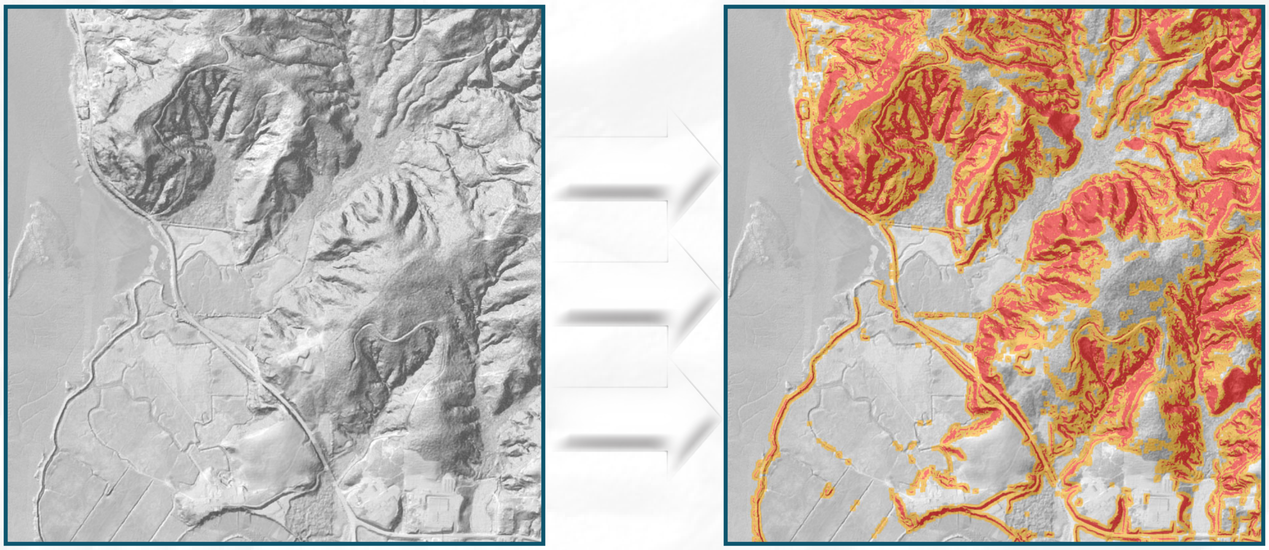
PROTOCOL FOR SHALLOW-LANDSLIDE SUSCEPTIBILITY MAPPING

by William J. Burns, Ian P. Madin, and Katherine A. Mickelson



SPECIAL PAPER 45

2012

OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

NOTICE

The Oregon Department of Geology and Mineral Industries is publishing this paper because the subject matter is consistent with the mission of the Department. This paper describes a method for preparing regional estimates of shallow-landslide susceptibility, and these methods may not be suitable for site-specific purposes. Landslides hazards for a specific site are best assessed through geotechnical or engineering geological studies by qualified practitioners.

Oregon Department of Geology and Mineral Industries Special Paper 45
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Special Paper 45

PROTOCOL FOR SHALLOW-LANDSLIDE SUSCEPTIBILITY MAPPING

By

William J. Burns[1], Ian P. Madin[1], and Katherine A. Mickelson[1]

2012

[1]Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, #28, Suite 965, Portland, OR 97232;

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 EXECUTIVE SUMMARY

Landslides are one of the most significant natural hazards in Oregon and cause millions of dollars in damage annually. Identifying areas susceptible to future landslides is a critical step in reducing landslide risk. This paper describes a standardized procedure for developing shallow-landslide susceptibility maps. This procedure is being used by the Oregon Department of Geology and Mineral Industries (DOGAMI) to produce standardized shallow-landslide susceptibility maps for areas of Oregon.

The shallow-landslide susceptibility map protocol combines an inventory of existing landslides (see DOGAMI Special Paper 42 [Burns and Madin, 2009a]) with hazard zones derived from a Factor of Safety (FOS) map and buffers.

This protocol also includes a map template for producing a standardized shallow-landslide susceptibility map at a scale of 1:8,000, tiled by quarters of U.S. Geological Survey (USGS) 7.5 minute quadrangles.

By identifying areas prone to future damaging landslides, this protocol and products produced by following this protocol can be used to help Oregon communities become more resilient to the impacts of landslide hazards.

2.0 INTRODUCTION

Worldwide, landslides cause billions of dollars in property damage and thousands of deaths every year (Hong and others, 2007). In the United States landslides cause an average of 25–50 deaths and over $2 billion in economic losses annually (Turner and Schuster, 1996; Spiker and Gori, 2003). Climate, geology, and topography combine to make Oregon a landslide-prone state, with landslide losses exceeding $100 million in direct damage during severe winter storms (Wang and others, 2002). Landslides are also a chronic hazard in Oregon, with annual average maintenance and repair costs for landslides in the state estimated at over $10 million (Wang and others, 2002). The growing Oregon population inevitably pushes development onto landslide-prone slopes, adding to population and infrastructure at risk (Figure 1). Mitigating the risk starts with having accurate, detailed, and comprehensive landslide hazard maps, including landslide inventory and susceptibility maps.

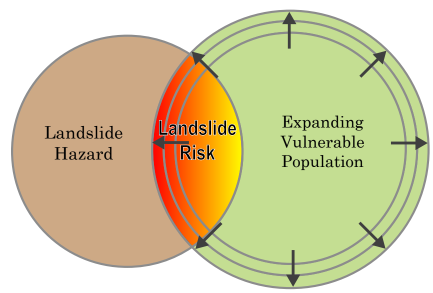


Figure 1. Risk diagram displaying the overlap of the landslide hazard and the vulnerable population (modified after Wood, 2007).

In 2005, DOGAMI began a collaborative landslide research program with the U.S. Geological Survey (USGS) Landslide Hazards Program to identify and understand landslide hazards in Oregon. The key initial finding was the importance of high-resolution lidar-derived digital elevation models (DEMs) for both inventory of existing landslides and modeling of landslide susceptibility areas (Burns, 2007). We use lidar DEMs with a resolution of 1 m to map the characteristic morphology of landslides with great completeness, accuracy, and precision, even in heavily forested areas.

In 2007, DOGAMI began to collect high-resolution lidar topographic data over large swaths of Oregon. With lidar data currently available for over 85% of the state population, DOGAMI has begun to systematically map landslides in Oregon, guided by DOGAMI Special Paper 42 (SP-42), Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery (Burns and Madin, 2009a). A complete SP-42 landslide inventory results in an ArcGIS-format geodatabase of landslide data that include landslide type, size, scarp height, estimated depth to failure plane, and confidence of identification.

With an accurate inventory in hand, the next step in a complete landslide hazard mapping program is to develop susceptibility maps for common types of landslides. This paper describes a protocol for using detailed landslide inventory data collected under the SP-42 guidelines, lidar topographic data, and geotechnical data to produce a standardized shallow-landslide susceptibility map. Coupled with the inventory map, the shallow-landslide susceptibility map can provide residents, local government, and developers with critical information for reducing landslide risk through planning and engineering. The protocol is intended to standardize and streamline DOGAMI's efforts to create shallow-landslide susceptibility maps in Oregon. It is also intended to serve as a guide for others who are interested in producing standardized shallow-landslide susceptibility maps and to help end users of these maps understand how the maps were created. To this end, we have included a detailed description of DOGAMI's shallow-landslide susceptibility mapping procedure and a template for standardized 1:8,000-scale shallow-landslide susceptibility maps based on quarters of USGS 7.5 minute quadrangles.

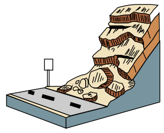
DOGAMI intends to use this protocol and template to complete standardized shallow-landslide susceptibility maps for as much of Oregon as funding and staff allow. By following and referencing this paper, maps can be made more quickly and consistently, and other parties can make maps that conform to this standard.

This study was funded in part by the U.S. Geologic Survey (USGS) Landslide Hazards Program under Cooperative Agreement #05CRGR0002.

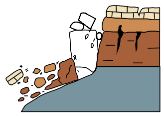
2.1 Shallow Landslides Defined

The term landslide includes a wide range of gravity-driven downslope movements of material that all have different speeds, sizes, frequencies of movements and triggering conditions, and very different resulting hazards. Landslide types differentiated in SP-42 include falls, topples, slides, spreads, and flows as illustrated in Figure 2 and Figure 3.

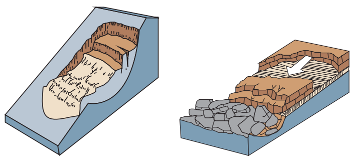
As the name implies, shallow landslides involve movement of a relatively thin layer of slope material and have a shallow failure plane (Figure 4). Shallow landslides in Oregon are typically slumps, translational slides, earth flows, or complex combinations of these types. In order to classify landslides as shallow, we need to know or estimate the depth to the failure plane, and define a depth threshold to separate shallow landslides from deep landslides. SP-42 details a method for calculating the estimated depth of failure using information about scarp height and adjacent slope angles, so that landslide inventories developed according to that protocol will include values for depth to failure plane. There is no widely accepted boundary value between deep and shallow landslides. We have selected 4.6 m (15 ft) as the boundary between shallow and deep-seated landslides based on the combination of several factors and results from other studies discussed in detail in SP-42.



Falls are near-vertical, rapid movements of masses of materials, such as rocks or boulders. The rock debris sometimes accumulates as talus at the base of a cliff.

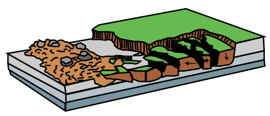


Topples are distinguished by forward rotation about some pivotal point, below or low in the mass.

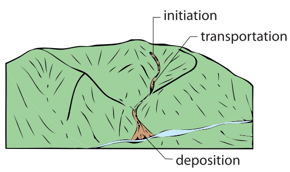


Slides are downslope movement of soil or rock on a surface of rupture (failure plane or shear-zone).

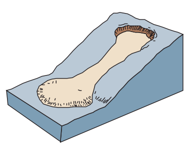
- **Rotational** slides move along a surface of rupture that is curved and concave.
- **Translational** slides displace along a planar or undulating surface of rupture, sliding out over the original ground surface.



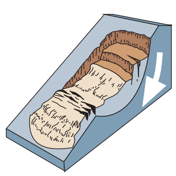
Spreads are commonly triggered by earthquakes, which can cause liquefaction of an underlying layer and extension and subsidence of commonly cohesive materials overlying liquefied layers.



Channelized Debris Flows commonly start on a steep, concave slope as a small slide or earth flow into a channel. As this mixture of landslide debris and water flows down the channel, it pick ups more debris, water, and speed, and deposits in a fan at the outlet of the channel.



Earth Flows commonly have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head.



Complex landslides are combinations of two or more types. A common complex landslide is a slump-earth flow, which usually exhibit slump features in the upper region and earth flow features near the toe.

Figure 2. Block diagrams and detailed descriptions of some of the most common types of landslides (modified from Highland [2004] and Varnes [1978]).

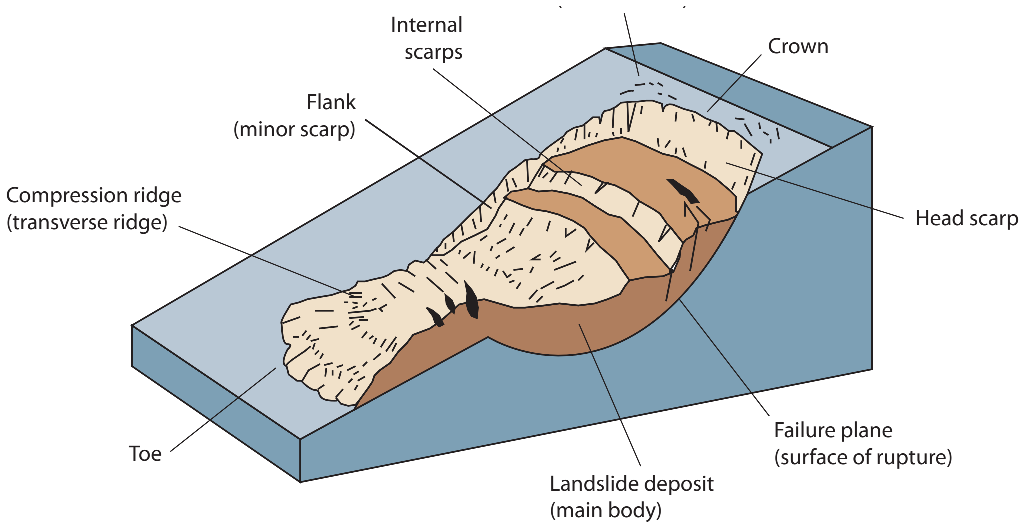


Figure 3. Block diagram of a slump-earth flow showing common features (modified from Highland [2004] and Varnes [1978]).

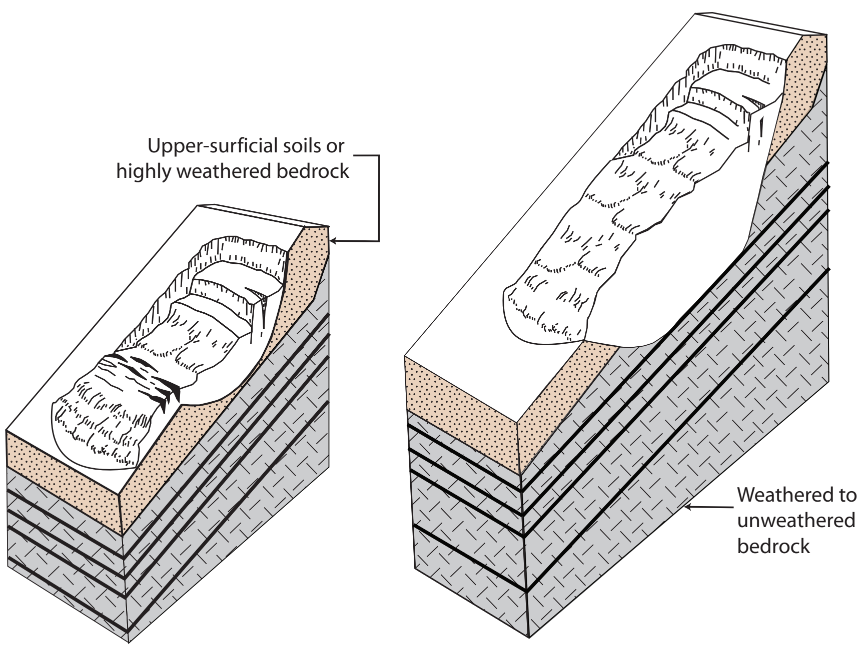


Figure 4. Examples of shallow and deep landslides.

