Delineating Landslide and Debris Flow Susceptibility in Western Oregon in Support of the Private Forest Accord

TerrainWorks

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Governor Brown states that "*this agreement* (the Private Forest Accord, PFA) *will help to ensure that Oregon continues to have healthy forests, fish, and wildlife, as well as economic growth for our forest industry and rural communities, for generations to come*"[1]. To meet these goals requires an understanding of how human interactions with the landscape will affect forests, fish, and wildlife. In Oregon, landslides and timber harvest are important components of this interaction. This document presents an overview of the background, approach, and methods concerning the prediction of landslide and debris-flow susceptibility in western Oregon. The focus here is on fish, and hence on interactions between landslides, forests, and river-stream environments.

1.0 Background

The ecology of river systems is driven by spatial and temporal variations in water flow – the flow regime (Poff et al., 1997). River ecology also responds to variations in channel and riparian morphology (Montgomery, 1999; Vannote et al., 1980). Sediment supply is an important control on this morphology, so the ecology of river systems is also driven by spatial and temporal variations in sediment supply (Wohl et al., 2015; Yarnell et al., 2006). Numerous studies find that landslides and associated debris flows[2] dominate the supply of sediment to streams in the Oregon Coast and Cascade Ranges naturally, even in the absence of land use (Benda and Dunne, 1987; Swanson et al., 1982). The same is found for mountainous terrain throughout the world (Kirchner et al., 2001; Lehre, 1982; Miller et al., 2002). In these environments, sediment supply varies dramatically in time and space, controlled by the timing, location, and size of landslide events; that is, by the disturbance regime (Benda et al., 1998; Nakamura et al., 2000). The disturbance regime is a fundamental factor in the ecology of river systems in these landscapes (Bisson et al., 2009; Reeves et al., 1995; Waples et al., 2009), so knowledge of how this regime functions is necessary to anticipate the consequences of landuse decisions (Newman, 2019). In this section, we briefly review our understanding of the role that landslides and debris flows play in the disturbance regime for steep terrain in Oregon and then look at how timber harvest might alter that regime.

When they occur, debris-flows overwhelmingly alter channels and riparian zones: steep channels may be completely scoured of stored sediment and wood debris, and riparian vegetation may be stripped for meters on either side. Deposition can bury channels and riparian zones destroying existing habitats. These are the obvious impacts; less obvious is what happens next. Neighboring populations of plants and invertebrates can rapidly recolonize impacted zones, with fish quickly following (Everest and Meehan, 1981; Foster et al., 2020; White and Harvey, 2017). Loss of riparian trees results in greater insolation with

[1] https://www.oregon.gov/newsroom/pages/NewsDetail.aspx?newsid=64523

[2] Landslides in Oregon often involve failure of shallow soils, typically less than 2 meters in depth, overlying bedrock on steep slopes. If the failed debris enters a topographically constrained channel on the hillslope, it can evolve into a fluidized slurry of mud, rocks, and logs, called a debris flow (also a debris torrent), that can travel long distances downslope, in some cases to deposit in channels and debris fans on the valley floor.

higher water temperatures and increased primary productivity (Danehy et al., 2012; Kiffney et al., 2004; Lamberti et al., 1991). Riparian vegetation grows rapidly, with shifts in species composition and abundance (Pabst and Spies, 2001), eventually reestablishing shade and lower water temperatures (Johnson and Jones, 2000). Flowing water rearranges sediment in the deposit, reforming pools and other channel features important to fish habitat (Roghair et al., 2002).

From the initiation site to the depositional zone, each debris-flow event can dramatically alter local channel and riparian environments, initiating a decades-long trajectory of changing vegetation and habitat conditions. In lower-gradient (e.g., <20%) fish-bearing channels, each deposit affects a relatively small portion of the channel network, but there may be thousands of potential debris-flow depositional sites, so the temporal sequence, spatial distribution, and abundance of debris flows sets, in part, the patterns of riparian and channel habitat diversity for fish-bearing channels within a basin (Benda et al., 2004b; Nakamura et al., 2000; Swanson et al., 1998). Large storms can simultaneously trigger vast numbers of landslides and associated debris flows (Robison et al., 1999; Turner et al., 2010). Particularly if associated with widespread forest disturbance such as wildfire (Benda and Dunne, 1997a, b), these spates of landsliding might produce changes in habitat type throughout an affected basin, potentially shifting for example, bedrock-dominated systems to channels buried in gravel (Reeves et al., 1995). Gravel is essential for spawning, but too much results in loss of surface water during low-flow seasons with consequent fish mortality (May and Lee, 2004). In debris-flow terrain, the history of debris-flow events acts in part to determine the abundance, distribution, and diversity of channel and riparian habitat types, both within a basin and across a region; a dynamic regime that fish species occupying these environments have evolved to capitalize on (Flitcroft et al., 2016; Miller et al., 2008; Naiman et al., 1992; Reeves et al., 1995).

Debris-flow deposits can strongly influence valley-floor geomorphology. The deposits create fans and terraces that shape stream and associated habitat characteristics (Benda et al., 2003a; Benda et al., 2004; Grant and Swanson, 1995; May and Gresswell, 2004). The large wood and boulders carried to the valley floor with these deposits create sources of roughness in channels that can persist for centuries (Benda, 1990). Large wood and boulders create flow diversions that form pools and obstructions that store sediment, adding to habitat diversity (e.g., Beechie and Sibley, 1997; Montgomery et al., 1996; Nakamura and Swanson, 1993; Roni et al., 2006). Thus, accumulations of boulders and large wood found at debris-flow fans (Bigelow et al., 2007), even in the absence of any recent debris-flow events, are associated with locally increased sediment accumulations and pool abundance (Benda et al., 2003).

The abundance, spacing, and relative size of debris-flow depositional sites thus creates a spatial template over which debris flows influence channel conditions. The magnitude of these debris-flow effects diminishes with the size of the receiving channel relative to the size of the deposit. Channels tend to increase in size downstream, so the morphological effects of debris flows tend to be spaced further apart as one moves downstream (Benda et al., 2004a). The relative role of debris flows in creating and modifying channel morphology thus varies with position in the fish-bearing portion of a channel network, being greatest in the smaller, upstream channels (Montgomery, 1999). Given the branched, hierarchical nature of river networks, these small channels can comprise most of the fish-bearing channel length.

As implied by the role of debris-flow-deposited large wood for introducing sources of channel roughness mentioned above, interactions between debris flows and forests are an important determinant of debris-flow effects across a channel network. These interactions start at the initiation sites, continue through the steep traversed nonfish channels, and persist through the depositional sites. Standing trees provide sources of wood for debris-flow transport in source areas and through traversal corridors. Debris flows also pick up downed wood that accumulates in the steep channels traversed by debris flows (May and Gresswell, 2003). Wood from trees and sediment falling into these channels accumulates over time, until a debris flow scours accumulated material and transports it downstream. Some portion of the accumulated wood is lost to decay, but wood buried in these small channels can persist for long periods. May (2002) found that the volume of wood in debris-flow deposits increased with longer runout length and that the diameter distribution of pieces in the deposit was independent of tree size in the stand traversed. The latter indicates that much of the wood in the deposit originated from pre-harvest stands and was stored in the traversed channel: a legacy of pre-harvest conditions The size distribution and abundance of trees in currently growing stands adjacent to debris-flow-prone headwater channels today thus dictate the size of wood carried to fish-bearing channels by debris flows in the future. Likewise, following a debris flow, accumulation of sediment in the scoured channel initially occurs upslope of trees that fall into the channel (May and Gresswell, 2003). Scoured channels lacking sources of large wood to act as sediment dams may persist as passageways for water-transported sediment to downstream channels.

Large wood incorporated into a debris flow from standing and down trees also reduces runout length (Booth et al., 2020; Ishikawa et al., 2003; Lancaster et al., 2003; May, 2002). Debris-flow volumes tend to increase with runout length, so deposit volumes tend to be larger for debris flows that traverse stands of smaller trees (May, 2002). Hence, the spatial distribution and size of standing trees and down wood across a basin influences the spatial distribution of debris-flow tracks and the locations and sizes of the resulting deposits within the channel network (Lancaster et al., 2003). As the size distribution of standing trees and down wood decreases, debris flows may extend further downslope, thus increasing the number of debris flows reaching fish-bearing channels.

The relative importance of debris-flow-deposited wood as a source of channel roughness depends on the amount and size of wood transported by the debris flow relative to the amount and size of wood already in the receiving channel (Montgomery et al., 2003). In industrial forests, which may currently lack riparian sources of large wood due to past timber harvests, the legacy wood carried by debris flows can thus provide the only source of newly recruited wood large enough (e.g., > 0.6m diameter) to effectively maintain alluvial cover in many fish-bearing channels. This legacy wood will eventually be depleted as well, as it is scoured from these steep headwater channels over time. For any individual debris flow, its runout length and the volume of sediment and wood it carries thus depends on a centuries-long history of forest disturbance, stand growth, tree fall, and landsliding along the channels it traverses. The consequences for a receiving fish-bearing stream depend in part on the centuries-long history of events that determine the size and abundance of wood it contains. Historical context is therefore an important factor when evaluating the effects of landslides on channel environments in western Oregon. Not until the 1970s were riparian buffers required for fish-bearing streams in Oregon (Everest and Reeves, 2007). Besides the loss of large channel-adjacent trees for tree-fall recruitment of wood to these channels, logging activities led to large quantities of slash and debris entering streams. This motivated the practice of stream cleaning, which continued until the late 1970s (House and Boehne, 1987). Between 1956 and 1976, the Oregon Game Commission removed large wood from channels for the mistaken purpose of enhancing fish habitats and passage (Oregon Department of Forestry, 2003). Additionally, between the mid-1800s and the early twentieth century, many streams in the Coast and Cascade Ranges experienced splash damming and log drives that resulted in the removal of naturally occurring wood jams and rocky obstructions (Miller, 2010b; Phelps, 2011; Sedell and Luchessa, 1981).

These past practices caused many channels to be scoured to bedrock (Miller, 2010a) and the lack of large wood now further contributes to lower volumes of gravel storage (Montgomery et al., 2003). Consequently, in-channel restoration efforts often place log structures in streams (Banks et al., 2001; Oregon Department of Forestry, 2003) to catch sediment and stream-transported wood and to create pools. Boulders have also been placed in channels to mimic debris-flow deposits and to enhance habitat complexity (Mueller, 2009). The artificial deposits of wood and boulders have been shown to create larger pool areas and to attract higher densities of juvenile coho and trout (Roni et al., 2006).

Ultimately, however, strategies for habitat restoration and maintenance in a managed landscape must seek to identify and preserve the processes and process rates that create and maintain needed habitats (Beechie et al., 2010; Rieman et al., 2006). Besides the historical context described above, how can ongoing timber harvest affect landslide and debris-flow processes and process rates? It is useful to consider this in terms of material fluxes; that is, the volume per unit time of debris-flow transported sediment and wood to fish-bearing streams. As discussed above, these material fluxes naturally vary in space and time in response to forest disturbances, storms, and floods. How can timber harvest alter these spatial and temporal patterns in fluxes of sediment and wood? An obvious way is through changes in the size and abundance of standing and down trees that provide sources of debris-flow-carried wood. These changes also alter debris-flow runout lengths, thus altering the proportion of debris-flow scoured material that gets carried to fish-bearing streams. Another important factor that we have not yet discussed is the influence of forest-stand characteristics on susceptibility to landslide initiation.

