Findings Report for the
Literature Synthesis of the Effects of Forest Practices on
Non-Glacial Deep-Seated Landslides and Groundwater Recharge

UPSAG
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1. **Does the study inform a rule, numeric target, performance target, or resource objective?**
   No. This project was a targeted literature review to update the state of the science and identify knowledge gaps with respect to the potential effects of forest practices on non-glacial deep-seated landslides and groundwater recharge.

2. **Does the study inform the Forest Practices Rules, the Forest Practices Board Manual guidelines, or Schedules L-1 or L-2?**

   Yes, this literature review and synthesis:

   - addresses questions posed by the Forest Practices Board's Proposal Initiation (2016) directed to UPSAG, CMER, and Policy concerning groundwater recharge to non-glacial deep-seated landslides, reactivation of dormant deep-seated landslides, run-out potential for deep-seated landslides, and sensitivity of non-glacial deep-seated landslides (NGDSLs) to forest practices;
   - supplements and adds context to the literature cited in Board's recently adopted BM 16 (2015), critical to more accurately assessing the potential impacts of forest practices on NGDSLs;
   - informs the Rule Group critical question "Are unstable landforms being correctly and uniformly identified and evaluated for potential hazard?";
   - is an extension of the literature synthesis for glacial deep-seated landslides completed in 2016; and
   - identifies current gaps in our knowledge and provides recommendations for filling those gaps by developing a Deep-Seated Landslide Research Strategy.

   This literature review does not:

   - directly inform Forest Practices Rules;
   - directly address any targets or research proposed in Schedules L-1 and L-2; or
   - directly answer any critical questions listed in the CMER Work Plan.

3. **Was the study carried out pursuant to CMER scientific protocols?**
   Yes. This project report was reviewed and approved by UPSAG and CMER consistent with the Protocol and Standards Manual. There was no Independent Scientific Peer Review (ISPR) since literature reviews are most often used by CMER to inform larger experimental

studies that later go through ISPR. However, the contractor's proposal included a review by a team of outside expert advisors to review and guide the project as it progressed.

4. What does the study tell us? What does the study not tell us?

- There is extensive peer-reviewed literature in geotechnical engineering and geomorphology oriented journals addressing case studies from around the world of deep-seated landslides, laboratory measurements of materials involved in deep-seated landslides, analyses of factors associated with deep-seated landslides, and development of mathematical models for predicting deep-seated landslide behavior.
- While there is extensive peer-reviewed literature on non-glacial deep-seated landslides, there is limited information on forest practices effects on these features. Since Koler et al. (1991), a CMER-sponsored literature review of this topic, no new studies directly examine or evaluate the influence of forest practices on non-glacial deep-seated landslide behavior. Therefore, most of the questions in the Board's PI prioritized by Policy and tasked to UPSAG and CMER, are not directly addressed by either peer-reviewed or other published studies. The studies referred to in the first bullet-list item above provide information from which answers to those questions can be inferred, but those inferences are hypothetical.
- Deep-seated landslides occur over a large range of spatial and temporal scales, as well as environmental conditions. Landform signatures may persist for thousands of years, even in the absence of recent landslide activity. Inventories of deep-seated landslides in Washington state show that landforms indicative of past landslide activity are widespread in some areas with topographic relief, and that these deep-seated landslides can occupy a large proportion of the landscape, covering more than half the surface area in some inventoried areas. In these inventories, most of the deep-seated landslides are classified as dormant or relict, based on criteria specified in the Forest Practices Board Manual (Section 16, Part 6.1, Table 2). Landslides classified as dormant or relict have undergone a history of high precipitation events and, in many cases, past forest harvests, with no evidence of reactivation, leading to the hypothesis that these landslides are insensitive to forest-practice activities. While this hypothesis is supported by the experience of field practitioners (e.g., field and air photo observations of individual deep-seated landslides, watershed analyses, and landslide hazard zonation projects), it has not been documented or quantitatively assessed in the peer-reviewed literature. Qualitatively, available evidence suggests that most landslides classified as dormant or relict pose little or no hazard and are insensitive to forest-practice activities, but it is unknown if that is true of all these landslides and information to test that assumption has not been systematically collected. Current forest-practice standards for assessment of deep-seated landslide hazards rely on evaluation of activity level (active, dormant, relict) and assume that lack of evidence of response to past forest practices indicates low probability of future response, but provide no quantitative justification for this assumption. Evaluation of this assumption is feasible, but requires data collection and analysis for the population of deep-seated landslides within areas where forest-practice activities occur.
- Deep-seated landslides occur over a large range of geologic and geomorphic settings and exhibit a variety of surface morphologies and temporal behaviors. Despite this great

