **Number of Contours to skip during Cutoff**. Check the box if for all CCM outputs, or leave the box unchecked if you only want landslide deposit extents.

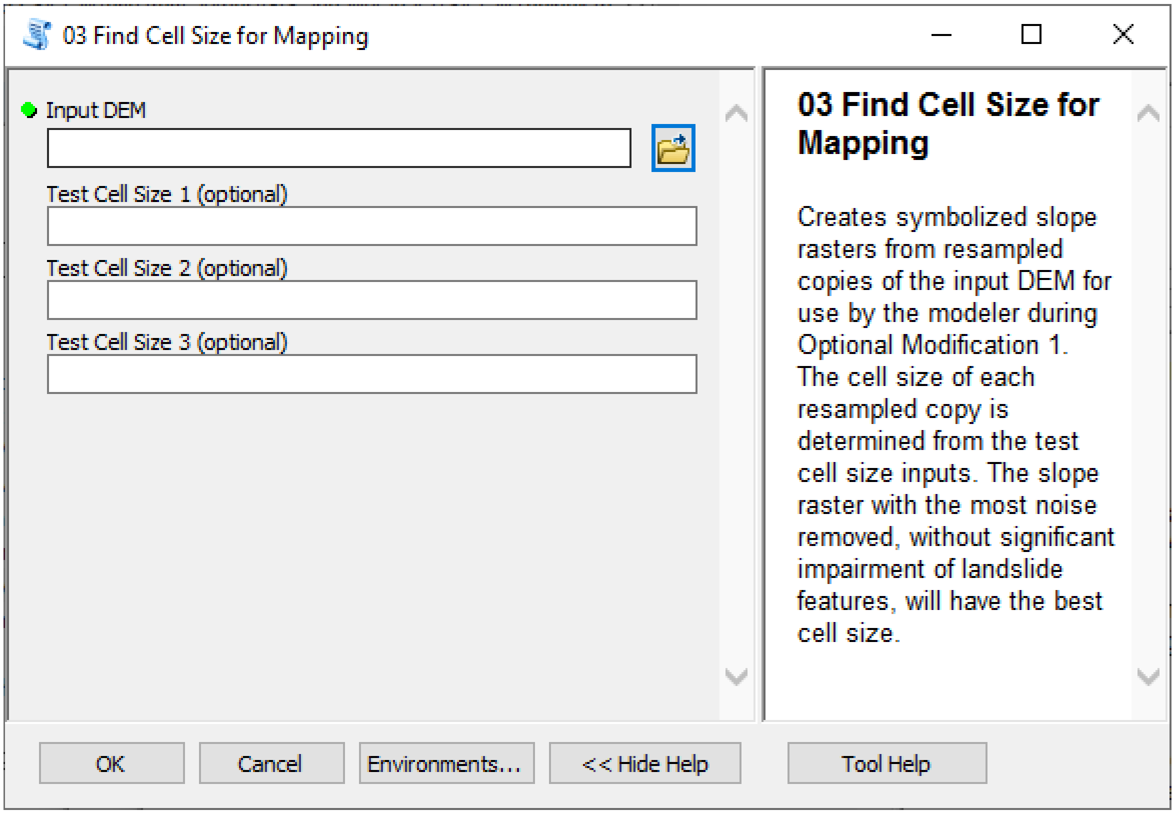
SICCM Process: Scarp Identification (SI) Fully Automated and Semi-Automated Modes*