3.0 METHODOLOGY

3.1 Overview

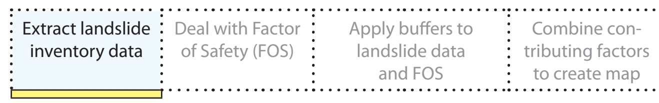
The method we use to identify areas susceptible to shallow landslides combines 1) areas of mapped shallow landslides extracted from an SP-42 inventory with 2) calculated factors of safety (FOS). These two contributing factors are then filtered and buffered, and the resulting four contributing factors are assigned to high, moderate, or low susceptibility zones. The four contributing factors (maps; see below) that are combined to create the final shallow-landslide susceptibility map are:

- **Inventory zone map:** mapped shallow-landslides from an SP-42 inventory
- **FOS class map:** map of Factor of Safety classes (high, moderate, and low)
- **Head scarp buffer map:** map of SP-42 inventory head scarp buffers
- **FOS buffer map:** map of moderate and high FOS Class buffers

The final susceptibility zones are displayed using a standardized map template. Each of these steps is described in sections 3.2 through 3.7. We use Esri ArcView® software and the 3D Analyst™ and ArcGIS® Spatial Analyst™ extensions for the GIS portion of this procedure. Unless otherwise specified, all rasters used have a cell size of 3 ft (1 m), which matches the native resolution of lidar data collected by DOGAMI.

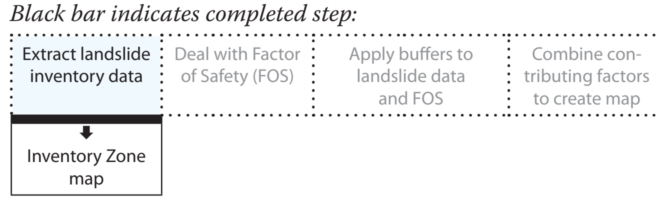
3.2 Extraction of Landslide Inventory

Note: To aid in understanding the sequence of steps required to complete the protocol, a small graphical "progress bar" is provided for each step. Yellow bar indicates current step.



The landslide inventory used in the shallow-landslide susceptibility protocol was developed following SP-42 standards. An example SP-42 map is shown in Figure 5, and a sample of landslide attribute data from this map/geodatabase is shown in Table 1. All shallow-seated landslide deposit polygons (except channelized debris flow deposits; i.e., fans) and their head scarp polygons are queried from the inventory database and converted to a raster map with a value of 3 (high-susceptibility zone) for the polygons. This is the **inventory zone map**.

Black bar indicates completed step:



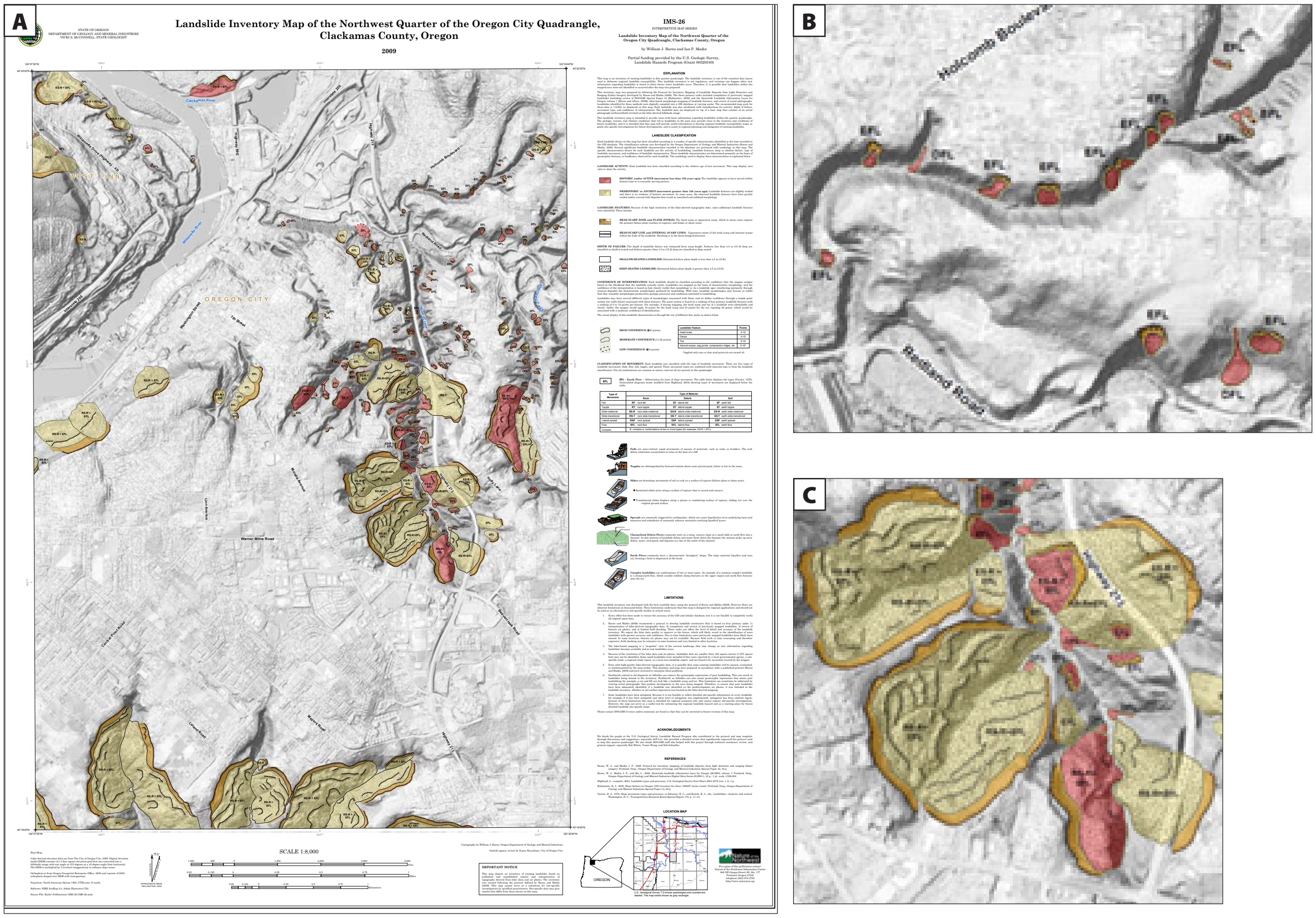


Figure 5. (a) Example of a DOGAMI landslide inventory map for the Oregon City quadrangle (DOGAMI IMS-26, actual map plate dimensions are 36 × 42 inches [Burns and Madin, 2009b]). The template includes explanation of the symbology used on the map including landslide activity, features, depth of failure, confidence of interpretation, and classification of movement. (b) An area in the northern portion of the map with many shallow landslides. (c) An area in the central portion of the map with generally large deep landslides.

Table 1. Example landslide inventory geodatabase table* (Burns and Madin, 2009b).

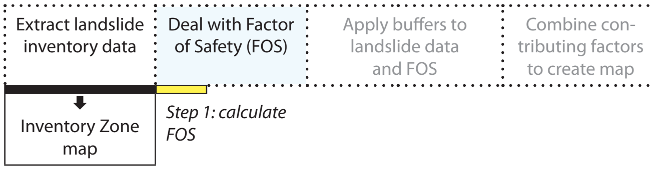
OBJECTID	SHAPE_Leng	SHAPE_Area	UNIQUE_ID	TYPE_MOVE	MOVE_CLASS	MOVE_CODE	CONFIDENCE	AGE
976	665.28829393800	14955.92269280000	Oregon_City_17	Flow	Debris Flow	DFL	Moderate (11-29)	Historic (<150yrs)
977	368.74027446700	5455.59656431000	Oregon_City_170	Flow	Debris Flow	DFL	High (=>30)	Historic (<150yrs)
978	542.66829747200	10992.82005570000	Oregon_City_171	Flow	Debris Flow	DFL	High (=>30)	Historic (<150yrs)
979	725.48317371700	15815.09065630000	Oregon_City_172	Flow	Debris Flow	DFL	High (=>30)	Historic (<150yrs)
980	635.83947679300	25833.35565330000	Oregon_City_173	Flow	Earth Flow	EFL	High (=>30)	Historic (<150yrs)
981	1295.76075306000	78588.00239690000	Oregon_City_174	Flow	Earth Flow	EFL	High (=>30)	Historic (<150yrs)
982	2745.38388612000	385769.04703800000	Oregon_City_175	Slide	Complex	RS-R+EFL	High (=>30)	Pre-Historic (>150yrs)
983	1476.62269809000	144910.93313100000	Oregon_City_176	Slide	Complex-Earth Slide-Rotational+Earth Flow	ES-R+EFL	Moderate (11-29)	Pre-Historic (>150yrs)
984	671.66180282100	29819.61018390000	Oregon_City_177	Flow	Earth Flow	EFL	Moderate (11-29)	Pre-Historic (>150yrs)
985	2067.76691857000	240197.09559000000	Oregon_City_178	Slide	Complex-Earth Slide-Rotational+Earth Flow	ES-R+EFL	High (=>30)	Historic (<150yrs)
986	6363.46488433000	1636933.77794000000	Oregon_City_179	Slide	Complex	RS-R+EFL	Moderate (11-29)	Pre-Historic (>150yrs)
987	441.31665802900	8700.82205880000	Oregon_City_18	Flow	Debris Flow	DFL	Moderate (11-29)	Historic (<150yrs)
988	605.04255044600	22854.23258460000	Oregon_City_181	Flow	Earth Flow	EFL	Moderate (11-29)	Historic (<150yrs)
989	1128.71921665000	40219.89008570000	Oregon_City_182	Flow	Debris Flow	DFL	High (=>30)	Historic (<150yrs)
990	4537.60120344000	966447.88196900000	Oregon_City_183	Slide	Complex	RS-R+EFL	High (=>30)	Pre-Historic (>150yrs)
991	3665.52714980000	625881.42477300000	Oregon_City_184	Slide	Complex	RS-R+EFL	High (=>30)	Historic (<150yrs)
992	3643.05658106000	713317.28781100000	Oregon_City_185	Slide	Complex	RS-R+EFL	High (=>30)	Pre-Historic (>150yrs)
993	465.52123138400	9138.63555378000	Oregon_City_186	Flow	Debris Flow	DFL	High (=>30)	Historic (<150yrs)
994	764.21787525400	23121.38473620000	Oregon_City_187	Flow	Earth Flow	EFL	High (=>30)	Historic (<150yrs)
995	743.76388204600	24203.91041030000	Oregon_City_188	Flow	Earth Flow	EFL	High (=>30)	Historic (<150yrs)

DATE_MOVE	NAME	GEOL	SLOPE	HS_HEIGHT	FAN_HEIGHT	FAIL_DEPTH	DEEP_SHAL	HS_IS1	IS1_IS2
		Tgsb	10.00000000000	0.00000000000	29.00000000000	0.00000000000		0.00000000000	0.00000000000
		Tt	10.00000000000	0.00000000000	8.00000000000	0.00000000000		0.00000000000	0.00000000000
		Tt	10.00000000000	0.00000000000	14.00000000000	0.00000000000		0.00000000000	0.00000000000
		Tt	10.00000000000	0.00000000000	13.00000000000	0.00000000000		0.00000000000	0.00000000000
		Tt	22.00000000000	15.00000000000	0.00000000000	13.90890000000	Shallow	0.00000000000	0.00000000000
		Tt	22.00000000000	17.00000000000	0.00000000000	15.76340000000	Deep	0.00000000000	0.00000000000
	Mountain View Cemetary Landslide	Tt	20.00000000000	75.00000000000	0.00000000000	70.48170000000	Deep	110.00000000000	125.00000000000
		Tt	20.00000000000	30.00000000000	0.00000000000	28.19270000000	Deep	80.00000000000	0.00000000000
		Tt	20.00000000000	17.00000000000	0.00000000000	15.97590000000	Deep	0.00000000000	0.00000000000
	Highway 213 Landslide	Tt	20.00000000000	45.00000000000	0.00000000000	42.28900000000	Deep	0.00000000000	0.00000000000
	Highway 213 Landslide	Tt	20.00000000000	25.00000000000	0.00000000000	23.49390000000	Deep	120.00000000000	0.00000000000
		Tgsb	10.00000000000	0.00000000000	5.00000000000	0.00000000000		0.00000000000	0.00000000000
	Highway 213 Landslide	Tt	22.00000000000	14.00000000000	0.00000000000	12.98160000000	Shallow	0.00000000000	0.00000000000
		Tt	10.00000000000	0.00000000000	10.00000000000	0.00000000000		0.00000000000	0.00000000000
		Tt	20.00000000000	65.00000000000	0.00000000000	61.08420000000	Deep	80.00000000000	80.00000000000
12/1/2005	Newell Creek Apartments Landslide	Tt	20.00000000000	80.00000000000	0.00000000000	75.18050000000	Deep	250.00000000000	0.00000000000
		Tt	20.00000000000	40.00000000000	0.00000000000	37.59020000000	Deep	250.00000000000	175.00000000000
	Highway 2								

IS2_IS3	IS3_IS4	HD_AVE	DIRECT	AREA	VOL	QUADNAME	Text
0.00000000000	0.00000000000	0.00000000000	45.00000000000	14955.90000000000	144573.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	90.00000000000	5455.57000000000	14548.20000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	90.00000000000	10992.80000000000	51299.60000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	292.50000000000	15815.00000000000	68531.80000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	90.00000000000	25833.30000000000	359312.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	112.50000000000	78587.70000000000	1238810.00000000000	Oregon_City	
0.00000000000	0.00000000000	118.00000000000	90.00000000000	385768.00000000000	27189600.00000000000	Oregon_City	
0.00000000000	0.00000000000	80.00000000000	360.00000000000	144910.00000000000	4085410.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	67.50000000000	29819.50000000000	476392.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	247.50000000000	240196.00000000000	10157700.00000000000	Oregon_City	
0.00000000000	0.00000000000	120.00000000000	225.00000000000	1111760.00000000000	26119500.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	45.00000000000	8700.79000000000	14501.30000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	360.00000000000	22854.10000000000	296684.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	292.50000000000	40219.70000000000	134066.00000000000	Oregon_City	
125.00000000000	0.00000000000	95.00000000000	315.00000000000	966444.00000000000	59034400.00000000000	Oregon_City	
0.00000000000	0.00000000000	250.00000000000	90.00000000000	625879.00000000000	47053900.00000000000	Oregon_City	
0.00000000000	0.00000000000	212.00000000000	315.00000000000	713314.00000000000	26813700.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	337.50000000000	9138.60000000000	30462.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	67.50000000000	23121.30000000000	300403.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	337.50000000000	24203.80000000000	419290.00000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	292.50000000000	13266.40000000000	35377.10000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	45.00000000000	4132.57000000000	8265.14000000000	Oregon_City	
0.00000000000	0.00000000000	0.00000000000	90.00000000000	8481.92000000000	25445.80000000000	Oregon_City	
0.00000000000	0.00000000000	150.00000000000	225.00000000000	262120.00000000000	3694940.00000000000	Oregon_City	

*This table has been split into three sections to show all the fields.