Debris-flow-triggering landslides primarily occur during intense rainstorms (Robison et al., 1999; Turner et al., 2010). Forest cover reduces landslide potential through the tensile strength provided by dense mats of roots (Schmidt et al., 2001) and by modulating peaks in soil pore pressures during storms (Dhakal and Sullivan, 2014; Keim and Skaugset, 2003; Keim et al., 2004). Loss of forests to wildfire, disease, and windstorms can thus locally increase storm-driven landslide rates for a decade or more until tree cover is re-established (Imaizumi et al., 2008; Sidle and Ochiai, 2006). The cadence of landsliding across a basin is thereby driven by the sequence and spatial distribution of storms and forest disturbances. Timber harvest can alter this cadence by increasing landslide rates (Benda and Cundy, 1990; Ketcheson and Froehlich, 1978; Montgomery, 1994; Oregon Department of Forestry, 2006; Reid and Dunne, 1984; Robison et al., 1999; Swanson et al., 1987; Swanson and Fredriksen, 1982; Swanson et al., 1977; Turner et al., 2010).

Susceptibility to landslide initiation varies substantially with terrain attributes, with the greatest susceptibility concentrated in steep, topographically convergent terrain (Miller and Burnett, 2007). Within any basin, the influence of timber harvest on landslide rates will increase as harvest extends into more susceptible zones. The basin-average landslide rate, which reflects the total number of landslides that occur over time, varies with both the susceptibility of the areas harvested to landslide initiation and the total susceptible area harvested. Harvest over a large area of low susceptibility can cause the same increase in overall rate over a basin as harvest over a smaller area of high susceptibility. The increase in susceptibility is highest several years after harvest and then decreases over time. This time window of increased vulnerability is thought to extend about 15 to 30 years after harvest (e.g., Sidle, 1992). Basin-wide increases in landslide rate will depend on the proportion of basin area with forest stands in this age range relative to the proportion under a non-managed disturbance regime (e.g., a wildfire regime). That proportion increases as the rotation period for harvest decreases.

The magnitude of harvest-related increases in landslide rate therefore depends on the location, spatial extent, and frequency (rotation period) of harvest. The consequences of these increases in landslide occurrence, in terms of flux of sediment and wood to fish-bearing streams, depends on several factors, including:

- the potential for debris-flow runout from the initiation sites to fish-bearing streams,
- the amount of material carried by a triggered debris flow to the fish-bearing stream, and
- the size and amount of wood available for debris-flow recruitment along potential runout tracks.

2.0 Predicting Shallow Landslide and Debris Flow Runout

Recognition of the ecological role of landslides and debris flows has led to calls to modernize the management of steep slopes in Oregon. To maintain the processes and process rates that create and preserve habitats in fish-bearing streams, patterns of timber harvest could be altered to avoid those hillslopes where loss of trees can increase rates of landslide-triggered sediment supply to streams and to maintain sources of large wood along the corridors traversed by debris flows (Burnett and Miller, 2007). This approach has been adopted by Oregon State Forest Management Plans and by HCPs that are in development as of 2021 on State Forest Lands, the Elliott State Forest, and private commercial forests (Private Forest Accord). Together, these HCPs involve over 50,000 km^2 of forest lands in Oregon. Effects of forest management on landslide processes and consequences for fish habitats are important issues in all three.

To maintain the processes and process rates by which debris flows create and modify habitats, the primary target is to minimize human-caused changes in the rate at which landslide and debris flows carry sediment and wood to fish-bearing streams.

Timber harvest can decrease the debris-flow flux of wood by reducing the size and abundance of:

- standing trees in landslide initiation zones and along debris-flow tracks available to be swept up by debris flows, and of
- trees that fall and accumulate in debris-flow-prone channels available to be scoured by debris flows.

Timber harvest can increase the rate at which material is deposited in fish-bearing streams by debris flows through

- reductions in the size and abundance of standing and down trees that cause increases in debris-flow runout length, thus increasing the proportion of debris flows that reach fish-bearing streams, and
- increases in susceptibility to landslide initiation.

To identify those locations where timber harvest should be avoided or altered to minimize or preclude these effects, we can define two objectives:

1. Limit changes in the rate of landslide initiation of debris flows that travel to fish-bearing streams.
2. Maintain sources of large wood along potential debris-flow-runout tracks to maintain sources for debris-flow-carried wood and to prevent increased runout length.

On industrial forest lands, we have a third objective:

3. Minimize the number of trees precluded from harvest.

To completely avoid changes in debris-flow fluxes of sediment and wood could render timber harvest economically unfeasible in these areas. There is a tradeoff between the first two and third objectives. Quantified measures of this tradeoff are needed to find a workable balance that "*will help to ensure that Oregon continues to have healthy forests, fish, and wildlife, as well as economic growth for our forest industry and rural communities, for generations to come".* The first steps for such quantified measures are analyses that can identify the source areas from which debris-flows that travel to fish-bearing streams originate and identify the travel corridors traversed by those debris flows. To evaluate the tradeoff involved in protecting the processes and process rates identified in the first two objectives while also harvesting trees requires analyses that can estimate the proportion of sediment and wood carried by debris flows to fish-bearing streams originating from designated leave-tree areas. Together, such analysis capabilities provide a measure of both the area precluded from harvest and the proportion of debris-flow-carried material originating from those areas.

Development of models for predicting locations of shallow landslides and debris-flow runout in western Oregon began in the early 1990s (Benda and Cundy, 1990). By the mid-1990s, digital elevation models were being employed for predicting susceptibility to shallow failures (Montgomery and Dietrich, 1994). Comprehensive landslide inventories, including landslides under forest canopy, following the large 1996 storms in the Coast Range (Bush et al., 1997; Robison et al., 1999) were used to build empirically calibrated landslide susceptibility and debris-flow runout models (Miller and Burnett, 2007, 2008). The advent of these tools, combined with the newly available higher-resolution digital elevation models (DEMs) from LiDAR, led to calls to identify and protect upland landslide and debris-flow sources of large wood to fish streams (Burnett and Miller, 2007; Reeves et al., 2016). As part of the PFA prescriptions for steep slopes to account for the ecological role of landslides and debris flows, the models of Miller and Burnett (2007, 2008) are being used to delineate areas susceptible to shallow failures and the runout of debris flows delivering to fish-bearing streams.

The Miller and Burnett (2007) model of shallow landslides is based on recognized causes of shallow landslide initiation in the Coast Range (Dietrich and Dunne, 1978; Dunne, 1991; Montgomery and Dietrich, 1994; Pierson, 1977). Shallow landslide potential is defined in terms of a topographic index that is based on hillslope steepness, planform curvature, and critical drainage area (area per unit contour length) (Miller and Burnett 2007). Landslide locations from the field-based landslide inventories (Robison et al. 1999) were used to calibrate the index for the purpose of associating landslide susceptibility (in terms of landslide density, number per km^2) to terrain attributes and forest cover. Landslide susceptibility is quantified in terms of the relative proportion of all landslides predicted to occur within particular topographic zones.

The Miller and Burnett (2008) model of debris flow runout is used to identify stream channels susceptible to traversal and deposition from debris flows. The model integrates susceptibility to landslides (as described above) into debris-flow initiation and estimates of runout probability. Thus, the two models are coupled. Critical parameters for predicting debris flow runout include channel steepness, channel confinement, tributary junction angles, and rates of debris scour and deposition (Miller and Burnett 2008).

For a watershed, these models characterize susceptibility to initiation of debris flows in terms of the proportion of all debris flows that travel to fish-bearing streams within the basin originating from some specified area of interest. These modes characterize channel susceptibility to debris-flow traversal in terms of the proportion of total debris-flow-track length expected within any subset of headwater streams (Burnett and Miller, 2007). Use of proportions provides a testable method for comparing debris-flow source areas and debris-flow-prone headwater channels: the model predicts what proportion of the total over the entire basin will be found within any subbasin. Initiation sites are ranked by the modeled probability of initiating a debris-flow that travels to a fish-bearing stream and then grouped by proportion. Sites with the highest initiation probability are grouped first, so the top 20%, for example, contains the least-stable sites in the basin and includes 20% of the observed (or expected) actual debris-flow-triggering landslides. Likewise, channels are ranked by the modeled probability of observing a debris flow and then grouped by proportion. The highest-probability channels are grouped first, so the top 20% include the headwater channels with the highest modeled probability of traversal by a debris flow and these channels are predicted to contain 20% of the total debris-flow-track length found in the analysis basin.

This characterization of susceptibility by proportion introduces a scale dependence: the ranking of any individual initiation site or channel depends on which other sites and channels are included in the analysis area. Source areas and channels are ranked by their relative importance (in terms of debris-flow delivery to fish-bearing streams) within a basin, not by the absolute probability value calculated. In using this measure of susceptibility, the choice of basin size is an important factor. A particular headwater channel may be a major contributor of debris-flow material within a small basin. Compared to channels in the larger watershed containing that basin, however, it may be a minor player. For the PFA, the basin size for characterizing the relative importance of headwater channels as debris-flow-delivery corridors of sediment and wood to fish-bearing streams is the 4th-field HUC[3], selected to match the NOAA-Fisheries designations for watersheds that contain ecologically significant independent populations of coastal coho salmon in the Oregon Coast Range (Waples, 1995).

To characterize source areas for debris flows, the basin size is the contributing area to each confluence of a non-fish-bearing headwater channel with a fish-bearing stream (generally first- and second-order channels based on the Strahler (1957) system). These two dramatically different spatial scales establish a hierarchical framework for buffer design, focusing first on identifying and ranking those headwater channels in the larger 4th-field watersheds that serve as debris-flow corridors where riparian zones provide sources of wood and act to modulate runout extent. Then the focus narrows to the subbasins feeding each debris-flow corridor to identify initiation sites where buffers can serve to modulate harvest-related alterations of debris-flow frequency.

In referring to frequency, we rely on an important assumption: that the spatial density of landslide occurrences and recent debris-flow tracks is an indicator of the temporal frequency of events. We lack a long time series of observed landslide and debris-flow locations, so to infer rate (number per unit area per unit time), we assume that the types of locations where we observe high densities of events now will also exhibit high densities in the future – that density correlates with rate. Such space-for-time substitution is widely used in studies of geomorphology and ecology (Hammond and Kolasa, 2014; Huang et al., 2019) and, in this case, is appropriate if the factors controlling landslide and debris-flow densities we observe are the same for landslides and debris flows in the future. In applying model results, it is

[3] https://water.usgs.gov/GIS/huc.html

important therefore to consider that assumption. If landslide locations and debris-flow behavior differ for different storm characteristics, storm sequences different than those to which the models are calibrated may produce spatial patterns of landslide and debris-flow density different than those predicted by the models. By monitoring landslide and debris-flow events over time, model predictions can be tested and, if shown to be in error, the models can be improved.

In the PFA prescriptions, the Miller-Burnett (2007, 2008) models, as applied in Burnett and Miller (2007), were used to: 1) identify source areas for landslides and debris flows that could potentially travel to fish-bearing streams, 2) identify travel paths for debris flows that could deliver sediment and large wood to those streams, and 3) rank source areas and traversal corridors by the relative frequency of event occurrences. A new application of the debris-flow runout model (Miller and Burnett, 2008) was then developed to rank source areas by the volume of material delivered to fish-bearing streams, described in more detail below.