diversity, studies from across the globe identify certain common features associated with deep-seated landslide landforms that aid in explaining landslide behavior. Translational, rotational, and earthflow movement of deep-seated landslides involves movement of material above a distinct shear zone. Material within the shear zone has been broken apart both by the failure that first initiated the landslide and by subsequent mechanical breakage as the landslide moved. While not universally true, the simple conceptual model is that the shear zone typically exhibits little or no cohesion, and has low permeability. The shear zone can act as an aquitard, causing groundwater to accumulate within the landslide body, thereby increasing pore water pressure. Thus, shear strength of the shear zone is inversely proportional to the depth of groundwater within the landslide body, so that landslide movement can be initiated when groundwater reaches some threshold level. This means that changes to the amount of water flowing into or out of a landslide body may alter landslide behavior.

- Most deep-seated landslides exhibit behavior characterized by relatively slow, intermittent movement. However, some landslides have moved suddenly at great speed (meters per second) and traveled large distances (> 1000m). Physical factors associated with these occurrences have been identified, but attempts to develop predictive models are confounded by multiple uncertainties.

5. What is the relationship between this study and any others that may be planned, underway, or recently completed?

This literature review and synthesis provides information to aid UPSAG in the development of a Deep-Seated Landslide Research Strategy to assess the effectiveness of the Forest Practices Rules, to evaluate the Forest Practices Board Manual 16 guidelines for deep-seated landslides, and to determine what degree performance targets specified by Schedule L-1 are being met. The synthesis identifies knowledge gaps and provides recommendations for filling those gaps.

A primary gap is documentation of which, if any, deep-seated landslides have shown signs of reactivation or acceleration after forest-practice activities and which have not. Lack of this information leads to subsequent gaps, so that deep-seated landslide characteristics associated with reactivation or sensitivity to forest practices have not been identified and the effectiveness of current guidelines for identifying deep-seated landslides that may respond to forest activities is unknown.

Recommendations involve a suite of possibilities for capitalizing on existing data (e.g., statistical analyses of landslide inventories, and other geotechnical studies), and new data (e.g., field surveys, instrumented monitoring, and verification of landslide movement using repeated topographic surveys).

6. What is the scientific basis that underlies the rule, numeric target, performance target, or resource objective that the study informs? How much of an incremental gain in understanding do the study results represent?

As a focused literature review, this project does not provide new effectiveness, validation or extensive monitoring and research. However, the knowledge gaps identified suggest a current lack in our ability to assess whether the Forest Practice Rules dealing with deep-

seated landslides are meeting the performance target and resource objectives specified in Schedule L-1 of the Forests & Fish Report (1999) later adopted by Forest Practices Habitat Conservation Plan (Appendix N, 2006). Essentially, the information to determine if timber harvest has or has not increased sediment delivered to streams by deep-seated landslides on a landscape scale (Schedule L-1 performance target for sediment) has not been collected largely due to spatial and temporal uncertainties. The literature review found no studies that address effects of forest practices on non-glacial deep-seated landslides directly, but the conceptual models developed for deep-seated landslides from studies worldwide do not rule out such effects. Future studies to be scoped in the Deep-Seated Landslide Research Strategy may lead to substantial gains in our understanding of the relative importance of deep-seated landslides as a source of sediment, the degree to which forest practices can alter rates of sediment production and delivery to a public resource or in a manner that threatens public safety, and improved methods for assessing deep-seated landslide behavior.