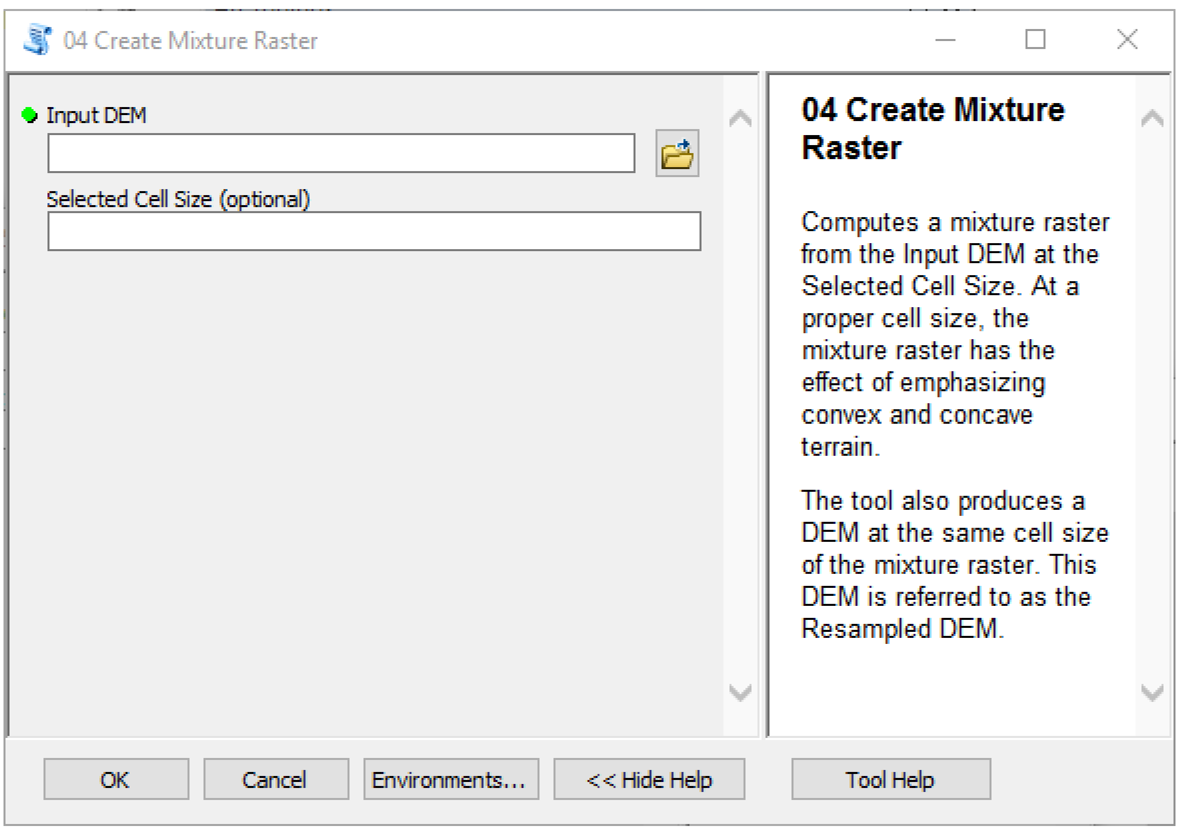


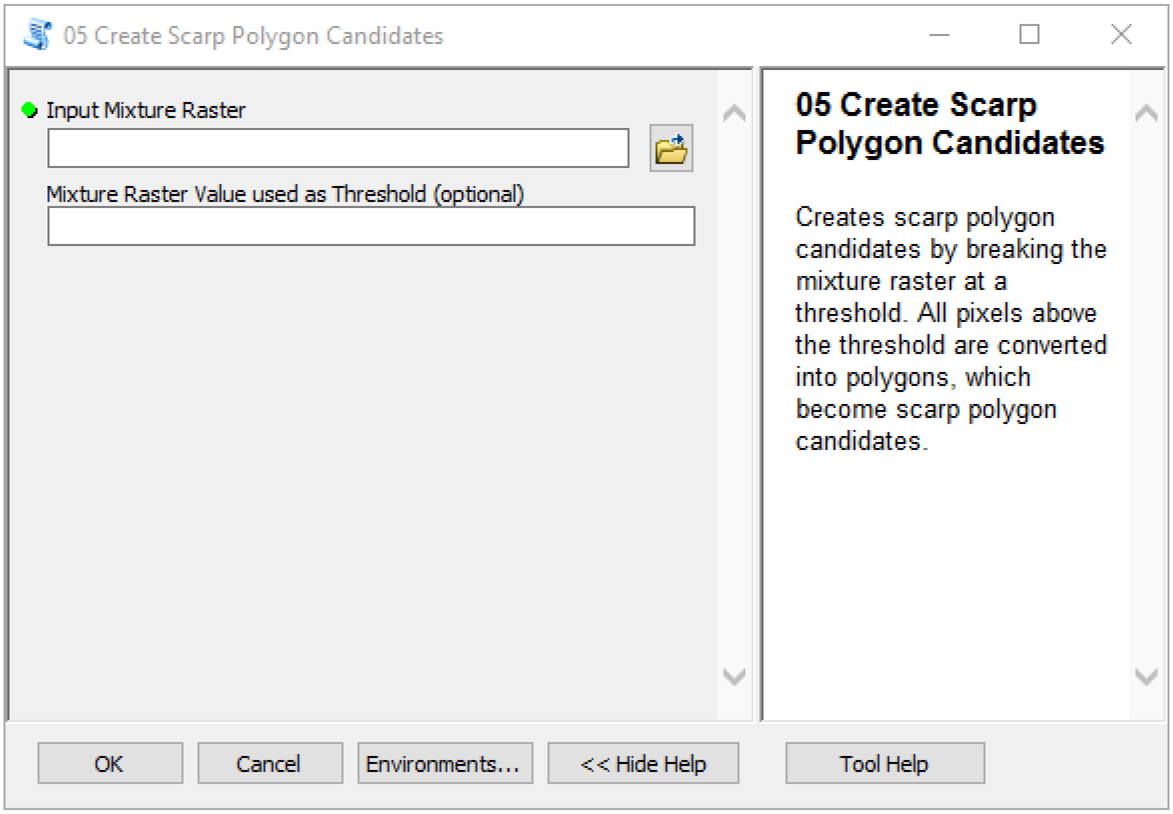
SICCM Toolbox Interface

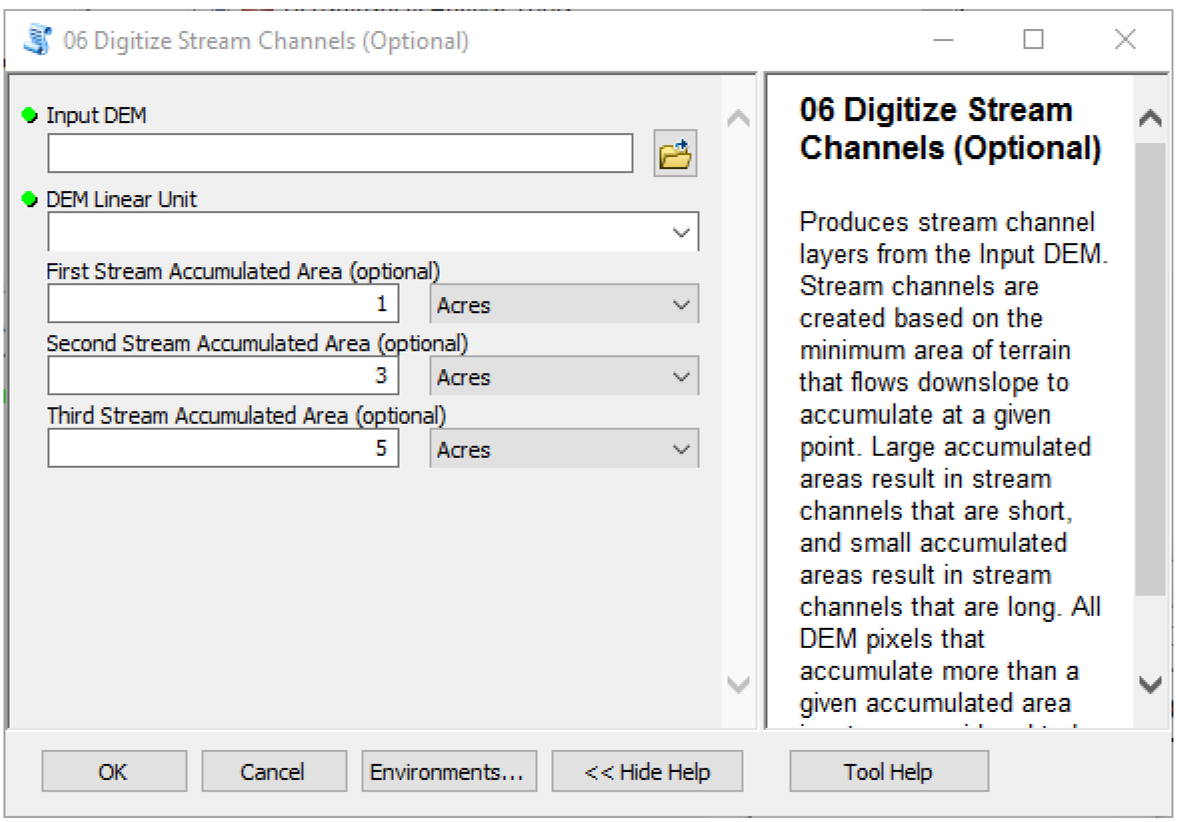


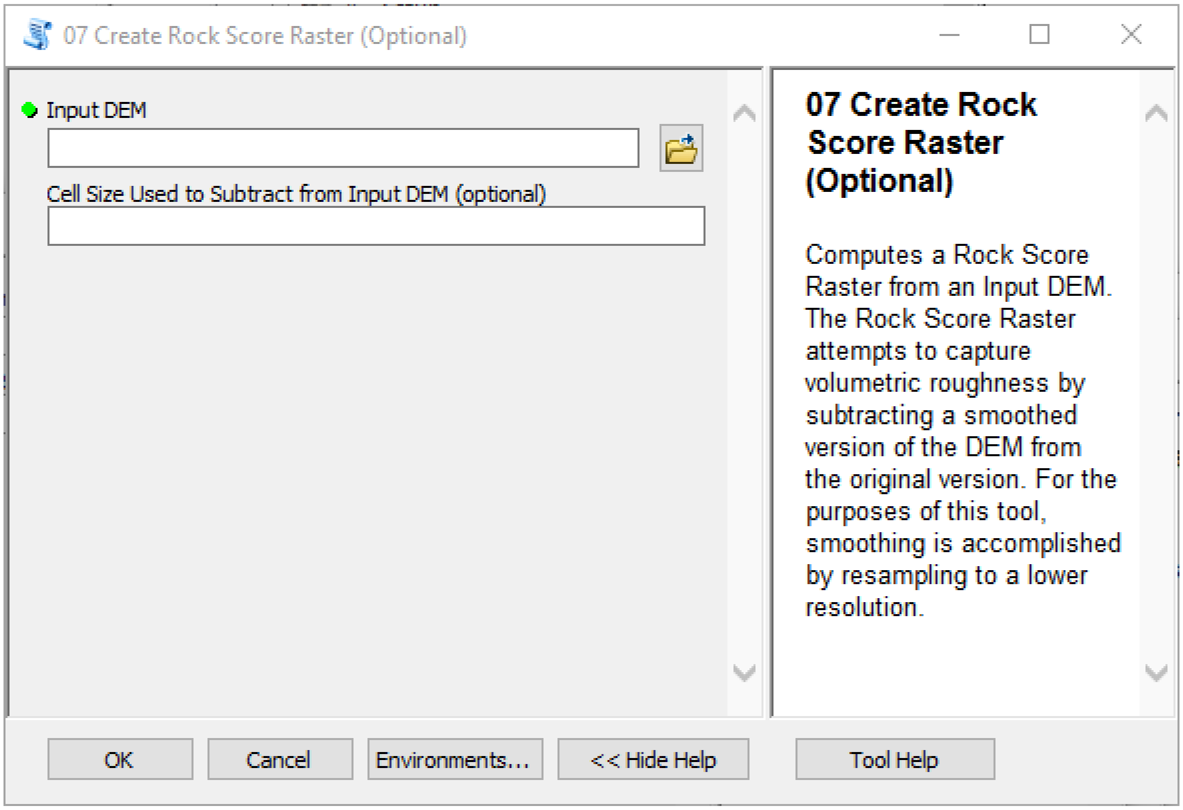