3.3 Calculation of the Factor of Safety



The mechanics of slope stability can be divided into two forces: driving forces and resisting forces. These two forces oppose each other, and the state of stability (limit-equilibrium analyses) existing in a slope can be thought of as their ratio:

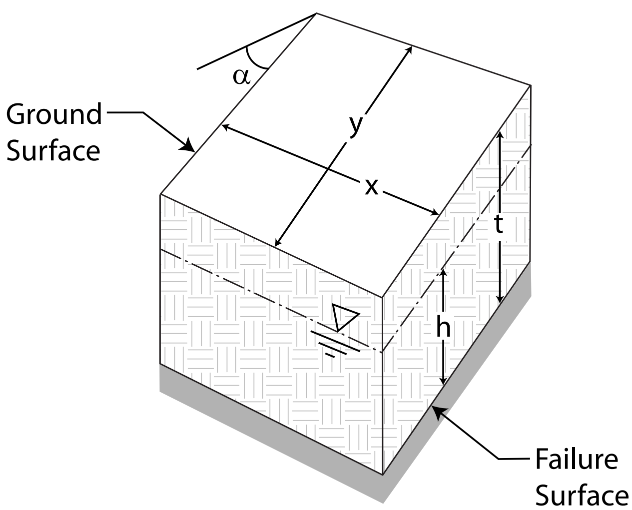
$$\frac{\text{resisting forces}}{\text{driving forces}}$$

When the material properties and geometry of a slope are examined, this simplified ratio becomes an equation called the Factor of Safety (FOS) against landsliding and is defined as (Cornforth, 2005):

$$\text{Factor of Safety (FOS)} = \frac{\text{total available shear resistance}}{\text{shear force needed for static equilibrium}}$$

A FOS > 1 would theoretically be a stable slope because the shear resistance (or strength) would be greater than the shear stress. A FOS < 1 would theoretically be an unstable slope because the stress would be greater than the shear strength. A critically stable slope would have a FOS = 1. Because it is impossible to know all conditions present within a slope, most geotechnical engineers and engineering geologists recommend that slopes with a FOS < 1.5 be considered potentially unstable (Turner and Schuster, 1996; Cornforth, 2005). Furthermore, in the State of Oregon Building Code (Oregon Residential Specialty Code, R404.5, 2008) a FOS of 1.5 is commonly required for design of slopes and slope structures such as retaining walls.

Software packages commonly used in GIS analyses to estimate the stability of slopes represented in data grids by calculating the FOS of each grid cell include SINMAP (Stability Index MAPping; Pack and others, 1999), SHALSTAB (Montgomery and Dietrich, 1994), LISA (Level I Stability Analysis; Denning, 1994), TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis; Baum and others, 2002). These programs calculate slope stability using an infinite slope equation analysis (Harp and others, 2006). For this protocol, we also use the infinite slope FOS equation, as illustrated in Figure 6, to calcu-



Material Properties

c' = Cohesion (effective)
ϕ' = Angle of Internal Friction (effective)
γ = Soil Density (unit weight)
γ_w = Groundwater Density (unit weight)

Other Variables

t = Depth to Failure Surface
m = Groundwater Depth Ratio
α = Slope Angle (degrees)
x = Horizontal Grid Distance (on DEM)
y = Vertical Grid Distance (on DEM)

$$\text{Factor of Safety (FOS)} = \frac{c'}{\gamma\, t \sin\alpha} + \frac{\tan\phi'}{\tan\alpha} - \frac{m\, \gamma_w \tan\phi'}{\gamma \tan\alpha}$$

Figure 6. Infinite slope analysis: diagram shows parameters for one digital elevation model (DEM) grid cell and the Factor of Safety (FOS) equation (Harp and others, 2006).

late the FOS for every grid cell in a map area (Harp and others, 2006).

Because the use of the infinite slope equation for regional stability analysis is limited to a grid type analysis, the results are a calculated FOS for each individual grid cell. This type of analysis does not consider the potential impact of adjacent slopes or three-dimensional effects. Therefore, a conservative approach that tends to underestimate the FOS is used in most steps to calculate the FOS. The limitations and results of this type of approach are discussed in section 5 of this report.

In order to calculate the FOS throughout any area, several datasets are necessary and are discussed in detail in sections 3.3.1–3.3.4:

- Geology—geotechnical material properties
- Groundwater height above failure surface
- Depth to failure surface
- Slope angle

3.3.1 Geology—Geotechnical Material Properties

The geotechnical material properties needed for the infinite slope analysis are cohesion, angle of internal friction, and soil density. Because regional maps of these properties are not available, we substitute the best available digital geologic map (e.g., Figure 7) and link the geologic units to material properties by either collecting local measurements if available or consulting the literature for data from similar units. Because the material properties can vary within a particular geologic unit we choose values that are conservative, that is, values near or at the low end of the range that result in lower FOS values to account for some of this variability.

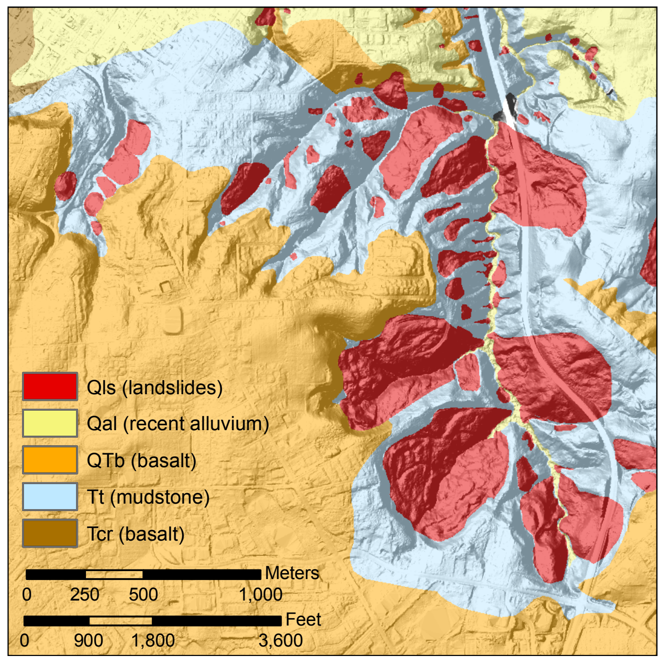


Figure 7. Example of a geologic-material properties map. Map is of a portion of the Oregon City quadrangle. Each geologic unit on the map has associated material properties shown in Table 2 (modified from Madin, 2009).

Because site-specific material properties are not available throughout the state, a table of general values related to different types of common geologic formations in Oregon is provided (Table 2). In areas where more detailed or more accurate material properties are available, those values should supersede the general values given in Table 2.

We convert the vector-based digital geologic map for the study area to a raster, with numeric values that code for each unit (e.g., the raster geologic unit codes [GeolCode field] for the area in Figure 7 would have geologic unit Qls = 1, Qal = 3, QTb = 6, Tt = 7, and Tcr = 6 so that we can perform GIS raster calculations with each geologic unit as a variable for preparing the FOS map (section 3.4).

3.3.2 Groundwater Height above Failure Surface

The height of the groundwater table above the failure surface varies widely from place to place and from season to season. We choose the most conservative case of complete saturation, in which the groundwater table is at the ground surface, and h in the FOS equation is equal to z^* (Figure 6). In areas where more detailed or more accurate groundwater data are available, those values should supersede the conservative complete saturation value used in this protocol.

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*. *In this paper, depth to failure surface is denoted by z rather than by the t of Harp and others (2006).

Table 2. General soil and rock material properties (Harp and others, 2006; Cornforth, 2005; Denning, 1994).

Common Lithology Description	Common Unit or Formation Name	Common Unit Label	Raster Value GeolCode	Angle of Internal Friction (ϕ) (degrees)	Cohesion (c) (kPa)	Cohesion (c) (lb/ft^2)	Unit Weight (saturated) (kN/m^3)	Unit Weight (saturated) (lb/ft^3)	Slope FOS>1.5	Slope FOS>1.25
Sheared landslide debris (silts, clays, sands)	landslide	Qls	—	10	0	0	19	122	3.0	4.0
Shearing mainly along deep failure plane	landslide, colluvium	Qls, Qc	1	28	0	0	19	122	9.5	11.5
Sand, silt, gravel, debris mixtures	artificial fill	Fill, Qf	2	30	0	0	19	122	10.5	12.5
Silt, sand	Quaternary alluvium, loess	Qal, Qff, Ql	3	30	0	0	19	122	10.5	12.5
Sand, gravel, boulders	Quaternary alluvium, gravel fan	Qal, Qcf	4	34	0	0	19	122	12.0	14.5
Sand, silt, clay, gravel	glacial till	Qva, Qt	5	34	10	209	19	122	16.5	19.5
Silty clay with boulders	Columbia River Basalt	Tcr	6	28	24	501	19	122	20.0	24.0
Silty sand, sandy silt, silty gravel	Troutdale Formation	Tt	7	30	10	209	19	122	14.5	17.5

3.3.3 Depth to Failure Surface

We have defined shallow landslides as having failure planes that are ≤ 15 ft (4.6 m) deep. Several lidar-based landslide inventories have been created over the past several years for Oregon including the City of Silverton (Burns and Mickelson, 2012), City of Oregon City, and the City of Astoria areas (Burns and Mickelson, 2010a,b). The shallow landslides mapped in each of these three studies have these mean depth to failure plane values: Silverton = 7.9 ft (2.4 m), Oregon City = 10.0 ft (3 m), and Astoria = 10.3 ft (10.1 m). Also, the shallow landslide dataset (LS-1) used in this study has a mean of 9.1 ft (2.8 m).

In cases where the material has cohesion, using 15 ft (4.6 m) for the z value (depth to failure plane) in the FOS equation results in the most conservative values, as illustrated in Table 3. Because we have chosen to make $h = z$, in cases where the soil has no cohesion the depth to failure plane term is not a factor in the equation (Cornforth, 2005). Therefore we use 15 ft (4.6 m) for both z and h in all cases.

3.3.4 Slope Angle

This protocol requires the use of a high-resolution lidar-derived bare-earth DEM to create a map of slope angles (in degrees) for each grid cell (Figure 8). We use the Slope tool from the Esri 3D Analyst or Spatial Analyst extension with default settings to create the slope map for analysis.

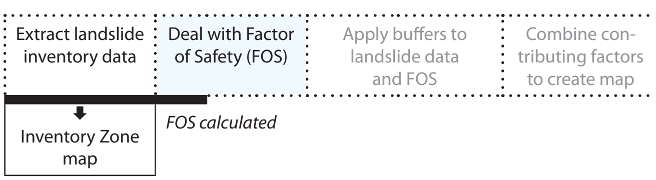


Table 3. Example Factor of Safety (FOS) values calculated for various slopes and values of z, using parameters for residual soil on basalt from Table 2.

Slope	Depth to Failure Plane (z)	Factor of Safety (FOS)
24	5	2.8
24	10	1.7
24	15	1.3
29	5	2.4
29	10	1.4
29	15	1.1

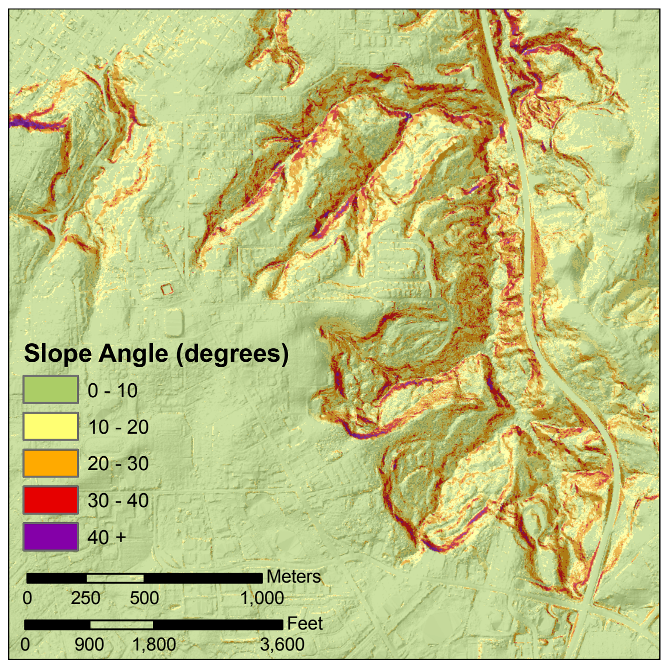
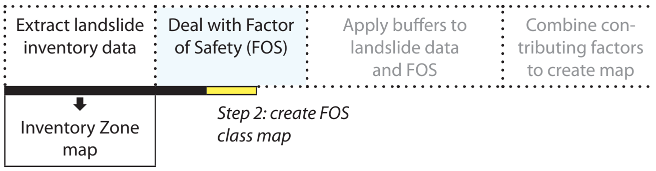


Figure 8. Example of a slope map created from the lidar-derived bare earth digital elevation model (DEM). Map is of a portion of the Oregon City quadrangle. For display, slope angles have been grouped into five slope categories.

3.4 Creation of the Factor of Safety (FOS) Class Map



Our approach to creating a GIS-based FOS class map using the parameters described in section 3.3 involves carrying out the FOS calculations in a spreadsheet to determine threshold slope values for each geologic unit. These threshold slope values are then used to define high, moderate, and low FOS classes (Table 4). For each geologic unit we query the slope map for the values that correspond to each class, then reclassify and mosaic together all the query rasters to produce the complete map.

We use a spreadsheet (provided as Appendix A) to calculate the FOS for each geologic unit in the map area by using the appropriate material property values and slope angles in increments of 0.5 degrees.