3.0 Model Application

3.1 Creation of a Synthetic River Network and Virtual Watershed

Basin hydrography is represented in digital form as a synthetic network, a stream layer in GIS (**Figure 1**), derived from high-resolution (1-m) LiDAR-generated DEMs. Delineated channels must accurately follow actual channel courses, they must extend upstream to include channelized portions of potential debris-flow corridors, and they must include attributes for determining likelihood of fish use and flow duration (perennial flow).

The DEM-traced channel courses follow geomorphic indicators of channel presence derived from the DEM. These indicators are used by the US Geological Survey for elevation-derived updates to the National Hydrographic Dataset[4] and include plan curvature (Florinsky, 2016) and flow accumulation calculated using the D-Infinity flow-direction algorithm (Tarboton, 1997). We preclude dispersion of flow along channelized flow paths, so once the criteria for channel initiation are met, D-8 flow directions are used (Clarke et al., 2008), in which flow path out of a DEM cell is directed to one of the eight adjacent cells. This introduces a bias for flow paths that do not follow one of these eight directions, which is corrected by tracking deviations along traced flow paths (Orlandini and Moretti, 2009).

Upstream extent of traced channels is determined using three criteria (Clarke et al., 2008; Miller et al., 2015).

1. Threshold for the product of specific contributing area and gradient squared $(A/b)S^2$, where A = contributing area to DEM cell, b = contour length crossed by flow out of the cell, S = surface gradient, calculated over a length scale appropriate for channel-forming processes (e.g., 20m).

2. Threshold for plan curvature. Topographic evidence of a channel is manifest as a crenulation in a contour line, measured as plan curvature. High curvature measured over a length scale appropriate for resolving a channel is interpreted as evidence of a channel.

[4] Methods for derivation of NHD flow paths from high-resolution elevation data are still in development and a citation is not currently available.

3. Threshold for flow length. The hillslope length scale over which the $(A/b)S^2$ and plan curvature thresholds must be met.

The product of contributing area and gradient squared is representative of the erosion potential of processes that create channels (Montgomery and Foufoula-Georgiou, 1993). This threshold is determined by plotting threshold value versus channel density on a log-log plot; an inflection in the plot indicates the point where delineated channels extend onto planar (unchannelized) hillslopes (Clarke et al., 2008). This inflection provides a rough measure of the degree to which the DEM can resolve valley and hillslope swale features. Plan curvature is a measure of local topographic convergence (i.e., the degree of crenulation of a contour line) and serves to further delineate potential channels resolved by the DEM. Finally, these two thresholds must persist for a specified flow length so that small depressions (e.g., tree-throw pits) are not identified as channel initiation sites. The area-slope threshold is calibrated from the DEM; the plan curvature and minimum length thresholds are set subjectively so that traced channels persist upslope to a point consistent with the expected upslope extent of channelized debris flows. Thresholds may be spatially variable to reflect different processes that form channels, e.g., landslides on steep slopes, overland flow, and subsurface piping on low-gradient slopes (Clarke et al., 2008). Likewise, threshold values vary regionally, reflecting differences in local conditions and in DEM characteristics, and should be recalibrated for each 4th-level HUC basin analyzed.

The channel network is represented digitally as a set of linked nodes; one node for each DEM grid point traversed by each channel (**Figure 2**). This data structure maintains information at the smallest spatial grain available from the elevation data. Channel attributes for each node, such as gradient and confinement, are calculated from the DEM[5]. These attributes are then applied in the models used for the PFA analyses. Fish-bearing streams (anadromous and resident), for example, are delineated using a fish presence/absence model (Fransen et al., 2006). Data attached to other GIS stream data can also be conflated to the synthetic network.

Flow paths are traced from every hillslope DEM cell so that all cells are associated with the channel node they drain to. This provides an explicit linkage between modeled hillslope processes, such as landslide and debris-flow runout, and the channels affected by these processes. Collectively, the integrated channel network-terrestrial environment is referred to as a virtual watershed (Barquin et al., 2015; Benda et al., 2015).

The model software implements a hydro-conditioning of the DEM that delineates flow paths out of all closed depressions (Soille, 2004). The DEM itself is not modified, because the original elevation data are necessary to accurately determine channel features. The resulting raster of flow directions provides the information needed for flow routing and creation of the synthetic network. The modeling described below does not require DEMs that were previously hydro-conditioned.

3.2 Delineate Landslide Initiation Sites and Debris Flow Traversal Corridors

Shallow landslides of the type that trigger debris flows tend to occur in particular landscape locations. Landslide initiation locations correlate well with topographic attributes of gradient and specific contributing area for a DEM cell calculated from within a local radius of the cell. To quantify this

[5] TerrainWorks has developed and implemented methods to estimate a large variety of attributes; descriptions are available at http://www.netmaptools.org/Pages/NetMapHelp/netmap_tools.htm

correlation, we predict landslide density (number per square kilometer as a measure of susceptibility) as a function of these topographic attributes (Miller and Burnett, 2007).

The calculated landslide density depends on the number of landslides observed, which varies with the number and magnitude of landslide-triggering storms that occur during the period of observation. Therefore, landslide density is used as a relative measure of spatial variation in susceptibility to landslide initiation. Spatial variations in landslide density are also driven by spatial variation of intensity during a single storm (Turner et al., 2010). With high-resolution DEMs, variations in landslide density are resolved at the scale of individual landforms, e.g., for individual bedrock hollows. The spatial extent of a landform, tens of meters, is small relative to the spatial extent of variations in storm intensity, which may span kilometers. Thus, to the degree that landform types are randomly distributed across variations in intensity, relative differences in landslide density across landform types are resolved[6]. To provide a quantitative measure of susceptibility, landslide density is translated to proportion of landslide occurrences found within any specified area (Burnett and Miller 2007) (**Figure 3**).

Debris flows in the Coast and Cascade Ranges tend to scour material and bulk up when traversing steep, confined channels. Debris-flow runout length correlates with scoured sediment volume; larger debris flows travel farther (May, 2002). Debris flows tend to lose material to deposition when traversing lower-gradient, unconfined channels and when they change direction at channel junctions (Benda and Cundy 1990). The probability that a debris flow will reach any point downslope decreases with distance and the rate of decrease is a function of gradient, confinement and changes in channel direction integrated along the flow path (Miller and Burnett 2008).

From each DEM cell with a calculated landslide density greater than zero, the potential debris-flow-runout path is traced downslope to a fish-bearing channel or until the calculated probability of continued runout goes to zero. If the probability is greater than zero at the intersection of the flow path with a fish-bearing stream, the value is assigned to the originating DEM cell. For all cells along the runout path, this prediction is then used to calculate the probability that a debris flow initiated upslope traverses the cell and continues to a fish-bearing stream (**Figure 4**). Traversal probability increases as the number and initiation potential of upslope initiation sites increases (**Figure 5**).

The traversal probability is used to delineate the expected path lengths of debris flows and to estimate the proportion of debris-flow length that occurs within a specified range of traversal probabilities. Headwater, non-fish channels are ranked according to the proportion of future debris flow lengths they are likely to contain (Burnett and Miller 2007) (**Figure 6**). Over any period, only a portion of these channels will experience debris flows, but those within the 20% bracket should contain 20% of the total debris-flow-track length within the basin and these channels should have the highest debris-flow-track density (length of debris flow track divided by total length of channels in this bracket). Likewise, channels in the 20-50% bracket should contain 30% of the total debris-flow-track length observed in the basin and have a lower debris-flow-track density than the 20% bracket, and a higher density than any higher percentage brackets.

As described above, loss of forest cover can increase landslide initiation potential and increase debris-flow runout lengths. The influence of forest cover is included in the Miller and Burnett (2007, 2008)

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[6] To identify relationships between storm characteristics and where within landforms landslides occur requires a more complex analysis that includes spatially distributed measures of storm intensity and duration.

landslide-initiation and debris-flow-runout models. To characterize debris-flow source areas and traversal corridors for the PFA modeling, a uniform mature forest cover is applied. Model outcomes thus focus on the immutable controls of topography on landslide initiation and debris-flow runout. Use of mature forest cover also focuses on those forest conditions associated with the lowest landslide susceptibility and the shortest debris-flow-runout lengths. These are the conditions sought with use of riparian and upslope leave-tree buffers. If the models were run with a different uniform forest cover, no forest for example, model outcomes should vary little because the calculated proportions rely on relative rates. If the calculated rates change the same amount everywhere, the relative values remain the same. If the models were run with spatially variable forest conditions, however, model outputs would change: predicted traversal probabilities would increase and the associated debris-flow corridor, subbasin, and source-area designations would be altered. The degree of alteration would depend on the spatial distribution of forest types. A uniform forest cover was used for the PFA modeling to provide a single delineation of process zones and relative process rates for designing prescriptions, rather than delineations that would vary a bit with each proposed buffer strategy. Sensitivity of model predictions to spatially variable forest cover have not yet been evaluated, but can be as the models are further applied.

The Miller-Burnett models were originally calibrated to the 1996 storm data (Bush et al., 1997; Robison et al., 1999) with topographic attributes derived from line-trace 10-m DEMs. The LiDAR DEMs available now provide much greater accuracy and precision for resolving topographic features. For application to the PFA, the models will be recalibrated using the best-available digital data.

3.3 Ranking Landslide Initiation Areas for Material Delivery to Fish-Bearing Streams

A new method was developed for characterizing source areas for debris flows in terms of the amount of material[7] carried to fish-bearing streams based on an estimate of relative debris-flow volume used in the Miller-Burnett (2008) model for debris-flow runout. In the model, the downstream extent of debris-flow runout is associated with the point where the volume of material scoured equals the volume deposited. The volume scoured is assumed proportional to the integral of the probability of scour along the runout path. Scour probability is a function of channel gradient and confinement measured from the DEM, calibrated to field-measured zones of scour along debris-flow tracks (Miller and Burnett, 2008; Robison et al., 1999). This estimate of scoured volume assumes that the volume available for scour is uniform along scour zones (the same assumption used by Reid et al., 2016). The volume deposited is assumed proportional to the volume scoured and the integral of depositional probability along the runout track. Larger-volume debris flows are assumed to deposit a larger volume per unit length, in accordance with empirical observation (Griswold and Iverson, 2002). Depositional probability is also a function of gradient and channel confinement measured from the DEM and calibrated to field-surveyed zones of deposition along debris-flow tracks. This model then provides a measure of debris-flow volume (volume scoured minus volume deposited) at each point along a potential debris-flow track. It is a relative measure, proportional to the average volume available for scour per unit length along the track. The volume of the

[7] This volume of material includes everything scoured along the runout track, both sediment and wood. May (2002) found that both sediment volume and wood volume in surveyed deposits increased with increasing runout length. However, the relative proportion of sediment to wood will depend on the relative rates at which each accumulates along the runout track, which may vary with location.

initiating landslide is not accounted for explicitly[8]. However, the scour zone for volume accumulation along the runout track extends through the initiation zone, so the initiating volume per unit landslide-scar length is assumed the same as the scour volume per unit length of the channel downslope. Based on measurements of sediment thickness and deposit geometries of hollows and debris flow-prone channels, the stored sediment volume per unit length was similar across the landforms (Benda, 1988).

Each DEM cell with modeled landslide density and probability of delivery greater than zero (**Figures 3 and 4**) is assumed to lie within a potential landslide-debris-flow initiation site. The volume of material carried by a debris flow to a fish-bearing channel is estimated for each potential initiation site as described above: the volume deposited in a fish-bearing stream is the volume scoured to that point minus the volume deposited. This represents deposit volume for a single debris-flow event. Modeled volume increases with the length, steepness, and confinement of the runout path, so the model indicates that the highest-volume debris flows tend to originate on the steep headwalls near the top of the subbasins feeding the headwater basins that drain to fish-bearing streams. Likewise, debris flows traversing planar slopes have small delivered volume because the lack of channel confinement favors rapid deposition.

