Unstable Slope Criteria Project: Study Design for Object-based Mapping with High-Resolution Topography

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Washington State
Cooperative Monitoring, Evaluation, and Research Committee (CMER)
Report

Unstable Slope Criteria Project: Study Design for Object-based Mapping with High-Resolution Topography

Prepared by
Upslope Technical Writing Group

Prepared for the
Upslope Processes Scientific Advisory Group
of the

Washington State Forest Practices Board
Adaptive Management Program
Washington State Department of Natural Resources
Olympia, Washington

January 2018 **CMER 2018.01.23**

Washington State Forest Practices Adaptive Management Program

The Washington Forest Practices Board (FPB) has adopted an adaptive management program in concurrence with the Forests and Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> Provide science-based recommendations and technical information to assist the board in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. (Forest Practices Rules, WAC 222-12-045)

To provide the science needed to support adaptive management, the FPB made the Cooperative Monitoring, Evaluation and Research Committee (CMER) a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with guidelines recommended in the FFR.

Report Type and Disclaimer

This report was initiated by the Unstable Slopes Technical Writing Group (TWIG). The report is intended to inform the Adaptive Management Program and provide information supplemental to the work of the Cooperative Monitoring, Evaluation and Research Committee (CMER) and the Upslope Processes Science Advisory Group (UPSAG).

This document was reviewed by CMER and was assessed through the Adaptive Management Program's independent scientific peer review process. CMER has approved this document for distribution as an official CMER document. As a CMER document, CMER is in consensus on the scientific merit of the document. However, any conclusions, interpretations, or recommendations contained within this document are those of the authors and may not reflect the views of all CMER members.

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Proprietary Statement

Full Reference

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UNSTABLE SLOPE CRITERIA PROJECT: STUDY DESIGN FOR OBJECT-BASED MAPPING WITH HIGH-RESOLUTION TOPOGRAPHY

TABLE OF CONTENTS

1. OVERVIEW OF UNSTABLE SLOPE CRITERIA PROJECT

The Unstable Slope Criteria Project is part of the Cooperative Monitoring, Evaluation, and Research (CMER) Committee's Mass Wasting Effectiveness Monitoring Program. This project addresses the Forests & Fish Report (FFR; United States Fish and Wildlife Service et al., 1999) Schedule L-1 research topic: "**Test the accuracy and lack of bias of the criteria for identifying unstable landforms in predicting areas with a high risk of instability" and to answer the rule group critical question posed by CMER: "Are unstable landforms being correctly and uniformly identified and evaluated for potential hazard?"**

In February 2018, the Technical Writing and Implementation Group (TWIG) for this project submitted to CMER the document "Unstable Slope Criteria Project – Research Alternatives"[1] (hereafter called Alternatives document) that articulated research objectives, reviewed current best-available-science for identification of unstable slopes, and proposed a set of five research projects. Subsequently, in April 2017, the Timber/Fish/Wildlife (TFW) Policy Committee (hereafter called Policy) approved the research projects recommended by the TWIG in the Alternatives document.

In response to initial Independent Scientific Peer Review (ISPR) comments of this document, aspects of the proposed Compare/Contrast Landslide Hazard Zonation Mass-Wasting Map Units with Rule-Identified Landforms (RIL) Project will be incorporated into subsequent projects.

This study design is only for Project 1; Automated Object-Based Landform Mapping with High Resolution Topography. This project will develop landform maps and landform mapping tools that will be used as baseline geomorphic data for subsequent projects, including development of estimates of relative landform susceptibility to landslides due to forest practices (Project 2).

The remaining set of three projects for which study designs have not yet been developed, are as follows:

1. Empirical Evaluation of Shallow Landslide Susceptibility and Frequency by Landform;

[1] Included as an appendix to this document.

2. Empirical Evaluation of Shallow Landslide Runout; and
3. Models to Identify Landscapes/Landslides Most Susceptible to Management.

The remainder of Section 1 provides background information for the Unstable Slopes Criteria Project and was copied from the CMER and Policy approved Alternatives document with minor changes. Section 2 contains the Object-Based Landform Mapping with High-Resolution Topography Study Design.

1.1 Administrative

1.1.1 Acronyms

CMER	Cooperative Monitoring Evaluation and Research
DEM	Digital Elevation Model
FFR	Forests & Fish Report
FPA	Forest Practice Applications
FY	Fiscal Year
GEOBIA	Geographic Object-Based Image Analysis
GIS	Geographic Information System
ISPR	Independent Scientific Peer Review
LHZ	Landslide Hazard Zonation
LiDAR	Light Detection And Ranging
MWMU	Mass Wasting Map Unit
QE	Qualified Expert
RIL	Rule-Identified Landform
ROC	Receiver-Operating-Characteristic
SEPA	State Environmental Policy Act
SR	State Route
TFW	Timber/Fish/Wildlife
TWIG	Technical Writing and Implementation Group
UPSAG	Upslope Processes Scientific Advisory Group
WAC	Washington Administrative Code
WADNR	Washington State Department of Natural Resources

WAU Watershed Administrative Unit

1.1.2 Unstable Slope Criteria TWIG members

Project Manager:	Emily Hernandez, Washington Department of Natural Resources
Current TWIG Members:	Julie Dieu, Rayonier (CMER Representative)
	Dan Miller, TerrainWorks
	Ted Turner, Weyerhaeuser
	Gregory Stewart, NWIFC (CMER Staff)
Former members	Netra Regmi (CMER Staff)
	Wendy Gerstel, Qwg Applied Geology
Rule Context:	WAC 222-16-050
Forest Practices Rule Group:	Unstable Slopes Rule Group/Mass Wasting Effectiveness Monitoring Program

FY[1] Budget	**FY 18**	**FY 19**	**FY 20**	**FY 21**	**FY 22**	**FY 23**
	$25,000	$50,000	$132,000	$0	$250,000	$240,000

[1]The state fiscal year runs from July 1 through June 30 of the following year and is named for the calendar year in which it ends (e.g., July 1, 2018 through June 30, 2019 is state FY 2019).

1.1.3 Problem Statement

It remains unclear whether the unstable slope criteria are adequate for identifying landforms potentially susceptible to slope instability from forest practices. If the unstable slopes criteria for regulated landforms are not adequate, some RILs will not be identified or reviewed and the Forest Practices Rules will not have their intended effect. Errors of commission, where landforms are judged incorrectly to be RIL, will occur as well.

1.1.4 Purpose Statement

Current criteria for identifying potentially unstable slopes are based on landforms that have relatively high landslide densities, that are influenced by forest practices, and that have the potential to threaten public safety or to deliver sediment to public resources causing significant adverse impact. The definitions and criteria were developed from field observations, regional research, and watershed-analysis data collected from various sources and methods. Observations of storm-induced landslides that have occurred since the current rules were developed have shown that a sizable proportion of landslides delivering sediment to public resources originate from terrain that does not meet current unstable-slope criteria in Washington Administrative Code (WAC 222-16-050 (1)(d)(i)). The results of CMER's Mass Wasting Effectiveness Monitoring Project (Stewart et al., 2013) indicate that of the 1,147 landslides that were found to directly deliver to public resources following the December 2007 storm, a substantial portion (between 29% and 41% depending on gradient estimates) originated from terrain that did not fit the definition of any named RIL. Furthermore, the authors state that "Landslides that originated outside of RIL were distributed throughout the study area, and block analysis of the relative occurrence of landslides outside of RIL showed that their occurrence did not appear to be correlated with either precipitation intensity or lithology." Likewise, as highlighted by the State Route (SR) 530 landslide that occurred on March 22, 2014, criteria for assessing delivery to public resources or risks to public safety may need reassessment. In their final report to Governor Inslee (2014), members of the SR 530 Landslide Commission recommended as a critical first step to "incorporate landslide hazard, risk, and vulnerability assessments into land-use planning, and to expand and refine geologic and geohazard mapping throughout the state." This series of projects will help further our understanding of potentially unstable slopes that fall outside current RIL criteria and, therefore, increase our ability to more accurately identify and map geohazards.

The 2015 CMER Work Plan identifies the Unstable Slope Criteria Project as a lean pilot project directed by the Washington Forest Practices Board (hereafter called the Board). The CMER Work Plan states that the project will evaluate the degree to which the landforms described in the unstable slopes rules and the Forest Practices Board Manual identify potentially unstable areas with a high probability of impacting public resources and public safety. The project is intended to evaluate the original FFR Schedule L-1 research topic: "Test the accuracy and lack of bias of the criteria for identifying unstable landforms in predicting areas with a high risk of instability." In response to the Board's direction to prioritize this project, in a February 6, 2014 memo, Policy directed CMER to prioritize development and implementation of the project and wrote that Policy was "particularly interested in the adequacy of the gradient, slope curvature, and probability of delivery criteria."

1.1.5 Critical Question

What modifications to the unstable slopes criteria and delivery-assessment methods would result in more accurate and consistent identification of 1) unstable slopes and landforms, 2) unstable slopes and landforms sensitive to forest-practices-related changes in landslide processes, and 3) locations susceptible to impacts from upslope landslides such that an adverse impact to public resources or a threat to public safety is possible?

1.1.6 Objectives

The objective of the project is to evaluate unstable slopes criteria and recommend specific modifications to the criteria so that unstable slopes with the potential to deliver sediment or debris to a public resource or that has the potential to threaten public safety can be identified more accurately and consistently.

1.2 Adaptive Management Context

Landslides are natural erosional processes, fundamental to the creation and persistence of landscape and habitat features essential to mountain ecosystems. However, landslides also impart significant socioeconomic and environmental costs (Schuster and Highland, 2001). Numerous studies conducted in the Pacific Northwest have shown that activities related to forest management have the potential to increase landslide occurrence (Dyrness, 1967; Megahan and Kidd, 1972; Swanson and Dyrness, 1975; Ketcheson and Froehlich, 1978; Amaranthus et al., 1985; Swanson et al., 1987; Robison et al., 1999; Jakob, 2000; Montgomery et al., 2000; Guthrie and Evans, 2004). Sediment delivered by landslides to surface waters can have adverse effects on water quality and stream habitat (Cederholm and Reid, 1987; Everest et al., 1987; Reeves et al., 1995; Geertsema and Pojar, 2007; Restrepo et al., 2009) as well as influence ecosystem processes in positive ways (Benda et al., 2003; Reeves et al., 2003; Geertsema and Pojar, 2007).

1.2.1 Definitions

Previous scientific research on landslides has typically focused on factors related to landslide susceptibility and risk. These terms have specific meanings in landslide research and in this document, so these and other important terms are defined below. Following Varnes (1984), and more recently Fell et al. (2008), we use the following definitions.

<u>Susceptibility</u>: Susceptibility indicates the potential for landslide impacts to occur, but without any explicit information on the frequency of occurrence. Impacts occur both in areas of landslide initiation, and downslope in areas affected by landslide runout and deposition. Susceptibility can be quantified in terms of the number or area of impacted sites per unit area (e.g., the number of observed landslide scars per unit area, the proportion of channel length occupied by recent debris-flow deposits), which can be translated to the probability of encountering evidence of a landslide impact at any site. For example, the probability that a point randomly chosen on a map falls within a landslide scar can be calculated from the landslide density associated with the location of the point. Measures of susceptibility can be

integrated over space to provide relative measures of landslide magnitude – for example, to create maps in terms of the proportion of landslides found in specific areas.

Rate (or frequency): Rate adds a temporal component to susceptibility; it specifies the number of occurrences observed, or expected, over a given period of time for a given area. If susceptibility is measured in terms of landslide density, number per square kilometer for example, then rate is measured as number per square kilometer per year. Rainstorms drive landslide occurrences, with the potential for landsliding at any site dependent on the intensity and duration of the storms or sequence of storms that occur. Intensities and durations can vary dramatically over space and time, even during single events, so the number of landslides triggered likewise varies dramatically over space and time (Turner, 2010). The potential for landsliding also varies with land cover, so that measured landslide rate for any area is a complex function of site conditions coupled to the sequence of storms over the period of measurement and the history of land-cover disturbances (Miller et al., 2003). This temporal and spatial variability in landslide occurrence causes measures of landslide density and associated rates to depend on the area and time period over which they are measured. For any region, variability in measured rates can decrease as the area and time period of measurement increases, because each measured rate will potentially include landslides triggered over a larger range of storm and land-cover characteristics.

Hazard: Hazard provides an indication of the potential for impact from a landslide that incorporates susceptibility (spatial relationships), probability of occurrence (frequency), and magnitude. It indicates the probability that a particular damaging impact occurs at a specific site, or within a specific area, over a specific time. It builds on landslide rate to incorporate information on effects of landslide size, volume, and content on landslide impacts. For example, a large landslide poses greater potential for damage to a building than a small landslide; a landslide containing large boulders poses greater potential for damage to a building than a landslide containing only mud; the potential for damage is greater at a site with landslides every 20 years than at a site with landslides every 200 years given equal proximity (distance), volume, and relative magnitude. Hazard can be quantified in terms of the rate at which landslides of a given type and size occur. For example, hazard can be expressed as the number of landslides > 1000 cubic meters per square kilometer per year for a specified area. And for a specified stream reach, hazard could be defined by the number of landslides > 1000 m3 depositing in the reach per year.

Risk: Risk incorporates the costs incurred by damage from a landslide. In quantitative terms, it is considered the product of hazard and cost. Note that risk and hazard are not necessarily equivalent. A site with a low frequency of landslide occurrence, and hence low hazard, may invoke a high consequence – loss of life, for example – so that the risk is high.

Probability: In the context of landslides, probability provides a measure of frequency of occurrence, both in space and over time. For example, we may talk about the probability of finding a landslide scar (or two, or three, or any number) within a specified area, or we may specify the probability that a landslide (of any size and type) will occur in any year within a specified area, or the probability that a debris flow will traverse a particular channel cross-section in any year. Quantitative measures of susceptibility and rate can both be specified in terms of probability, but it is important that the details of what the probability refers to be carefully described. Probability can vary from zero to one, with zero indicating that the event cannot happen and one indicating that the event will happen.

Likelihood: Although "probability" and "likelihood" are often used interchangeably in statistics, likelihood indicates the probability of observing a specific quantity or outcome given the parameters under which it occurs or is measured. We can calculate, for example, the likelihood (probability) of observing three heads in five coin tosses, or of getting a seven in throwing a pair of dice. In this context, one could calculate the likelihood that a proposed forest practice will cause movement on a potentially unstable slope and the likelihood for delivery of sediment to a stream if a landslide were to occur. Given the stochastic nature of landslide triggering events, and the large range of specific site conditions that influence landslide occurrence, these calculations must be based on characteristics of any individual site relative to the characteristics of the population of sites where landslides occur. The terms "probability" and "likelihood" are both used in WAC (e.g., WAC 222-10-030).

Landform: Landforms are categorized by characteristic physical attributes such as elevation, slope, curvature, aspect, geologic structure and stratigraphy, soil type and development, and topographic position. Current forest practices criteria for the identification of potentially unstable slopes focus primarily on slope, curvature, and topographic position.

1.2.2 Washington's Forest Practices Rules

The Washington Forest Practices Act was enacted in 1974 and the Forest Practices Rules have undergone numerous changes since that time. In 1999, a diverse group of stakeholders including tribes, forest landowners, state and federal governments, environmental groups, and other interests, wrote the FFR. The FFR contains strategies for protecting water quality and aquatic and riparian-dependent species on non-Federal forestlands in Washington. In 2001, the Washington State Legislature and the Board amended the Forest Practices Act and its corresponding Forest Practices Rules to incorporate recommended changes from the report.

The Forest Practices Rules were adopted by the Board, and WAC 222-10-030 requires that the Washington Department of Natural Resources (WADNR) develop policies that minimize management-related increases in the potential for landslides that could deliver sediment or debris to a public resource or threaten public safety. Public resources are defined as water, fish, wildlife, and capital improvements of the state or its political subdivisions (WAC 222-16). The WAC does not specifically define public safety, but a WADNR memo dated 6/13/2014 titled "Review of FPAs with Potential to Affect Unstable Slopes" targets the following: homes, businesses, barns, major public roads, and permanent recreation trails and/or developments as capital improvements related to public safety.

Potentially unstable slopes and landforms are defined in WAC 222-16-050 (1)(d)(i). Section 16 of the Board Manual contains guidelines for identifying these features, and these guidelines are used by field practitioners (e.g., forest engineers) and Qualified Experts (QEs). In the Board Manual, unstable slopes and landforms are referred to collectively as RIL. WAC 222-16-050 requires that road building and timber-harvest activities proposed on RIL that have the potential to deliver sediment or debris to a public resource, and have been field verified by WADNR, be classified so that they receive additional environmental review under the State Environmental Policy Act (SEPA) described by WAC 222-10-030. This review is performed by a QE who must evaluate 1) the likelihood that the activity will cause movement or contribute to further movement of potentially unstable slopes, 2) the likelihood of delivery to a public resource if a landslide occurs, and 3) if delivery might occur in a manner that threatens public safety.

WAC 222-24-010 outlines goals for road maintenance and WAC 222-24-050 requires that all forest roads owned by large landowners be improved and maintained to the standards of the WAC by July 1, 2021. To facilitate this, WAC 222-24-051 requires that large landowners submit Road Maintenance and Abandonment Plans and annual accomplishment reports thereafter. Specific to the reduction of road-related landslide rates are the increases in stream-crossing culvert sizes, the installation of additional cross-drain culverts, and side-cast pullback of unstable road prisms.

1.2.3 Development of Rule-Identified Landforms

In the early 1990's, a methodology for watershed analysis was developed by the TFW Community. By 1992, it was formalized in the forest practices rule language (WAC 222-22) and a detailed methodology was provided in Board Manual Chapter 11. One of the modules was titled "Mass Wasting" - its overarching objective was to limit forest-practices-related landslides in a watershed administrative unit (WAU) through the writing of prescriptions specific to the processes of that WAU. These were then the rules that applied within that WAU. The mass wasting assessment was accomplished by doing a landslide inventory from multiple years of historic aerial photography that, in turn, guided the analyst in the characterization and mapping of potentially unstable slopes and the identification of forest practices that caused or contributed to landslides in these unstable slopes. Field work was encouraged to validate landslide occurrence, triggers (i.e., the forest practices activity that contributed to a landslide) and the mapping of the unstable slopes, and to improve the characterization of individual Mass Wasting Map Units (MWMUs). There were three key shortcomings of the mass wasting assessment. One, because little was known about potentially unstable landforms, no standard nomenclature was applied to similar features in different WAUs. An example of this is “inner gorges” versus “gullies.” Two, there was little guidance about the assignment of hazard levels, which resulted in “Very High,” “High,” “Moderate” and “Low” being relative within each WAU and not comparable across the broader landscape. Three, elevation data available at that time, 1:24,000-scale topographic maps and 10-m Digital Elevation Models (DEMs), were of insufficient resolution for delineating many individual RIL and other landforms.