From the calculated FOS values in the spreadsheet, we pick the slope angles that produce FOS values closest to 1.5 and 1.25. A FOS value of 1.5 is considered by the geologic and engineering communities as stable and a FOS value of 1.25 is considered moderately stable. These are the threshold slope angles for that particular geologic unit and are used to build GIS queries to produce the FOS class map. In order to account for variability in geotechnical parameters, we group the FOS in classes. We use the raster calculator function in the Esri Spatial Analyst toolbox to build two queries for each geologic unit in the map area. One query is for all areas with slopes between the threshold values (Moderate class), and the other query is for slopes above the high (FOS = 1.25) threshold value (High class). So, for example, to select the appropriate values to go with the calculated values displayed in Table 4 (we used the GeolCode 1 for unit Qls), we build the following queries to apply to the geology and slope rasters:

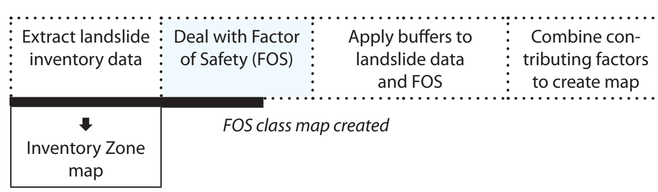
Query 1 (Moderate class): GeolCode = 1 AND Slope >= 9.5 AND Slope <= 11.5

Query 2 (High class): GeolCode = 1 AND Slope > 11.5

The resulting rasters have values of 1 where the condition is true and 0 where it is false. We then repeat this process for each geologic unit in the area. To compile all of the geology/critical slope value queries into a map, we first reclassify (by using the Esri Spatial Analyst Reclassify tool, Figure 9) the individual FOS class rasters following the scheme in Table 5, so that each raster now represents an FOS-based susceptibility zone. We then combine all of the reclassified FOS rasters (using the Esri Spatial Analyst Mosaic To New Raster tool, Figure 10) to produce the final **FOS class map**, a single grid divided into areas of high susceptibility = 3, moderate susceptibility = 2, and low susceptibility = NoData.

Table 4. Sample Factor of Safety (FOS) calculations from spreadsheet for geologic unit landslide deposits (GeolCode Qls =1) of Table 2. Threshold values marked in yellow.

Slope (Degrees)	Factor of Safety (FOS)	
1.0	14.48	**Low** FOS class (FOS >1.5, slope <9.5°)
1.5	9.65	
2.0	7.24	
2.5	5.79	
3.0	4.82	
3.5	4.13	
4.0	3.61	
4.5	3.21	
5.0	2.89	
5.5	2.63	
6.0	2.41	
6.5	2.22	
7.0	2.06	
7.5	1.92	
8.0	1.8	
8.5	1.69	
9.0	1.60	
9.5	1.51	
10.0	1.43	**Moderate** FOS class (FOS 1.25–1.5, slope 9.5°–11.5°)
10.5	1.36	
11.0	1.3	
11.5	1.24	
12.0	1.19	**High** FOS class (FOS <1.25, slope >11.5°)
12.5	1.14	
13.0	1.09	
13.5	1.05	
14.0	1.01	
14.5	0.98	



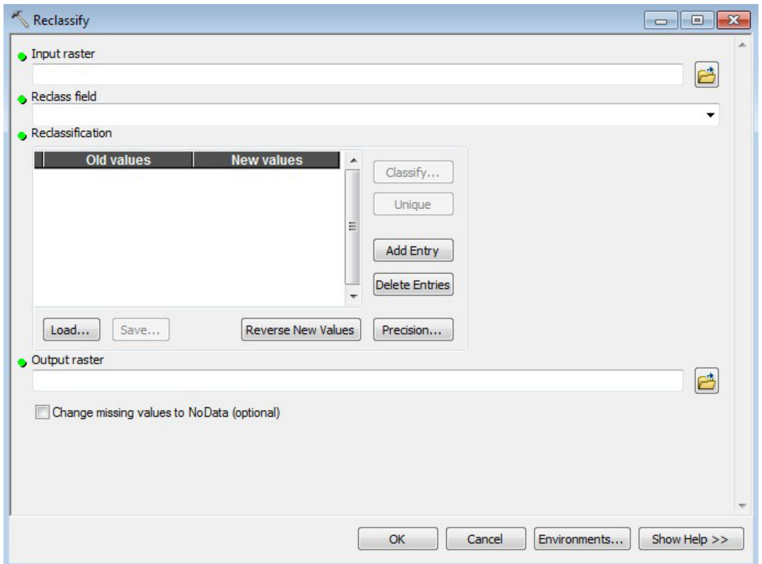


Figure 9. Example of dialog box for the Esri Spatial Analyst Reclassify tool.

Table 5. Reclassification scheme to convert individual unit Factor of Safety (FOS) rasters to susceptibility zones.

FOS	Old	New	Susceptibility
≤ 1.25	0	NoData	—
≤ 1.25	1	3	High
1.25 – 1.5	0	NoData	—
1.25 – 1.5	1	2	Moderate

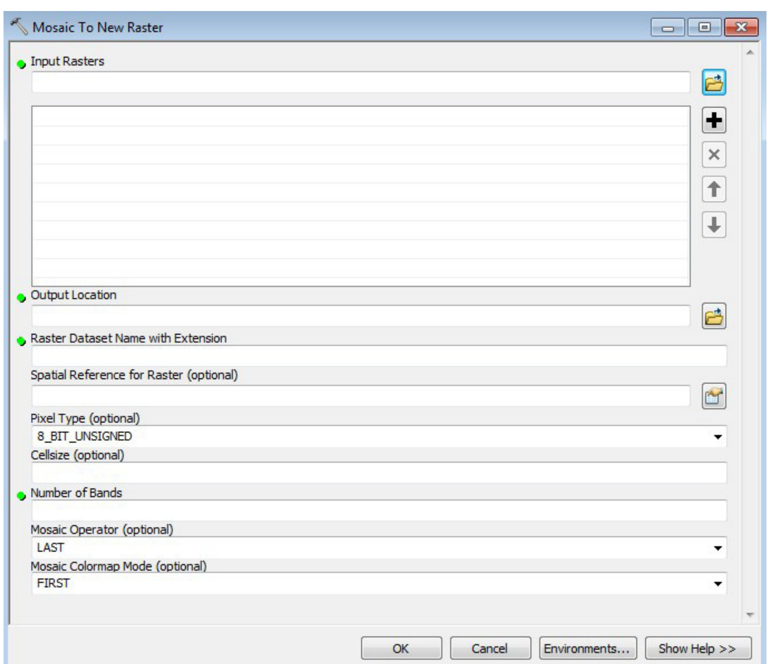
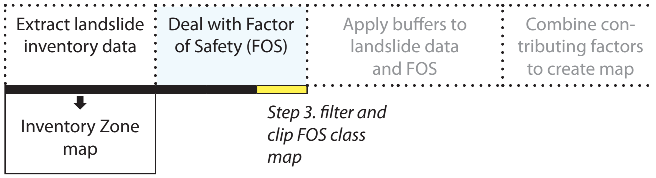


Figure 10. Example of dialog box for the Esri Spatial Analyst Mosaic To New Raster tool used to create the raw susceptibility zone raster. Cell type can be changed to 2_Bit as there are only two values (2 and 3).

3.5 FOS Class Map Filtering and Clipping



3.5.1 Need for Filter

The bare-earth lidar DEMs available for Oregon typically have a raster cell size of 3 ft^2 (1 m^2). When the FOS class map (section 3.4) is prepared using a slope map with such high resolution, many areas with shallow-landslide susceptibility are falsely classified as having moderate or high susceptibility. This occurs because many fine-scale topographic features are represented in the lidar DEM that do not have sufficient vertical or lateral extent to pose a significant shallow landslide hazard. The lidar DEM resolves features like ditches, small retaining walls, road cuts, and other steep slopes having low vertical relief (Figure 11) that are common in developed landscapes. These features return low FOS values (high susceptibility class) because of their steep slope angles and can be extensive in many developed areas, particularly when the buffering steps (described in section 3.6) expand these falsely classified hazard zones over significant parts of the map.

3.5.2 Methods Tested

We examined eight GIS approaches to reduce the overprediction of susceptibility introduced by the FOS calculation. We selected a study area including flat agricultural areas and steep slope areas near Silverton, Oregon, for which we had complete lidar coverage and a complete SP-42 landslide inventory. The goal was to remove areas of high or moderate susceptibility associated with low relief steep slopes without reducing our success in identifying areas with significant shallow-landslide susceptibility. The methods we examined included:

- **Native grid**—FOS class map made with native 3 ft^2 (1 m^2) DEM converted to native 3 ft^2 (1 m^2) slope grid (Figure 12A).
- **Resized slope grid**—FOS class map made with native 3 ft^2 (1 m^2) DEM converted to native 3 ft^2 (1

Figure 11. Photo looking down a residential street in east Portland that displays low vertical relief but steep slopes. Elevation change of slope is roughly 3 feet (1 m). Photo location is shown in Figure 14 and Figure 15 (green dot).

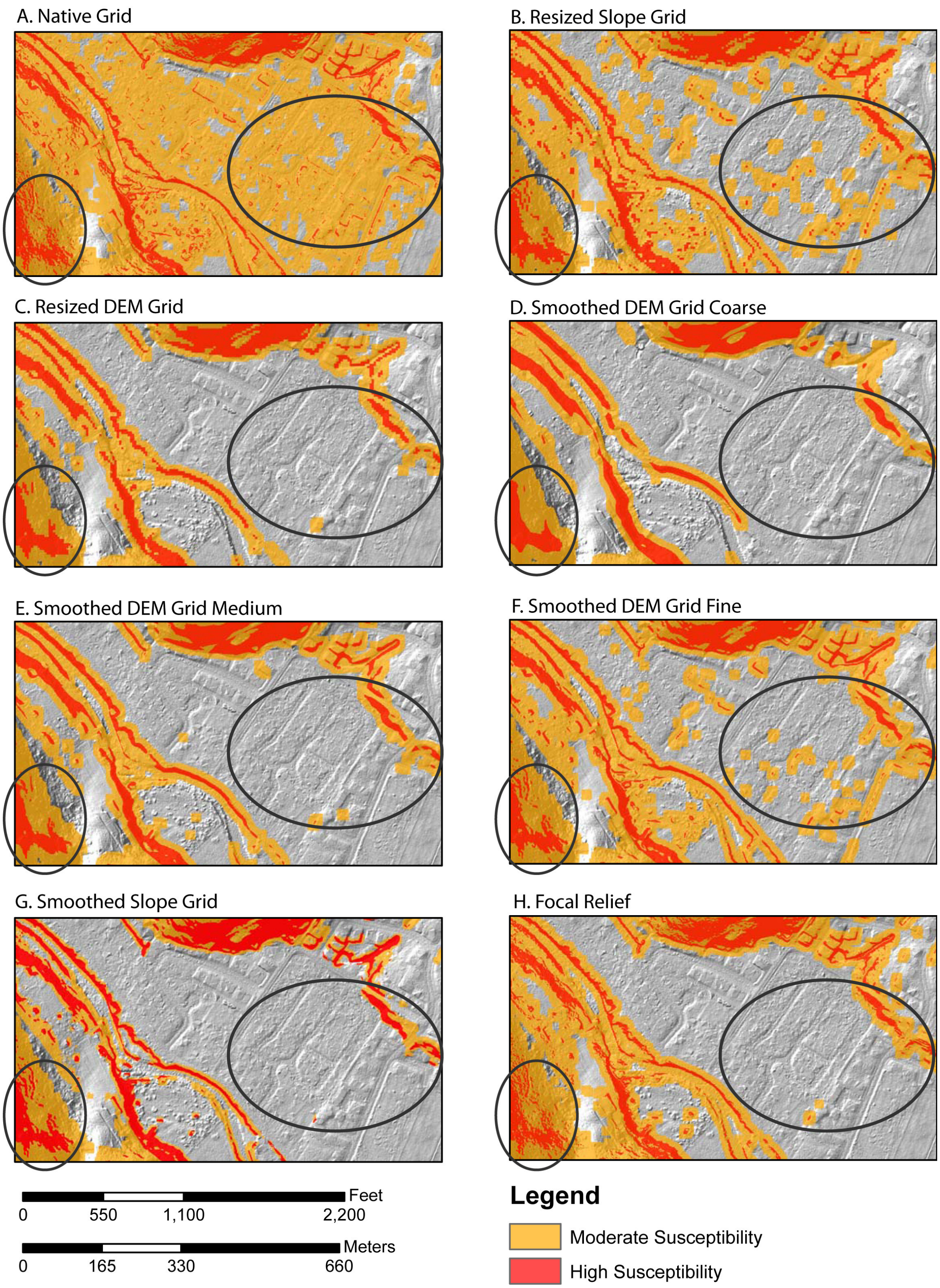


Figure 12. Sample from the Silverton study area used to test alternative methods for reducing the impact of low steep slopes on susceptibility zones. For comparison, note areas with potential for overgeneralization (small ovals) and areas with low-relief steep slopes that should not be included (large ovals).

m^2) slope grid. This slope grid was then resampled (grid sized) to 15 ft^2 (4.6 m^2) cells (Figure 12B).

- **Resized DEM grid—**FOS class map made with native 3 ft^2 (1 m^2) DEM resampled to 15 ft^2 (4.6 m^2). This resampled DEM was then converted to a 15 ft^2 (4.6 m^2) slope grid (Figure 12C).
- **Smoothed DEM grid coarse—**FOS class map made with native 3 ft^2 (1 m^2) DEM that was smoothed with Spatial Analyst Focal Statistics tool (neighborhood analysis; Figure 13A) by applying the mean value of a 60 ft^2 (18 m^2) neighborhood. This smoothed DEM was then converted to a slope grid (Figure 12D).
- **Smoothed DEM grid medium—**FOS class map made with native 3 ft^2 (1 m^2) DEM that was smoothed with Spatial Analyst Focal Statistics tool (neighborhood analysis; Figure 13A) by applying the mean value of a 30 ft^2 (9 m^2) neighborhood. This smoothed DEM was then converted to a slope grid (Figure 12E).
- **Smoothed DEM grid fine—**FOS class map made with native 3 ft^2 (1 m^2) DEM that was smoothed with Spatial Analyst Focal Statistics tool (neighborhood analysis; Figure 13A) by applying the mean value of a 15 ft^2 (4.6 m^2) neighborhood. This smoothed DEM was then converted to a slope grid (Figure 12F).
- **Smoothed slope grid—**FOS class map made with 3 ft^2 (1 m^2) slope grid derived from native 3 ft^2 (1 m^2) DEM and then filtered (smoothed) with Spatial Analyst Focal Statistics tool (neighborhood analysis; Figure 13A) using the mean value of a 15 ft^2 (4.6 m^2) neighborhood (Figure 12G).
- **Focal relief—**FOS class map made with native 3 ft^2 (1 m^2) DEM converted to native 3 ft^2 (1 m^2) slope grid. Portions of the FOS class map were then clipped (removed) with the focal relief grid. The focal relief grid was derived by filtering the native 3 ft^2 (1 m^2) DEM with Spatial Analyst Focal Statistics tool (neighborhood analysis, Figure 13A) using the range of values in a 15 ft^2 (4.6 m^2) neighborhood. Areas with a range of values less than 5 ft (1.5 m) (in other words, less than 5 ft of vertical relief across the 15 ft^2 neighborhood) were clipped from the FOS class map (Figure 12H).