Estimates of single-event volumes are useful for anticipating the degree to which single events may impact the receiving channel and for ranking source areas in terms of the potential magnitude of those impacts. It is also useful to examine these volumes in the context of the frequency with which the events are likely to occur. Over time, a small-volume event that occurs more frequently may provide as much material to the fish-bearing channel as a large-volume event that occurs infrequently. We can expand this perspective to the population of sites across a basin to characterize landslide source areas in terms of the total flux of sediment and wood carried to the fish-bearing network by landslides and debris flows over any increment of time. Frequency of occurrence provides an estimate of the probability that an event will occur within any time interval: if the average frequency for an initiation site is once every 100 years, then the probability of an event in any year is 0.01. When we look at delivery of sediment to fish-bearing channels over some interval of time – a year, or a harvest rotation – from a population of sites, we can translate relative frequency to likely number of events: in any year, or over a harvest rotation, we are likely to see a higher proportion of high-frequency sites triggering debris flows than low-frequency sites. The total flux of sediment and wood to fish-bearing channels within a basin thus depends on both the likelihood of occurrence and the event volume associated with all potential initiation sites. To characterize spatial patterns in the rate at which source areas deliver material to fish-bearing streams, we must account for both the volume and likelihood of occurrence of a delivering debris flow from each potential initiation site. We do this by multiplying the modeled single-event volume for each site by the estimated probability of landslide occurrence (for a DEM cell, this is the landslide density multiplied by the area of the cell) and modeled debris-flow delivery. Based on our substitution of space-for-time discussed above, this value is proportional to the probability of initiating a delivering debris flow in any year, or equivalently, dividing by some constant multiple of the recurrence interval. This gives a time-averaged volume delivered to the

[8] Benda (1988) estimated that the proportion of the initiating landslide volume to total debris flow volume in first- and second-order channels was 26% to 12%. May (2002) found that the proportion of debris-flow-deposit volume associated with the initiating landslide varied for debris flows in different forest age classes and for debris-flows initiating at forest roads. For this model, we would need to relate the initiating volume to attributes measurable from the DEM and other remotely sensed data. Lacking data to identify and calibrate such a relationship, we assume for now that the volume per unit length of the initiating landslide is the same as the volume per unit length scoured from the channel downslope of the landslide.

fish-bearing network for each initiation site. We can now rank initiation sites in terms of their likely contribution to the annual basin-wide supply of sediment and wood by debris flow to the fish-bearing channel network.

The concept of recurrence interval provides a translation of probability to a measure of time that may provide insight to debris-flow processes. The actual time between debris flows at any site is essentially an unpredictable random process. The recurrence interval is an estimate of the average time interval. It is the inverse (one over) the probability of occurrence in any year and allows us to rank sites in terms of the relative frequency of events. In modeling wood recruitment for the State Lands and Elliot State Forest HCPs, we needed estimates of recurrence interval to calculate the amount of wood that could accumulate between debris-flow events. Recurrence intervals are typically on the order of centuries to millennia for an individual initiation site (e.g., Benda and Dunne, 1987; Montgomery et al., 2000; Reneau and Dietrich, 1991). Traversal by debris flows through downslope channels may occur considerably more frequently, because these channels receive debris flows from multiple upslope initiation sites, so recurrence intervals for debris-flow deposition in valley-floor streams may be considerably shorter: decades to a couple of centuries. The constant of proportionality relating probability of traversal to a recurrence interval was set so that the average estimated recurrence for debris-flow deposition at 2nd- and 3rd-order channel junctions matched those estimated from other studies (Lancaster et al., 2010; May and Gresswell, 2004) (**Figure 7**) and so that the modeled mean rates of wood recruitment from upslope fell within the ranges observed from field studies (Carlson, in prep). Modeling of relative rates of debris-flow flux of material to fish-bearing streams, as done for the PFA, requires only a measure of relative frequency, not an explicit recurrence interval. We refer to these estimates of relative flux as time-averaged rates. We do not need to specify a recurrence interval for this application because we do not need the absolute magnitude, we only need the relative difference in magnitude from site to site.

Source areas can now be ranked in terms of the relative modeled rates at which they provide debris-flow-delivered material to fish-bearing streams. For a specified area or basin, a cumulative distribution is created by summing the ranked time-averaged-deposit volumes from smallest to largest. The summed values are divided by the total, giving a cumulative distribution ranking of DEM cells. The cumulative distribution can be interpreted in terms of the proportion of total deposit volume accumulated over a time period long enough for many debris flows to have occurred that originate from any portion of the entire area. The spatial scale chosen for calculating this cumulative distribution is the contributing area of a nonfish to fish-bearing channel confluence (**Figure 8**). For each of these small basins, sediment source areas are identified and delineated in terms of the modeled proportion of the total flux of debris-flow-transported material deposited into the fish-bearing stream at the basin mouth.

The delineated zones indicate where timber harvest would have the greatest expected impact on the rate of sediment delivery out of the subbasin by debris flow and show where buffers might be placed to reduce harvest-related changes in material flux to fish-bearing streams. These zones lie predominantly in steep, convergent zones just below the ridge-top landings used for cable yarding of logs out of these subbasins. Leave-tree buffers in these source areas can block access to a large portion of the subbasin, so it is expected that yarding corridors might be placed through some of these zones. We anticipate that buffer extents will encompass only some agreed-upon subset of the delineated zones, targeting those with the highest modeled rates. Yarding corridors may still be necessary through these subzones. Any chosen subzones will still exhibit a range of sensitivity to harvest. To help target yarding-corridor placement, these subzones can be further subdivided in terms of modeled probability of initiation and delivery. To do this, for all DEM cells within a chosen subzone, the modeled landslide density is multiplied by the modeled probability of delivery to a fish-bearing stream, giving a delivery-weighted density. Following Burnett and Miller (2007), these values are ranked from smallest to largest and summed to give a cumulative distribution, which is then normalized by the total. This delineates the subzone (called Trigger Sources, Figure 9) in terms of the proportion of expected delivering initiation events (**Figure 9**). These areas are approximately equivalent to the trigger hollows of Benda and Cundy (1990). We assume that areas within the subzone that produce the highest proportion of events will be those areas most sensitive to tree removal.

Miller and Burnett (2008) found that probability of scour differed with forest-cover type, being greater in younger stands. As described previously, a uniform mature forest cover was used for the PFA modeling. Application of spatially variable stand types along debris-flow-traversal corridors will result in changes in the spatial pattern of predicted delivered volume proportions. Sensitivity of these model predictions to variable forest cover has not yet been evaluated, but can be as the models are more broadly applied.

4.0 Summary

To summarize, the models are used to identify two process zones and to rank those zones in terms of process rates:

1. ***Debris-Flow Runout****.* These are headwater channels with a modeled probability of traversal by a debris flow originating upslope that continues to a fish-bearing stream downslope. Flowing water through these ephemeral channels generally lack the transport capacity to move the sediment and wood that falls into them, so this material accumulates over time until picked up by a debris flow. Riparian zones along these corridors are thus source areas for wood carried by debris flows to fish-bearing streams. Over any period of time, only a portion of the identified debris-flow traversal corridors will be traversed by a debris flow; the corridors are ranked by the modeled probability that they will be traversed. This probability is expressed in terms of the proportion of the total debris-flow-track length included within any subset of the corridors, starting from those with the greatest probability of traversal. This measure provides a physical quantity with which to interpret and test model predictions: 20% of observed debris-flow track length should lie within those channels ranked from zero to 20%; 50% of the track length should lie within those ranked from zero to 50%, and so on. The modeled proportion is related to the relative frequency of traversal: channels in lower percentage brackets experience more frequent debris flows.

2. ***Sediment Source Areas****.* The surface area draining to each debris-flow traversal corridor is delineated from the confluence of the corridor with a fish-bearing stream. The delineated area defines a subbasin within the much larger 4th-field HUC analysis basin. Within each subbasin, the initiation sites for debris flows that can carry material to the fish-bearing stream at the subbasin mouth are identified. These are the sediment source areas for that subbasin. Ideally, leave-tree buffers intended to prevent increased rates of sediment production will be targeted for those sites from which initiated debris flows will deliver the most sediment; these buffers are intended to prevent increased rates of landsliding caused by timber harvest in those zones. To identify those zones, the source areas are ranked in terms of the proportion of material carried to the fish-bearing stream originating from each initiation site within the subbasin. The volume of material delivered to the fish-bearing stream varies from year to year; none in most years, a lot in others. Likewise, the volume

potentially delivered varies across the source areas; debris flows from some sites are likely to deliver only a small volume, those from other sites can deliver a huge volume. In those years that debris flows occur, the specific sites from which they originate are unknown beforehand, but based on the modeling, it is known which sites are more or less likely to fail. To identify those sites from which increased rates of landsliding will result in the largest increased rate of sediment delivery, we account for both the likely volume of delivered material and the likelihood that a site will fail and trigger a debris flow. To do this, we rank initiation sites in terms of the estimated time-averaged volume of sediment delivered: the calculated delivery volume associated with a debris-flow event from the initiation site multiplied by the probability of initiation and delivery for a debris flow from that initiation site. Summed over all initiation sites within a subbasin, this gives the time-averaged volume of debris-flow-delivered sediment for the subbasin. The source areas are then delineated into zones based on the proportion of total time-averaged volume volume originating from within each zone, ordered from highest to lowest.

5.0 Discussion

We have described how computer models can be used to aid in the design of upslope and headwater riparian buffers to minimize harvest-related impacts to landslide and debris-flow fluxes of sediment and wood to fish-bearing streams. Methods for using such models have been previously proposed (Burnett and Miller, 2007), but the two HCPs and the Private Forest Accord now in development in Oregon are the first examples where these methods have been implemented in management planning. In the context of forest practices in Oregon, landslide-hazard assessment has traditionally depended on field-based observations and the judgment of experienced professional geologists. Can such models contribute to this established methodology?

Consider again the first three objectives listed for harvest planning in debris-flow-prone terrain:

1. Prevent changes in the rate of landslide initiation of debris flows that travel to fish-bearing streams.
2. Maintain sources of large wood available to landslides and debris flows for transport to fish-bearing streams,
3. Maintain sources of large wood along potential debris-flow-runout tracks to prevent increased runout length.

These objectives could potentially be met using detailed field surveys. There would be debate about the details at individual sites, but overall field techniques could be used to identify sites subject to landslide initiation and debris-flow delivery to fish-bearing streams. It would entail a very large field campaign to survey all potential initiation sites and headwater channels across any region, but conceptually it is possible.

Now recall the fourth objective:

1. Minimize the number of trees precluded from harvest.

Determining the buffer extent required to establish an appropriate balance between the first three and fourth objectives is the crux in stakeholder debates. Here, professional judgment can fall short, because each professional may have a different answer. The models described contribute to this debate by providing a quantitative, hence testable, and consistent measure of 1) the amount of protection, in terms of the proportion of events, afforded by any proposed buffer scenario versus 2) the area (number of trees) precluded from harvest. Such an analysis requires determining how much the potential for debris-flow delivery at one site differs from that at another, and then ranking the many thousands of sites across a region. Such an analysis is not possible using field interpretations alone.