Approximately 50 WAUs underwent the watershed analysis assessment, although many of those did not complete the administrative processes of prescription writing and SEPA review. During the FFR negotiations, a review of watershed analysis mass wasting assessments and other sources (e.g., Benda et al., 1997) indicated that a high proportion of landslides were associated with certain, definable landforms. Nine watershed analyses were examined as representatives for distinct regions of western Washington (Kiona, East Fork Tilton, Kosmos, Upper Green Sunday, Lester, Willapa Headwaters, Lower North River, Hoko and North Fork Calawah). In these analyses, four specific landforms were found consistently in landslide-prone areas: inner gorges, convergent headwalls, bedrock hollows, and deep-seated landslides. These four landforms accounted for over 82% of the landslides inventoried during the nine watershed analyses (Toth and Dieu, 1998). This value may underrepresent the actual significance of these four landforms in those watershed analyses, because many landslides of the remaining 18% were small and did not deliver sediment to a stream channel (Toth and Dieu, 1998).

Field-measured ground-surface gradient is an important factor for identifying these landforms. The gradient threshold for landsliding obtained from the watershed analyses was substantiated with additional field measurements from central Washington and Oregon showing that 80% of observed shallow-rapid landslides occur on slopes with gradients of 70% or greater (Dent et al., 1998; Dragovich et al., 1993). It was noted that these data may not be applicable in the case of deep-seated landslides or in geologic material that is significantly less competent than the geologic formations in the Washington and Oregon studies.

Discussions subsequent to Toth and Dieu (1998) led to specific areas of deep-seated landslides (i.e., toes and glacial groundwater recharge areas) being identified, and led to outer edges of meander bends being separated from more continuous inner gorges. The final set of potentially unstable landforms was briefly identified in Appendix C of the FFR and was later incorporated into WAC and the Board Manual.

The RIL identified in WAC 222-16-050 (1(d)) are:

A. Inner gorges, convergent headwalls, or bedrock hollows with slopes steeper than 35 degrees (70%);
B. Toes of deep-seated landslides, with slopes steeper than 33 degrees (65%);
C. Groundwater recharge areas for glacial deep-seated landslides;
D. Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; or
E. Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes.

Section 16 of the Board Manual contains illustrated guidelines for identifying each of the RIL. Inner gorges are characterized by steep (greater than 70%), straight or concave side slope walls with at least 10 feet of relief, and commonly have a distinctive break-in-slope with more stable terrain above the break. Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. The upper portion of a convergent headwall is usually formed of numerous bedrock hollows separated by knife-edged ridges. Bedrock hollows are spoon-shaped areas of convergent topography; they are typically 30-300 feet wide, have developed through repeated landslide initiation, and are considered potentially unstable when their gradient is 70% or greater. Toes of deep-seated landslides define the terminus of a landslide deposit, and where these are adjacent to a stream and the slopes are greater than 65%, they are defined as a RIL. Groundwater recharge areas of glacial deep-seated landslides are defined as upslope areas where groundwater in glacial deposits contributes subsurface water to a deep-seated landslide. The outer edge of a meander bend of a stream is an unstable landform where stream undercutting is over-steepening valley walls or high terraces.

In addition to specific landform definitions, other areas (Category E) may contain features indicating the presence of potentially unstable slopes. Indicators such as hummocky or benched topography; scarps or cracks; fresh debris deposits; displaced or deflected streams; jack-strawed, leaning, pistol-butted, or split trees; water-loving vegetation and others may be used. Individually these observations do not prove that slope movement is occurring or imminent, but cumulatively they may indicate the presence of potentially unstable slopes.

1.2.4 Landslide Hazard Zonation (LHZ) Protocol and Accomplishments

Subsequent to the development of the RIL as derived from watershed analysis mass wasting reports and other early work, UPSAG (Upslope Processes Scientific Advisory Group) developed the Landslide Hazard Zonation Protocol (WADNR, 2005). In basic form, the LHZ Protocol is like the watershed analysis mass wasting module - a historic landslide inventory of a WAU leads to identification and mapping of MWMUs, these are characterized, their forest-practices-related triggers are identified, and hazard ratings are established. However, two of the three shortcomings of the mass wasting module were corrected. First, landforms meeting the descriptions of the rule-identified landforms were to be identified as such, and then non-RIL MWMUs could be established to characterize other landforms with landslide occurrence. Second, hazard ratings were set for ranges of landslide densities normalized for the length of the available historic aerial photography records so that comparison across WAUs was possible. The third shortcoming, lack of quality DEMs, was corrected only for those places where Light Detection and Ranging (LiDAR) DEMs were available.

Implementation of the LHZ Project occurred in three phases. Phase 1 archived all the mass wasting assessments of completed watershed analyses; because these had already received both peer review looking at the validity of the module results and SEPA review of the entire watershed analysis including the prescriptions, these were accepted without additional review. Phase 2 was the review and acceptance or rejection of all the mass wasting assessments for incomplete watershed analyses; most of these were accepted with little or no revision, but a couple were rejected as inadequate products. Phase 3 was the actual implementation of the LHZ Protocol on previously unstudied WAUs (or those couple that were rejected during Phase 2). Additionally, WADNR State Lands geologist utilized the LHZ Protocol to evaluate blocks of WADNR land.

1.3 Research Objectives

The primary objective of the Forest Practices Unstable Slopes rules is to avoid impacts from management-induced landslides on public resources and public safety. The research objective is to reduce errors associated with the unstable slope criteria. Those errors include: 1) misidentification of RIL, 2) exclusion of unstable slopes that do not meet RIL criteria (i.e., not identifying unstable slopes), and 3) inclusion of stable slopes that meet RIL criteria (i.e., identifying stable slopes as unstable).

Two data sources, unavailable when RIL definitions were originally derived, provide new information for better characterizing these errors: large storms have provided additional landslide data, particularly for landslide locations under intense rainfall, and we have high-resolution LiDAR-derived DEMs that provide detailed topographic information. Additionally, computer-based analysis tools have been developed to take advantage of these data resources.

To meet this objective, this set of projects seeks to capitalize on newly available data and analysis tools to evaluate and refine RIL definitions, to provide map-based products that serve as effective screening tools in identifying RILs, to provide accurate statistics about where and how many landslides occur on Washington's timberlands, and to better assess how forest practices can alter landslide hazards. These tasks have been divided into a sequence of projects, each of which builds on the products of those before. Division of tasks into sequential projects allows us to learn as we progress, so that subsequent project designs can respond to lessons learned. Below we briefly describe the objectives for each project.

OBJECT-BASED LANDFORM MAPPING

- Identify methods for consistent automated delineation of landforms using computer-based techniques and high-resolution LiDAR DEMs, and potentially other data sources.
- The automated landform model will provide the baseline geomorphic context from which to evaluate landslide susceptibility and runout, and it will incorporate data from process-based models to train the automated classification of landforms.

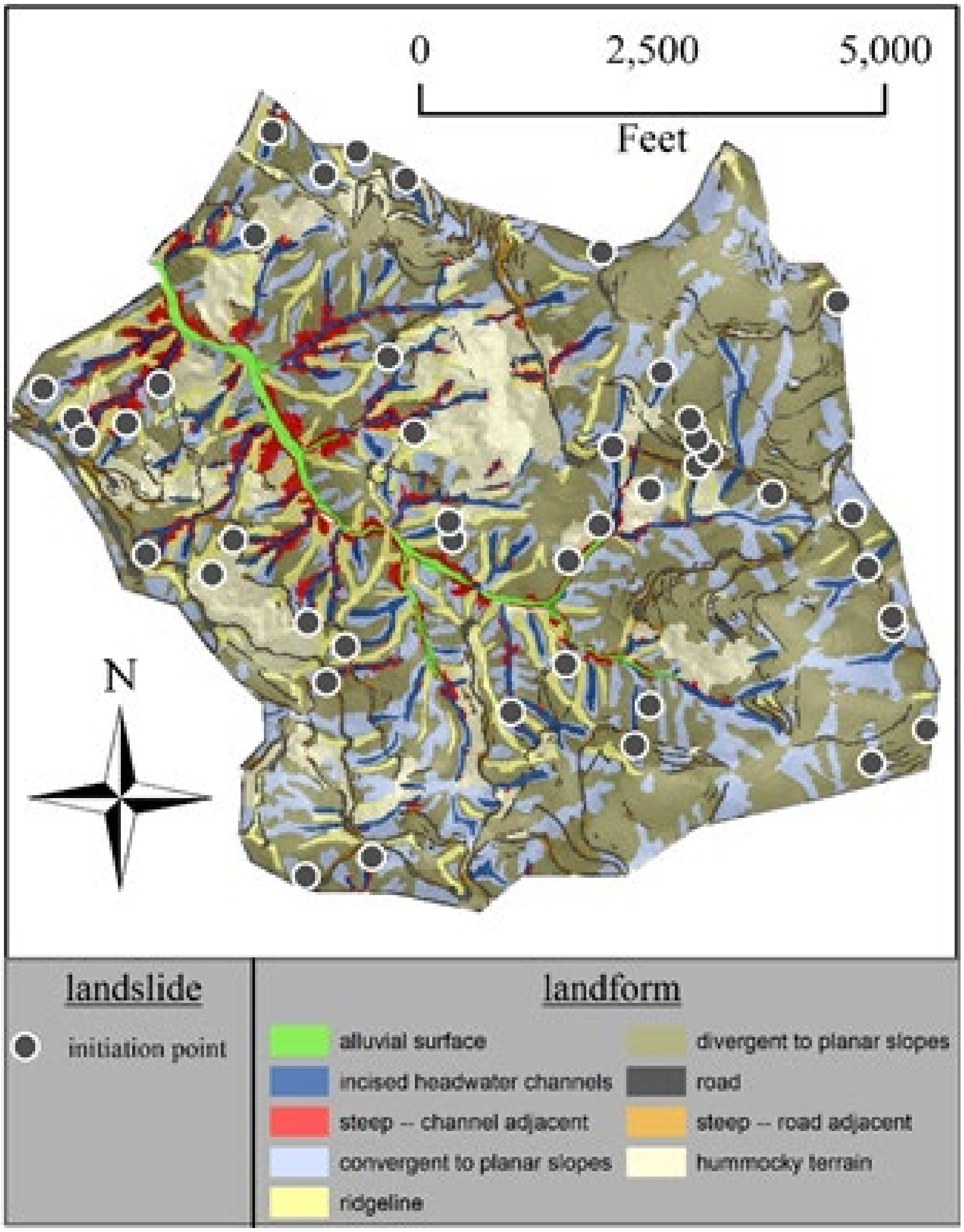

Figure 1. Landform map with mapped landslide initiation points superimposed (Shaw et al., 2017)

Compare/contrast LHZ with RIL

- Ensure that any landforms that have been identified as potentially unstable in previous work, but that are not currently included as a RIL, are included in the set of landforms that methods developed in the Object-Based Landform Mapping Project are able to delineate.
- Identify a set of high-quality MWMUs to compare to the landforms delineated in the Object-Based Landform Mapping Project.
- After considering comments from Independent Scientific Peer Review (ISPR), we have decided to incorporate aspects of this project into subsequent projects and so this will no longer stand alone as a separate project.

Empirical Evaluation of Landform Susceptibility

- Use observed shallow landslide initiation locations, dates, and potentially other information such as landslide size, to derive empirical estimates of the relative susceptibility of each landform type to landslide initiation (Figure 1) and, if feasible, to estimate landslide rates as functions of storm characteristics and land cover for each landform.
- Evaluate and adjust methods for landform delineation to best resolve unstable portions of the landscape.
- Derive statistics to show the relative importance of each landform type as a potential source of landslides over basin- to state-wide scales.

Empirical Evaluation of Runout

- Use observed shallow landslide runout extents to calibrate empirical models for landslide runout.
- Incorporate runout potential into landform definitions.

Process-based Modeling of Management Effects to Susceptibility

- For potentially unstable landform types, use process-based models to better estimate sensitivity of each landform type to changing conditions, such as loss of forest cover from harvest, fire or disease, and toe-slope excavation for roads or by streams.

With these projects, we continue to focus on landforms as the spatial template for assessing landslide potential. Recent advances in landslide hazard assessment rely on digital data that are typically in raster (gridded) format. Hence, results of these analyses are also rasters. Such results can be summarized into maps with the precision of the underlying data (e.g., meter scale for LiDAR DEMs). However, such results do not readily translate to narrative criteria for identification of potentially unstable slopes on the ground and for areas where analyses have not been performed. Currently, Washington's forest practice rules rely on on-the-ground identification of potentially unstable slopes based on the RIL narrative definitions. Map-based assessments can aid in identifying potentially unstable sites, but the final determination of landslide hazard is based on field observations.

We recognize, however, the potential for computer-based analyses to usefully augment field-based assessments. Mass-wasting processes respond to landscape controls over a large range of spatial scales. High-resolution LiDAR data can resolve gullies a meter wide, bedrock hollows tens of meters wide, headwalls spanning hundreds of meters, and deep-seated slumps extending over a kilometer. Topographic attributes can be quantified and compared to thousands of landslide locations to provide empirical correlations relating precisely defined topography to landslide initiations. Detailed digital topography also provides input data for process-based models that can further characterize slope sensitivity to changing conditions. Without detailed topographic surveys, ground-based observations cannot precisely quantify topographic attributes, so maps that provide such information can inform ground-based assessments. Narrative criteria remain key to ensure that field operators recognize potentially unstable ground. With the availability of high-resolution LiDAR DEMs and advanced computer analyses, however, map-based products should prove increasingly reliable and able to discern spatial relationships that can be difficult to perceive on the ground. The sequence of projects identified for the Unstable Slope Criteria Project seeks to capitalize on these resources to assess the efficacy of current RILs and, if appropriate, to refine RIL definitions. The projects will also provide methods for improved map-based screening tools and for providing map- or GPS-based information to aid ground-based hazard assessments.

These projects use a combination of empirical and process-based modeling strategies. With an empirical strategy, we rely on observed evidence of landslide initiation and runout to identify the physical landform characteristics associated with the observed landslides to build statistical models to predict potential for landslide occurrences. With a process-based strategy, we use conceptual understanding of physical processes to build numerical models to predict potential for landslide occurrences. Empirical approaches are constrained by the range of observations available; process-based approaches are constrained by the limits of our conceptual understanding. Both approaches are constrained by the availability of site-specific information.

These projects are focused on processes associated with shallow landslides. Deep-seated landslides are addressed by the UPSAG in a separate sequence of projects. Both shallow and deep-seated landslides respond to topographic, geologic, hydrologic, and land-use factors, but shallow landslides tend to react over small temporal and spatial scales relative to deep-seated landslides. To fully address landslide hazards, it is necessary to examine the full range of scales.

However, given the large range (meters to kilometers, hours to centuries), it is also necessary to focus specific studies on limited portions of that range, and the division of landslide types into shallow (failure surface within rooting depth of trees) and deep-seated (failure surface below the rooting depth) provides a rational process-based criteria for determining that focus. However, we recognize interactions across scales: deep-seated landslides alter topography and hydrology in ways that affect shallow landslide susceptibility.

Evaluation and potential improvement of RIL as indicators of potentially unstable slopes should bring us closer to the performance target of keeping landslide occurrences in managed forests to the natural background rate, but this sequence of projects will not tell us if that is so because they do not provide an assessment of what the background rate is.

2. Object-Based Landform Mapping with High-Resolution Topography

Slope stability regulations governing forest practices are based on landform susceptibility to landslides. Landform maps alone do not quantify landslide susceptibility or prescription effectiveness. However, landform maps provide the baseline from which to calculate landslide susceptibility across a population of landforms. Proper normalization of landslide densities requires accurate mapping of landform area at watershed scales. Few objective, comprehensive, reproducible, multi-scale landform classification and mapping tools currently exist (Shaw et al., 2012, 2017).

This study seeks to develop an automated, computer-generated landform-mapping tool to systematically detect and delineate landforms across a variety of terrain types. Consistent with forest practices rules, the landforms created by this project will have discrete spatial boundaries. With a systematic method for delineating landforms, we can reduce observer bias and then do better at empirically estimating susceptibility by looking at the historic density or rate of mass wasting in different landforms. Methods developed with this study can be used to evaluate the consistency of the MWMUs from the LHZ Project and will provide the landform mapping required by the subsequent study, "Empirical evaluation of shallow landslide susceptibility and frequency by landform."

For the purposes of this study, a landform is a discrete landscape feature that can be described using topographic attributes and whose boundaries can be delineated on a map (Shaw et al., 2017). These topographic attributes may be characterized over a range of spatial scales so that a landform map may focus on individual landform elements, specific bedrock hollows for example, or on an assembly of landforms, such as the population of hollows within a large headwall. The ability to delineate landforms over a range of spatial scales will provide flexibility for generating maps at different scales and for comparing computer generated products to existing maps.

Landform mapping, also known as terrain mapping, has proven an effective strategy for identifying landforms prone to landslide initiation and delivery of material to streams in the Pacific Northwest. A detailed protocol for landform mapping was developed in British Columbia (British Columbia Ministry of Forests, 1999; Howes and Kenk, 1997) based on identification of terrain attributes associated with landslide activity following timber harvest and road building (e.g., Rollerson, 1992; Rollerson et al., 2001; Rollerson et al., 2002). In Washington, the Watershed Analysis program (Washington Forest Practices Board, 1997) and LHZ Project (WADNR, 2005) focused on identification and mapping of landslide- and delivery-prone landforms. The outcomes from Watershed Analysis are reflected in the RIL specified in the Washington State Forest Practices Rules (WAC 222-16-050 and Board Manual Section 16) for identification of potentially unstable slopes. Although various schemes and terminology for classification of landforms in a mountainous terrain have been used (Drăguţ and Blaschke, 2006; Jacek, 1997; MacMillan et al., 2000), this study will follow the landform terms and definitions for shallow rapid landslides in Board Manual Section 16 (Guidelines for Evaluating Potentially Unstable Slopes and Landforms). Subsequent studies in this series may modify those criteria and will identify additional landslide-prone landforms, if present.

2.1 MAPPING STRATEGIES

This section describes methods used for landform mapping, which is traditionally done using geomorphic criteria. These criteria may or may not explicitly include landslides. With this project we seek to evaluate methods for landform mapping based on geomorphic criteria. Subsequent projects will be used to refine landform definitions to best characterize landslide susceptibility, both for initiation and runout, and the changes in susceptibility associated with forestry land uses.

Approaches for mapping landforms range from classic field surveys (Savigear, 1965), to combined field surveys and topographic and aerial or satellite photographic mapping (Ray, 1960), to automated mapping using digital topographic data (Drăguţ and Blaschke, 2006; Hay and Castilla, 2008; Regmi et al., 2014; Rasmussen and Regmi, 2016; Shaw et al., 2017). The recent availability of high-resolution digital elevation data, which provides three-dimensional information of landscape elements over a range of spatial scales, has increased the utility of automated mapping techniques. The ability to quantify landform shape over meter to kilometer scales allows characterization of landform features that may be difficult to visualize in the field.