Each of the eight resulting susceptibility maps (A–H, Figure 12) was visually evaluated for its success at capturing the landslides in the inventory with moderate and high hazard zones and its ability to remove regionally flat areas from the moderate and high hazard zones thereby reducing those areas incorrectly identified as susceptible.

The **focal relief** approach (Figure 12H) was judged to produce the best result because it substantially reduces the number of moderate and high susceptibility classes in flat areas, such as plowed fields, while capturing virtually all of the mapped landslides (compare Figure 12A and Figure 12H). This method works through analysis of the neighborhood surrounding a single raster cell (Figure 13A). The range of elevation change (relief) is calculated for the entire neighborhood and that range value is assigned to the cell. Then the next cell is examined and so on. The two ideal results are:

1. The entire neighborhood is flat with no elevation change (Figure 13B) and a low focal range value and thus unlikely to be susceptible to shallow-seated landslides.
2. The neighborhood is nearly all flat, except the elevation change which takes place between 2 adjacent raster cells in a single step (Figure 13D). Low values of focal range will have low susceptibility because the total height of the slope is not sufficient to generate a significant landslide.

However, another possibility is that the entire neighborhood is continuously sloping (Figure 13C) and the elevation change is equal to the focal range. Larger values of focal range correspond to steeper slopes (see Table 6), which are more susceptible to shallow landslides.

Table 6. Maximum slope values corresponding to different focal relief range values.

Focal Relief Range Values	Resultant Maximum Slope Angle (Degrees)
3 ft (1.0 m)	11.5
4 ft (1.2 m)	15
5 ft (1.5 m)	18.5
6 ft (1.8 m)	22

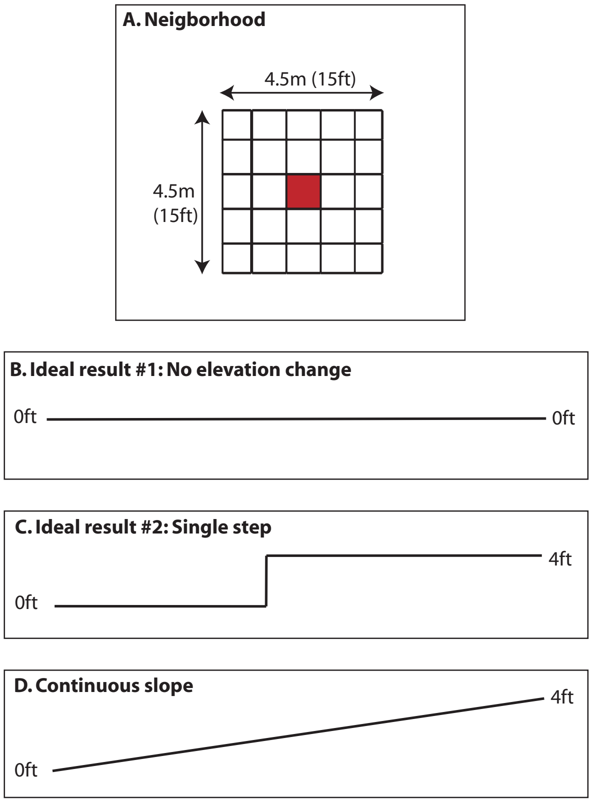


Figure 13. (A) Focal relief analysis on a cell (red) using a 15 ft^2 (4.5 m^2) neighborhood. Ideal results for various topography are (B) no elevation change and (C) single step. Another possibility is (D) continuous slope.

Clipping areas out of the FOS class map that have low values of focal relief range therefore removes (1) flat areas, (2) areas with continuous but gentle slopes, or (3) areas with steep slopes but low relief (i.e., a near-vertical step). The third case targets exactly the kind of features that we intend to reduce, whereas the first case has no impact and the second case impacts the FOS class map only if the focal range value is large, corresponding to steeper slopes. Therefore it is important to select the correct value of focal range to use as the threshold for clipping the FOS class map.

3.5.3 Selecting Appropriate Focal Relief and Focal Range Values

To test the effects of various values of focal relief, we selected an area where we had multiple landslide inventory databases and abundant lidar data—roughly 370 mi^2 (1,000 km^2) centered on the Portland, Oregon, urban area (Figure 14). In order to examine how well each of the focal relief values performed, we ran a parametric spatial statistical analysis with three landslide databases. The first database (LS-1) consists of 1,517 shallow landslides identified spatially by polygons (Burns, 2009a,b; Madin, 2009; Madin and others, 2008; Madin and Niewendorp, 2008; DOGAMI unpublished data) and created following the protocol outlined in SP-42 (Burns and Madin, 2009a). This database was examined in two ways: 1) as an aggregated area of all the landslide polygons, and 2) as individual landslide polygons.

The second landslide database (LS-2) consists of 649 shallow landslides that occurred during severe storms in 1996-1997 and are identified spatially as points (Burns and others, 1998); 309 of these point records were converted to polygons (Drazba, 2008) using lidar DEMs and the original field notes from Burns and others (1998).

The third database (LS-3) consists of the pre-failure slope angles measured at each of the 1,517 shallow landslide sites in the LS-1 database discussed above. Each slope measurement was taken adjacent to the landslide; this slope represents the likely slope angle before each landslide failed and changed the slope.

To test the effects of the various focal ranges, we created a test FOS class map of the study area and applied buffers (described in section 3.6) to produce the raw FOS class map shown in Figure 15. Areas of high (red) and moderate (orange) susceptibility cover much of the map, not only in the steep, landslide-prone Portland Hills that traverse the study area to the northwest but also in flat residential neighborhoods (see inset, Figure 15) where there is little significant hazard. Although this map is very effective at capturing identified landslide sites from all three databases (Table 6), it does so at the cost of including 68% of the study area—including obviously flat areas—in the high and moderate hazard zones.

We then prepared four FOS class maps by clipping the raw FOS class map using the focal range raster and range values of 3, 4, 5, and 6 ft (approximately 1, 1.2, 1.5, and 2 m), then applying buffers the same way as for the unclipped map. We compared how well each of these maps captured the sites from the three landslide databases, as well as the sacrifice in terms of the amount of the map area included in high and moderate zones. The results of the analysis are summarized in Table 7.

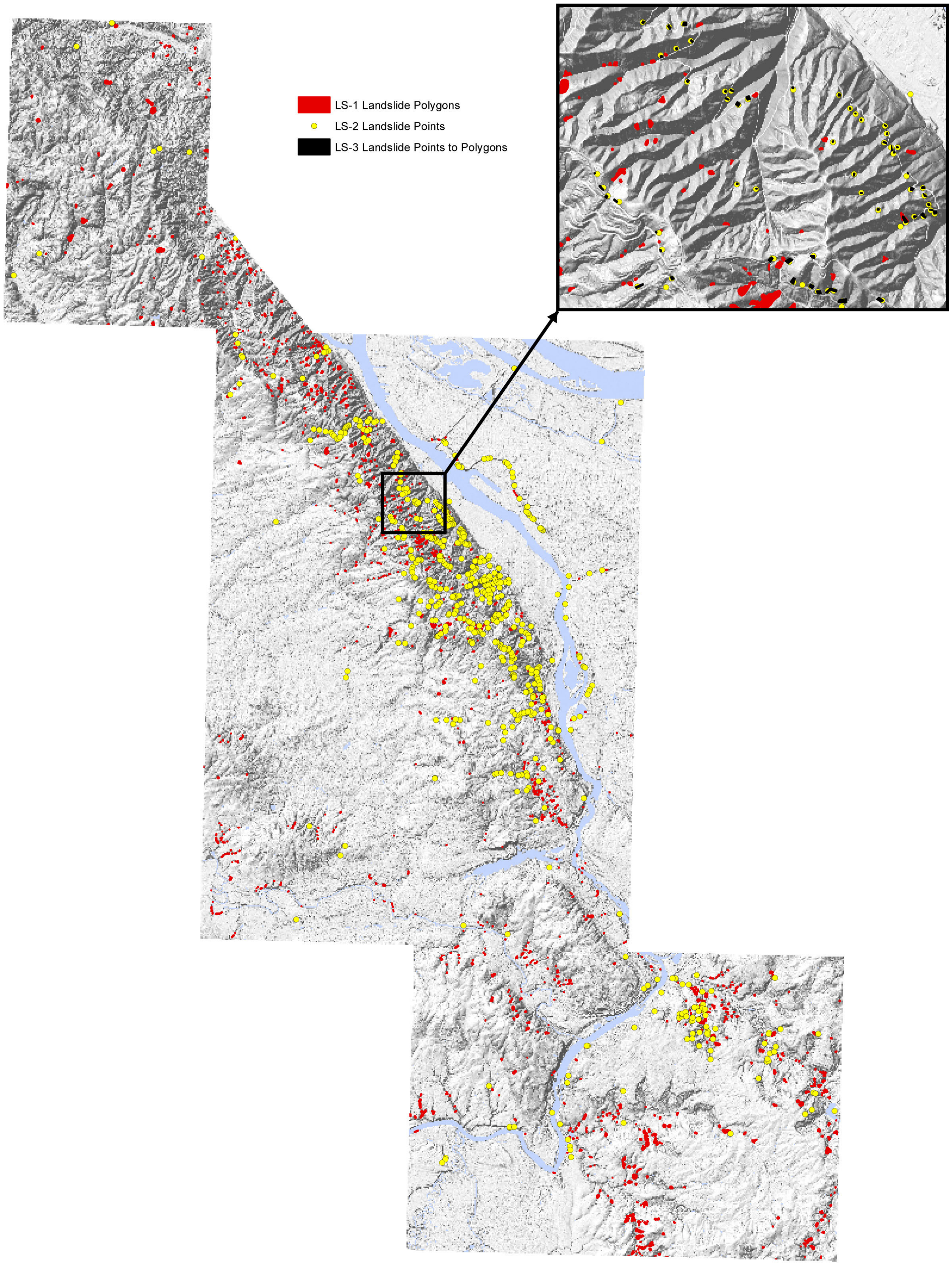


Figure 14. Map of the area used to test focal range values. The three landslide databases (LS-1, LS-2, and LS-3) are displayed on the map.

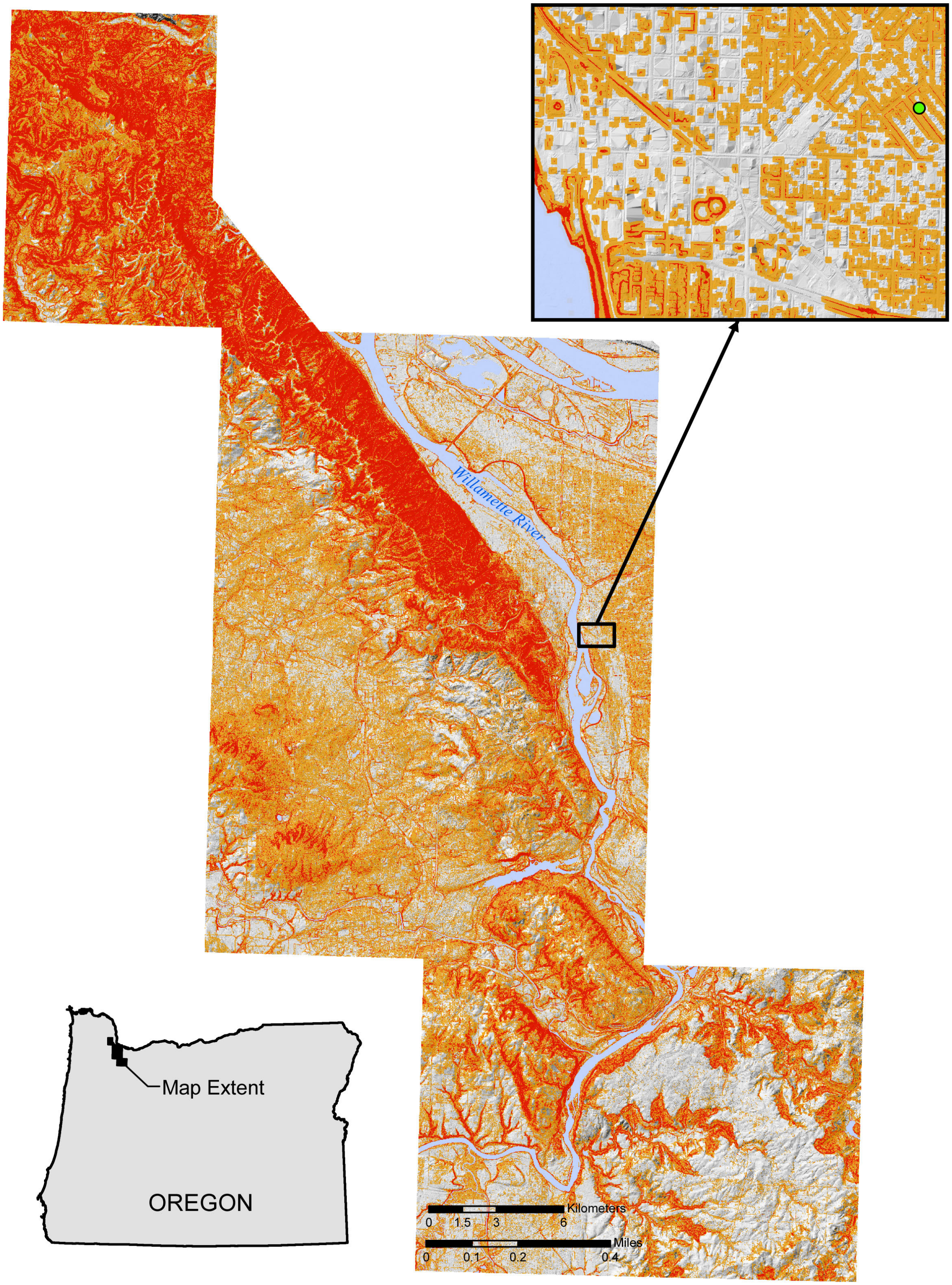


Figure 15. Raw Factor of Safety (FOS) zone map (red = high, orange = moderate, gray = low) for the test area. Black outlines are mapped landslides developed following SP-42 (Burns and Madin, 2009a). Green dot in inset is the Figure 11 photo location.