In applying a model, it is important to understand how the model represents the processes we seek to characterize and, thereby, to recognize how the models might fall short in predicting future events. We are attempting to describe processes that vary in space and time. Our strategy is to create maps showing how proportions vary over space: debris-flow-source areas in terms of the proportion of material flux to fish-bearing streams originating from each initiation site and headwater channels in terms of the proportion of debris-flow events they contain. These proportions involve an element of time. Landslides and debris flows are discrete events, so the number that occurs and the proportion of that number contained in any specified area or set of channels depends on the total area observed and the total period of observation. These scale dependencies introduce an intrinsic source of uncertainty in model predictions.

Of the many thousands of landslide initiation sites and debris-flow corridors that might exist within a 4th-field HUC basin, we do not know which ones will experience an event over any period of time, we can only know at which locations events are more or less likely to occur. Because there are random elements[9] driving landslide occurrence, in some cases a landslide will occur in a less likely location and not in a more likely location. This randomness creates uncertainty in predictions of proportions and the degree of uncertainty varies with the number of events counted, which varies with the spatial and temporal scales over which predictions and observations are made.

Ability to predict the proportion of landslide events and debris-flow-track length that will occur within any subarea of an analysis basin is a key component of the models presented here. With monitoring, this is a testable prediction, providing a data-driven means of evaluating model performance. However, the inherent uncertainty in these predictions, as described above, could limit the usefulness of such tests. The smaller the area monitored and the shorter the time period of observation, the larger is the uncertainty in predictions of proportion. A prediction that 20% of debris-flow tracks will occur within some specific subset of headwater channels, plus or minus 20%, is not a useful test. This uncertainty was not addressed in negotiations for buffer designs in the Oregon HCPs or PFA. It is possible, however, to estimate the magnitude of this uncertainty based on the area and time period of observation. As monitoring strategies are developed for collecting information to test and improve the models used to aid in buffer design, estimates of uncertainty will be required to determine the amount of data required for meaningful tests of the models and to help with interpretation of the data collected.

Estimates of debris-flow-deposit volume is an important addition to the models presented here. These estimates are used to rank source areas for debris flows for placement of upslope buffers. These estimates are also phrased in terms of the proportion of total material delivered to fish-bearing streams and can, conceptually, be tested by monitoring mobilized volumes. Such monitoring would require a herculean field effort, particularly over a spatial extent sufficient to provide an acceptable level of certainty for

[9] Use of the term "random" here reflects in part our lack of knowledge about the details of physical conditions at each site. A new rodent burrow might create a conduit for water flow that alters the hydrology and triggers a landslide; a tree may become diseased and its roots may die, decreasing local effective soil strength. Conditions that affect landslide susceptibility can vary in space and time in ways that we cannot ascertain, creating an element of randomness in which potential landslide locations actually fail over any period.

testing model predictions. Differencing of high-resolution lidar point clouds, overlapping in spatial extent but collected in different years, provides a potentially viable alternative (e.g., Bernard et al., 2021; Fernández et al., 2021).

The uncertainty described above is an inherent property of the processes driving landslide and debris-flow occurrences. There are (at least) three ways in which the data used to calibrate the models can also introduce bias and uncertainty: 1) The accuracy and precision with which landslide initiation locations and debris-flow runout paths are mapped and translated to digital base maps constrains the accuracy to which landslide-prone landforms can be resolved and runout lengths estimated, 2) systematic exclusion of certain landslides, such as those hidden under forest canopy when aerial photographs are used to identify landslide locations or when only landslides and debris flows with runout to a stream channel are included in field surveys can produce bias in model results, and 3) the sequence of storms that triggered the observed events can also produce bias if different storms tend to trigger landslides in different locations. These issues are briefly elaborated below.

5.1 Precision and Accuracy

The Miller-Burnett models (2007, 2008) were calibrated to field-surveyed landslide and debris-flow-runout inventories conducted after extreme storms in February and November of 1996 (Robison et al., 1999). Within the eight study areas, field crews walked up all channels with sustained gradients less than 40% and recorded the runout track and initiation location of every landslide and debris flow that deposited material in the channels. This method provided a census of all landslides that impacted channels. To associate the surveyed locations with topographic attributes, these locations were transcribed into a GIS and overlain on a digital elevation model. Locations were recorded using 1:6000-scale aerial photographs and 1:24,000-scale topographic maps. Most landslides were hidden under forest canopy and not visible on the photos. GPS units were used for location in only the two study areas surveyed after the November storm. The accuracy and precision of the digitized landslide locations is not known; Miller and Burnett (2007) assumed that the correct initiation point was located somewhere within a 60-meter-diameter circle centered on the digitized initiation point. This was consistent with the length scale to which topographic features could be resolved with the 10-meter-cell size DEMs derived by interpolation of 40-foot contour lines on 1:24,000-scale topographic maps available at that time. This length scale is sufficient to resolve the headwalls at the upper extent of the small headwater basins tributary to fish-bearing streams, but each headwall may contain dozens of bedrock hollows within which landslides typically originate. The calibrated model gives the landslide density associated with any set of topographic attributes, so when integrated over any study area it will produce the correct number of landslides, but variations in density are only resolved with a precision of 60 meters or more, insufficient to pinpoint individual hollows. Predictions can be no more precise or accurate than the data used to calibrate the models.

Now, however, LiDAR-derived DEMs can provide far higher precision and accuracy. LiDAR point clouds are commonly interpolated to gridded DEMs with a cell size of one meter, a data density 100 times greater than the 10-meter DEMs previously available. With these DEMs, individual landslide initiation sites can be resolved. These newer, higher-precision DEMs were used with the Miller and Burnett (2007, 2008) models for the HCP and PFA analyses, but with 10-meter smoothing to match the precision of the original DEMs used for model calibration. Model predictions are still constrained by the precision of the digitized landslide locations, but the LiDAR-derived DEMs provide more accurate delineation of landform features. Comparison of an updated landslide inventory using a portion of the 1996-storm-study landslide locations with a 1-m lidar base map shows that the existing calibration provides good representation of landslide initiation locations. However, the increased resolution of channel confinement along runout tracks with the higher-resolution Lidar DEMs results in an increase in predicted debris-flow-track length compared to that using a 10-m DEM (**Figure 10**). Ongoing data collection and analysis efforts will include recalibration of the models to the new DEMs. Recalibration should provide the same basin-wide results for any analysis basin, because the models are calibrated to give the observed proportions of initiation sites and runout-track lengths, but the resolution of high- and low-susceptibility sites should be more precise, reflecting the ability of the higher-resolution data to better resolve topographic controls on landslide initiation and runout.

5.2 Detection Bias

The ability to see landslides in aerial photographs varies with landslide size and the degree of forest cover. Small landslides are hidden under tree canopy, so a large proportion of landslide events may not be detected with aerial-photograph-based inventories (Brardinoni et al., 2003; Robison et al., 1999). The degree of bias can be estimated, but at the cost of increased uncertainty (Miller and Burnett, 2007; Turner et al., 2010). Field-based inventories can potentially locate every landslide within a study area, even those hidden under tree canopy, but the logistics and effort required for ground-based surveys can constrain such efforts to relatively small areas and to only a portion of the landslides, such as those that runout to stream channels (Robison et al., 1999; Stewart et al., 2013). Smaller sample sizes translate to larger uncertainty (Miller et al., 2003). Aerial-photo-based inventories can provide large, but potentially biased samples; field surveys can provide small, but unbiased samples, though usually only of a subset of landslides (e.g., those intersecting stream channels).

New data sources might help to reduce detection bias. Sequential lidar acquisitions reveal changes in elevation between the acquisition dates that can be used to precisely locate landslides and obtain estimates of mobilized volume and runout extent (Bernard et al., 2021). As sequential lidar datasets become available, this data source should be utilized to produce new landslide inventories.

5.3 Storm Sequences

If landslide locations or types vary with storm characteristics (Wieczorek, 1987), empirical models to characterize landslide susceptibility will reflect the particular storm or storms that triggered the inventoried landslides used to calibrate the model. The number of landslides triggered during a storm varies immensely with rainfall intensity (Turner et al., 2010). Field surveys are therefore typically initiated after intense storms when there are many landslides to count (Robison et al., 1999; Stewart et al., 2013; Turner et al., 2010). Models relying on such data, such as those used here, then reflect landslide locations associated with those particular storms. Extreme storms can trigger thousands of landslides within a basin, far more than associated with more frequent storm events, so it may be that landslide-triggered fluxes of material to fish-bearing streams are primarily associated with such intense storms and models calibrated to such storm-related data will accurately reflect long-term spatial patterns. But we do not know that, so continued monitoring of landslide locations associated with the full range of possible storm events is needed to evaluate model results and to recalibrate the models if needed.

Here too, new data sources can be utilized to better constrain storm-related influences on landslide location and density. Gridded precipitation data based on terrestrial radar, satellite infrared and microwave imagery, and rain gauge records are available at a variety of spatial and temporal resolution (e.g., Kidd and Levizzani, 2022; Binetti et al., 2022; Thornton et al., 2021; Prat and Nelson, 2015). Several decades of such data at 1 to 4 km spacing and hourly to daily time increments are available across the US. Together with sequential lidar, these new data sources provide an opportunity to dramatically improve our understanding of topographic and storm controls on landslide susceptibility.

6.0 Conclusion

The set of methods described here incorporates three key factors for providing information to guide development of forest-practice prescriptions in landslide-prone terrain:

1. The linkages between upslope zones of landslide initiation and downslope zones of deposition are explicitly recognized and quantified. The potential for debris-flow delivery of material to a fish-bearing stream is calculated for every potential initiation site and the potential for traversal by a debris flow that travels to a fish-bearing stream is calculated for every non-fish channel. Upslope source areas for landslides and debris-flow corridors can be ranked by the potential for landslide initiation, the potential for delivery to a downslope resource, and by the relative volume of material provided to fish-bearing streams.
2. The interaction of all initiation sites and runout zones are explicitly recognized and quantified. A single depositional site in a fish-bearing stream may receive debris flows from dozens of upslope initiation sites. The calculated probability for debris-flow traversal of a non-fish channel and deposition in a fish-bearing channel represents the cumulative potential of all upslope initiation sites and runout paths.
3. Results of these linked models are testable. The models predict where a certain proportion of landslide-initiation and debris-flow-depositional events will occur. In an adaptive-management context, these methods can be tested and improved using data obtained by monitoring of landslide and debris-flow events over time.

Testing and improvement of these methods will require both ongoing development of software tools for data analysis, particularly for evaluation of uncertainty in model predictions, and ongoing monitoring of landslide events and collection of information on landslide locations, runout extent, deposit volume, and characteristics of the landslide-triggering storms.