For example, LiDAR shaded-relief imagery can reveal deep-seated landslide features in stark detail, thereby greatly improving the precision and completeness of deep-seated landslide inventories (e.g., Burns and Madin, 2009; Slaughter et al., 2017). Furthermore, detailed field surveys can be costly and time consuming, and geomorphic mapping from topographic maps and aerial photographs may incur bias associated with an analyst's prior experience and interpretation of features observed. Off-the-shelf software and tools that couple image processing and Geographic Information System (GIS) functionalities (i.e., eCognition, ArcGIS) are now being used to identify and delineate landforms from digital topographic data (Blaschke and Drăguţ, 2003). These digital data involve a regular grid of values that relate information associated from surface geometry, physical properties, and eco-hydro-geomorphic processes at each point in the grid. Individual grid points are referred to as pixels or cells.

A variety of approaches are used for delineating and classifying landforms from digital data:

1) pixel-based (Irvin et al., 1997);
2) object-based (Drăguţ and Blaschke, 2006; Shaw et al., 2017); and
3) spectral analysis (Booth et al., 2009; Regmi et al., 2014; Bellugi et al., 2015).
4) Contour Connection Method (Leshchinsky et al., 2015)

Pixel-based techniques assign each pixel in a DEM to a landform type (or class) according to the topographic attributes that define each landform type. As a simple example, pixels may be classified as "steep," "gentle," or "flat" based on the slope gradient calculated from the DEM. Object-based techniques operate on objects consisting of many homogeneous pixels grouped together in a meaningful way. Each object forms a distinct and contiguous map polygon. As a simple example, areas consisting primarily of "steep" pixels may be grouped into objects (map polygons) representing "steep hillslopes," areas consisting primarily of "gentle" pixels grouped into objects representing "gentle hillslopes," and areas consisting primarily of "flat" pixels into objects representing areas of low topographic relief, like flood plains. The computer-based algorithms used to group pixels into objects are collectively referred to as image segmentation routines. Spectral techniques characterize topography in terms of the spatial scales over which topographic variations occur and can thus quantify differences in surface roughness that may indicate differences in landform type and landform age (Booth et al., 2009; Regmi et al., 2014). The difference among these approaches is the way the datasets are used with various mathematical expressions, and the degree of reliance on expert-based decisions.

In this study, we propose to use pixel- and spectral-based information as inputs to an object-based mapping process (Figure 2). Two major components of object-based mapping are segmentation and classification. Existing approaches of image segmentation can be categorized as thresholding or point-based (e.g., grey-level thresholding to a binary image; Al-Amri and

Kalyankar, 2010; Shaw et al., 2017), edge-based (e.g., edge detection techniques; Mueller et al., 2004; Shaw et al., 2017) and region-based (e.g., split and merge, and region growing; Levi and Rasmussen, 2014; Rasmussen and Regmi, 2016; Shaw et al., 2017) and multiresolution segmentation (Baatz, 2000). The Contour Connection Method (Leshchinsky et al., 2015) identifies deep-seated landslide deposits which are not a focus for this landform mapping project.

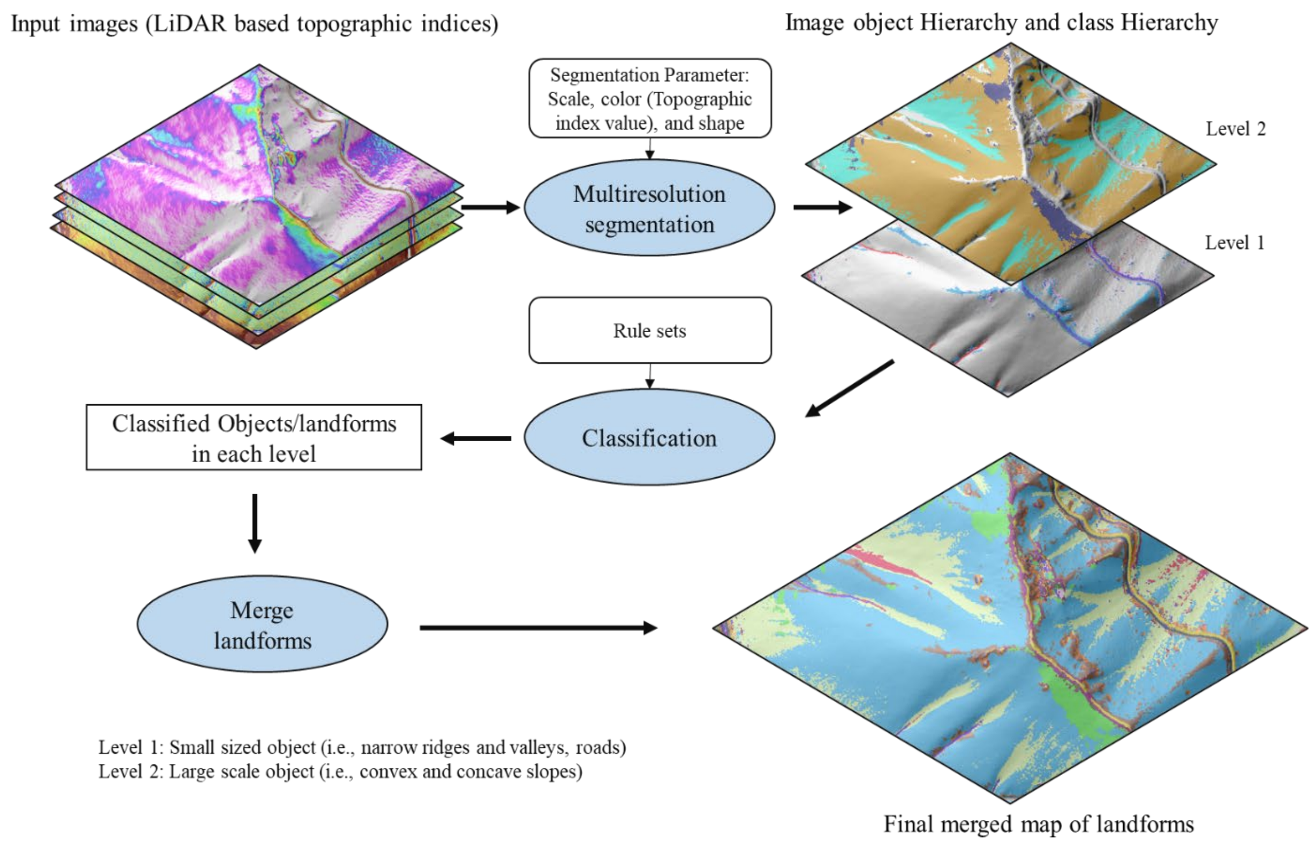

Figure 2: A schematic diagram showing theoretical processes involved in object-based image segmentation and classification. The specific segmentation and classification processes for this project will be defined during implementation.

There are several different approaches to classification:

1) Rule-based classification;
2) Supervised classification; and,
3) Unsupervised classification.

Rule-based classification involves specification of the combination and range of topographic attributes associated with each landform type. The rules that specify these combinations and ranges may be defined qualitatively based on an analyst's experience, or quantitatively by overlaying classified landform polygons mapped from field surveys and aerial-photograph analyses onto digital raster data of topographic attributes, such as slope, curvature, and landscape position (e.g., Ho et al., 2012). Such rule-based, overlay analyses have been used for detecting landslide scars (e.g., Hölbling et al., 2012) and for evaluating automated landform mapping (Irvin et al., 1997).

Supervised classification involves use of previously mapped landforms (e.g., a suite of landforms mapped by an expert) for a portion of the study area with which to define the topographic attributes to assign to each landform type. The previous mapping provides a training topographic dataset for calibrating the classification rules or model to apply to the remaining area. Various supervised approaches exist in the literature, including the use of self-organizing map techniques (Hosokawa and Hoshi, 2001), and machine learning approaches, such as random forest modeling, and neural network analysis.

Unsupervised classification uses mathematical algorithms to automatically determine clusters of pixels of similar spectral characteristics and to classify clusters into different classes. The Iterative Self-Organizing Data Analysis clustering approach (Tou and Gonzalez, 1974) is a widely applied technique that has successfully been used in mapping alluvial landforms and soil assemblages in the southwest US (Levi and Rasmussen, 2014; Rasmussen and Regmi, 2016), as well as in mapping landuse/landcover, landform and other landscape elements (Irvin et al., 1997). Multi-resolution segmentation is a form of unsupervised classification.

eCognition is a software package that provides a comprehensive collection of algorithms tailored to the different aspects of image analysis including segmentation and classification. The user can choose from a variety of segmentation algorithms. Classification methods include rule-based and supervised classification. The final product is one or more map layers representing features of interest. For example, Figure 3 compares pixel (Washington SLPSTAB model from Vaugeois and Shaw, 2000) and object-based landform recognition in eCognition using the same geomorphometric variables (Shaw et al., 2017).

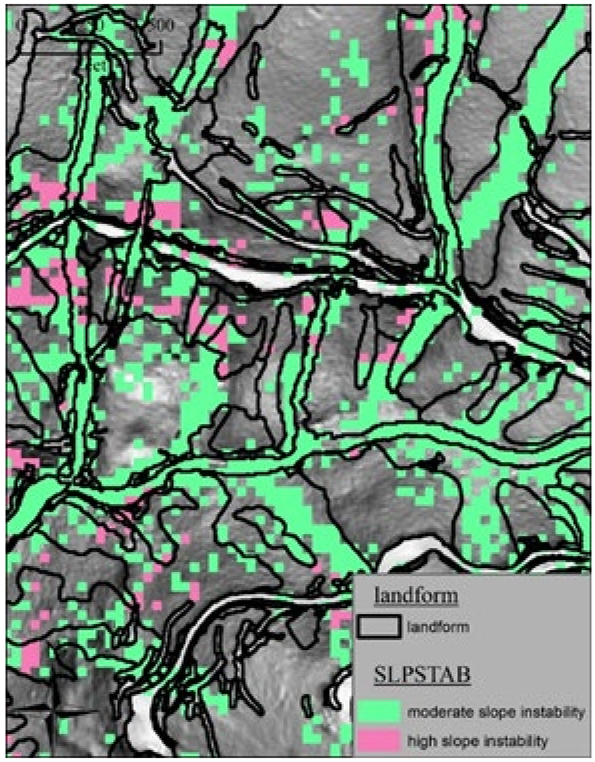

Figure 3. Comparison of pixel vs. object-based segmentation using eCognition to define steep and convergent landforms in Washington (Shaw, et al., 2017)

2.2 RESEARCH APPROACH

The study will develop an object-based landform mapping approach by using high-resolution LiDAR DEMs, geologic and soil maps, and multi-spectral imagery as the primary data sources; with LiDAR point clouds, topographic derivatives of the bare earth model, and GIS layers as inputs. Object-based mapping can also take the output from process-based models of slope stability as input data for delineating landforms. Direct estimates of landslide susceptibility can then be included in the criteria for landform delineation and the study will evaluate the effect on delineated landforms of including process-based model results as inputs for object-based mapping. The goal will be to determine the simplest set of inputs needed to discreetly identify the current set of shallow-rapid RIL (i.e., WAC 222-16-050(1)(d)(i)(A)) as well as a suite of non-RIL landforms to determine how landslide susceptibility may be distributed in other geomorphic contexts. We will use publicly available algorithms to create the topographic indices and will use eCognition software to perform the segmentation and classification, including unsupervised classification if multiresolution segmentation is employed. We will use both rule-based and supervised classification methods to identify landforms and we will compare eCognition landform mapping of discrete landforms that were classified remotely with field-derived RIL maps produced by a qualified expert of known unstable slopes.

Development of an object-based landform map requires several steps:

1. LiDAR data processing;
2. Calculation of topographic indices;
3. Process-based unstable slope modeling;
4. Object-based segmentation and classification;
5. Model evaluation; and
6. Model extrapolation.

2.2.1 LiDAR Data Processing

In forested landscapes, high-resolution LiDAR elevation data commonly exhibit local variability due to the presence of pits associated with the upheaval or decay of tree roots (Roering et al., 2010), or dense vegetation that has been misclassified as bare earth (Lashermes et al., 2007). High-resolution LiDAR DEM should thus be smoothed at a scale larger than that at which such noise occurs (Jyotsna and Haff, 1997; Furbish et al., 2009). Lashermes et al. (2007) suggested smoothing over a 12m radius for LiDAR topographic data of the South Fork Eel River in California and Roering et al. (2010) suggested a 15 m radius for LiDAR topographic data in the Oregon Coast Range.

Although smoothing can be useful for reducing effects of noise in analysis of DEMs, it can also hinder delineation of edges and sharp transitions between different topographic elements. Smoothing algorithms that adjust the degree of smoothing based on local topographic (or image) attributes, such as that described by Perona and Malik (1990) for reducing noise while enhancing edges in photographs, can provide noise reduction while maintaining information on linear and edge features, such as channels and sharp breaks in slope (see review in Passalacqua et al., 2015).

The optimal smoothing length scale and algorithm may vary depending on attributes of the DEM, the landscape it represents, and the features of interest. It will be necessary to experiment with different length scales and smoothing algorithms to determine those best suited for minimizing effects of noise in the DEM for calculation of topographic indices.

2.2.2 Calculation of Topographic Indices

Topographic indices that characterize the surface geometries of a landscape will be derived from LiDAR DEMs. A variety of such indices have been used to identify landforms and to identify landslide-prone terrain (see compendia in Florinsky, 2016; Hengl and Reuter, 2009; Soille, 2004; Wilson, 2018). Basic elevation derivatives of slope and curvature provide a broad starting point: Florinsky (2016) defines 14 types of curvature (see also Shary, 2012), each of which quantifies different aspects of topographic form. Combinations of slope and curvature have been used in a variety of landform classification systems (see compendia in MacMillan and Shary, 2009) and for automated landform mapping (e.g., Levi and Rasmussen, 2014; Rasmussen and Regmi, 2016; Shaw et al., 2017). Other indices offer potentially useful measures of topographic attributes. Geomorphons (Jasiewicz and Stepinski, 2013) provide a classification of 498 unique topographic patterns; the topographic position index (Weiss, 2001) and deviation from mean elevation (Gallant and Wilson, 2000) classify landscape elements based on relative vertical location (DeReu et al., 2013; Lindsay et al., 2015); several measures of roughness have been used to classify landscape elements in terms of texture (Booth et al., 2017; Coblentz et al., 2014); line-of-sight analyses provide a length-dependent measure of surface relief, summarized as topographic “openness” (Yokoyama et al., 2002), and used to distinguish different landform elements (Prima et al., 2006). All of these are derived from a DEM and can be calculated using open-source software (e.g., Miller, 2003).

These indices are all dependent on the length scale over which they are measured. By adjusting that length scale, a hierarchy of topographic elements can be identified in terms of relative size. For example, a convergent headwall may span hundreds of meters, but within it may be a dozen or more bedrock hollows, ranging in width from ten to tens of meters, or perhaps many even smaller swales and gullies. We need topographic indices that will characterize each of these landforms: the 100+ meter headwall, the 10+ meter hollow, and the 1+ meter swale. We will calculate topographic indices over this range of length scales (e.g., Koenders et al., 2014; Prasicek et al., 2014; Lindsay et al., 2015) so that landforms of different sizes can be identified from topographic indices developed at different scales.

2.2.3 Process-based Unstable Slope Modeling

A variety of conceptual models describe our understanding of how landslides occur. These conceptual models identify certain processes and associated physical attributes as important controls on landslide potential. These physical attributes include such things as surface topography, land cover, soil depth, and soil hydrologic and geotechnical properties. Empirical studies find that these attributes correlate well with landslide locations, providing confidence in our conceptual understanding.

To the extent that we can characterize these physical attributes, we can then build mathematical models to describe and quantify these processes and calculate landslide potential. Such process-based models can concisely organize topographic, hydrologic, and geotechnical information into a single variable that both reflects the influence of the pertinent physical attributes and incorporates the process interactions that affect the potential for landslide occurrence.

The output of a process-based model, in terms of a spatially distributed estimate of landslide susceptibility or probability, can serve as an input for object-based landform mapping. Landforms can then be delineated directly in terms of expected variations in landslide potential.

There are, however, certain caveats. These arise from three primary types of limitations:

1. Incomplete, inadequate, or unavailable data for the physical attributes;
2. Inadequate or unavailable software for implementing process-based models; and
3. Inadequate computing facilities for running process-based models of the complexity and resolution required to fully represent the hydrologic, geomorphic, and geotechnical processes involved.

To overcome these limitations, process-based models employ a suite of simplifications, assumptions, and estimates. For example, many process-based models of shallow landsliding apply assumptions of limit equilibrium in which failure is assumed to occur instantaneously along a discrete slip surface; plane strain (the infinite slope approximation) in which forces are assumed to vary only in the vertical plane; steady-state rainfall for which pressure head (pore pressures) can be calculated as a function of steady-state rainfall intensity (ignoring time-dependent processes of infiltration and subsurface flow, or effects of antecedent conditions); and a surface-parallel phreatic surface which requires the implicit assumption of greatly anisotropic soil hydraulic conductivity (Iverson, 2000). Even with these simplifications, these models still require detailed information on soil depth and geotechnical properties which, when unavailable, requires further estimates based on assumed soil types.

Despite all these simplifications, assumptions, and estimates, such models predict spatial patterns of landslide susceptibility that mostly match observed patterns of landslide occurrence (e.g., Strauch et al., 2018), so we think it useful to employ such models to provide potential inputs for object-based mapping. Model predictions are generally improved, in terms of tightening the match between areas of high predicted susceptibility and high observed density, as certain simplifications are replaced with more complete representations (Anagnostopoulos et al., 2015; Formetta et al., 2016). However, we recognize the potential for process-based models to mislead. Since model performance is based on the match between predicted zones of high landslide potential and observed zones of high landslide density, assessment of a model's ability to characterize landslide susceptibility is empirical and subject to the same limitations of all empirical evaluations: the models are tested only against the range of observations that they are compared to. These comparisons involve landslide inventories that include landslide occurrences over a limited time span. A different landslide inventory, that included a different set of landslide-triggering storms, could result in different conclusions about the adequacy of any process-based model. For example, time-dependent modeling of infiltration and associated slope stability suggest that the minimum factor of safety associated with a storm depends on rainfall intensity, rainfall duration, soil conductivity, and antecedent soil moisture (Zhang et al., 2011). Hence, the locations most susceptible to landsliding may change with changing storm characteristics. Given that landslide densities associated with very high intensity rainfall (e.g., greater than a 125-year recurrence-interval, 24-hr event) may be an order of magnitude greater than those associated with more common intensities (Turner et al., 2010), it is important to know how storm characteristics affect landslide location. Some landforms may have few or no landslides most of the time (say for storms with less than a 125-year recurrence interval) but may have many landslides during extreme events. A process-based model that does not properly account for time-dependent infiltration cannot reproduce that behavior. These are important considerations but can wait to be addressed with the last project in the sequence: Physical Modeling of Landslide Initiation. Now we simply want to incorporate process-based models as inputs for object-based mapping of landforms, with the understanding that landform definitions may evolve with subsequent projects.