Table 7. Results of parametric spatial statistical analysis of the comparing raw and clipped focal relief maps to the landslide databases.

	Raw Factor of Safety (FOS), %	Focal Relief, %			
		3 ft (0.9 m)	4 ft (1.2 m)	**5 ft (1.5 m)**	**6 ft (1.8 m)**
Percent of study area in moderate or high zone (includes overprediction of impact of low steep slopes on susceptibility zones)	68	52	42	34	28
Lidar based landslide inventory (LS-1)					
Percent of aggregated landslide inventory within moderate or high hazard zone	98	95	***90***	82	73
Percent of each individual inventoried landslide polygon touching (minimum 9 grid cells) moderate or high hazard zone	99.9	99.9	***99.9***	99.8	99.8
Field based landslide inventory (LS-2)					
Percent of landslide inventory points within moderate or high hazard zone	92	91	***89***	87	84
Percent of 1996-1997 landslide inventory polygons within moderate or high hazard zone	99	99	***99***	99	99
Pre-landslide slope angle database (LS-3)					
Percent of slopes included that are higher than the minimum pre-failure slope angle from the inventory (5 degrees)	100	96	***89***	81	59

We selected the focal range value of 4 ft (1.2 m) as the appropriate value to use, based on its very high capture rate for all three landslide databases coupled with a substantial reduction in the overprediction of the amount of the map area included in the hazard zones. This choice is further supported by the observation that the Oregon Residential Specialty Code (chapter 4, section R404.1.3; 2008) states that "landscape" type retaining walls can be constructed if the wall supports less than 48 inches (4 ft or 1.2 m). In other words, undesigned cuts and fills (with "landscape" type walls) are allowed as long as they do not exceed 4 ft (1.2 m) in height and have a flat (non-sloping) backfill. Most, if not all cities and counties have adopted the state building code. Because one of DOGAMI's goals is for city and county governments to use these maps as part of their local building code regulations, we think it is appropriate to match the existing allowable height of 4 ft with the focal height of 4 ft, which effectively removes these nonconsequential slopes from the hazard zone.

An example of the final **FOS class map** for the test area using the 4 ft (1.2 m) focal range value is shown in Figure 16.

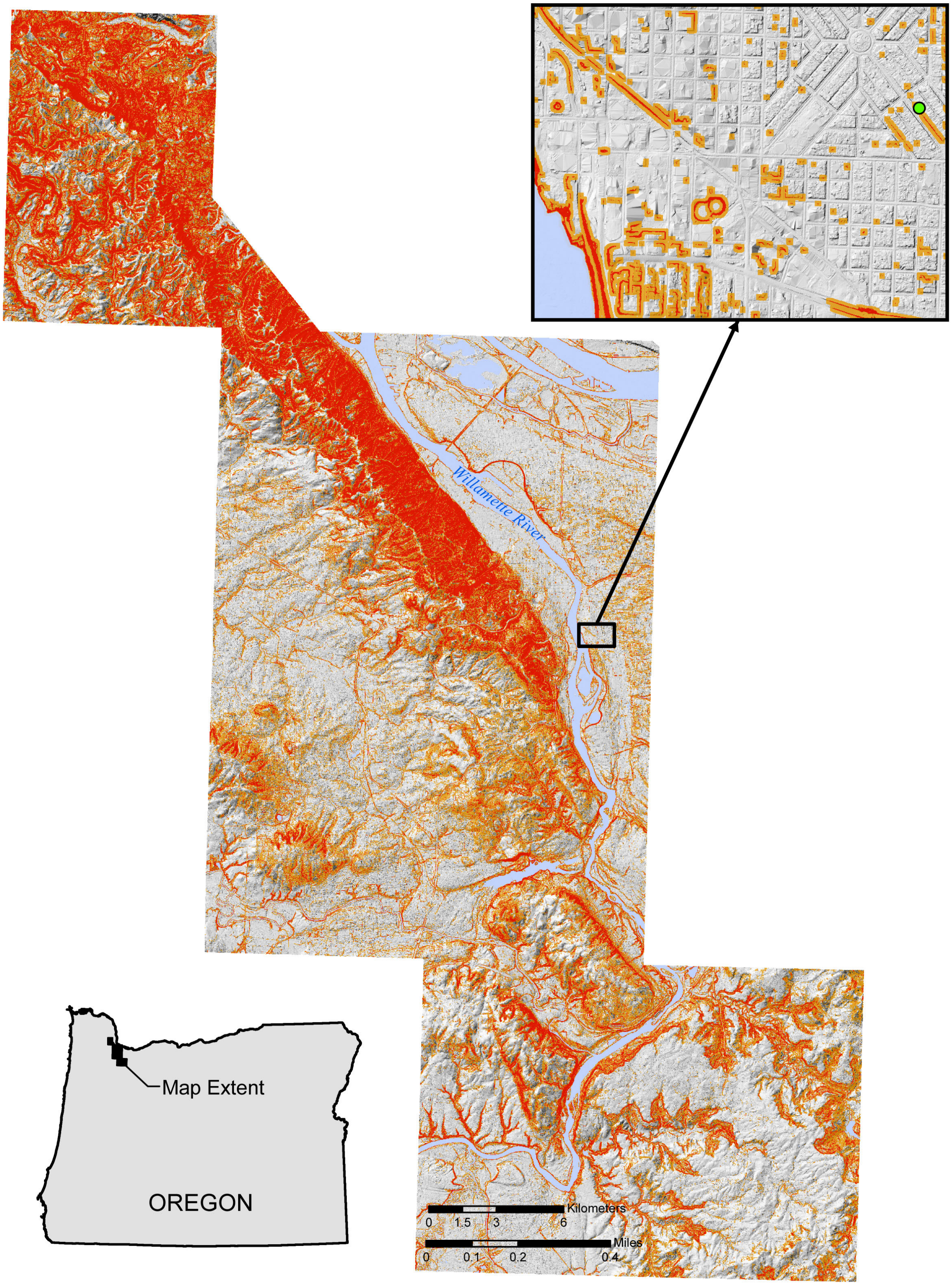
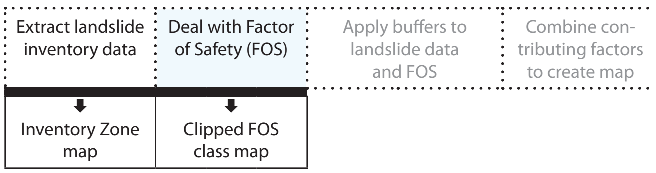


Figure 16. Factor of Safety (FOS) class map for the test area clipped using a focal range value of 4 ft (1.2 m) (red high, orange moderate, gray low). Black outlines are mapped landslides developed following SP-42. Green dot in inset is the photo location in Figure 11. Also see Figure 12H (focal relief) example.

3.5.3 Clipping the FOS Class Map

To clip the raw **FOS class map** using the focal relief, we first use the Esri Spatial Analyst Focal Statistics tool using a 15 ft^2 (4.6 m^2) neighborhood and the range statistic type (Figure 17). We then use the raster calculator to select all values ≤ 4 ft, which produces a clipping raster that has a value of 0 where the focal range is ≤ 4 and a value of 1 when the focal range is > 4. We then multiply the raw FOS map by the clipping raster, which makes all FOS values in areas with a focal range ≤ 4 equal to 0 and preserves the FOS values in areas with focal range > 4. The resultant raster is the **clipped FOS class map**.



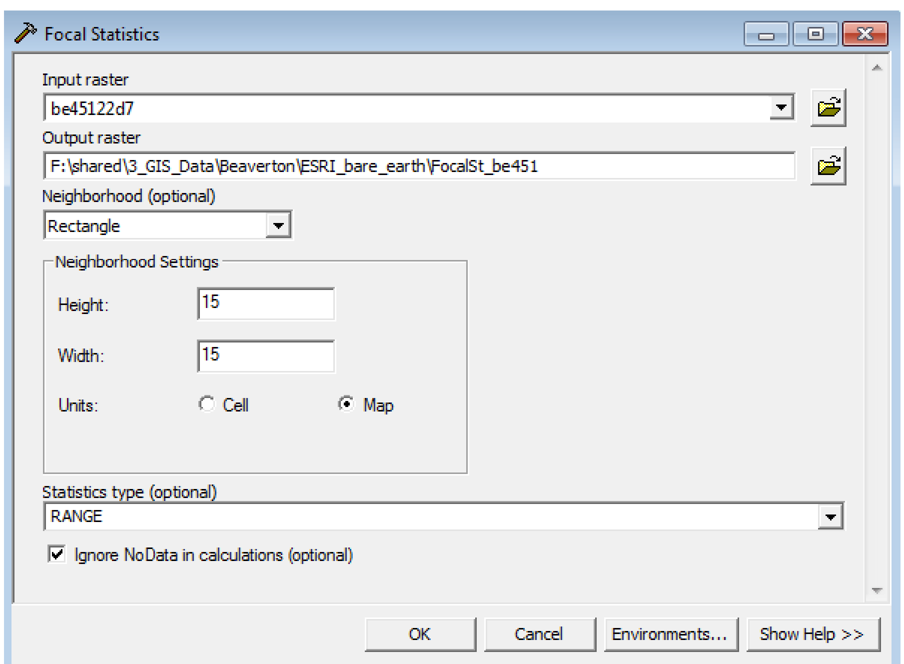


Figure 17. Example of dialog box for the Esri Spatial Analyst Focal Statistics tool.

3.6 Buffers

One disadvantage of a slope stability analysis using a raster or grid-based infinite slope equation is that the analysis looks at each raster cell independently. The FOS is calculated in the same way regardless of where the cell falls on a slope or where it sits in relation to important topographic features or changes. Because the location of a cell can have an important impact on the landslide susceptibility, we have developed two buffers: 1) a head scarp buffer to address the elevated hazard around existing landslides and 2) a FOS buffer to address the impact of slope position on hazard zones.

3.6.1 Landslide Head Scarp Buffer

Extract landslide inventory data	Deal with Factor of Safety (FOS)	Apply buffers to landslide data and FOS	Combine con-tributing factors to create map
Inventory Zone map	Clipped FOS class map	*apply landslide head scarp buffer*	

Most landslides tend to have a steep head scarp above the failed mass. The head scarp area will commonly fail retrogressively or a separate landslide will form above the head scarp, because of the loss of resisting forces directly adjacent and below the head scarp (Figure 18C, area labeled V and outlined in red). In these instances the cell-based FOS map returns a low hazard value for the flat areas adjacent to and above the head scarp, but the proximity to the head scarp clearly increases the susceptibility.

To account for the increase in susceptibility of the area above head scarps, we apply a 2 horizontal to 1 vertical ratio (2H:1V) head scarp buffer (Figure 18B). The 2H:1V ratio is commonly used in geotechnical engineering because the slope angle of a 2H:1V slope is equal to 26 degrees (Figure 18A). This is important because most natural, unfailed (non-landslide) geologic units have an angle of internal friction or equivalent shear strength of at least 26 degrees.

To create the head scarp buffers, we query all of the shallow landslide head scarp polygons from the landslide inventory and apply a buffer of 30 ft (9 m), which is twice the depth of failure (15 ft) we have defined for shallow landslides. We then convert the buffer polygons into a raster in which the polygon areas have a value of 3 (high susceptibility zone). This is the **head scarp buffer map**.

Extract landslide inventory data	Deal with Factor of Safety (FOS)	Apply buffers to landslide data and FOS	Combine con-tributing factors to create map
Inventory Zone map	Clipped FOS class map	Head scarp buffer map	

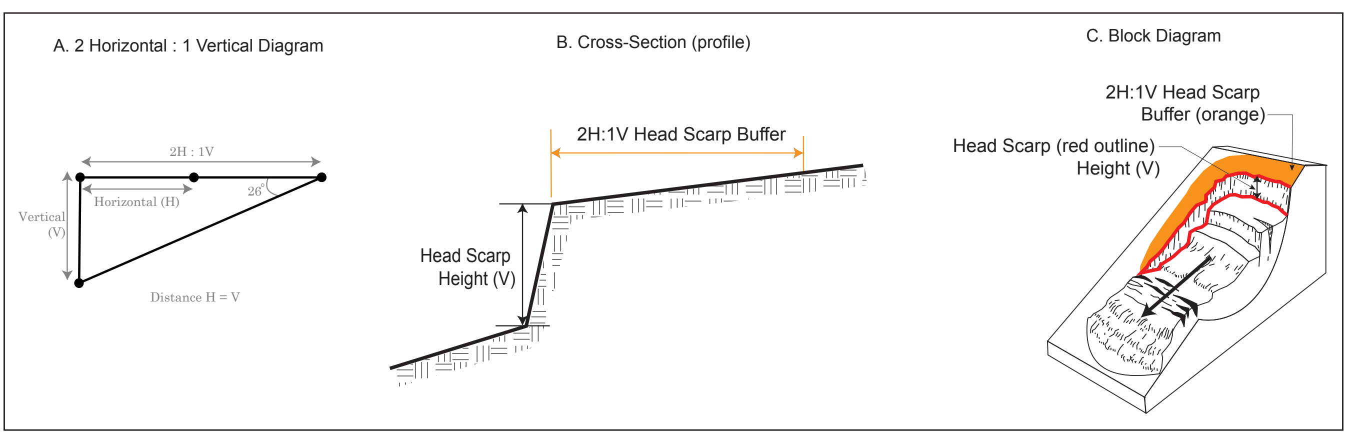
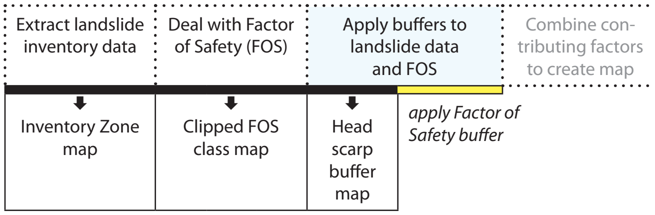
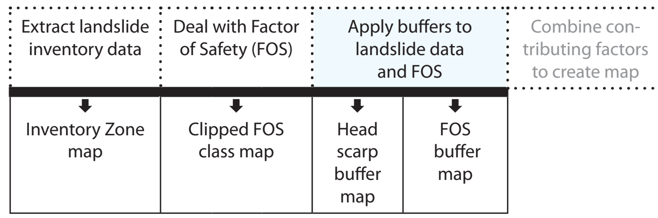


Figure 18. Diagram of the 2H:1V head scarp buffer (red on block diagram).