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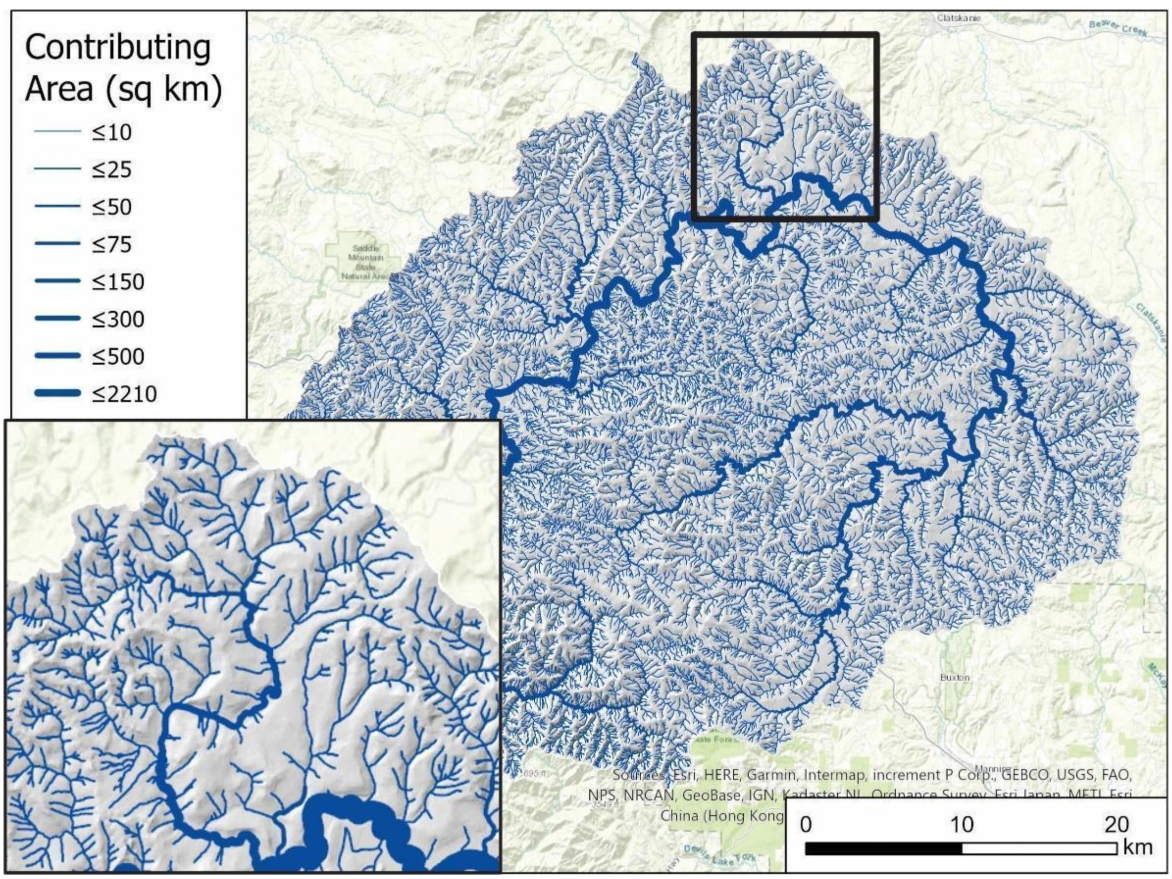

Figure 1. A synthetic stream network is shown for the Nehalem River watershed in northwest Oregon.

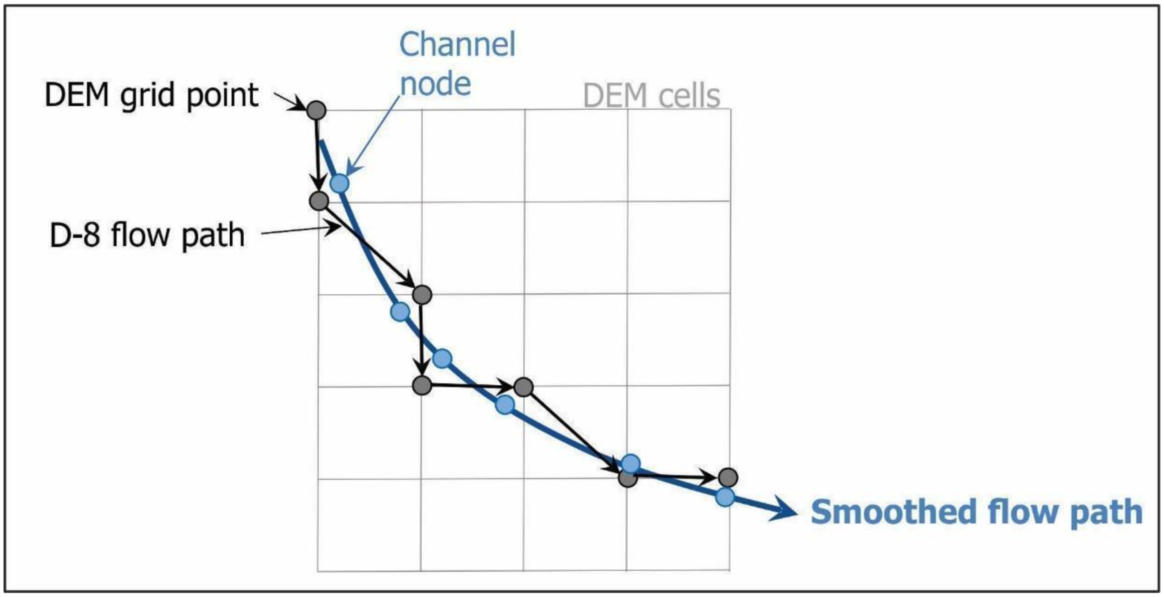

Figure 2. A digital channel network is typically represented in a GIS (Geographic Information System) as a set of connected lines (arcs). Each arc can be assigned a set of attributes, such as channel size and gradient, etc. In the FPA analysis, a synthetic channel network is represented as a set of linked nodes; one node for each DEM grid point traversed by each channel.

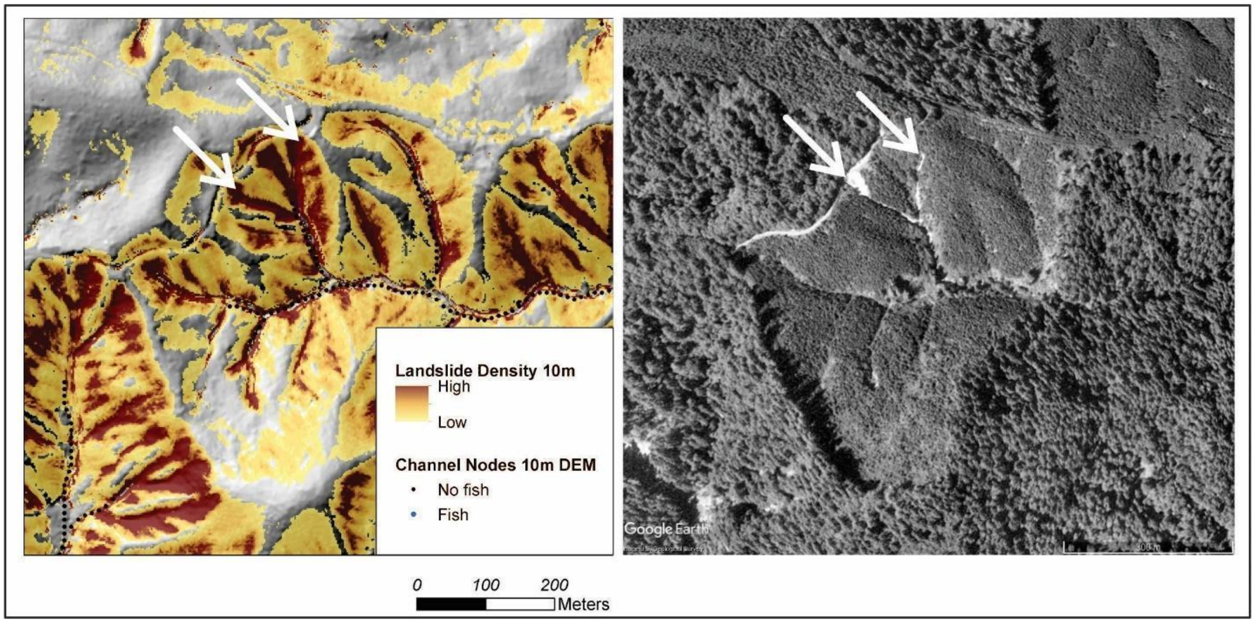

Figure 3. Landslide density (#/km^2) varies with topographic attributes in a coastal Oregon watershed. Topographic locations associated with landslide occurrences have a high density. Example shown is from the central Oregon Coast Range.

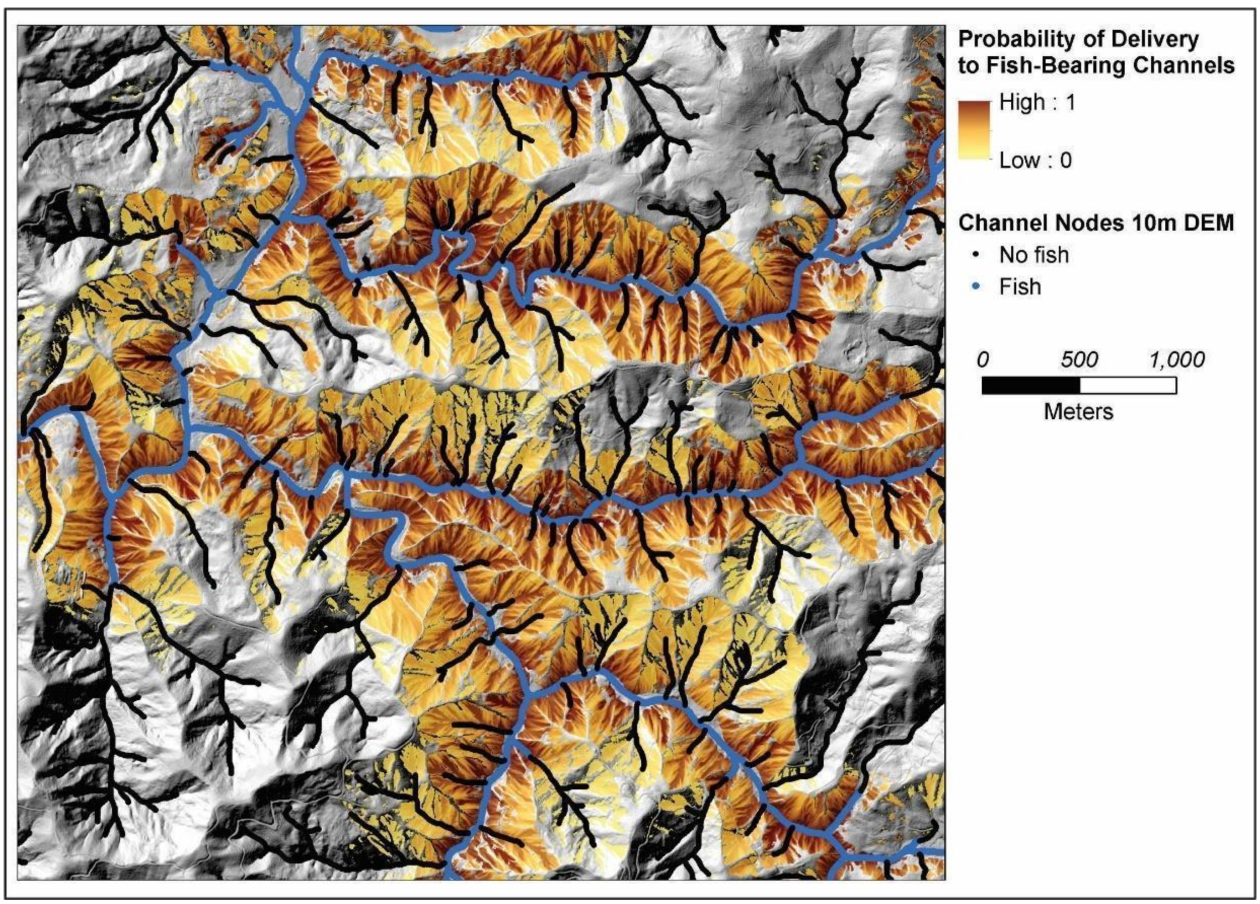

Figure 4. Probability of sediment delivery is calculated for each DEM (2m LiDAR) cell.