So which process-based models should we use? Current RILs recognize two primary mechanisms for shallow-landslide initiation: increase in pressure head (or loss of soil suction) sufficient to trigger failure (e.g., bedrock hollows, convergent headwalls), and undercutting of slope toes (inner gorges, outer edges of meanders). In identifying appropriate models for characterizing these processes, we need to consider data availability and computational requirements. The models used will need to be applied broadly over the entire state and may need to be applied with high-resolution DEMs. We therefore require models for which input parameters can be obtained or estimated from available geologic and soils mapping, and that can be run over very large areas with available computer resources. Several infinite-slope, steady-state options exist for assessing hydrologic landslide triggers. SHALSTAB (Montgomery and Dietrich, 1994) can be applied at appropriate spatial scales using existing software.

Recently Strauch et al. (2018) presented a model that includes the ability to estimate spatial variability in soil depth using a model of soil evolution, to apply frequency distributions of soil parameters (including effective root cohesion) to address uncertainty in parameter values, and to address uncertainty in future recharge using macroscale hydrologic models. That suite of models is implemented in the modeling platform LandLab and could potentially be applied statewide. There are fewer options for process-based modeling of landslides triggered by undercutting of slope toes. Miller (1995) and Miller and Sias (1998) describe a modeling approach that will work for this purpose and that can be implemented within the Netstream suite of programs (Benda et al., 2007; Miller, 2003).

2.2.4 Object based segmentation and classification

The objective is to identify methods for consistent, accurate, and automated mapping of landforms from high-resolution digital data using object-based segmentation and classification of topographic indices. Although efforts will be guided by existing precedents (e.g., Shaw et al., 2017), primary tasks will be to experiment with different types of indices, with different spatial scales at which indices are calculated, and with different rules for segmentation and classification using eCognition. Such experimentation is iterative: a set of indices is chosen, a set of rules applied, the results evaluated, and shortcomings in those results guide development of the next sets of indices and rules.

Initial indices and rule sets will be based on those described from similar studies reported in the literature (e.g., DeReu et al., 2013; Gruber et al., 2017; Jiang et al., 2018; Shaw et al., 2017). These indices and rules will focus on geomorphic characteristics associated with landslide initiation and runout. Evaluation will be done by comparing model-delineated landforms to landform maps drawn manually from photogrammetric and topographic map analyses and from field traverses. Comparisons will be made by visual observation and quantitative overlay analyses. Quantitative analyses will include use of confusion matrices and receiver-operating-characteristic (ROC) curves (e.g., Dou et al., 2015) to measure the degree of mismatch between modeled and manually drawn maps and between modeled and field-surveyed transects.

2.2.5 EVALUATION OF MAPPED LANDFORMS

We cannot anticipate now the precise degree to which automated procedures might match manually drawn maps and field interpretations, or even the degree to which they can or should match, since lidar-derived DEMs and computer analyses can provide nuanced measures of topographic attributes at multiple scales with a consistency that cannot be replicated with manual mapping techniques or even field work (Shaw et al., 2017). Likewise, some features visible on the ground cannot be resolved remotely. The literature on this topic to date provides little insight: the only quantitative comparison we found (Gruber et al., 2017) matched field interpretations for only about half the sites examined, although qualitative comparisons suggest that automated mapping can perform well (Coblentz et al., 2014; Jasiewicz and Stepinski, 2013; Regmi and Rasmussen, 2018). Current RIL definitions rely on explicit topographic criteria that can be measured and mapped directly using a DEM, so we expect that automated techniques can identify RIL-like landforms with good qualitative performance, which is consistent with the findings of Shaw et al. (2017). This project will quantify the degree to which such automated mapping from high-resolution lidar-derived DEMs match photo and field interpretations.

We recognize, however, that direct comparison to landform maps produced through traditional analyses may not provide a true measure of model success. Photogrammetric, topographic-map, and field-based analyses may exhibit observer bias, are constrained by lack of quantitative measures of terrain attributes, and are hindered by limits to line-of-sight observations on the ground (Shaw et al., 2017); automated methods can miss key features that are only visible from field surveys. We still think that quantitative comparisons of model results to maps produced by traditional means are necessary to provide context: How well do computer-generated maps match the interpretations of experienced practitioners? Model success, however, must be based on consistency in model results and in the degree to which delineated landforms resolve variations in landslide susceptibility. That is the task for the next project: Empirical Evaluation of Shallow Landslide Susceptibility and Frequency by Landform.

2.2.4 EXTRAPOLATION OF LANDFORM-MAPPING RULES

It is likely that a single mapping approach will not work adequately for the entire State of Washington, which has diverse topography associated with varying lithology, climate zones and tectonic activity. The statistical distribution of the topographic attributes in one landform type in one area may be significantly different from that of another area. From this viewpoint, this study will evaluate landform-mapping performance first in a training area and then test the validity in three additional areas with significantly different climatic and geomorphic settings. Such a study will help us determine the best model calibration parameters and rule sets that can be applied to various climatic and geomorphic settings as part of the next study in the Unstable Slope Criteria Project (the Empirical Evaluation of Shallow Landslide Susceptibility and Frequency by Landform Project described above). We expect that rules for delineation of landforms will evolve with subsequent projects that evaluate susceptibility to landslide initiation and runout, and sensitivity to forest practices. The goal with this current project is to develop an efficient and consistent methodology for identifying and delineating landforms.

2.3 STUDY SITES

The automated mapping methodology will first be developed and applied for a limited pilot area, using high-quality MWMU mapping for the North Fork Calawah WAU. The Mass Wasting Reanalysis performed for this WAU provides detailed landform maps that have been well vetted through extensive field transects (see Figure 2; Dieu, 2015). Ability of the developed techniques to accurately reproduce these maps will provide a good test of the applicability of automated landform mapping for hazard assessment.

After we develop landform mapping rules and methods for the pilot study area, we will apply and evaluate them in three additional LHZ areas with high quality LiDAR data and MWMU maps. We will seek to select training and testing areas in significantly different soil-, hydro- and eco-geomorphic conditions, although the range of environments that can be included will be constrained by the location of available LHZ and LiDAR data. If we find the model does not adequately represent landforms in the LHZ areas, we will adjust model parameters as needed. For example, we anticipate that different landscapes may require topographic indices calculated over different spatial scales.

2.4 STUDY DELIVERABLES

The following are the products expected from this study:

- Vector-based multi-scale landform maps as baseline GIS files for the pilot and three additional study areas;
- The frequency distribution and the statistics of topographic attributes describing each landform;
- Comparison of frequency distributions and statistics of topographic attributes between manual and automated landform maps;
- Tools for producing all topographic indices;
- eCognition rule-sets and codes; and
- A report describing our experience using LiDAR and object-based models to identify specific categories of unstable landforms as found at the project scale, the transferability of such models, lessons learned, and recommendations for future research.

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APPENDIX. UNSTABLE SLOPE CRITERIA PROJECT - RESEARCH ALTERNATIVES

Table of Contents

1 Administrative

1.1 Unstable Slope Critera TWIG Members

Project Manager:	Howard Haemmerle, WADNR				
TWIG Members:	Julie Dieu, Rayonier (CMER Representative)				
	Dan Miller, Earth Systems Institute				
	Gregory Stewart, NWIFC (CMER Staff)				
	Ted Turner, Weyerhaeuser				
Rule Context:	WAC 222-16-050				
Forest Practices Rule Group:	Unstable Slopes Rule Group/Mass Wasting Effectiveness Monitoring Program				
FY Budget	**2017/18**	**2018/19**	**2019/20**	**2020/21**	**2021/22**
	$50,000	$150,000	$250,000	$250,000	$150,000

1.2 Problem Statement

It remains unclear whether the unstable slope criteria are "adequate" for identifying features potentially susceptible to slope instability from forest practices. This includes associated hazards as well as sites that should receive review by a Qualified Expert. If the unstable slopes criteria are not adequate, some potentially unstable slopes will not be identified or reviewed and the Forest Practices Rules will not have their intended effect.

1.3 Purpose Statement

Current criteria for identifying unstable slopes are based on landforms and processes that have relatively high landslide densities, that are influenced by forest practices, and that have the potential for sediment delivery to public resources causing significant adverse impact. The definitions and criteria were developed from field observations, regional research, and watershed-analysis data collected from various sources and methods. Observations of storm-induced landslides that have occurred since the current rules were developed have shown that a sizable proportion of landslides delivering sediment to public resources originate from terrain that does not meet current unstable-slope criteria in rule (WAC 222-16-050 (1)(d)(i)). The results of CMER's Mass Wasting Effectiveness Monitoring Project (Stewart et al. 2012) indicate that of the 1,147 landslides that were found to directly deliver to pubic resources following the

December 2007 storm, a substantial portion "originated from terrain that did not fit the definition of any named RIL". Furthermore, the authors state that "Landslides that originated outside of RIL were distributed throughout the study area, and block analysis of the relative occurrence of landslides outside of RIL showed that their occurrence did not appear to be correlated with either precipitation intensity or lithology". Likewise, as highlighted by the SR 530 landslide that occurred on March 22, 2014, criteria for assessing delivery to public resources or risks to public safety may need reassessment.[2] In their final report to Governor Inslee (2014), members of the SR 530 Landslide Commission recommended as a critical first step to "incorporate landslide hazard, risk, and vulnerability assessments into land-use planning, and to expand and refine geologic and geohazard mapping throughout the state." This project will help further our understanding of potentially unstable slopes that fall outside current RIL criteria in rule, and therefore increase our ability to more accurately identify and map geohazards.

The 2015 CMER Work Plan identifies the Unstable Slope Criteria Project as a lean pilot project directed by the Washington Forest Practices Board. The CMER Work Plan states that the project will evaluate the degree to which the landforms described in the unstable slopes rules and Board Manual identify potentially unstable areas with a high probability of impacting public resources and public safety. The project was intended to evaluate the original Forests & Fish Report Schedule L-1 research topic: "Test the accuracy and lack of bias of the criteria for identifying unstable landforms in predicting areas with a high risk of instability." In response to the Board's direction to prioritize this project, in a February 6, 2014 memo, the TFW Policy Committee (Policy) directed CMER to prioritize development and implementation of the project, and wrote that Policy was "particularly interested in the adequacy of the gradient, slope curvature, and probability of delivery criteria."

1.4 Critical Question

What modifications to the unstable slopes criteria and delivery-assessment methods would result in more accurate and consistent identification of 1) unstable slopes and landforms, 2) unstable slopes and landforms sensitive to forest-practices-related changes in landslide processes, and 3) locations susceptible to impacts from upslope landslides such that an adverse impact to public resources or a threat to public safety is possible?

[2] Recent revisions to the Board Manual provide updated guidelines for assessing runout.

1.5 Objectives

To evaluate unstable-slopes criteria and recommend specific modifications to the criteria so that RILs and potential for delivery can be identified consistently.

2 Adaptive Management Context

Landslides are natural erosional processes, fundamental to the creation and persistence of landscape and habitat features essential to mountain ecosystems. However, landslides also impart significant socioeconomic and environmental costs (Schuster and Highland, 2001). Numerous studies conducted in the Pacific Northwest have shown that activities related to forest management have the potential to increase landslide occurrence (Amaranthus et al., 1985; Dyrness, 1967; Guthrie and Evans, 2004; Jakob, 2000; Ketcheson and Froehlich, 1978; Megahan and Kidd, 1972; Robison et al., 1999; Swanson et al., 1987; Swanson and Dyrness, 1975a) and that sediment delivered by landslides to surface waters has had an adverse effect on water quality and stream habitat (Cederholm and Reid, 1987; Everest et al., 1987; Geertsema and Pojar, 2007; Restrepo et al., 2009).

In response to concerns over the impacts of landsliding, the Washington Forest Practices Board (WFPB) adopted new rules in 2001 that contain specific measures designed to reduce management-related influences on landslide occurrence. One performance target for the Washington State Forest Practices Adaptive Management program is to limit landslide occurrence in managed forests to the "natural background" rate. Specific to forest roads, performance targets specify no landslides triggered by new roads and a reduction in the rate of landslide initiation from old roads.[3]

2.1 Definitions

Previous scientific research on landslides has typically focused on factors related to landslide susceptibility and risk. These terms have specific meanings in landslide research and in this document, so these and other important terms are defined below. Following Varnes (1984), and more recently Fell et al. (2008), we use the following definitions.

<u>Susceptibility</u>: Susceptibility indicates the potential for landslide impacts to occur, but without any explicit information on the frequency of occurrence. Impacts occur both in areas of landslide initiation, and downslope in areas affected by landslide runout and deposition.

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[3] http://www.dnr.wa.gov/Publications/fp_am_ffrschedulel1.pdf

Susceptibility can be quantified in terms of the number or area of impacted sites per unit area (e.g., the number of observed landslide scars per unit area, the proportion of channel length occupied by recent debris-flow deposits), which can be translated to the probability of encountering evidence of a landslide impact at any site. For example, the probability that a point randomly chosen on a map falls within a landslide scar can be calculated from the landslide density associated with the location of the point. Measures of susceptibility can be integrated over space to provide relative measures of landslide magnitude – e.g., to create maps in terms of the proportion of landslides found in specific areas.

Rate (or frequency): Rate adds a temporal component to susceptibility; it specifies the number of occurrences observed, or expected, over a given period of time. If susceptibility is measured in terms of landslide density, number per square kilometer for example, then rate is measured as number per square kilometer per year. To some degree, rate is implicit in susceptibility. An area with higher landslide rate will have more landslides (per unit time and unit area) than an area with lower density and, thus, will also have higher landslide density (if evidence of landslides persists for the same time in each case). Therefore, variations in measures of susceptibility can indicate variations in landslide rate. However, because landslides are usually triggered by rain storms, and the number of landslides triggered increases with increasing rainfall intensity, landslide rate varies over time depending on the sequence of landslide-triggering storms. Likewise, during any storm event, rainfall intensity varies spatially, so landslide rate and associated density varies over space and time.

Hazard: Hazard provides an indication of the potential for impact from a landslide; it indicates the probability that a particular damaging impact occurs at a specific site, or within a specific area, over a specific time. It builds on landslide rate to incorporate information on effects of landslide size, volume, and content on landslide impacts. For example, a large landslide poses greater potential for damage to a building than a small landslide; a landslide containing large boulders poses greater potential for damage to a building than a landslide containing only mud; the potential for damage is greater at a site with landslides every 20 years than at a site with landslides every 200 years. Hazard can be quantified in terms of the rate at which landslides of a given type and size occur. For example, hazard can be expressed as the number of landslides $> 1000\ m^3$ per square kilometer per year for a specified area. And for a specified stream reach, hazard could be defined by the number of landslides $> 1000\ m^3$ depositing in the reach per year.

Risk: Risk incorporates the costs incurred by damage from a landslide. In quantitative terms, it is considered the product of hazard and cost. Note that risk and hazard are not necessarily equivalent. A site with a low frequency of landslide occurrence, and hence low hazard, may invoke a high cost – loss of life, for example – so that the risk is high.

Probability: In the context of landslides, probability provides a measure of frequency of occurrence, both in space and over time. For example, we may talk about the probability of finding a landslide scar (or two, or three, or any number) within a specified area, or we may specify the probability that a landslide (of any size and type) will occur in any year within a specified area, or the probability that a debris flow will traverse a particular channel cross-section in any year. Quantitative measures of susceptibility and rate can both be specified in terms of probability, but it is important that the details of what the probability refers to be carefully described. Probability can vary from zero to one, with zero indicating that the event cannot happen and one indicating that the event will happen.

Likelihood: Although “probability” and “likelihood” are often used interchangeably, in statistics, likelihood indicates the probability of observing a specific quantity or outcome given the parameters under which it occurs or is measured. We can calculate, for example, the likelihood (probability) of observing three heads in five coin tosses, or of getting a seven in throwing a pair of dice. In this context, one could calculate the likelihood that a proposed forest practice will cause movement on a potentially unstable slope and the likelihood for delivery of sediment to a stream if a landslide were to occur. Given the stochastic nature of landslide triggering events, and the large range of specific site conditions that influence landslide occurrence, these calculations must be based on characteristics of any individual site relative to the characteristics of the population of sites where landslides occur. This is the realm of empirical studies, described below.

2.2 WASHINGTON’S FOREST PRACTICES RULES

The Washington Forest Practices Act was enacted in 1974 and the Forest Practices Rules have undergone numerous changes since that time. In 1999, a diverse group of stakeholders including tribes, forest landowners, state and federal governments, environmental groups, and other interests, wrote the Forests & Fish Report (FFR). The FFR contained strategies for protecting water quality and aquatic and riparian-dependent species on non-Federal forestlands in Washington.[4] In 2001, the Washington State Legislature and the Washington Forest Practices Board (WFPB) amended the Forest Practices Act and its corresponding Forest Practices Rules to incorporate recommended changes from the report.

[4] http://www.dnr.wa.gov/Publications/fp_rules_forestsandfish.pdf

The Forest Practices Rules were adopted by the WFPB, and Washington Administrative Code (WAC) 222-10-030 requires that the Washington Department of Natural Resources (WDNR) develop policies that minimize management-related increases in the potential for landslides that could deliver sediment or debris to a public resource or threaten public safety. Public resources are defined as water, fish, wildlife, and capital improvements of the state or its political subdivisions (WAC 222-16). The WAC does not specifically define public safety, but a WDNR memo dated 6/13/2014 titled "Review of FPAs with Potential to Affect Unstable Slopes" targets the following: homes, businesses, barns, major public roads, and permanent recreation trails and/or developments as capital improvements related to public safety.

Potentially unstable slopes and landforms are defined in WAC 222-16-050 (1)(d)(i). Section 16 of the Board Manual contains guidelines for identifying these features and these guidelines are used by field practitioners (e.g., forest engineers) and Qualified Experts (QE).[5] In the Board Manual, unstable slopes and landforms are referred to collectively as Rule-Identified Landforms (RIL).[6] WAC 222-16-050 requires that road building and timber-harvest activities proposed on RILs that have the potential to deliver sediment or debris to a public resource, and have been field verified by WDNR, be classified so that they receive additional environmental review under the State Environmental Policy Act (SEPA) described by WAC 222-10-030. This review is performed by a QE who must evaluate 1) the likelihood that the activity will cause movement or contribute to further movement of potentially unstable slopes, 2) the likelihood of delivery to a public resource if a landslide occurs, and 3) if delivery might occur in a manner that threatens public safety.

WAC 222-24-010 outlines goals for road maintenance and WAC 222-24-050 requires that all forest roads owned by large landowners be improved and maintained to the standards of the WAC by July 1, 2021. To facilitate this, WAC 222-24-051 requires that large landowners submit Road Maintenance and Abandonment Plans (RMAP) and annual accomplishment reports thereafter. Specific to the reduction of road-related landslide rates are the increases in stream-crossing culvert sizes, the installation of additional cross-drain culverts, and side-cast pullback of unstable road prisms.

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[5] Qualified Experts are licensed engineering geologists with demonstrated experience in the forested environment as approved by WDNR (WAC 222-10-030 (5)).