3.6.2 Factor of Safety Buffer



The FOS values we calculate with the infinite slope equation are derived for each cell in the map area in isolation. This means that the FOS values do not take into account where on a particular slope the cell lies. As shown in the block diagram in Figure 19, there is a difference between a cell with an FOS value > 1.5 (stable) that is located immediately adjacent to the zone of FOS values < 1.5 (potentially unstable), and one that is far from the edge of a steep slope. Because landslides that originate on the steep slope may extend back into the flat area above the slope or out on to the flat area at the foot of the slope, we apply a 30 ft (9 m) buffer (twice the defined depth to failure for shallow landslides) for all areas with a calculated FOS ≤ 1.5. We create the buffer by using the Esri Spatial Analyst Expand tool (Figure 20) on the clipped FOS class map. The output from this step is then reclassified, setting values of 2 and 3 equal to 2. This results in the **FOS buffer map**, which has values of 2 (moderate susceptibility) or NoData (Figure 21).



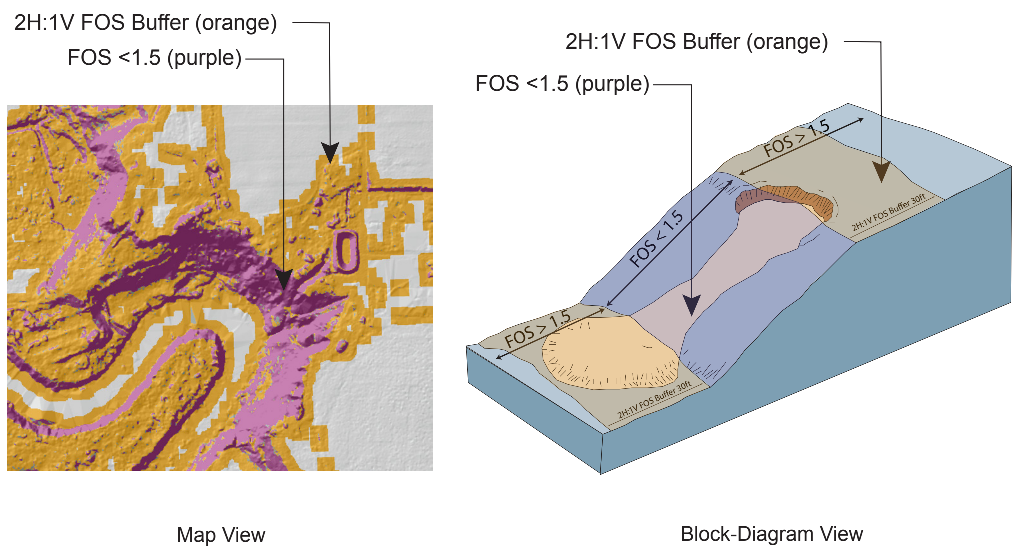


Figure 19. Diagram of the 2H:1V buffer (orange) applied to all Factor of Safety (FOS) less than 1.5 (purple).

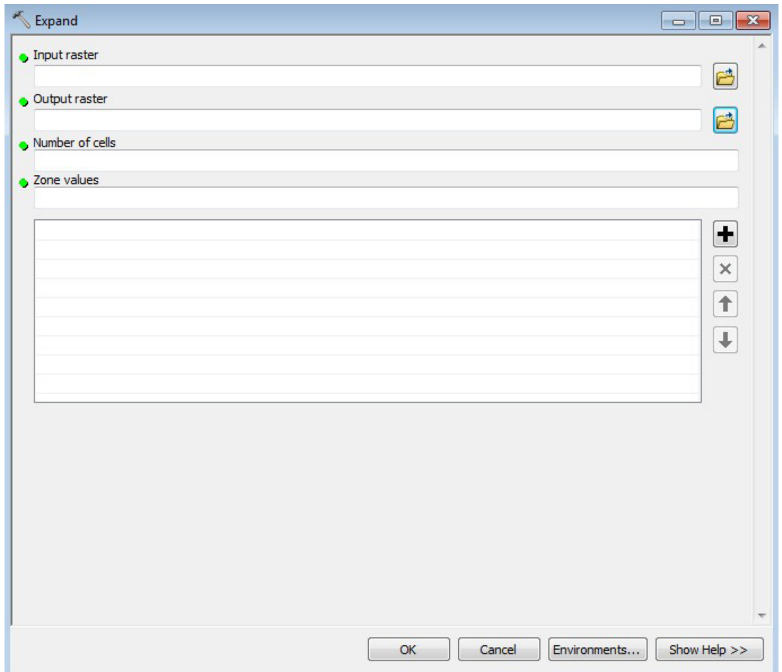


Figure 20. Example of dialog box for the Esri Spatial Analyst Expand tool used to create Factor of Safety (FOS) buffer map. Number of cells = 10 corresponds to a 30-ft (9 m) buffer when used with a 3-ft cell grid.

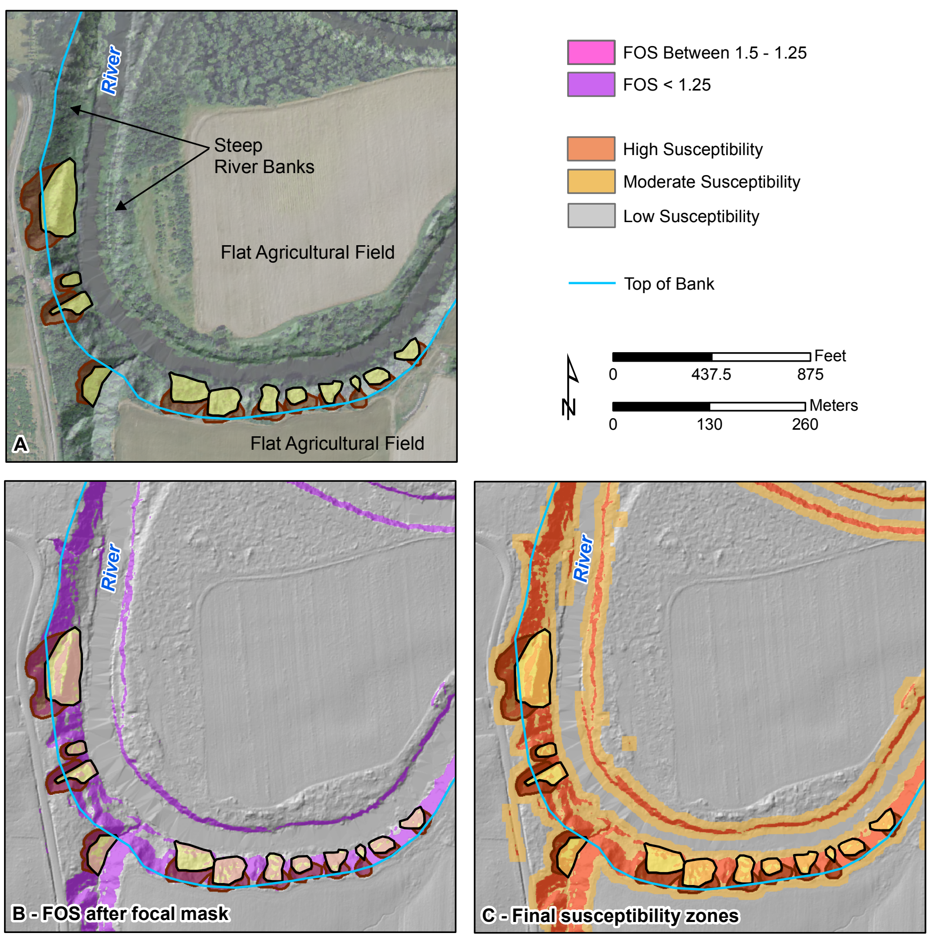
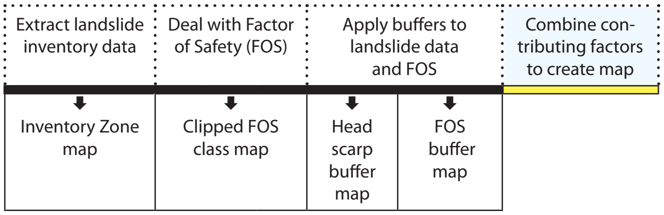


Figure 21. Example of head scarps and Factor of Safety (FOS) buffers. (A) Result of landslide inventory displaying the top of head scarps above the top of the locally steep slope (river bank) area. (B) clipped FOS zone map. (C) clipped FOS zone map with head scarp and FOS buffers added.

3.7 Final Susceptibility Map



To create the final shallow-landslide susceptibility map, we combine the four layers we created:

- Inventory zone map (values are 3 or High)
- Clipped FOS class map (values are 3 or High and 2 or Moderate)
- Head scarp buffer map (values are 3 or High)
- FOS buffer map (values are 2 or Moderate)

The layers are combined using the Mosaic To New Raster tool (Figure 10) using FIRST for the Mosaic Operator method, with the rasters ordered first to last as follows:

1. Inventory Zone map
2. Head Scarp Buffer map
3. Clipped FOS Zone map
4. FOS Buffer map

The result is the final **shallow-landslide susceptibility map** (see Figure 22). The contributions to the final map from the layers are summarized in Table 8.

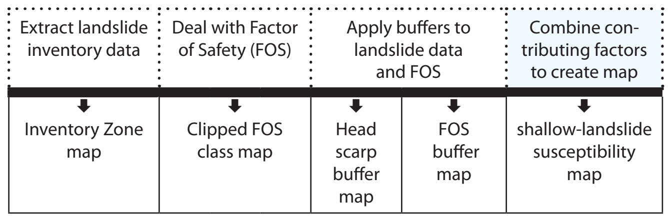
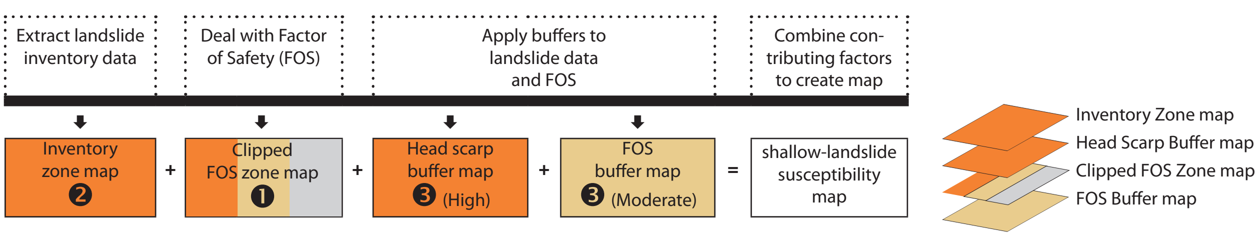


Table 8. Summary of factors contributing to the final shallow-landslide susceptibility map.

Contributing Factors	Final Susceptibility Zones		
	High	Moderate	Low
❶ Factor of Safety (FOS)	less than 1.25	1.25 –1.5	greater than 1.5
❷ Landslide Deposits and Head Scarps	included	—	—
❸ Buffers	2H:1V (head scarps)	2H:1V (FOS less than 1.5)	—

Map layers that contribute to the mosaicked final map:



4.0 SHALLOW LANDSLIDE SUSCEPTIBILITY MAP TEMPLATE

A map template (one quarter of a USGS 7.5-minute quadrangle at 1:8,000 scale) was developed as part of this protocol to provide a consistent display of the results of the susceptibility mapping. The template includes standardized collar elements, a simplified description of methods, disclaimers, and legend elements. An example is shown at reduced scale in Figure 21.

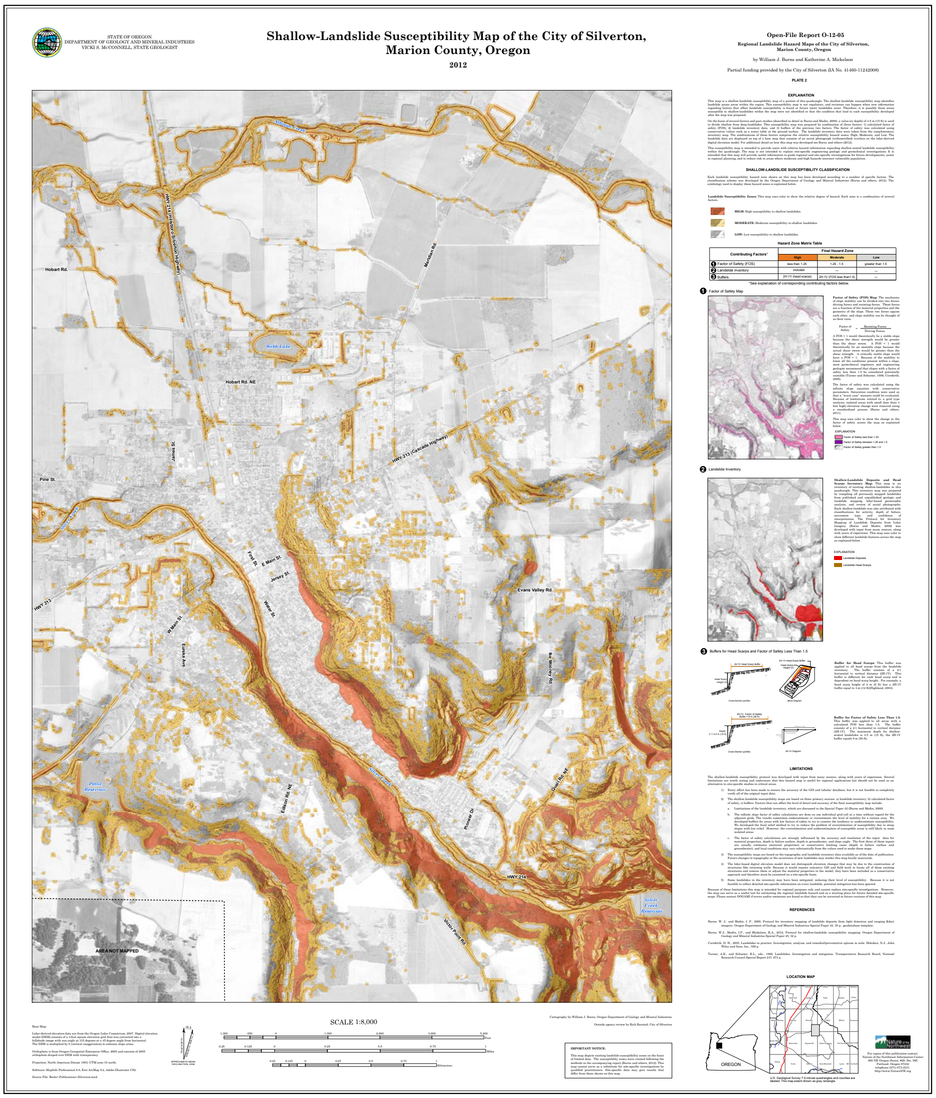


Figure 22. Example shallow-landslide susceptibility map for Silverton area.