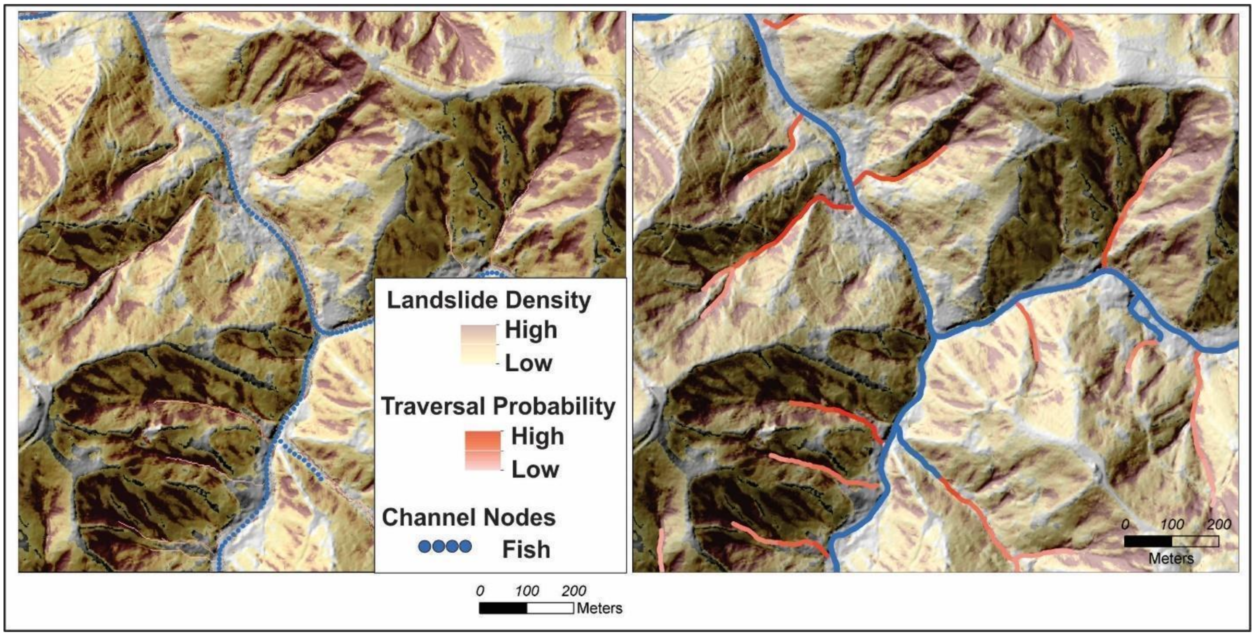

Figure 5. Predicted landslide density (left) and debris flow traversal probability for an area in the Oregon Coast Range using 2m LiDAR DEMs. Flow paths with high probability of being traversed in route to a fish-bearing channel show up as thin red lines. (right) Predictions overlayed onto synthetic stream network; blue lines are fish-bearing channels.

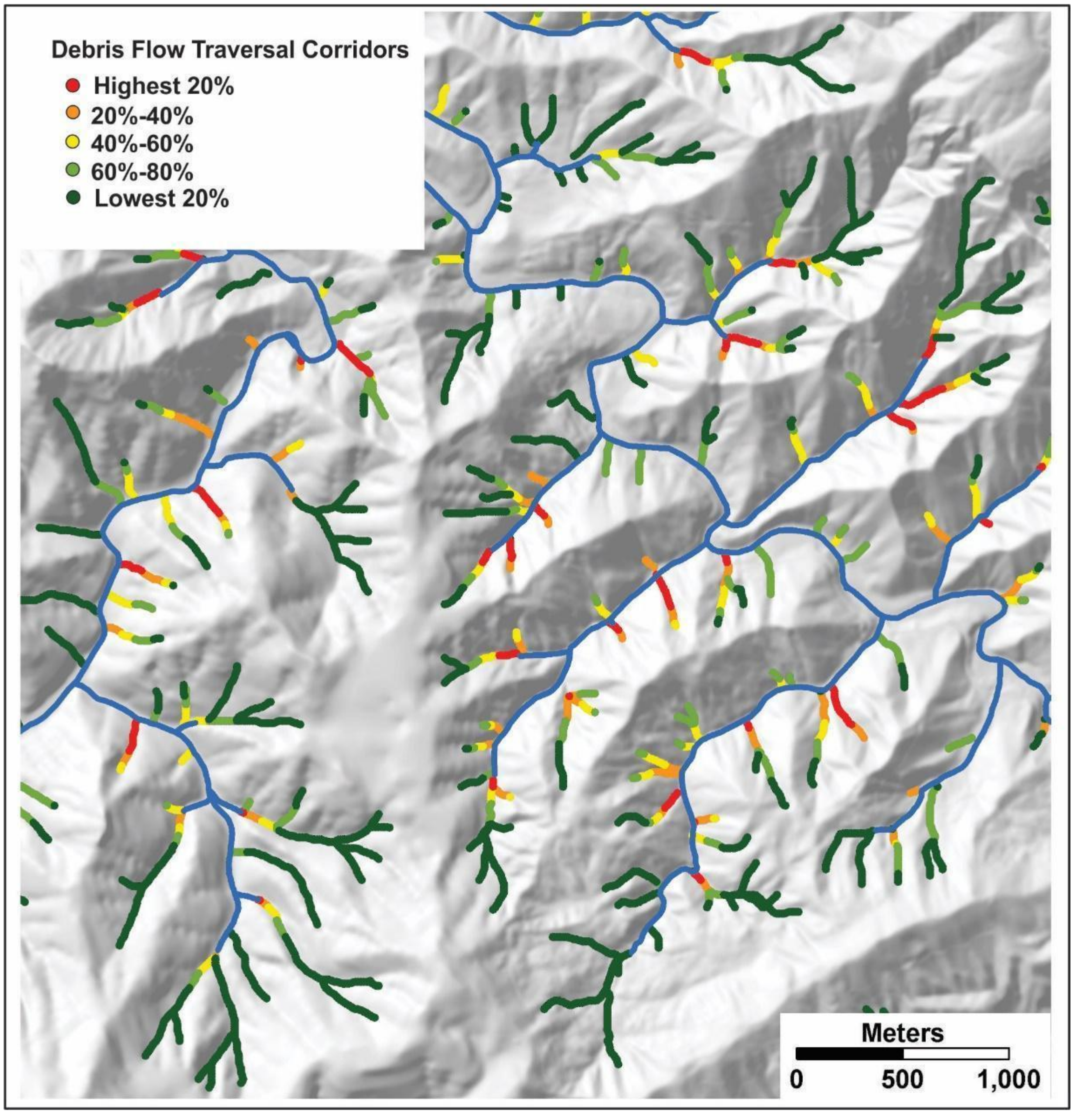

Figure 6. Model predictions of non-fish channels showing proportion of future debris flows that travel to fish streams.

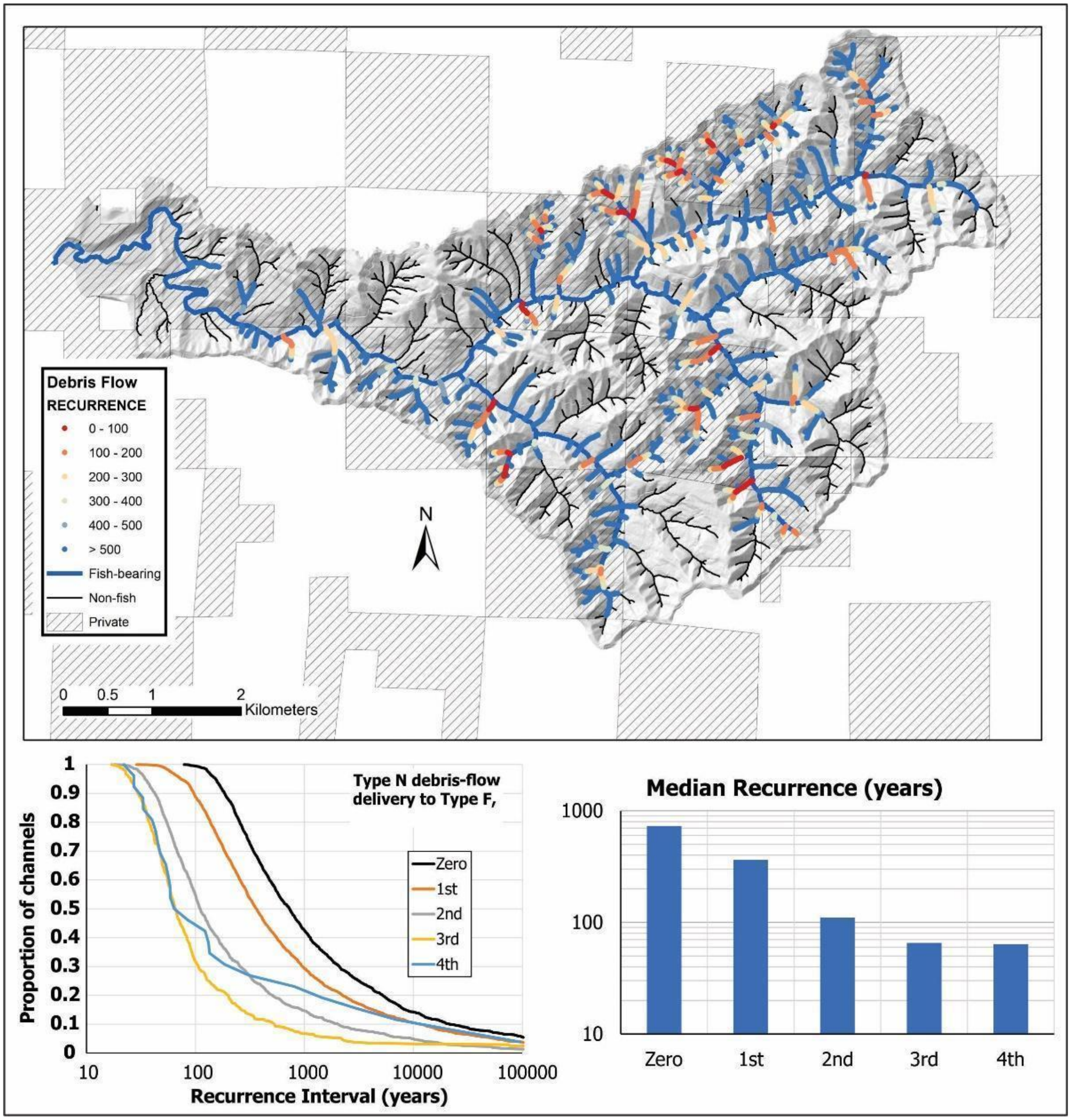

Figure 7. Predicted recurrence intervals of landslides (zero-order) and debris flows in first- through fourth-order channels for a subbasin in the central Oregon Coast Range (Miller, in prep.).