[6] http://www.dnr.wa.gov/Publications/fp_board_manual_section16.pdf

2.2.1 Rule-Identified Landforms

During the FFR negotiations, a review of Washington watershed analyses and other sources (e.g., Benda et al., 1997) indicated that a high proportion of landslides were associated with certain, definable landforms.[7] Nine watershed analyses were examined as representatives for distinct regions of western Washington (Kiona, East Fork Tilton, Kosmos, Upper Green Sunday, Lester, Willapa Headwaters, Lower North River, Hoko and North Fork Calawah). In these analyses, four specific landforms were found consistently in landslide-prone areas: inner gorges, convergent headwalls, bedrock hollows, and deep-seated landslides.[8] These four landforms accounted for over 82% of the landslides inventoried during the nine watershed analyses (Toth and Dieu, 1998). This value may underrepresent the actual significance of these four landforms in those watershed analyses, because many landslides of the remaining 18% were small and did not deliver sediment to a stream channel (Toth and Dieu, 1998).

Field-measured ground-surface gradient is an important factor for identifying these landforms. The gradient threshold for landsliding obtained from the watershed analyses was substantiated with additional field measurements from central Washington and Oregon showing that 80% of observed shallow-rapid landslides occur on slopes with gradients of 70% or greater (Dent et al., 1998; Dragovich et al., 1993a). It was noted that these data may not be applicable in the case of deep-seated landslides or in geologic material that is significantly less competent than the geologic formations in the Washington and Oregon studies.

Discussions subsequent to Toth and Dieu (1998) led to specific areas of deep-seated landslides (i.e., toes and glacial groundwater recharge areas) being identified, and led to outer edges of meander bends being separated from more continuous inner gorges. The final set of potentially unstable landforms were briefly identified in Appendix C of the FFR, and were later incorporated into WAC and the Board Manual.

The RIL identified in WAC 222-16-050 (1(d)) are:

A. Inner gorges, convergent headwalls, or bedrock hollows with slopes steeper than 35 degrees (70%);
B. Toes of deep-seated landslides, with slopes steeper than 33 degrees (65%);
C. Groundwater recharge areas for glacial deep-seated landslides;
D. Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; or

[7] These analyses focused on “shallow-rapid” landslides - those involving sudden failure of shallow soils.

[8] Deep-seated landslides can create large, persistent landforms, including steep headscarp and toe areas prone to shallow landslide occurrence.

E. Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes.

Section 16 of the Board Manual contains illustrated guidelines for identifying each of the RIL. Inner gorges are characterized by steep (greater than 70%), straight or concave sideslope walls with at least 10 feet of relief, and commonly have a distinctive break-in-slope with more stable terrain above the break. Convergent headwalls are funnel-shaped landforms, broad at the ridgetop and terminating where headwaters converge into a single channel. The upper portion of a convergent headwall is usually formed of numerous bedrock hollows separated by knife-edged ridges. Bedrock hollows are spoon-shaped areas of convergent topography; they are typically 30-300 feet wide, have developed through repeated landslide initiation, and are considered potentially unstable when their gradient is 70% or greater. Toes of deep-seated landslides define the terminus of a landslide deposit, and where these are adjacent to a stream and the slopes are greater than 65%, they are defined as a RIL. Groundwater recharge areas of glacial deep-seated landslides are defined as upslope areas where groundwater in glacial deposits contributes subsurface water to a deep-seated landslide. The outer edge of a meander bend of a stream is an unstable landform where stream undercutting is over steepening valley walls or high terraces.

In addition to specific landform definitions, other areas (Category E) may contain features indicating the presence of potentially unstable slopes. Indicators such as hummocky or benched topography; scarps or cracks; fresh debris deposits; displaced or deflected streams; jack-strawed, leaning, pistol-butted, or split trees; water-loving vegetation and others may be used. Individually these observations do not prove that slope movement is imminent, but cumulatively may indicate the presence of potentially unstable slopes.

2.3 Research Objectives

The primary objective of the Forest Practices Unstable Slopes rules is to minimize the impact of management-induced landslides on public resources and public safety. An error in the process occurs if areas subject to management-induced landslides that can deliver to a public resource, or affect public safety, do not receive review by a QE. The research objective is to reduce errors associated with the unstable slope criteria. Those errors include: 1) misidentification of RILs, 2) exclusion of unstable slopes that do not meet RIL criteria, and 3) inclusion of stable slopes that meet RIL criteria.

3 Best Available Science Summary

3.1 Natural Factors Influencing Slope Stability

An extensive body of literature examines the factors influencing slope stability. Case studies of landslide occurrence on managed forest landscapes focus primarily on shallow-rapid landslides, either at the scale of individual landslides or over entire watersheds. Most are based on retrospective analyses of landslide occurrence after high-intensity storms. These case studies seek to identify the factors that contributed to slope failure. Relevant studies of natural factors affecting slope stability are briefly discussed below.

3.1.1 Precipitation

Landslides commonly occur in response to high-intensity rainstorms and/or snowmelt events that release large volumes of water over a period of days, particularly when relatively heavy rainfall has occurred during the preceding weeks (Caine, 1980; Campbell, 1975; Crosta and Frattini, 2003; Dai and Lee, 2001; Godt et al., 2006; He and Beighley, 2008; Jakob et al., 2006; Jakob and Weatherly, 2003; Rahardjo et al., 2001; Stewart et al., 2013; Tsai, 2008). Slope stability is reduced as soil moisture increases because of the added weight of water, the loss of water-surface tension in the unsaturated portion of the soil, and the hydrostatic forces exerted on the soil mass once the soil is saturated, which reduces frictional resistance of particles to downslope movement (Duncan et al., 2014; Terzaghi et al., 1996).

3.1.2 Topographic Factors

Shallow landslides occur predominantly on steep, convergent slopes. As slope gradient increases, so does the down slope component of the gravitational forces acting upon soil particles. Convergent slopes tend to accumulate soil over time and focus subsurface flow, which increases the likelihood of soil saturation and failure (Dietrich and Dunne, 1978; Montgomery et al., 2000).

3.1.3 Lithology and Soil Properties

Studies have documented regional differences in landslide rates that appear to be related to differences in lithology and geologic history (Montgomery et al., 1998; Sarikhan et al., 2008; Thorsen, 1989). Orientation of the bedding and fractures in the bedrock may also influence the specific location of landslides (Montgomery et al., 1997).

3.2 Forest Management Effects on Slope Stability

Landslides are a natural occurrence in western Washington, but forest practices may alter both physical and biological factors that influence slope stability. The following is a brief summary of potential forest-management effects.

3.2.1 Hydrologic effects

Forest canopy intercepts a substantial portion of incoming precipitation. Evaporation of the intercepted water reduces the amount that falls to the ground and infiltrates into the soil. In the Pacific Northwest, interception losses can account for up to 47% of the annual precipitation (Bauer and Mastin, 1997). Removal of forest canopy eliminates interception losses and thereby increases soil moisture, evident by increased groundwater levels and stream flows following timber harvests (e.g., Johnson et al., 2007; Keim and Skaugset, 2003; Lewis et al., 2001). The removal of canopy enhances snow accumulation and melt, which can also increase peak soil moisture (Coffin and Harr, 1992; Jennings and Jones, 2015; Marks et al., 1998; Storck et al., 2002)

Shallow soils overlying low-permeability substrates, like glacial till or intact rock, can become saturated under high rates of infiltration, so that an intense storm can trigger shallow landslides. However, the consequences of timber-harvest-related loss of canopy interception and associated increased infiltration for shallow landslide potential are uncertain. During intense storms, the evaporation rate of intercepted water is small compared to the rate of precipitation, so that infiltration rates and shallow pore pressures during the storm are not greatly affected by presence of forest canopy (Dhakal and Sullivan, 2014). Forest cover may, however, affect shallow landslide occurrence by smoothing the transfer of water to the soil, thereby modulating peak pore pressures (Keim and Skaugset, 2003).

In deeper soils, pore pressures respond to cumulative infiltration over time scales spanning multiple storms. Deep-seated landslides can react to sequences of storms spanning weeks, months, even years. Canopy interception and transpiration of water by trees reduces the cumulative infiltrated water volume. Deep-seated landslides, therefore, respond to patterns of recharge (precipitation minus losses to interception and transpiration), rather than to patterns of precipitation (Vallet et al., 2015a). Harvest-caused reductions in interception and transpiration may thereby increase potential for deep-seated landslide activity (Miller and Sias, 1998; Swanston et al., 1988).

Pore pressures are proportional to the depth of saturation in soil and rock. Groundwater in the saturated zone can flow laterally, so spatial patterns in rates of groundwater recharge associated with infiltrating water and groundwater discharge at springs and streams drive groundwater flow systems and govern spatial and temporal patterns of saturation depth. Groundwater levels and pore pressures within unstable slopes may thereby respond to infiltration and recharge at locations upslope (Vallet et al., 2015b). Temporal changes in recharge rates change these patterns (Malet et al., 2005). This means that the transient increase in recharge associated with timber harvest may increase saturation depths within unstable slopes distant from the harvest itself. Recharge to deep-seated landslides has been shown to extend over two kilometers upslope for sites in the Alps (Binet et al., 2007). Current RIL C, groundwater recharge areas for glacial deep-seated landslides, addresses the potential for harvest to alter saturation depths in areas downslope. However, we have found no empirical studies that examine the importance of the groundwater recharge area (beyond a landslide boundary) to landslide activity. Neither is this process limited to glacial deep-seated landslides; recharge from upslope has been observed for bedrock landslides (Binet et al., 2007).

3.2.2 Loss of root strength

Evidence suggests that tree roots contribute to stability of shallow soils on steep slopes. Root systems provide resistance to gravitational forces that pull soil masses downhill (Riestenberg and Sovonick-Dunford, 1983; Schmidt et al., 2001a). Timber harvest may reduce root reinforcement when roots from harvested trees are decaying and new roots from growing trees are expanding (Burroughs and Thomas, 1977; Sidle, 1991, 1992; Ziemer, 1981), with total root strength at a minimum between approximately 4 and 10 years after harvest (Schmidt et al., 2001a; Sidle, 1991, 1992). Field and simulation studies illustrate that vegetation leave areas can significantly reduce landslide volumes by retaining available root strength in areas prone to failure (Dhakal and Sidle, 2003; Imaizumi et al., 2008; Preti, 2013; Roering et al., 2003; Schwarz et al., 2010). Following a large landslide-producing storm in December 2007, a study on Washington State Forest Practices Rules found that harvest units with intact forest (i.e., buffers) on unstable landforms had landslide densities that were lower than units where unstable landforms were harvested (Stewart et al., 2013).

3.2.3 Road construction

Landslide inventories in the Pacific Northwest have established that roads in steep terrain have historically been responsible for a high proportion of landslides in managed forests (e.g., Robison et al., 1999). Poor construction techniques and inadequate drainage were believed to be the main causes (Furniss et al., 1991; Sessions et al., 1987), though it has been shown that roads intercept groundwater and change hydraulic patterns leading of slope failure in some cases (Dutton et al., 2005; Mirus et al., 2007; Wemple and Jones, 2003).

Landslides associated with forest roads often initiate from sidecast road fill material perched on steep slopes. Road failures can occur when stream-crossing or drainage culverts become plugged and excessive runoff is concentrated on unstable slopes. The use of uncompacted fill and the inclusion of organic material (logs) in road fill have also been found to contribute to slope failures (Burroughs et al., 1976). Modern road building techniques include 1) the construction of steeper grades which reduces road mileage and 2) the complete removal of excavated material to lower gradient waste areas. These and other techniques have significantly reduced road landslide frequency (Sessions et al., 1987), but hydrologic alteration remains difficult to avoid (Borga et al., 2004; Montgomery, 1994).

3.3 Natural Factors Affecting Landslide Runout

In certain situations, a shallow landslide can evolve into a debris flow, a fluidized slurry of soil, organic debris, and water (Iverson, 2014). Debris flows can travel long distances at high velocity. As they traverse steep channels, they can entrain material as they move downslope and grow in size (Benda and Cundy, 1990). Debris flows can render sites susceptible to landslide impacts, even though they may be far removed from the points where landslides originate. The hazard posed by a potential landslide site to downslope streams, therefore, depends on the potential for landslide initiation, the changes in debris volume during transport, and the distance the landslide travels.

A debris flow may stop as a discrete deposit, such as at a road fill, on a debris fan, or as a sediment wedge above wood accumulations; or it may deposit gradually along a significant length of channel. In general, gradients are steep at initiation sites, remain steep where scour-to-bedrock occurs, and moderate in transport and deposition areas. Traveling through broader, lower-gradient channels, they can form extensive valley-filling deposits and fans (Lancaster and Casebeer, 2007). Debris-flow deposits in confined channels can temporarily block a channel and trigger a dam-break flood (Coho and Burges, 1993). Through these processes, debris flows form an important mechanism for transport of sediment and woody debris to valley floors (Benda and Dunne, 1987; May, 2007; May and Gresswell, 2003) and can cause important geomorphic and ecologic effects on river networks (Benda, 1990; Benda et al., 2004b; Benda et al., 2003b; Bigelow et al., 2007). Ecosystems have evolved to deal with a certain frequency of such effects (Reeves et al., 1995). Changes to that frequency can trigger ecosystem changes that are viewed as detrimental if they involve loss of valued resources, such as fisheries.

3.4 Forest Management Effects on Runout

Runout length has been strongly correlated with event volume, such that larger events travel further than small events. It is also found that landslides and debris flows originating from roads and in clearcuts tend to travel further than those from forested slopes (e.g., Robison et al., 1999; May 2002). These observations indicate that characteristics of forest cover along channels can potentially alter the volume, content, and travel distance of debris flows. Empirical studies find that, in some cases, debris flows tend to travel further, continuing to lower-gradient channels, and with higher erosion volumes through younger stands (Guthrie et al., 2010; Ishikawa et al., 2003; Johnson et al., 2000; Miller and Burnett, 2008b; Robison et al., 1999). Finally, large trees or large woody debris scoured or entrained by debris flows reduce runout distances (May, 2002; Lancaster et al., 2003; Robison et al., 1999), which means that a lack of large trees or large woody debris because of present or past forest practices may increase runout distances. Collectively, these observations suggest that road prisms and timber harvest along debris-flow runout pathways may increase runout distance.

3.5 Mass Wasting Impacts

Forest landslides are most likely to affect aquatic organisms through scour and sediment deposition along stream corridors (Cederholm and Reid, 1987). While landslides cause direct mortality to inhabitants of reaches in the runout path, the deposited material can provide a source of suspended sediment and bedload that can alter channel characteristics downstream and thereby affect stream-dwelling organisms over much longer distances. The very large volumes of sediment delivered to streams through mass wasting can greatly exceed the annual capacity of fluvial transport, and subsequent sedimentation impacts can persist for many years (Benda and Dunne, 1997; Dietrich and Dunne, 1978). Impacts may include sediment deposition in spawning and rearing habitat of salmonids and other aquatic organisms (Cederholm and Reid, 1987; Everest et al., 1987).

While excessive sediment delivery is associated with habitat degradation, aquatic habitat can also benefit from the delivery of gravel and large wood and boulders, which form critical components of habitat (Benda et al., 2003a; Geertsema and Pojar, 2007; Restrepo et al., 2009). Temporal and spatial patterns of landslide delivery of sediment and wood to streams act to create the spatial distribution of aquatic and riparian habitat types found in a river system (Benda et al., 2004b). Changes in the frequency of landslide occurrence, or in the source and volume of sediment and wood contained in landslide deposits, will change the distribution and abundance of different habitat types (Benda et al., 2004a). Such changes have profound ecological and management implications (Reeves et al., 1995), but are difficult to anticipate or detect, because they involve the accumulation of landslide impacts over regional extents and long decadal time periods.

3.6 Research Approaches: Empirical and Physical

Two general approaches are used to determine where landslides occur: empirical, which rely on observed evidence, and physical (also known as process-based), which rely on conceptual understanding of landslide processes. Because landsliding at any particular site is infrequent, evidence-based empirical approaches typically aggregate information from many observed sites and use statistical techniques or other approaches to identify characteristics in the observed sample that can be generalized in predictions that apply to the larger unobserved population. Physical approaches differ in that they seek to describe the underlying physics behind what happens during specific events at specific sites. The key physical processes are identified through monitoring, such as the work of Bill Dietrich and his students at Coos Bay, and through field and laboratory experiments, such as the work by Richard Iverson and his colleagues with the debris-flow flume at the H.J. Andrews Experimental Forest in Oregon. Observations and measurements from these studies are used to construct conceptual and mathematical models of the processes involved. Each approach has certain advantages and disadvantages.

An empirical approach is commonly used when the physical processes are not fully known or when the site information needed to apply a physical model (e.g., soil depth) is unavailable. With empiricism, we use the past as the key to the future, and assume that traits associated with past landslides will be similarly associated with future landslides. Empirical approaches are often used for shallow landslides, because these occur in sufficient numbers to provide abundant data for building conceptual or statistical models of susceptibility and hazard.

Landslide inventories provide the primary data for development of empirical models to identify areas susceptible to shallow-landslide initiation. The set of observed landslides constrains empirical results, and our observations may not include examples of every possible type of landslide occurrence. In addition, the future may bring unprecedented events that cause behaviors not previously observed. Likewise, the degree to which empirical results calibrated to one region can be reliably applied to another depends on how similar the two regions are, so extrapolation of empirical models to other areas can involve an unknown level of uncertainty. Finally, different methods produce different measures of the propensity for landsliding, and the accuracy and precision of remotely mapped landform type and extent varies with the quality and scale of available resources, so care must be taken in comparing results from different methods. A variety of approaches can be used for such comparisons, all of which involve comparison of the predicted level of susceptibility to actual landslide locations.

Physical models allow predictions for conditions that have not been observed; for example, to estimate landslide susceptibility in areas lacking landslide inventories, or to evaluate how changes in land cover might affect landslide susceptibility. Physical models assume knowledge of the processes involved and require data about site conditions, such as soil depth, that may not be available. In research, physical models are often used to articulate concepts and to pose hypotheses to test those concepts. In land management, models are commonly used to anticipate the future and to examine possible outcomes of different decisions or scenarios. For both types of uses, it is important that the reliability of model data be evaluated by comparing predictions against empirical data. So, although physical models can be used without a landslide inventory, an inventory is needed to validate model predictions. A large range of statistical techniques are used to assess different options in model development, and work progresses on techniques for assessing the reliability of model predictions.

The literature contains many examples of development and use of both types of models. Brenning (2005), Kanungo et al. (2009), Pardeshi et al. (2013), and Corominas et al. (2014) provide reviews. Likewise, a variety of user interfaces for applying both empirical and physical models are being developed (Benda et al., 2007; Mergili et al., 2014; landlab.github.io/#/), which can greatly simplify the application of such models.

3.7 Areas of Research

3.7.1 Shallow Landslides

Much of the research in steep forested areas has focused on shallow-rapid landslides, because they occur relatively frequently, in high densities, and the material runout can cause significant damage.