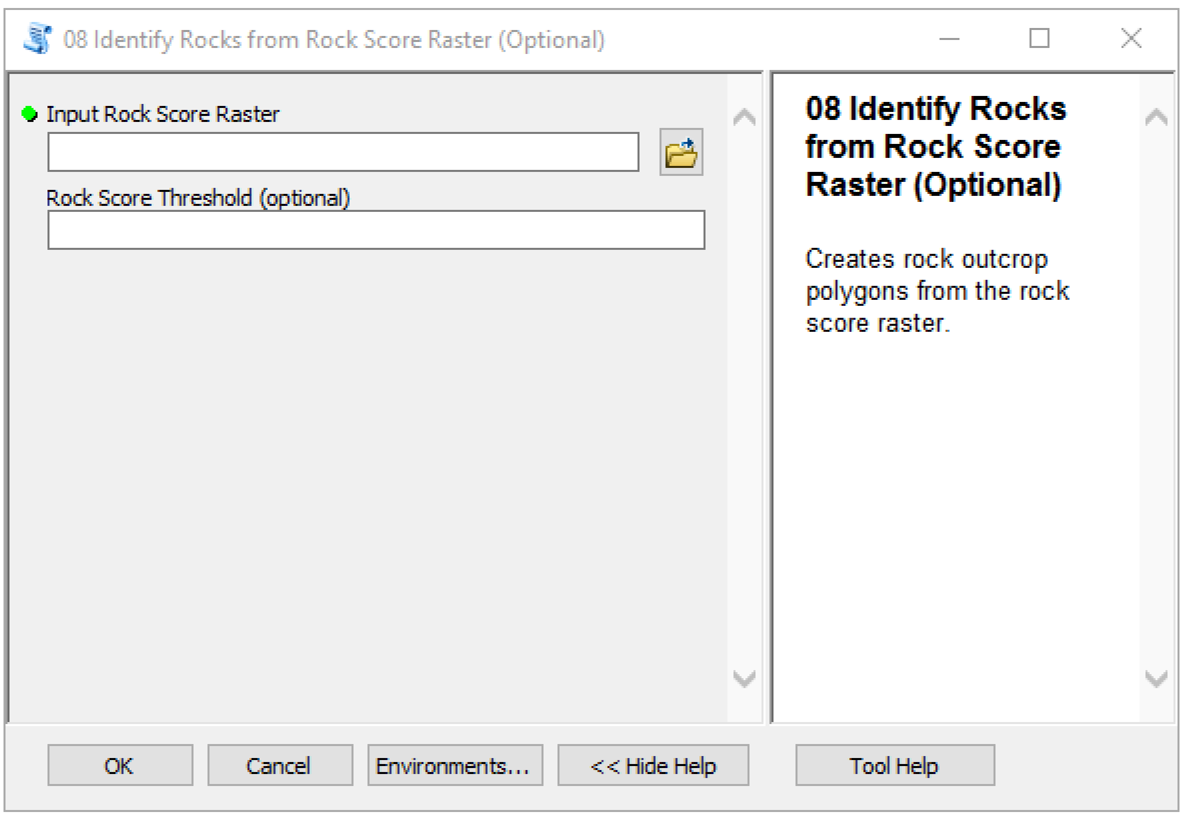

03 Find Cell Size for Mapping
Input DEM
Test Cell Size 1 (optional)
Test Cell Size 2 (optional)
Test Cell Size 3 (optional)
03 Find Cell Size for Mapping
Creates symbolized slope rasters from resampled copies of the input DEM for use by the modeler during Optional Modification 1. The cell size of each resampled copy is determined from the test cell size inputs. The slope raster with the most noise removed, without significant impairment of landslide features, will have the best cell size.
OK
Cancel
Environments...
<< Hide Help
Tool Help