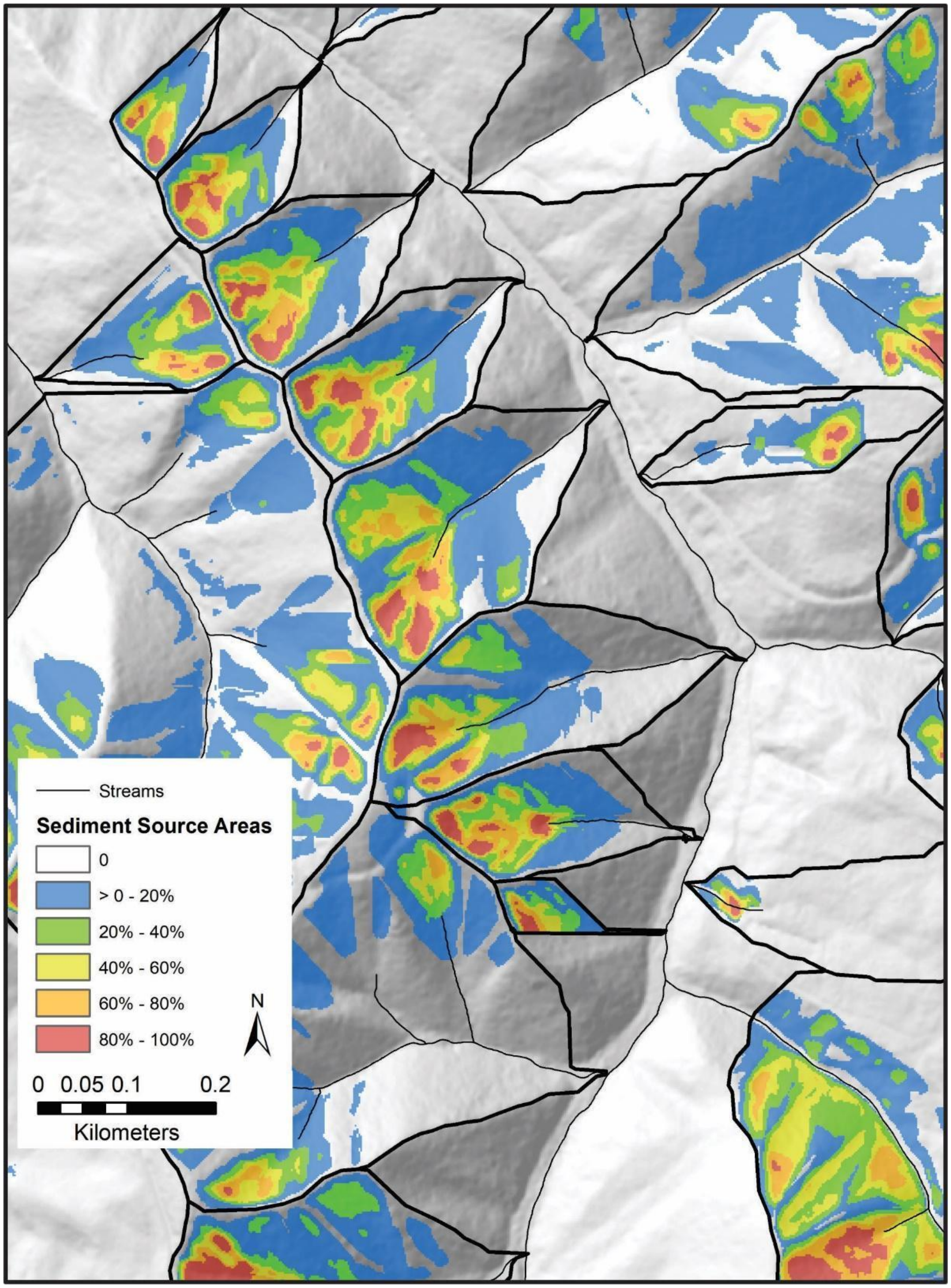

Figure 8. Predicted sediment source areas within debris flow traversal corridor subbasins.

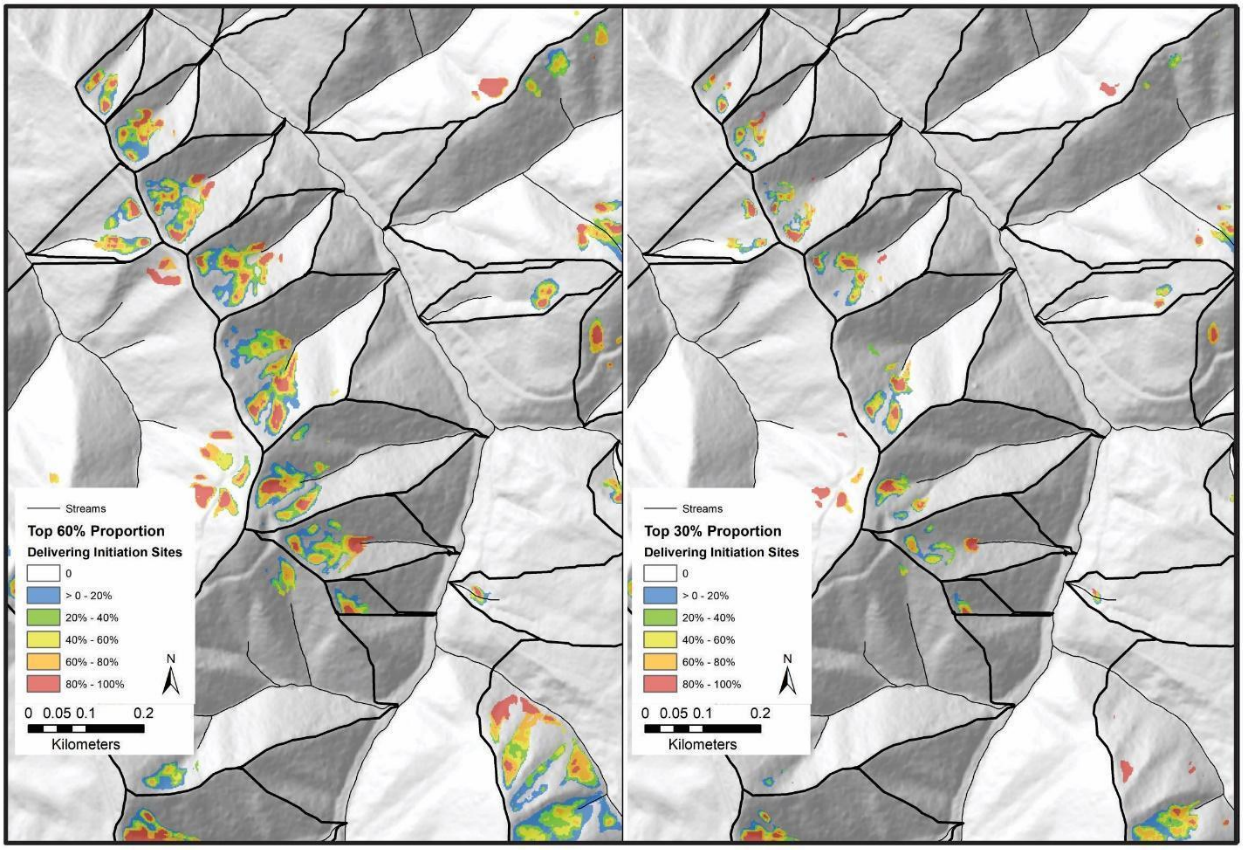

Figure 9. Within a selected subset of sediment source areas (Figure 8), the zones with the highest modeled landslide susceptibility and probability of sediment delivery can be identified and ranked from largest to smallest. Illustrative examples show the ranked failure probability and delivery potential identified within the highest 60% and 30% of the predicted sediment source areas.

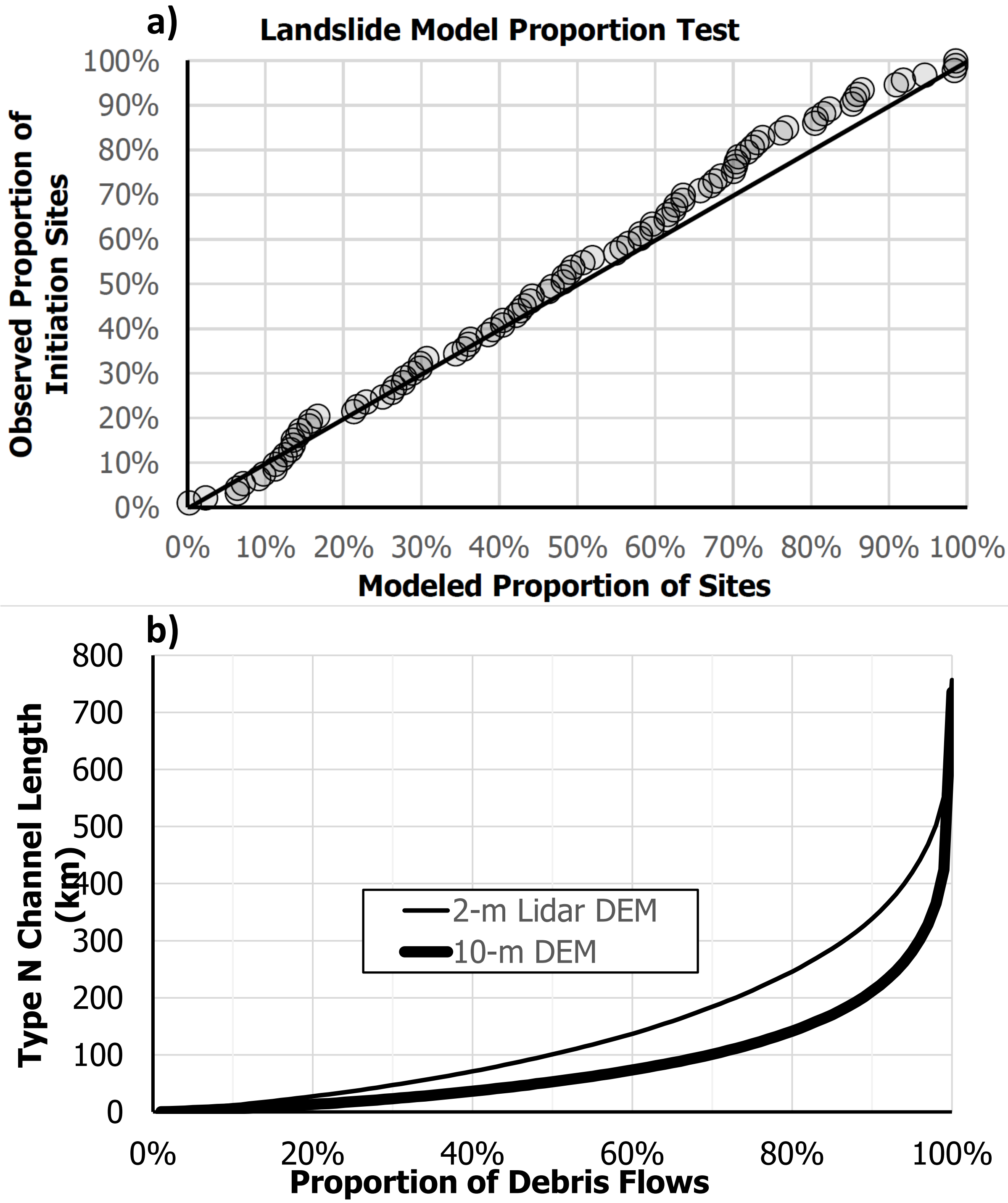

Figure 10. a) The current model calibration for landslide initiation sites indicates locations of landslides from the ODF 1996 Storm Study sites (Robison et al., 1999) repositioned using post-storm aerial photography and high-resolution lidar DEM basemaps. A perfect match would follow the 1-to-1 dark-black line. b) Compared to the 10-m DEM, a 2-m Lidar DEM indicates similar total debris-flow non-fish channel length (757 km vs 736 km), but greater length for a given proportion of debris-flow-track length. These results are for the Siletz Basin. b)