3.7.1.1 Susceptibility to initiation

For shallow landslides, susceptibility mapping focuses on determining where new shallow-rapid landslides may occur.

3.7.1.1.1 Empirical approaches

Landslide locations can be mapped using field surveys that, if done thoroughly, can provide a complete census of all landslides occurring in a particular area in response to one or more storms during a single winter season. On-the-ground observations provide a variety of clues as to mechanisms and potential management triggers, though one or more causal mechanisms can rarely be exclusively determined.

Field surveys are labor intensive and time consuming, and since shallow landslides typically leave scars visible on aerial photographs, inventories are more commonly collected by mapping landslide scars from photos or other remotely sensed imagery. Remotely mapped inventories, however, suffer from detection bias (Pyles and Froehlich, 1987), in that a portion of the landslides are not included in the inventory because they are not visible in the imagery. When comparing landslides counted in forested versus non-forested (e.g., recently harvested) areas, detection bias results in fewer counted landslides in forested areas (Brardinoni et al., 2003; Miller and Burnett, 2007; Turner et al., 2010).

Landslides at any particular site may be infrequent – potentially separated by many centuries – so evidence of instability may be lacking during a field visit, but the potential for future landslide activity at that site may still exist. Therefore, landslide inventories have a false-negative bias; they identify sites that recently failed under a set of conditions, rather than identify sites with the potential for failure. Usually, characteristics of landslide sites are extrapolated to nearby sites of similar characteristics that have not recently failed, but might do so in the future. This is how an empirical landslide inventory creates a susceptibility map beyond just those recently failed sites.

Statistical techniques for using digital landslide inventories with GIS data to map landslide susceptibility have expanded dramatically in recent years following the widespread availability of high-resolution imagery and elevation data. Many case studies have been published using a wide variety of techniques, including the likelihood ratio, logistic regression and other generalized linear and additive models, artificial neural networks, and decision trees, along with a host of studies comparing different techniques (e.g., Brenning, 2005; Dou et al., 2015; Mahalingam et al., 2016; Pourghasemi et al., 2013; Pradhan, 2013; Vorpahl et al., 2012). Because statistical techniques mathematically relate predictors to outcomes, model probabilities can often be expressed in terms of landslide density (the number, or area, or volume of landslides per unit area) or susceptibility.

Using statistically derived empirical models to predict landslide density provides a simple way for validating model results. These models provide predictions that vary from point to point depending on spatial variation in the terrain attributes used in the model. By presenting susceptibility in terms of landslide density, results can be translated to the relative number of landslides expected over different portions of a watershed, or within different landforms. Susceptibility can be mapped in terms of the proportion of landslides we expect to find within different zones (Chung, 2006; Miller, 2008; Spies et al., 2007). This also provides an intuitive way to compare the performance of different models. For example, we may seek the model that predicts the greatest proportion of landslides within the smallest area (Figure 1). If landslide inventories include information on date of occurrence, landslide rate (frequency) can be estimated. If information on the rainfall patterns associated with landslide occurrence are known, landslide density can be determined as a function of rainfall intensity (Turner et al.,

2010) and landslide frequency determined from precipitation records (Reid, 1998; Reid and Page, 2002).

Empirical observations also indicate increased landslide susceptibility associated with timber harvest and forest roads (Brardinoni et al., 2002; Goetz et al., 2015; May, 2002; Swanson and Dyrness, 1975b), even after accounting for differences in topographic attributes between sites and detection bias (Brardinoni et al., 2003; Miller and Burnett, 2007). Recent efforts seek more direct connections, relating landslide locations with details of forest structure. It may therefore be feasible to empirically assess landform sensitivity to forest practices. However, many factors complicate empirical efforts seeking to identify influences of forest practices on landslide density or rate. In examining landslides associated with the large storm of December, 2007, Turner et al. (2010) found that differences in landslide density across different forest-age classes are dependent on rainfall intensity. Rainfall is a difficult confounding factor in interpreting landslide density, because precipitation data are not typically available at the spatial and temporal resolution needed to associate landslide occurrence with rainfall intensity. Miller et al. (2003) describe another issue – in examining landslide densities associated with large storms in western Oregon, they found scale dependence in results comparing landslide density across stand ages. As with any stochastic process, variability in measured density increased as the study area decreased, but they also found that the distribution of observed density values changed with the size of the area examined, so that conclusions based on inventories collected over a 10 km^2 area differed from those collected over a 100 km^2 area.

3.7.1.1.2 Physical models

Many physical models have been developed for shallow-landslide initiation. These models rely on several simplifications of what we understand to be the actual physical phenomena. Such simplifications are needed to create models that can be practicably applied; we seek to simplify, but still adequately represent the controlling processes.

The primary simplifications are that soil movement occurs in only two dimensions and parallel to a planar ground surface (plane strain, as implied by the infinite slope approximation), that failure occurs simultaneously across the entire slip surface (limit equilibrium) rather than progressively from an initial point of failure, that rainfall is uniform over time (steady-state conditions), and that water flowing through the saturated zone in the soil travels parallel to the ground surface. These simplifications allow calculation of a factor of safety (the ratio of forces acting to hold soil in place to those acting to move it downslope) in terms of ground surface slope, soil depth, soil geotechnical properties (bulk density, cohesion, friction angle), and degree of soil saturation.

Figure SEQ Figure * ARABIC 1: Empirical models can map susceptibility in terms of landslide density. Integrating density over area gives number of landslides. If the integration is performed from areas with lowest to highest density, we can create a plot showing the proportion of total area that encompasses a given proportion of observed landslides. We generally seek the model that best resolves landslide locations; that is, that indicates the highest proportion of landslides within the smallest area. This graph compares four different measures of susceptibility, including the SHALSTAB model (Dietrich et al., 2001). This figure is from Miller (2004); note that reversing the axis gives the success-rate curve advocated by Chung and Fabbri (2003).

Even though greatly simplified, these models still require a number of input parameters, of which ground-surface slope is the only one that is directly measured for typical hazard assessments. A variety of approaches are used, therefore, to estimate soil depth, soil geotechnical properties, and depth of saturation. These range from simply applying uniform values thought to be appropriate (e.g., Burns et al., 2012), to finding the range of results corresponding to the range of possible input values (e.g., Pack et al., 1998; Raia et al., 2014b) or back calculated to yield observed landslide locations (Koler, 1998), to applying other physical or empirical models to estimate these quantities (e.g., Dietrich et al., 1995; Montgomery, 1994).

Other approaches seek to remove some of the restrictive simplifications. Shallow landslides are thought to be triggered by high levels of soil saturation during rainstorms, so a common approach is to remove the assumption of steady-state rainfall by using a simple hydrologic model to estimate saturation depths in the soil (e.g., Wu and Sidle, 1995). Iverson (2000) and others (e.g., Malet et al., 2005) have expanded on this approach to incorporate more realistic patterns of groundwater flow (as implemented in the TRIGRS model, Baum et al., 2008; Raia et al., 2014b). Other efforts add a third dimension to better estimate landslide location and size (Bellugi et al., 2015; Mergili et al., 2014).

Publications describing physical models typically include empirical validation comparing model results to observed landslide locations. Such comparisons can be done using the same statistical techniques applied in development of empirical models. In this case, the results of the physical model provide the independent variable used to explain or predict landslide susceptibility, typically in terms of landslide density.

Physical models provide a direct way to examine implications of forest practices – to the extent that the effects of forest practices on landslide processes are known and characterized. For example, tree roots can act to hold soil in place, effectively increasing the shear strength of soils (Schmidt et al., 2001b), so the potential effects of timber harvest on loss of root strength, and subsequent increased susceptibility to landslides, can be estimated by applying physical models with and without the added soil strength associated with tree roots (e.g., Montgomery et al., 2000; Wu and Sidle, 1995).

3.7.1.2 Shallow landslide runout

In addition to the research on where and under what conditions landslides initiate, there is a growing body of research focused on predicting the runout path to assess downslope hazard.

3.7.1.2.1 Empirical models

Debris-flow runout distances within valleys or inner gorges and across debris fans have been studied across the Pacific Northwest (Benda and Cundy, 1990; Fannin and Wise, 2001; Guthrie et al., 2010; May, 2002; Miller and Burnett, 2008b; Prochaska et al., 2008; Robison et al., 1999). These studies show that gradient, topographic confinement, and changes in flow direction along the debris-flow travel path are primary controls on runout distance. The potential for debris-flow impacts to any point in a stream network depends on the total number of landslide sites that can generate debris flows that could deliver sediment to that point. Burnett and Miller (2007) and Miller and Burnett (2008) show how models for landslide initiation and runout can be linked and integrated over all potential initiation sites and runout paths to estimate these hazards.

Benda and Cundy (1990) describe an empirically derived method for predicting potential impacts from debris flows. The technique uses easily measured topographic criteria (channel slope, channel confinement, and tributary junction angle) to predict maximum debris flow runout distance from the point of initiation in steep mountain channels. Comparison with a large dataset in Oregon determined that only 10% of debris flows travel further than the Benda and Cundy (1990) predictions (Robison, et al. 1999), but May and Gresswell (2003) provide data that serves to emphasize that many debris flows deposit upstream of this maximum estimate.

The Oregon Department of Forestry developed technical guidelines to maintain regulatory compliance with the landslides and public safety rules for shallow, rapidly moving landslides (including debris flows and open slope debris slides; Oregon Department of Forestry, 2003a, b). These methods were developed and tested using data from debris flows in the Oregon Coast Range and the Washington Cascades (Benda and Cundy, 1990; Robison et al. 1999; and Benda, 1999). Technical Note Number 2, *High Landslide Hazard Locations, Shallow, Rapidly Moving Landslides and Public Safety: Screening and Practices*, is intended for use by engineers and foresters in conducting initial public safety screening and provides gradient, confinement, and runout metrics for channelized and open slope topography for determining the downslope extent of landslide hazards. Technical Note Number 6, *Determination of Rapidly Moving Landslide Impact Rating*, assists geotechnical specialists in completing detailed, field-based investigations of associated upslope hazards and downslope public-safety risks. Although intended for use within the context of Oregon's regulations, these methods can be applied throughout the Pacific Northwest for predicting shallow-rapid landslide runout and delivery potential. An Oregon Department of Forestry study of 361 debris flows (Robison et al., 1999) validated the model, and numerous resource professionals in the Pacific Northwest have reported good success in applying it to mountain debris flows regionally.

The UBCDFLOW model of Fannin and Wise (2001) is based on field observations of landslides from clearcuts. Four sites in coastal British Columbia with 449 events were used to develop the model for predicting debris flow travel distance in confined and unconfined (open) slopes. All of the sites were glaciated and included areas in western Vancouver Island with similar geology and climate as Washington State. The model, complete with a user guide and tutorial, is available at http://dflow.civil.ubc.ca/.

The Tolt Watershed Analysis contains mass wasting prescriptions for determining landslide delivery potential based on physical processes from empirical results in northwestern Washington and western Oregon.[9] In this method, delivery potential for a hypothetical mass failure is determined by considering topographic conditions at the failure initiation site, along the runout path, and in the deposition zone. The assessment is based on slope gradient changes as material travels downslope. If a failure becomes channelized, it becomes a debris flow. As debris flow deposition continues downslope, the potential for a dam-break flood is evaluated based on channel confinement. Estimated runout distances are provided as outputs from the above hillslope and up-channel geomorphology.

3.7.1.2.2 Physical models

Debris flows present a daunting set of physical processes. These include interactions of vast numbers of silt, sand, and gravel particles suspended in a viscous fluid (Iverson, 1997) to incorporation of trees and logs (Lancaster et al., 2003). Experiments show that conditions for triggering debris flows are acutely sensitive to soil characteristics and water content (Iverson et al., 2000) and that material properties evolve with deformation (Iverson, 2005). These processes have been studied in field and lab experiments, and incorporated into detailed physical models that accurately describe debris flow behavior (e.g., George and Iverson, 2014; Iverson and George, 2014). However, these models require numerous data on soil characteristics and information on initial and boundary conditions that are not generally available, so hazard assessments still rely primarily on empirical models (Iverson, 2014).

3.7.2 Deep-Seated Landslides

Deep-seated landslides involve movement of material extending below the rooting depth of plants, typically greater than 2 meters. They are examined separately from shallow landslides because they involve different hydrologic processes, differences in slide mechanics, and differences in our ability to evaluate susceptibility and hazard.

[9] Weyerhaeuser Timber Company 1993.

3.7.2.1 *Initiation of deep-seated landslide movement*

For shallow landslides, susceptibility and hazard mapping focus on identifying areas where new landslides may occur. For deep-seated landslides, the focus tends to be on identifying which existing landslide features may experience activity (see Forest Practice Board Manual Section 16 for description of deep-seated landslide activity levels), rather than on where new landslides will occur.

3.7.2.1.1 Empirical approaches

As with shallow landslides, a landslide inventory is the starting point for empirical determinations of landslide susceptibility and hazard. Deep-seated landslides have traditionally been identified and mapped from field observations and aerial photo interpretation (Dragovich et al., 1993a, b; Gerstel et al., 1999). In the last decade, the advent of high-resolution LiDAR-derived digital elevation models (DEM) has brought the availability of detailed shaded-relief imagery, from which deep-seated landslide features can be readily seen and mapped (Burns and Madin, 2009). Mapping from LiDAR shaded-relief imagery has increased awareness of the abundance of deep-seated landslide features in many areas (Haugerud, 2014; McKenna et al., 2008; Schulz, 2004; Van Den Eeckhaut et al., 2005).

Deep-seated landslide inventories can be used to identify site characteristics associated with the presence or absence of landslide features (Roering et al., 2005). This is similar to susceptibility mapping for shallow landslides, which seeks to identify the characteristics associated with observed landslide locations. Deep-seated landslides, however, can create features that persist for millennia. Deep-seated landslide inventories based on mapping of landslide features can therefore include landslides that formed long ago, under different environmental conditions, and are currently stable. Thus, deep-seated landslide inventories may include both stable and unstable features. To assess susceptibility requires some way to distinguish the two. Several studies seek to relate topographic attributes of landslide features to landslide age (Glenn et al., 2006; Goetz et al., 2014; LaHusen et al., 2016), but we have found no examples in the literature of empirical methods for predicting levels of landslide activity based solely on morphology.

Many studies examine triggers for deep-seated landslide movement (Geertsema et al., 2006; Pánek and Klimeš, 2016; Van Asch et al., 2009). These triggers include seismic shaking (Allstadt et al., 2013; Highland, 2003), erosion or excavation of landslide toe slopes (Eilertsen et al., 2008; Stark et al., 2005), and increased pore pressures associated with periods of high precipitation (Van Asch et al., 2009). Some researchers seek to identify rainfall patterns associated with the onset or acceleration of landslide movement (Prokešová et al., 2013). This approach is not well suited for identifying potentially active landslides, because the precipitation patterns that trigger motion tend to be complex, unique for each landslide, and not readily predictable (Floris and Bozzano, 2008).

3.7.2.1.2 Physical models

Deep-seated instability is a persistent problem for engineered slopes, road alignments, dam construction, and surface mining, which has prompted considerable effort into characterizing the processes of deep-seated landsliding and in development of physical models of these processes (e.g., Clague and Stead, 2012; Duncan et al., 2014; van Asch et al., 2007). These models are typically used for detailed, site-specific analyses, but they have also been applied for regional assessments of landslide susceptibility (Brien and Reid, 2008; Mergili et al., 2014; Miller, 1995). Such models tend to require a fairly high level of user expertise and effort, and have not yet been widely applied, although continuing development of sophisticated user interfaces (e.g., http://www.slopestability.org/) may expand accessibility of such approaches to a larger audience.

To distinguish potentially active from inactive landslides regionally would require application of such models landslide-by-landslide. We have found no examples of such applications in the literature, although with the increasing availability of digital topographic, geologic, and climate data, such an approach is becoming feasible.

A particular advantage of physical models is the ability to examine landslide response to different scenarios. Although examples are relatively few, such models have been used to examine potential response of individual landslides to changes in land cover (Malet et al., 2005; Van Beek and Van Asch, 2004) and timber harvest (Miller and Sias, 1998).

3.7.2.2 Deep-seated landslide runout

Material mobilized in shallow landslides tends to disintegrate and deposit on landforms distinct from those where the landslides initiated. Material mobilized in deep-seated landslides, however, may remain relatively intact, moving as a semi-coherent block or earthflow. Movement may be incremental, with long periods of quiescence (Petley and Allison, 1997).

3.7.2.2.1 Empirical approaches

Most deep-seated landslides exhibit intermittent, relatively slow (centimeters to meters per year) movement. There may be associated shallow landslides that peel off the toe, margins and scarps (Regmi et al., 2014; Reid et al., 2003), but in most cases where the rate of downslope movement is small, the body of a deep-seated landslide poses little downslope hazard. However, large, deep-seated landslides can mobilize millions of cubic meters of material that, under certain conditions, travel long distances (> one kilometer) at high speeds (meters per second). Those few deep-seated landslides that do fail catastrophically can, therefore, extract a large toll (Petley, 2012), as we were reminded in March 2014 by events near Oso (Wartman et al., 2016).

Because deep-seated landslides can pose large risk to downslope populations, the runout extents of many of these landslides have been measured to provide an empirical database. These compilations have been used to relate runout length to a variety of site and landslide characteristics, including material properties, elevation difference from the top of the landslide scarp to the base of the final deposit, the relative angle between the failed hillslope and surface receiving the deposit, the landslide area, the deposit volume, or some combination of these factors (Hattanji and Moriwaki, 2009; Hungr et al., 2005; Hunter and Fell, 2003; Iverson et al., 1998; Legros, 2002; McDougall et al., 2012). These methods rely on the statistics of the population of sites included in the inventoried examples, which can be presented in terms of an exceedance probability and translated to maps showing estimated susceptibility to inundation from an upslope landslide. However, they suffer from the limitations of all empirical approaches in that extrapolation of results is uncertain.

They also suffer from lack of information on the potential for catastrophic failure. As described above, most deep-seated landslides pose little downslope hazard most of the time, and many may pose no hazard at all. However, Geertsema et al. (2006) document 38 large, catastrophic landslides over a 30-year period in northern British Columbia, suggesting that evaluation across larger landscapes and time intervals might improve our understanding by bolstering the available dataset.

3.7.2.2.2 Physical models

A variety of physical models for deep-seated landslide runout have been developed (Hungr et al., 2005; see reviews in McDougall et al., 2012) with ever increasing sophistication (e.g., Iverson and George, 2016; Iverson et al., 2015). These models require a high degree of user expertise and are not yet widely used for regional hazard evaluation. This state of affairs will likely change as user interfaces also become more sophisticated (i.e. easier to use). For now, however, we focus our attention on the empirical models described previously.

4 Unstable Slope Criteria Research Projects

Step 4 in the TWIG process involves identifying potential research alternatives. The TWIG was unable to identify an alternative that did not require new research. The TWIG identified seven research projects, each of which addresses some component of the research objectives. These projects can be used independently (for some cases) or combined to provide alternatives. Here we present these projects. In section 5, we discuss alternatives involving these projects. If Policy approves follow-up work on one or more of the alternatives, a study design containing detailed methods for site selection and layout, data collection, and analysis will be developed.