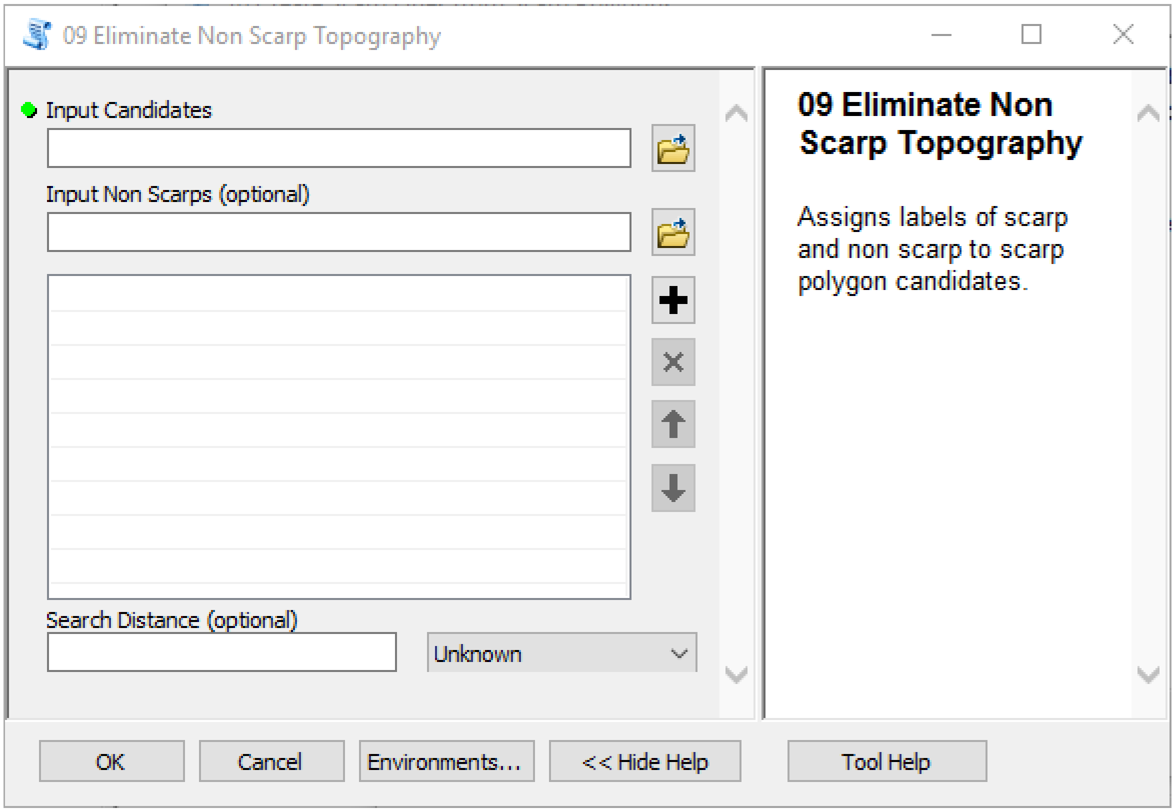

04 Create Mixture Raster
Input DEM
Selected Cell Size (optional)
04 Create Mixture Raster
Computes a mixture raster from the Input DEM at the Selected Cell Size. At a proper cell size, the mixture raster has the effect of emphasizing convex and concave terrain.
The tool also produces a DEM at the same cell size of the mixture raster. This DEM is referred to as the Resampled DEM.
OK
Cancel
Environments...
<< Hide Help
Tool Help

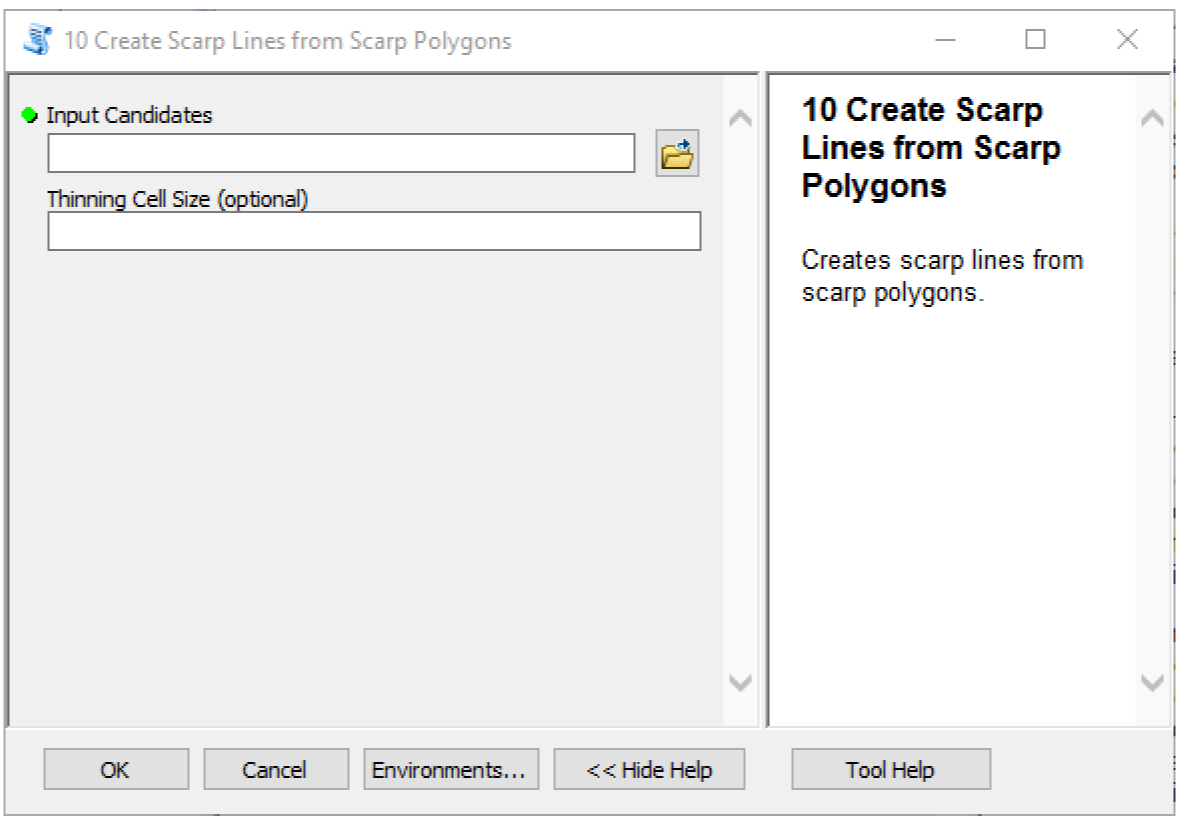

05 Create Scarp Polygon Candidates
Input Mixture Raster
Mixture Raster Value used as Threshold (optional)
05 Create Scarp Polygon Candidates
Creates scarp polygon candidates by breaking the mixture raster at a threshold. All pixels above the threshold are converted into polygons, which become scarp polygon candidates.
OK
Cancel
Environments...
<< Hide Help
Tool Help