5.0 LIMITATIONS OF MAPS PRODUCED USING THIS PROTOCOL

Limitations of the input data and modeling methods we use to make these maps are such that the maps are not suitable to answer site specific questions. The maps should be used only for regional or community-scale purposes. The following list of specific limitations is included as part of the standard material on the susceptibility map template (Figure 22).

1. Every effort has been made to ensure the accuracy of the GIS and tabular database, but it is not feasible to completely verify all original input data.
2. The shallow-landslide susceptibility maps are based on three primary sources: a) landslide inventory, b) calculated Factor of Safety, and c) buffers. Factors that can affect the level of detail and accuracy of the final susceptibility map include:
   a. Limitations of the landslide inventory, which are discussed in SP-42 (Burns and Madin, 2009a).
   b. The infinite slope Factor of Safety calculations are done on one individual grid cell at a time without regard to adjacent grids. The results sometimes underestimate or overestimate the level of stability for a certain area. We developed buffers for areas with low factors of safety to try to counter the tendency to underestimate susceptibility. We developed the focal relief method to try to reduce the problem of overestimation of susceptibility due to steep slopes with low relief. However, overestimation and underestimation of susceptible areas is still likely in some isolated areas.
   c. Factor of safety calculations are strongly influenced by the accuracy and resolution of the input data for material properties, depth to failure surface, depth to groundwater, and slope angle. The first three of these inputs are usually estimates (material properties) or conservative limiting cases (depth to failure surface and groundwater); local conditions may vary substantially from the values used to make these maps.
4. The susceptibility maps are based on topographic and landslide inventory data available as of the date of publication. Changes in topography or the occurrence of new landslides may render this map locally inaccurate.
5. The lidar-based digital elevation model does not distinguish elevation changes that may be due to the construction of structures like retaining walls. Because it would require extensive GIS and field work to locate all existing structures and remove them or adjust their material properties in the model, the structures have been included as a conservative approach and therefore must be examined on a site-specific basis.
6. Some landslides in the inventory may have been mitigated, thereby reducing their level of susceptibility. Because it is not feasible to collect detailed site-specific information on every landslide, potential mitigation has been ignored.

6.0 POTENTIAL USES OF SHALLOW LANDSLIDE SUSCEPTIBILITY MAPS

Shallow-seated landslide susceptibility maps created using this protocol are intended to provide regional and community-scale information to help avoid or properly engineer development in susceptible zones, plan for landslide disasters, and mitigate landslide risk for existing development in susceptible areas. For example, the maps can aid in:

- Identification of very high hazard areas
- Identification of areas for possible buyouts in life-threatening hazard areas
- Evaluation of environmental and sustainability issues
- Identification of vulnerable areas that may require planning considerations
- Estimation of potential losses from specific hazard events (before or after a disaster hits)
- Prioritization of mitigation measures to reduce future losses
- Development of City development regulation ordinances
- Issuance of building permits or proposed grading permit conditions
- Public works planning and operations
- Regional risk-reduction planning and activities
- Neighborhood-scale risk-reduction activities
- Emergency management
- Public awareness campaigns

7.0 ACKNOWLEDGMENTS

Funding for this project was provided by the State of Oregon and by the U.S. Geologic Survey Landslide Hazards Program under Cooperative Agreement #05CRGR0002.

We thank the people at the USGS Landslide Hazards Program who contributed to this protocol through discussions and suggestions including Bill Schulz, Rex Baum, Jeff Coe, Jon McKenna and, especially, Jonathan Godt and Ed Harp, who provided a detailed review that improved this paper. We would also like to thank Erica Koss from the City of Portland, who provided a review that improved this paper.

We would like to thank DOGAMI staff who helped work on this project through technical assistance, review, and general assistance, especially Vicki McConnell, Yumei Wang, and Deb Schueller.

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9.0 APPENDIX A—FACTOR OF SAFETY CALCULATOR

The information shown in this appendix is also available on the CD-ROM in Adobe Acrobat PDF file and Microsoft Excel spreadsheet file formats. Formulas in the equation below from Harp and others (2006) refer to cells in the Excel spreadsheet.

Effective cohesion	c'	0	lb/ft²	First portion of equation	C$1/(C$3*C$5*SIN(C10*PI()/180))
Effective internal friction	ϕ'	28		Second portion of equation	(TAN(C$2*PI()/180))/(TAN(C10*PI()/180))
Unit weight (soil)	γ	122	lb/ft³	Third portion of equation	(C$7*C$4*TAN(C$2*PI()/180))/(C$3*TAN(C10*PI()/180))
Unit weight (water)	γ_w	64	lb/ft³	Factor of Safety	D10+E10-F10
Depth to failure surface	t	15.0	ft		
Proportion of slope thickness saturated	m	1.0			
Slope	α	see table below	deg.		

$$FS = \frac{c'}{\gamma t \sin\alpha} + \frac{\tan\phi'}{\tan\alpha} - \frac{m\gamma_w \tan\phi'}{\gamma \tan\alpha}$$

Slope (α)	1	2	3	Factor of Safety
1.0	0.00	30.46	15.98	14.48
1.5	0.00	20.31	10.65	9.65
2.0	0.00	15.23	7.99	7.24
2.5	0.00	12.18	6.39	5.79
3.0	0.00	10.15	5.32	4.82
3.5	0.00	8.69	4.56	4.13
4.0	0.00	7.60	3.99	3.61
4.5	0.00	6.76	3.54	3.21
5.0	0.00	6.08	3.19	2.89
5.5	0.00	5.52	2.90	2.63
6.0	0.00	5.06	2.65	2.41
6.5	0.00	4.67	2.45	2.22
7.0	0.00	4.33	2.27	2.06
7.5	0.00	4.04	2.12	1.92
8.0	0.00	3.78	1.98	1.80
8.5	0.00	3.56	1.87	1.69
9.0	0.00	3.36	1.76	1.60
9.5	0.00	3.18	1.67	1.51
10.0	0.00	3.02	1.58	1.43
10.5	0.00	2.87	1.50	1.36
11.0	0.00	2.74	1.43	1.30
11.5	0.00	2.61	1.37	1.24
12.0	0.00	2.50	1.31	1.19
12.5	0.00	2.40	1.26	1.14
13.0	0.00	2.30	1.21	1.09
13.5	0.00	2.21	1.16	1.05
14.0	0.00	2.13	1.12	1.01
14.5	0.00	2.06	1.08	0.98

Slope (α)	1	2	3	Factor of Safety
15.0	0.00	1.98	1.04	0.94
15.5	0.00	1.92	1.01	0.91
16.0	0.00	1.85	0.97	0.88
16.5	0.00	1.80	0.94	0.85
17.0	0.00	1.74	0.91	0.83
17.5	0.00	1.69	0.88	0.80
18.0	0.00	1.64	0.86	0.78
18.5	0.00	1.59	0.83	0.76
19.0	0.00	1.54	0.81	0.73
19.5	0.00	1.50	0.79	0.71
20.0	0.00	1.46	0.77	0.69
20.5	0.00	1.42	0.75	0.68
21.0	0.00	1.39	0.73	0.66
21.5	0.00	1.35	0.71	0.64
22.0	0.00	1.32	0.69	0.63
22.5	0.00	1.28	0.67	0.61
23.0	0.00	1.25	0.66	0.60
23.5	0.00	1.22	0.64	0.58
24.0	0.00	1.19	0.63	0.57
24.5	0.00	1.17	0.61	0.55
25.0	0.00	1.14	0.60	0.54
25.5	0.00	1.11	0.58	0.53
26.0	0.00	1.09	0.57	0.52
26.5	0.00	1.07	0.56	0.51
27.0	0.00	1.04	0.55	0.50
27.5	0.00	1.02	0.54	0.49
28.0	0.00	1.00	0.52	0.48
28.5	0.00	0.98	0.51	0.47
29.0	0.00	0.96	0.50	0.46
29.5	0.00	0.94	0.49	0.45

Slope (α)	1	2	3	Factor of Safety
30.0	0.00	0.92	0.48	0.44
30.5	0.00	0.90	0.47	0.43
31.0	0.00	0.88	0.46	0.42
31.5	0.00	0.87	0.46	0.41
32.0	0.00	0.85	0.45	0.40
32.5	0.00	0.83	0.44	0.40
33.0	0.00	0.82	0.43	0.39
33.5	0.00	0.80	0.42	0.38
34.0	0.00	0.79	0.41	0.37
34.5	0.00	0.77	0.41	0.37
35.0	0.00	0.76	0.40	0.36
35.5	0.00	0.75	0.39	0.35
36.0	0.00	0.73	0.38	0.35
36.5	0.00	0.72	0.38	0.34
37.0	0.00	0.71	0.37	0.34
37.5	0.00	0.69	0.36	0.33
38.0	0.00	0.68	0.36	0.32
38.5	0.00	0.67	0.35	0.32
39.0	0.00	0.66	0.34	0.31
39.5	0.00	0.65	0.34	0.31
40.0	0.00	0.63	0.33	0.30
40.5	0.00	0.62	0.33	0.30
41.0	0.00	0.61	0.32	0.29
41.5	0.00	0.60	0.32	0.29
42.0	0.00	0.59	0.31	0.28
42.5	0.00	0.58	0.30	0.28
43.0	0.00	0.57	0.30	0.27
43.5	0.00	0.56	0.29	0.27
44.0	0.00	0.55	0.29	0.26
44.5	0.00	0.54	0.28	0.26

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Slope (α)	1	2	3	Factor of Safety
45.0	0.00	0.53	0.28	0.25
45.5	0.00	0.52	0.27	0.25
46.0	0.00	0.51	0.27	0.24
46.5	0.00	0.50	0.26	0.24
47.0	0.00	0.50	0.26	0.24
47.5	0.00	0.49	0.26	0.23
48.0	0.00	0.48	0.25	0.23
48.5	0.00	0.47	0.25	0.22
49.0	0.00	0.46	0.24	0.22
49.5	0.00	0.45	0.24	0.22
50.0	0.00	0.45	0.23	0.21
50.5	0.00	0.44	0.23	0.21
51.0	0.00	0.43	0.23	0.20
51.5	0.00	0.42	0.22	0.20
52.0	0.00	0.42	0.22	0.20
52.5	0.00	0.41	0.21	0.19
53.0	0.00	0.40	0.21	0.19
53.5	0.00	0.39	0.21	0.19
54.0	0.00	0.39	0.20	0.18
54.5	0.00	0.38	0.20	0.18
55.0	0.00	0.37	0.20	0.18
55.5	0.00	0.37	0.19	0.17
56.0	0.00	0.36	0.19	0.17
56.5	0.00	0.35	0.18	0.17
57.0	0.00	0.35	0.18	0.16
57.5	0.00	0.34	0.18	0.16
58.0	0.00	0.33	0.17	0.16
58.5	0.00	0.33	0.17	0.15
59.0	0.00	0.32	0.17	0.15
59.5	0.00	0.31	0.16	0.15

Slope (α)	1	2	3	Factor of Safety
60.0	0.00	0.31	0.16	0.15
60.5	0.00	0.30	0.16	0.14
61.0	0.00	0.29	0.15	0.14
61.5	0.00	0.29	0.15	0.14
62.0	0.00	0.28	0.15	0.13
62.5	0.00	0.28	0.15	0.13
63.0	0.00	0.27	0.14	0.13
63.5	0.00	0.27	0.14	0.13
64.0	0.00	0.26	0.14	0.12
64.5	0.00	0.25	0.13	0.12
65.0	0.00	0.25	0.13	0.12
65.5	0.00	0.24	0.13	0.12
66.0	0.00	0.24	0.12	0.11
66.5	0.00	0.23	0.12	0.11
67.0	0.00	0.23	0.12	0.11
67.5	0.00	0.22	0.12	0.10
68.0	0.00	0.21	0.11	0.10
68.5	0.00	0.21	0.11	0.10
69.0	0.00	0.20	0.11	0.10
69.5	0.00	0.20	0.10	0.09
70.0	0.00	0.19	0.10	0.09
70.5	0.00	0.19	0.10	0.09
71.0	0.00	0.18	0.10	0.09
71.5	0.00	0.18	0.09	0.08
72.0	0.00	0.17	0.09	0.08
72.5	0.00	0.17	0.09	0.08
73.0	0.00	0.16	0.09	0.08
73.5	0.00	0.16	0.08	0.07
74.0	0.00	0.15	0.08	0.07
74.5	0.00	0.15	0.08	0.07

Slope (α)	1	2	3	Factor of Safety
75.0	0.00	0.14	0.07	0.07
75.5	0.00	0.14	0.07	0.07
76.0	0.00	0.13	0.07	0.06
76.5	0.00	0.13	0.07	0.06
77.0	0.00	0.12	0.06	0.06
77.5	0.00	0.12	0.06	0.06
78.0	0.00	0.11	0.06	0.05
78.5	0.00	0.11	0.06	0.05
79.0	0.00	0.10	0.05	0.05
79.5	0.00	0.10	0.05	0.05
80.0	0.00	0.09	0.05	0.04
80.5	0.00	0.09	0.05	0.04
81.0	0.00	0.08	0.04	0.04
81.5	0.00	0.08	0.04	0.04
82.0	0.00	0.07	0.04	0.04
82.5	0.00	0.07	0.04	0.03
83.0	0.00	0.07	0.03	0.03
83.5	0.00	0.06	0.03	0.03
84.0	0.00	0.06	0.03	0.03
84.5	0.00	0.05	0.03	0.02
85.0	0.00	0.05	0.02	0.02
85.5	0.00	0.04	0.02	0.02
86.0	0.00	0.04	0.02	0.02
86.5	0.00	0.03	0.02	0.02
87.0	0.00	0.03	0.01	0.01
87.5	0.00	0.02	0.01	0.01
88.0	0.00	0.02	0.01	0.01
88.5	0.00	0.01	0.01	0.01
89.0	0.00	0.01	0.00	0.00
89.5	0.00	0.00	0.00	0.00
90.0	0.00	0.00	0.00	0.00