1. Compare/Contrast Landslide Hazard Zonation Mass Wasting Map Units with RIL.
2. Regional Assessment of Missing RIL by Qualified Experts.
3. Object-Based Landform Mapping with High-Resolution Topography.
4. Empirical Evaluation of Shallow Landslide Susceptibility and Frequency by Landform.
5. Empirical Evaluation of Shallow Landslide Runout.
6. Physical Models to Identify Landforms and Shallow Landslides Most Susceptible to Management.
7. Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform.

To aid in evaluating each of the proposed projects, the TWIG identified specific requirements needed to address the purpose, critical question, and objective as described in Section 1.3. These requirements are posed here as five questions:

1. How will the proposed project ***determine current*** criteria accuracy and bias for characterizing unstable landforms (i.e., RILs) in terms of the probability of landslide occurrence and delivery?
2. How will the proposed project determine *current* ability to estimate the influence of forest practices as measured by changes in the probability of landslide occurrence and delivery for unstable landforms?
3. How will the proposed project *improve* criteria accuracy and reduce bias for characterizing unstable landforms in terms of the probability of landslide occurrence and delivery?
4. How will the proposed project *improve* ability to characterize the influence of forest practices as measured by changes in the probability of landslide occurrence and delivery for unstable landforms?
5. How will the proposed project *improve* consistent interpretation of unstable slope criteria?

We refer to these questions as the "How will" list and include answers to each in the following descriptions of each project.

4.1 COMPARE/CONTRAST LANDSLIDE HAZARD ZONATION MASS WASTING MAP UNITS WITH RIL

Those Phase 3 watershed administrative units (WAU) and state land blocks that utilized the Landslide Hazard Zonation (LHZ) Protocol can be reviewed to: 1) Determine how many observed landslides are occurring in mass wasting map units (MWMU) that meet rule-identified landform definitions (WAC 222-16-050 (1)(d); 2) Determine how many observed landslides are occurring in MWMU that do not meet RIL definitions; and 3) Identify, verify and characterize those non-RIL landforms and estimate their spatial distribution.

4.1.1 Details of Approach

1. Acquire all completed LHZ products (WDNR website). Bin MWMU into the RIL types and hold others as probable non-RIL MWMU. Summarize basic data. (This step was done by a TWIG member several years ago.)
2. Interview LHZ authors (most are known to be available). The interview questions would be: 1) Were the MWMU binned into the correct RIL types? 2) What do you remember about the non-RIL? 3) How much field work went into characterizing non-RIL?
3. Conduct a field review focused on the non-RIL MWMU. First, validate the landslide inventory that caused the creation of a non-RIL MWMU (i.e., are there a set of field-verifiable landslides that justify the non-RIL MWMU?). Second, if the landslide inventory justifies the non-RIL MWMU, then confirm the characterization or better characterize the non-RIL MWMU with field-derived data and descriptions.
4. Extrapolate the potential for the non-RIL MWMU beyond the WAU. If it potentially is a state-wide high-hazard landform, it may be reasonable to only provide a description. Where the non-RIL MWMU is regional, this may mean providing a map of the lithology, or other constraining factors, where the non-RIL MWMU might exist. If the lithology is not extensive, it may be possible to map within the lithology those areas where the non-RIL MWMU is known to occur or may be inferred to exist. Some guidance about which decision to make would have to be part of the Study Design to keep the project within budget/timeline.
5. Produce report and map.

4.1.2 Products

- Summarized inventory of non-RIL and RIL Mass Wasting Map Units (MWMUs) from the Landslide Hazard Zonation (LHZ) Project.
- A map showing identified non-RIL MWMUs with the landslide inventory used to validate the MWMUs, both within and beyond the area of the LHZ analysis, and field-based criteria for the MWMUs.
- The relative landslide density for all MWMUs. Comparison of relative densities will then be used to evaluate consistency in landslide inventories across MWMUs, across Watershed Administrative Units (WAUs), and between analysts. This is important because densities are influenced by mapping criteria, resolution of available mapping data, and analyst bias (e.g., lumping versus splitting of areas delineated in each MWMU).
- Frequency distributions of topographic attributes (e.g., gradient, curvature) for each MWMU, which will be used to evaluate consistency in how MWMUs are delineated across WAUs and between analysts, and to seek distinct digital signatures for each MWMU type. (This product might be LiDAR-based if sufficient data exist, but is likely to be built on 10-m DEM for consistency between LHZ Project areas.)

4.1.3 "How will" list

1. This project will help identify whether there are additional landforms that might merit becoming named RILs in WAC 222-16-050 (i.e., it addresses bias). It will not address whether the current RIL criteria could be modified so they more accurately define areas of high hazard (i.e., accuracy).
2. Does not explicitly characterize RIL or non-RIL sensitivity to forest practices.

3. This project will locate and provide preliminary criteria for unstable slopes that could become named RIL (either state-wide or regional), as well as existing RILs that may not exhibit significant hazard and risk in specific regions.
4. This project will not improve characterization of landform sensitivity to forest practices.
5. This project may provide more consistent landform criteria (numeric and narrative) and more complete mapping (e.g., extent of non-RILs outside of LHZ projects).

4.1.4 Uncertainties

- LHZ MWMUs may not provide a representative sample of landslide-prone terrain across Forests & Fish Report (FFR) lands, so some potentially unstable non-RIL may not be identified.
- The proportions of mapped landslides that are false positives and false negatives (detection bias) are unknown. This would potentially bias the landslide densities that would be calculated.
- MWMUs may contain mapped areas that do not meet MWMU criteria. Unmapped areas may contain landforms that meet MWMU criteria. This could bias landslide densities by including or not including area associated with the unstable landform.
- Topographic attributes based on 10-m DEM may be biased.

4.1.5 Relative Cost/Time Estimates

Cost of $80,000 and one year for actual work and report writing. Assumes one qualified expert part time for one year.

4.2 Regional Assessment of Missing RIL by Qualified Experts

One method for answering the question "Could modifications to the unstable slopes criteria result in more accurate and consistent identification of those landforms that are likely to have an adverse impact to public resources or public safety?" is to ask Qualified Experts (QE). This method relies on expert opinion rather than quantitative methods. Because Washington State already maintains a list of Qualified Experts and relies on them for SEPA analysis related to potentially unstable slopes and landforms (WAC 222-10-030), it would be relatively easy to ask them to weigh-in on this important topic.

4.2.1 Details of Approach

A set of survey questions would be developed and sent to the list of QE with the objective of identifying possible non-RIL landforms, potential improvements to existing RIL criteria, and geographies where RIL susceptibility is not significant. Group meetings within WDNR regions might be used to finalize those possible non-RIL landforms, and then the contractor would perform small-scale landslide inventories from aerial photography. Field work would validate each landslide inventory and data collected during the effort would be used to develop field descriptions of the unstable landforms.

4.2.2 Products

- Compilation of qualified expert's (QE's) opinions for non-RILs across the entire state.
- Aerial-photo-based landslide inventory for selected non-RIL locations.
- A map showing identified non-RIL MWMUs with the landslide inventory used to validate the MWMUs, and field descriptors of the MWMUs based on QE input and field visits.

4.2.3 "How will" list:

1. This project may qualitatively address accuracy and bias at a course scale by identifying regional variations in criteria based on the experience and professional judgment of QEs.
2. Does not explicitly characterize RIL or non-RIL sensitivity to forest practices.
3. Will provide preliminary criteria for non-RILs and suggestions for modification of criteria for existing RILs.
4. Will not improve characterization of landform sensitivity to forest practices.
5. Improved interpretation of criteria is possible, but unlikely.

4.2.4 Uncertainties

- Relying on input from a nonrandom sample (those who are willing) of participants, who may not have similar thresholds for identifying other features that should serve as RILs, introduces a source of bias.
- Without landform mapping, we will not know the relative importance of identified non-RIL landforms in terms of the proportion of landslide-prone area they occupy.
- Without landslide inventories spanning all landslide-prone landform types, we will not know how the identified non-RIL landforms compare to RIL landforms in terms of landslide density or proportion of all landslides.

4.2.5 Relative Cost/Time Estimates

The initial part of this effort would probably take less than a month and cost between $500 - $5,000 depending on whether it was contracted out or performed in-house by UPSAG, and whether individuals would be incentivized to participate (e.g., name entered into a raffle to win something). Air photo landslide inventory and field validation and description of landforms would depend on landform extent and vary between 6 months and 1 year and probably cost $50-75k.

4.3 Object-based Landform Mapping with High Resolution Topography

This project would use object-based methods to map landforms for the purpose of calculating landslide susceptibility.

4.3.1 Details of Approach

Landform maps provide the baseline from which to calculate landslide susceptibility based on the density or rate of landslide occurrence across the population of landforms. Existing landform mapping techniques have primarily utilized manual methods (e.g., stereo air photos, topographic maps, and DEM-based hillshade derivative maps) that are time consuming, subject to bias, and have not universally employed high-resolution topographic data or systematic detection and mapping techniques (e.g., MWMUs from watershed analysis and the Landslide Hazard Zonation projects in Washington that were conducted for forest practices applications).

Furthermore, prior work to correlate spatial distributions of landforms and landslides has focused primarily on single landform assemblages, such as steep and convergent topography (e.g., SLPSTAB and SHALSTAB). Quantifying relative landslide densities across the landscape, not just within currently regulated terrain features, requires geospatial tools to comprehensively, objectively, and reliably extract and classify landforms across diverse terrain and all landform types.

This project would develop an automated, computer-generated landform mapping tool to systematically detect and delineate landforms across a variety of terrain types. These landforms will include existing RILs, and other terrain elements where landslides may occur, such as planar slopes, ridge noses, and roads. This project would employ geographic object-based image analysis (GEOBIA), which has shown promise for segmenting high-resolution topographic data into spatial objects that can be mapped and classified (Blaschke et al., 2008; Drăguţ and Blaschke, 2006). Landform mapping models using GEOBIA techniques can segment variable landscapes into discrete landform polygons based on topographic derivatives, such as slope gradient and curvature, among others.

Extracting and classifying landform features with high-resolution LiDAR DEM data using object-based image analysis techniques is now being developed in Washington and Oregon (e.g., Shaw et al., 2012). Therefore, this project may be able to use landform mapping models currently in development. Model data would potentially support analysis for proposed Projects 4, 5 and 6.

4.3.2 Products

- Automated procedure for landform mapping from high-resolution DEMs (and potentially other data sources). This procedure will consist of a set of rules used with software for image segmentation, such as eCognition. Input data for segmentation may include topographic attributes derived from other software sources.
- Validated landform maps based on manual mapping from LiDAR shaded imagery, maps of derived topographic attributes (such as slope), aerial photography, and field surveys. These will be created

for a small set of diverse areas across the state and would validate landforms delineated with the automated procedures.

- Determination of the accuracy and precision with which landforms (MWMUs) can be delineated using high-resolution elevation data with image segmentation software.
- Depending on the obtainable accuracy and precision, this project can provide quantifiable and replicable rules for delineating landforms, both RIL and non-RIL. The delineated landforms can be used as a baseline for estimating landslide densities by landform type (Project 4) and estimating spatial extent of specific landforms.

4.3.3 "HOW WILL" LIST:

1. Will provide objective mapping of landforms that can be compared to existing hand-drawn MWMUs.
2. Does not explicitly characterize RIL or non-RIL sensitivity to forest practices.
3. Does not address criteria accuracy or bias (these are addressed in Project 4). Does provide more accurate landform mapping.
4. Will not improve characterization of landform sensitivity to forest practices.
5. Provides consistent delineation of landforms, but will not improve unstable slope interpretation based on non-topographic field indicators (e.g., vegetation, tension cracks, evidence of local hydrogeology).

4.3.4 UNCERTAINTIES

- It is unknown, until this project is done, to what accuracy and precision an automated procedure can be used for landform mapping.
- Accuracy and precision may depend on quality of the LiDAR point-cloud data and derived DEMs. LiDAR coverage is spatially limited so the extent of unstable landform delineation will also be spatially limited.

4.3.5 RELATIVE COST/TIME ESTIMATES

Estimated one-year at a cost of about $210,000 if contracted out. This work may be performed by CMER staff with experience in object-based landform mapping for the cost of time and equipment.

4.4 EMPIRICAL EVALUATION OF SHALLOW LANDSLIDE SUSCEPTABLITY AND FREQUENCY BY LANDFORM

This project applies empirical methods to characterize susceptibility for initiation of shallow landslides. This entails two tasks: 1) Identify existing landslide inventories that are suitable to the task, or collect new landslide inventories; and 2) rank landforms, both RIL and non-RIL, in terms of susceptibility to shallow landslide initiation. Susceptibility will be defined as relative landslide density, or if feasible, landslide rate. Landforms will also be examined in terms of the cumulative area occupied by each landform type and the proportion of all landslides initiating in each landform type. This project requires the landform mapping provided by Project 3 (Automated Landform Mapping)

4.4.1 Details of Approach

Landslide inventories provide a primary data source for this project. The inventories used would need to be evaluated for detection bias and for the degree to which the areas from which the inventories were collected provide a representative sample of potentially unstable landforms. Bias can be evaluated through examination of landslide size distributions (e.g., Miller and Burnett, 2007; Wood et al., 2015) and correlation of air-photo detected landslides with ground-based observations (Turner et al., 2010). Evaluation of how well the sampled landforms represent the relative abundance of different landforms throughout FFR lands would require extensive landform mapping to determine the frequency distribution of landform types; this mapping is provided by Project 3. Landform mapping would be re-evaluated to minimize landform size, maximize landslide densities, and aid development of field-based criteria.

4.4.2 Products

- A set of landslide inventories sampling landscape types across the state.
- Measures of relative landslide density for the set of landforms delineated in Project 3 for areas with landslide inventories.
- Measures of the proportion of landslides originating within each landform for any specified area (e.g., within a WAU and across all WAUs where landslide inventories are available.)
- Ranking of landforms by proportion of landslides produced.
- Maps showing landforms in terms of relative landslide density and proportion of all landslides.

4.4.3 "How will" list:

1. Will provide landslide densities and rates normalized to objectively mapped landforms to compare to existing assumptions regarding relative densities, rates, and proportions of landslides by RIL.
2. Could be used to infer sensitivity to forest practices based on differences in density and rates associated with land cover data and presence of roads.
3. Will improve accuracy and reduce bias by comparing normalized data across landforms.
4. May provide improved empirical associations between normalized landslide data and forest practices.
5. May provide improved interpretation of relative susceptibility of individual RILs (e.g., variability in susceptibility among bedrock hollows of variable gradient and curvature, and in different lithologies and climatic conditions).

4.4.4 Uncertainties:

- This project is unlikely to provide information about the sensitivity of landforms to specific influences from forest practices (e.g., soil strength vs. canopy effects on hydrology).
- If error rate or bias in landslide inventories varies across landform type, the ranking of landforms as landslide sources may be in error.
- Landslide inventories do not sample the entire range of potential rainfall events and may not include the entire range of landslide volumes.
- May miss "known" non-RIL if one of Projects #1 or #2 is not done. These projects provide a partial validation test of results from Project 4.

4.4.5 Relative Cost/Time Estimates

Estimated two years at a cost of about $200,000.

4.5 Empirical Evaluation of Shallow Landslide Runout

This project is a potential compliment to Project #4. It would identify the landform characteristics downslope of landslide initiation locations associated with delivery of landslide sediment to streams. This will help to expand the characterization of RILs to better determine likelihood of delivery.

4.5.1 Details of Approach

This project would build on existing empirical models for debris-flow runout and inundation (Benda et al., 2007; Benda and Cundy, 1990; Fannin and Wise, 2001; Guthrie et al., 2010; Hofmeister and Miller, 2003; Hofmeister et al., 2002; Miller and Burnett, 2008b; Prochaska et al., 2008; Reid et al., 2016; Rickenmann, 1999), using these initially to evaluate data needs and then collecting data to calibrate and test different modeling approaches.

4.5.2 Products

- Compendium of runout distances for shallow landslides and debris flows in Washington (and potentially in areas with similar site conditions).
- Improvement and calibration of existing empirical models specifying probable runout length based on site characteristics.

4.5.3 "How will" list

1) Calibrated models from this alternative can be applied to existing MWMUs to calculate a probability for delivery. These calculated values might be ranked and compared to the potential for delivery originally estimated for each MWMU. Note that this exercise can probably only be applied using GIS-based runout models; field-based models could be applied to only a small number of MWMUs.

2) There is nothing to evaluate, in terms of accuracy and bias, in current estimates of the influence of forest practices on delivery. Although a number of empirical studies indicate that runout distance is affected by forest vegetation along the runout path, this observation has not translated to general considerations of how forest practices alter potential for delivery. Downslope stand characteristics and the effects of timber harvest are not considered in assessing potential for delivery from upslope landforms.
3) Will improve accuracy and reduce bias by providing quantitative methods for estimating probability of delivery.
4) May provide improved empirical associations between forest practices and potential for delivery (e.g., the relative influence of topographic attributes vs stand characteristics along runout paths on delivery).
5) Will provide consistent methodologies for both GIS-based and field-based estimates of probability for delivery.

4.5.4 Uncertainties

- Calibration of some models requires delineation of zones of scour, transitional flow, and deposition along debris-flow tracks. Calibrations based on aerial-photo interpretation will suffer from inability to precisely delineate these zones.
- Data sources may be insufficient (i.e., too few examples) to provide robust calibration (confidence intervals may be large), particularly for detecting sensitivity to forest practices or the relative influence of landslide size/volume and flow properties.
- Calibration will not include runout from the entire range of potential storm events or landslide volumes.
- Runout length probabilities will depend on input variables that may be poorly constrained.

4.5.5 Relative Cost/Time Estimates

Approximately $90,000. This could be done concurrently with Project 4 (Empirical Landslide Initiation) over a time period of 2 years.

4.6 Models to Identify Landscapes/Landslides Most Susceptible to Management

Although landslide susceptibility assessments based on landslide inventories are widely used, there are several limitations to empirical assessment of landslide hazard including a) the assumption that landslides occur due to the same combination of factors throughout a study area, b) the fact that different landslides have different causal mechanisms and therefore require separate assessments, and c) the variability in geologic and structural settings that affect landslide response across wide areas (Corominas et al., 2014). Even where we can assume that the same set of causal factors are in play, many of these factors vary in time. In western Washington for example, shallow-rapid landslide susceptibility varies with precipitation intensity and stand age and, for a given topographic setting and landslide type, the likelihood of a landslide will be greatest in areas with high precipitation on relatively young stands (Turner et al., 2010). In order to correlate landslides with land use and precipitation, it is important to map the situation that existed when the landslides occurred (Corominas et al., 2014). Finally, since landslide hazard is the probability of landslide occurrence within a specific period of time, empirical assessments should be based on landslide inventories that provide insight into spatial and temporal frequencies as well as landslide magnitude (Varnes and IAEG Commission on Landslides and Other Mass Movements on Slopes, 1984). The availability of datasets with variation in space, time, and (storm/landslide) magnitude is, and will remain, a limiting factor (Corominas et al., 2014; Guzzetti et al., 2005; van Westen et al., 2008).