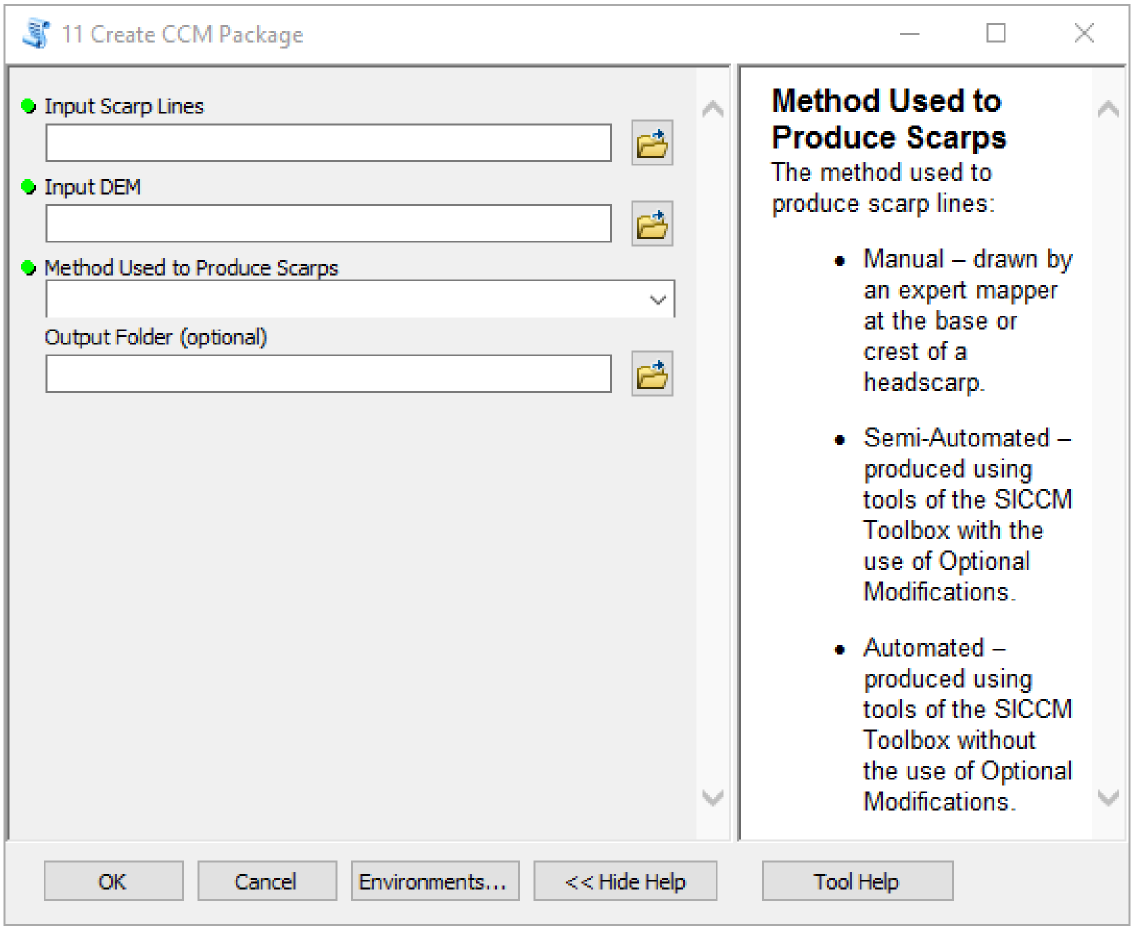

06 Digitize Stream Channels (Optional)
Input DEM
DEM Linear Unit
First Stream Accumulated Area (optional)
1
Acres
Second Stream Accumulated Area (optional)
3
Acres
Third Stream Accumulated Area (optional)
5
Acres
06 Digitize Stream Channels (Optional)
Produces stream channel layers from the Input DEM. Stream channels are created based on the minimum area of terrain that flows downslope to accumulate at a given point. Large accumulated areas result in stream channels that are short, and small accumulated areas result in stream channels that are long. All DEM pixels that accumulate more than a given accumulated area
OK
Cancel
Environments...
<< Hide Help
Tool Help