In the absence of the robust landslide inventories, the optimal method for estimating both temporal and spatial probability is dynamic modeling where changes in hydrological conditions are modeled using daily (or larger) time steps based on rainfall data (van Westen et al., 2008). These models typically incorporate empirical or physics-based equations and input parameters that are either static or dynamic. This type of model has been successfully used to assess landslide hazard in the Oregon Coast Range, Seattle, and Italy (Baum et al., 2011; Salciarini et al., 2008; Salciarini et al., 2006). In Seattle, the USGS TRIGRS model was able to identify locations of 92% of historical shallow landslides in southwest Seattle with unstable areas occupying 26% of the slope areas steeper than 20° (Baum et al., 2014). Recent advances involving probabilistic Monte Carlo approaches to distributed modeling have helped overcome the difficulty in obtaining accurate values for the several variables that describe the material properties of the slopes, thereby improving the predictive power of the models (Raia et al., 2014a).

4.6.1 Details of Approach

We would probably partner with the USGS and/or an academic institution to use the spatially distributed mathematical model for Transient Rainfall Infiltration and Grid-based Slope Stability (TRIGRS) with probabilistic input parameters (TRIGRS-P) to predict shallow-rapid landslide hazard over a limited area (e.g., ~ 100km^2 or 40 mi^2) of western Washington where LiDAR is available (~3m pixel). The TRIGRS model combines an analytical solution to assess the pore pressure response to rainfall infiltration into unsaturated soil with an infinite-slope stability calculation to estimate the timing and locations of slope failures. Pore-pressures and factors of safety are computed on a cell-by-cell basis and can be displayed or manipulated in a grid-based geographic information system (GIS). Input data are high-resolution topographic data and simple descriptions of initial pore-pressure distribution and boundary conditions.

One problem with trying to use a physical landslide model over large areas is the difficulty of obtaining sufficient, spatially distributed information on the mechanical and hydrological properties of the terrain. We would use the probabilistic approach to model parameterization incorporated in TRIGRS-P to partially overcome this limitation. In TRIGRS-P, multiple simulations are performed with different sets of parameter input values randomly chosen from probability distributions. The different model runs are then analyzed jointly to infer local stability or instability conditions as a function of input parameters (Raia et al., 2014a). Models can incorporate different ranges of precipitation intensities (e.g., current and predicted future) as well as different stand conditions to determine relative sensitivity to forest practices.

Model results could be evaluated against landslide inventory data.

4.6.2 Products

- Predictions of landslide initiation probability for specific landforms.
- Predictions for the effects of forest management on landslide initiation probability for specific landforms.

4.6.3 "How-will" list

1. Model predictions provide a quantitative ranking of probability of landslide occurrence (not delivery) by landform to compare to current estimates of inherent landform instability (e.g., high, moderate, low).
2. Model predictions provide a quantitative ranking of changes in probability of landslide occurrence in response to forest practices by landform. These predictions can be compared to current assumptions.
3. May improve accuracy and reduce bias in assessing probability of landslide occurrence (not delivery) by providing a quantitative estimate of probability for each landform.
4. Will improve our ability to characterize the relative sensitivity of landforms to forest practices by providing a quantitative estimate of the change in landslide hazard associated with forest practice activities.
5. Quantitative estimates of instability may indicate that regional differences in geology and climate can influence relative stability, so that the importance of different landforms as landslide sources may vary from region to region. Accounting for regional differences may lead to more consistent interpretation of unstable slope criteria.

4.6.4 Uncertainties

Physical models are simplifications of reality and input parameters must often be estimated. Some input parameters cannot be estimated (e.g., bedrock fracture flow). To determine confidence in model results requires validation of model predictions against observations.

4.6.5 Relative Cost/Time Estimates

This would probably be a 2-year effort at the budgeted amount of $100,000 per year.

4.7 Empirical Evaluation of Deep-Seated Landslide Susceptablity and Frequency by Landform

This project applies empirical methods to characterize susceptibility for landslide initiation and runout for deep-seated landslides. This entails several tasks:

1. Identify existing landslide inventories that are suitable to the task, or collect a landslide inventory.
2. Identify and map potentially unstable landforms.
3. Identify characteristics that distinguish active from inactive deep-seated landslides. Because deep-seated landslides exhibit a large range of site characteristics, physical models would be used to synthesize these characteristics into useful metrics related to landslide activity. Such metrics could provide indicators for groundwater recharge, relative factors of safety values, and sensitivity of the landslide to changes in pore pressures and slope geometry (e.g., road construction, stream erosion). These metrics would be calculated for a population of landslides and used as input to empirical models to estimate the potential for landslide activity.
4. Assemble a database of runout lengths. Compare these to other compendia of runout measurements and, if feasible, calibrate empirical models for runout to these local data.

These tasks are focused on landslide susceptibility. In performing these tasks, sensitivity to forest practices will be examined in relation to natural factors by looking for differences in susceptibility with stand characteristics and presence of forest roads.

4.7.1 Details of Approach

Tasks for deep-seated landslides also require detailed inventories of landslide features. The current activity status of each landslide would need to be included as a data attribute for Task 3.[10] Landslide activity level could then be compared to a variety of potential controlling factors, including characteristics of landslide body topography, topographically defined estimates of the groundwater recharge area, and local geology, land cover, climate, and natural triggers.

To provide data on downslope hazards in Task 4, the runout extent of deep-seated landslide deposits would also need to be mapped (e.g., Hattanji and Moriwaki, 2009) and evaluated to determine the degree to which the deposits have been eroded or hidden by subsequent geomorphic processes.

All of the above tasks require high-resolution topographic data, which limits application to areas with LiDAR.

[10] Such an inventory has been assembled for glacial deep-seated landslides as part of the Glacial Deep-Seated Landslide Literature Review project.

4.7.2 PRODUCTS

- Compendium of site characteristics associated with populations of active and inactive deep-seated landslides.
- Statistical analysis of differences in the frequency distributions of characteristics for active and inactive landslides. Potential models to predict probability of landslide activity in terms of these characteristics. GIS tools for quantifying characteristics and applying models to predict probability of activity.
- Inventory of deep-seated landslide runout distances that includes comparison with world-wide compendia of such measurements and a regional calibration of empirical runout models. GIS tools to apply runout models.

4.7.3 "HOW WILL" LIST

1) This project seeks to provide a method to estimate the probability that a deep-seated landslide is active in terms of measurable features and associated RILs, including toes of deep-seated landslides with slopes steeper than 65%, groundwater recharge zones to glacial deep-seated landslides, landslide body or margin inner gorge, and non-RIL features (fresh scarps, surface roughness). The influence of specific factors, including current RILs (WAC 222-16-050 (1)(d)(1) B and C) and non-RILs (e.g., toes of deep-seated landslides with slopes less than 65%), can then be compared to see if current RILs identify those features most directly associated with probability of deep-seated landslide activity. This alternative also seeks to provide a consistent method to estimate probable runout extent for deep-seated landslides.
2) This project seeks to determine if features that may influence landslide response to forest practices, such as groundwater recharge areas, are important factors in estimating probability of landslide activity. This is not a direct assessment of sensitivity to forest practices, but it might help to indicate if current RILs (RIL C, groundwater recharge areas, for example) is an important determining factor for landslide activity.
3) This project should provide a consistent, quantitative measure of the probability of landslide activity based on attributes of landslide features. This should improve accuracy and reduce bias in identifying natural factors that impose important controls on deep-seated landslide activity.
4) This project may or may not be able to resolve a management signal on the probability of landslide activity. However, if it is successful in identifying the primary influences on landslide activity, the potential for forest practices to affect those features and processes can be better evaluated. Potential effects of forest practices must be evaluated in context with inherent, non-forestry related factors that provide first-order control on deep-seated landslide activity, such as changes in mass balance (e.g., erosion of landslide toes by streams) and external triggers (e.g., seismic).
5) This project seeks to identify landscape features and landslide characteristics associated with landslide activity. It should clarify criteria for deep-seated landslides and improve consistency in identifying landforms indicative of deep-seated landslide activity.

4.7.4 UNCERTAINTIES

- We do not know with what level of confidence landslide activity can be predicted using GIS-based measurements of landslide characteristics. Determining the level of confidence is one of the goals of the project, but we don't know ahead of time what level of confidence is possible.

- We do not know, prior to doing the project, how sensitive predictions of landslide activity will be to the quality of available data (e.g., point density in the LiDAR point cloud, scale of geologic and soils maps).
- The landslide inventory may not provide a representative sample of deep-seated landslides.

4.7.5 Relative Cost/Time Estimates

Estimated one year at a cost of about $260,000.

5 Discussion

5.1 General Considerations

In evaluating research alternatives, the TWIG considered the following points:

- RILs provide a systematic protocol for identifying and delineating sites with a "high risk of failure"(Schedule L-1 performance target). In applying the RILs to condition forest practices, the Forests & Fish Report and SEPA require that RILs be considered in a context that includes:
    a) Delivery to streams and other public resources, and impacts to public safety,
    b) Temporal and spatial scales pertinent to landscape processes,
    c) Determinations of ***probability*** of landslide occurrence and delivery,
    d) Ability to detect increases over "natural background rates," and
    e) Ability to determine if such increases are caused by forest practices.

- A ***quantitative*** measure of susceptibility and hazard is required to provide information for CMER and Policy to evaluate the degree to which potentially unstable areas have a high probability of impacting public resources and public safety, to test accuracy and lack of bias, and to determine adequacy of the criteria. To quantify susceptibility requires consistent delineation of landforms and calculation of landslide density (and if possible, landslide rate) for each landform type, both for initiation and for delivery. Relative landslide hazard among landform types requires measures of delivery probability and spatial extent of landforms. We need these measures to:
    a) Rank all landforms in terms of the proportion of delivering landslides[11] originating from each. This provides a measure of the probability of impacting public resources and threatening public safety for each landform. With a measure of probability, the degree to which current RILs identify areas with a high probability of such impacts can be determined and the adequacy of the criteria can be evaluated.
    b) Determine how the ranking of landforms varies regionally. This allows evaluation of the accuracy and adequacy of RIL criteria by region across the state. Regional differences in geology, climate, and natural history may require regional differences in the criteria for RILs.

[11] A "delivering" landslide impacts a public resource or poses a hazard to public safety. Not all landslides deliver in this sense, and we need to be able to distinguish those sites that can produce delivering landslides from those that cannot.

c) Determine how the ranking of landforms varies with different data sources and techniques for landform and landslide mapping. Landform and landslide mapping are the basis for determining hazard and risk. To assess accuracy and bias, we need to know how differences in landform delineation and landslide identification affect resultant measures of landslide density and rate.

d) Determine how the ranking of landforms varies with storm history. Storm characteristics and management history interact to affect landslide density, so the importance of different landforms as sources of delivering landslides may vary spatially and temporally depending on the sequence of past storms. Certain landforms may become important landslide sources only under rare circumstances, whereas others may be chronic sources. To determine the adequacy of RIL criteria requires ranking both rare and chronic source areas in terms of the cumulative impacts and threats they pose.

- RILs must be defined in terms that field practitioners can use to consistently and precisely identify and delineate potentially unstable landforms on the ground. Current RIL criteria are largely narrative, which may be resulting in variability in landform identification among practitioners. To apply quantitative analysis techniques to assess susceptibility and hazard, however, we must also be able to identify and delineate the same RILs consistently using remotely sensed data. And this, in turn, would reduce field practitioner bias.

- Empirical determinations of landslide susceptibility and hazard are based on the relative density and frequency of landslide occurrence within a population of interest. Unbiased landslide densities require both unbiased landslide inventories and unbiased landform inventories, or at least statistical estimates and corrections of bias.

- Most of the existing landslide inventories, including LHZ, contain biases that limit the inference that can be drawn from them. Limitations include the lack of random sampling, landslide detection bias, and lack of extensive field verification. Recent advances in our ability to quickly create high-resolution shaded-relief images using LiDAR has led to new programs for landslide mapping within the Washington Department of Geology. Improved landslide inventories should lead to better empirical determinations of factors associated with landslide initiation.

- Forest Practices Rules are not intended to eliminate landslide occurrence, or regulate all landform types that might experience a landslide, but are intended to minimize increase over natural background rates from harvest on high risk sites. The sensitivity of different landforms to different forest practices remains an area of scientific uncertainty and is a source for stakeholder debate. Physical models are useful tools for evaluating effects of specific forest practices on landslide susceptibility and frequency, but to identify these effects may require very detailed models. The more detailed the model, the more difficult it is to reliably apply it over very large spatial domains. Detailed physical models may, therefore, be most appropriately applied to specific landforms where sensitivity to forest practices is questioned and model parameters can be reasonably constrained.

5.2 Recommendation

The TWIG proposes a series of studies that focus on key aspects of unstable-landform criteria (Table 1). This program leverages existing data and new techniques to provide a suite of options for incrementally updating the current Forest Practices Unstable Slopes rules.

The TWIG recommends starting with the Automated Landform Mapping project (Project 3, Table 1, and Table 2). Consistent landform identification is a study objective and an unbiased landform inventory is required for a quantitative assessment of landslide susceptibility and hazard. The mapping project would begin with currently named RILs and then expand into mapping other potentially unstable landforms. One source for other potentially unstable landforms are LHZ MWMUs that are not included in named RILs (Project 1). Once potentially unstable landforms have been objectively mapped, the program could begin to calculate landslide densities and rates across landforms to quantitatively assess their susceptibility (Project 4). With a landform inventory in hand, we could: (1) assess sensitivity to Forest Practices using physical models (Project 6), (2) selectively address runout criteria (Project 5), and (3) evaluate relevant field-based criteria.

Table 1: Project alternatives and TWIG recommendations.

Project	1. Compare MWMU with RIL	2. QE survey	3. Automated landform mapping	4. Empirical initiation	5. Empirical runout	5. Physical modeling of initiation	7. Deep seated
Suggested project order	2) Compare newly mapped landforms and existing MUMU.	N/A	1) Start with this project and map current RIL	3) Calculate landslide densities and rates for landforms and revaluate landform mapping.	5) Evaluate runout on potentially unstable landforms.	4) Model sensitivity to forest practices in landforms where sensitivity is questionable.	Continue to let UPSAG work on deep-seated.
Outcomes	Susceptibility (relative landslide density) by MWMU. Evaluation of consistency in current criteria.	A description of un-named unstable landforms and preliminary set of field data.	Landforms delineated from remotely sensed data.	Landforms characterized in terms of landslide density (and potentially rate).	Landforms characterized in terms of delivery potential.	Landforms characterized in terms of sensitivity to forest practices.	Deep-seated landform characterization.
Approx. Cost	$80k	$50-75k	$50-210k	$200k	$90k	$200k	$260
Approx. Time	1 year	0.5-1 year	1 year	2 years	1 year	2 years	1 year
Required skills	GIS, experience with image- and field-based landslide mapping.	Writing, GIS, experience with image- and field-based landslide mapping.	Computer programming, understanding of image filtering and segmentation algorithms, GIS scripting, experience with image- and field-based landform (terrain) mapping.	Computer programming, broad understanding of statistical methods, experience with image- and field-based landslide mapping.	Computer programming, broad understanding of statistical methods, experience with image- and field-based landslide mapping.	Computer programming, broad understanding of hydrology, and geomorphology, statistical methods.	Experience with image and field-based landslide mapping, field geology including stratigraphy and geophysics, statistical methods.
Advantages	Leverages past work and not	Leverages existing knowledge.	Objective, replicable.	Objective, replicable, quantitative,	Objective, replicable, quantitative,	Directly addresses	Addresses unstable slopes criteria for

	doing this project may mean that previously identified non-RIL are not captured in a broader random sample. It also provides a quantitative measure of landslide density based on MWMU.		Not constrained to existing MWMU delineations. Leverages new data (LiDAR).	testable, updateable.	testable, updateable.	sensitivity to forest practices.	deep-seated landslides.
Disadvantages	Bias in past work jeopardizes ability to accurately assess MWMUs in terms of landslide hazard or sensitivity to forest practices. May be unable to estimate confidence in results. No quantitative measure of runout potential.	Previous attempt to identify regional landforms (RLIP) using this approach was not very successful. Unknown degree of bias in existing knowledge. Output is likely to be qualitative rather than quantitative.	Potential that feasible methods and available data are unable to delineate landforms with sufficient resolution and accuracy for RIL definition. High-quality LiDAR data not available everywhere (yet).	Depends on success of Automated Landform Mapping. Subject to bias in inventory – although methods can be used to assess the degree of bias. Accuracy dependent on size of inventory. No measure of runout potential	Landslide runout depends on many factors so runout extent is inherently probabilistic.	Validation is difficult, perhaps impossible because soil strength and hydrologic variables are not spatially constant and field determination of a sufficient sample of these variables would be prohibitively expensive and time consuming.	Available data may be insufficient to resolve controls on deep-seated landslide behavior.

Table 2. Alternatives

Recommended Alternatives						
	Alternative	**Rank in terms of preference**	**~ Cost**	**Duration if done concurrently (yrs)**	**Duration if done sequentially (yrs)**	**Products**
1	Landform Mapping + Compare MWMU/RIL + Empirical Initiation	3	\$330,000 - \$490,000	3 - 4	4 - 5	Landform maps, Validation against MWMU/RIL, Landform susceptibility
1a	Landform Mapping + Empirical Initiation	Lower cost option	\$250,000 - \$410,000	3 - 4	3 - 4	Landform maps, Landform susceptibility
2	Landform Mapping + Compare MWMU/RIL + Empirical Initiation + Empirical Runout	2	\$420,000 - \$580,000	3 - 4	5 - 6	Landform maps, Validation against MWMU/RIL, Landform susceptibility, Delivery potential
2a	Landform Mapping + Empirical Initiation + Empirical Runout	Lower cost option	\$340,000 - \$500,000	3 - 4	5 - 6	Landform maps, Landform susceptibility, Delivery potential
3	Landform Mapping + Compare MWMU/RIL + Empirical Initiation + Empirical Runout + Physical Modeling	1	\$620,000 - \$780,000	4 - 5	5 - 6	Landform maps, Validation against MWMU/RIL, Landform susceptibility, Delivery potential, Sensitivity to Forest Practices
3a	Landform Mapping + Empirical Initiation + Physical Modeling	Lower cost option	\$450,000 - \$610,000	4 - 5	5 - 6	Landform maps, Landform susceptibility, Sensitivity to Forest Practices,
3b	Landform Mapping + Compare MWMU/RIL + Empirical Initiation + Physical Modeling	Lower cost option	\$530,000 - \$690,000	4 - 5	5 - 6	Landform maps, Validation against MWMU/RIL, Landform susceptibility, Sensitivity to Forest Practices

The next step in the LEAN process is for CMER and Policy to review the alternatives. If Policy approves a scope of work, CMER will have the TWIG develop a study design and begin work.

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