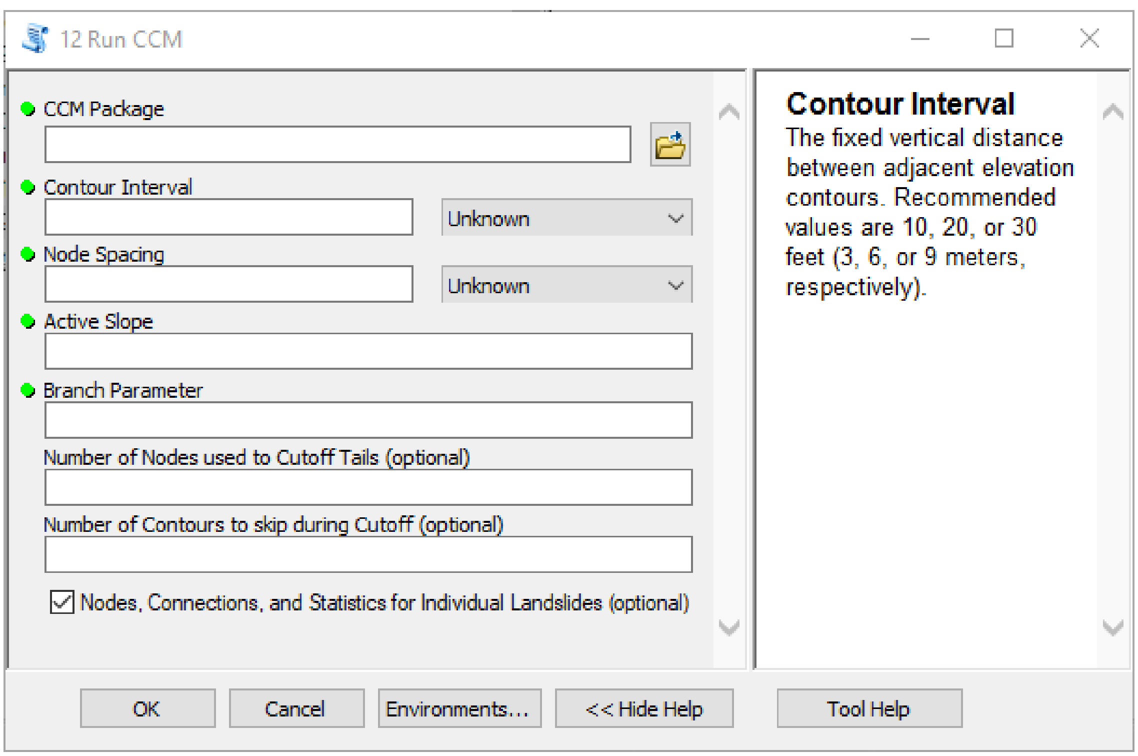

07 Create Rock Score Raster (Optional)
Input DEM
Cell Size Used to Subtract from Input DEM (optional)
07 Create Rock Score Raster (Optional)
Computes a Rock Score Raster from an Input DEM. The Rock Score Raster attempts to capture volumetric roughness by subtracting a smoothed version of the DEM from the original version. For the purposes of this tool, smoothing is accomplished by resampling to a lower resolution.
OK
Cancel
Environments...
<< Hide Help
Tool Help


08 Identify Rocks from Rock Score Raster (Optional)
Input Rock Score Raster
Rock Score Threshold (optional)
08 Identify Rocks from Rock Score Raster (Optional)
Creates rock outcrop polygons from the rock score raster.
OK
Cancel
Environments...
<< Hide Help
Tool Help


09 Eliminate Non Scarp Topography
Input Candidates
Input Non Scarps (optional)
Search Distance (optional)
Unknown
OK
Cancel
Environments...
<< Hide Help
Tool Help
09 Eliminate Non Scarp Topography
Assigns labels of scarp and non scarp to scarp polygon candidates.


10 Create Scarp Lines from Scarp Polygons
Input Candidates
Thinning Cell Size (optional)
OK
Cancel
Environments...
<< Hide Help
Tool Help
10 Create Scarp Lines from Scarp Polygons
Creates scarp lines from scarp polygons.


11 Create CCM Package
Input Scarp Lines
Input DEM
Method Used to Produce Scarps
Output Folder (optional)
Method Used to Produce Scarps
The method used to produce scarp lines:
Manual – drawn by an expert mapper at the base or crest of a headscarp.
Semi-Automated – produced using tools of the SICCM Toolbox with the use of Optional Modifications.
Automated – produced using tools of the SICCM Toolbox without the use of Optional Modifications.
OK
Cancel
Environments...
<< Hide Help
Tool Help


12 Run CCM
CCM Package
Contour Interval
Unknown
Node Spacing
Unknown
Active Slope
Branch Parameter
Number of Nodes used to Cutoff Tails (optional)
Number of Contours to skip during Cutoff (optional)
Nodes, Connections, and Statistics for Individual Landslides (optional)
Contour Interval
The fixed vertical distance between adjacent elevation contours. Recommended values are 10, 20, or 30 feet (3, 6, or 9 meters, respectively).
OK
Cancel
Environments...
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