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

July 25, 2016

1. **Does the study inform a rule, numeric target, performance target, or resource objective?**
   No

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

   Yes.

   This project is a review and synthesis of relevant information from recent literature, focusing on material published since the last review of literature on this topic in 1992. The review included a sample of geotechnical reports providing glacial deep-seated landslide risk assessments for forest practice applications. The topics covered by this review are relevant to the Unstable Slopes Rule Group: in particular, for addressing how forest practices on groundwater recharge areas for glacial deep-seated landslides might affect landslide behavior (WAC 222-16-050(1)(i)(C)).

   Information reviewed in this study is pertinent to SEPA policies for potentially unstable slopes and landforms (WAC 222-10-030), in that it may aid in estimates of the likelihood that a proposed forest practice will cause movement of potentially unstable slopes or landforms, and in determining likelihood of delivery of sediment or debris to any public resources, or in a manner that would threaten public safety.

   Literature reviewed is pertinent to the Glacial Deep-Seated Landslide Program Rule-Group Critical Questions:

   - Does harvesting of the recharge area of a glacial deep-seated landslide promote its instability?
   - Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslide and/or their groundwater recharge areas?

   Information from the reviewed literature may aid in improving landslide assessments to better achieve Schedule L-1 resource objectives of clean water and substrate and maintenance of channel-forming processes.

   - Although the physical controls on deep-seated landslide appear to be relatively well understood, the effects of forest practices on landslide behavior have not been explicitly examined and must, therefore, be inferred. However, few guidelines exist for inferring these effects, and analytical tools for estimating the magnitude of any effects are not used for hazard and risk assessments.
   - Two Rule-Group Critical Questions have been posed concerning glacial deep-seated landslides. (UPSAG also provided a set of seven questions to address with the study synthesis). However, to date, no systematic analysis of existing data has been done to seek answers to these questions, and observations or measurements that might be used to

answer these questions have not been specified and are not, therefore, systematically included in geotechnical reports. SEPA policies require analysis of the likelihood that the proposed forest practices will cause movement on the potentially unstable slopes or landforms, or contribute to further movement of a potentially unstable slope or landform; and the likelihood of delivery of sediment or debris to any public resources, or in a manner that would threaten public safety. However, the Forest Practices Board Manual provides few procedures or standards for calculating these likelihoods.

3. Was the study carried out pursuant to CMER scientific protocols?

This project went through UPSAG and CMER review; there was no ISPR review. In addition, the contractor assembled a team of outside advisors to review and guide the project as it progressed. It was approved by UPSAG and CMER.

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

This study does not provide any definitive answers for the critical questions, because no studies examine these issues directly.

From information available in recently published studies and reviews, we may infer:

- Glacial deep-seated landslides in geomorphic settings common to Washington (pro-glacial lake deposits overlain by glacial outwash sediments, all of which have been over-ridden by an ice sheet) exhibit behavior typified by intermittent movement triggered by increased groundwater pore pressures.
- Landslide sensitivity to pore-pressure increases is governed by site geometry; bank erosion of a landslide toe, for example, can increase response to pore-pressure fluctuations.
- Groundwater pore pressures at the depths typical of deep-seated landslide shear zones typically respond to recharge patterns averaged over multiple precipitation events, potentially extending over seasonal to multiyear time scales.
- Preferential flow paths within landslide bodies, such as tension cracks, promote rapid pore-pressure responses to precipitation events. These responses are over-printed on seasonal to multiyear pore-pressure fluctuations. Thus long-term patterns of recharge can pre-dispose a landslide for renewed motion, and a short series of precipitation events may trigger movement.
- Forest harvest increases the proportion of precipitation that infiltrates the soil to become either shallow subsurface runoff or recharge to groundwater. The magnitude of these increases can be estimated within a fairly broad range of values based on annual precipitation. The range in estimated changes may be reduced by using meteorological-data time series for specific sites. Effects of harvest on the water budget decrease to zero over a period of 12 to 25 years.
- Water infiltrating soils overlying low-permeability substrates, such as lodgement till and some types of bedrock, travels laterally as shallow subsurface saturated flow through the soil. Depending on topography and the spatial pattern of substrates, some of this water enters stream channels and contributes to storm runoff. Another portion may flow to

areas with more permeable substrates, such as glacial outwash, and there percolate to contribute to groundwater recharge.

- Pore-pressure responses to spatial and temporal patterns of recharge can be estimated as functions of distance, topography, and soil diffusivity.
- Although glacial deep-seated landslides typically exhibit intermittent slow to relatively rapid (meters per minute) movement persisting over periods of elevated pore pressure, some large landslides can suddenly fail catastrophically with extremely rapid movement (meters per second) and long runout distances. The conditions that trigger such catastrophic failure are not fully understood.
- Empirical methods can be used to estimate potential runout length for large landslides.

UPSAG also requested that the synthesis document include “recommendations for future research and guidance in developing a strategy for dealing with gaps in our knowledge of glacial deep-seated landslides”.

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

The literature synthesis focused on the effects of forest practices on glacial deep-seated landslides and groundwater recharge. That synthesis found that very few studies examined the effects of forest practices on landslides specifically, but many studies examined issues important for understanding and anticipating these effects. Based on the available literature, a research approach was recommended that uses mapping and characterizing glacial deep-seated landslides to define characteristic profiles and develop generalized models of the landslides. An assessment of the stability of the slide could then be conducted using hydrologic and groundwater modeling to evaluate groundwater response and landslide sensitivity to groundwater changes. UPSAG will utilize this literature synthesis to develop a glacial deep-seated landslide research strategy. UPSAG is initiating scoping of a pilot project for mapping and characterizing glacial deep-seated landslides in Pierce County, where high quality topographic data exist as the first step in this process. Based on the results of the pilot mapping, the next steps will be to expand the mapping, develop characteristic landslide profiles and begin stability analysis.

<u>Recommendations</u>:

a) Develop standard tools and protocols for site characterization. These tools could include GIS-based analyses for:
    - Delineation of the topographically defined contributing area to a landslide; division of the contributing area into zones contributing to storm runoff, runoff recharge, and direct recharge; and estimates of total recharge (as a function of mean annual precipitation) to the landslide.
    - Estimate of change in recharge to a landslide associated with a proposed timber harvest.
    - Extraction of the surface topography of the landslide and automatic generation of stability indices and sensitivity to pore-pressure changes.

- Sensitivity of the landslide to bank erosion or channel incision at the landslide toe.

b) Include observations and measurements that can inform studies to answer the critical questions and provide estimates of likelihood (for effects on landslide movement and delivery) in all landslide risk assessments. These observations and measurements may include:
   - Accurately digitized landslide-feature polygons.
   - Consistent terminology for field-based indicators of landslide type, level of landslide activity, and materials involved.
   - Comparison of landslide characteristics to a representative sample of landslides with known activity levels.
   - Maps delineating possible runout extent in the event of catastrophic failure.

c) Use these tools with existing data sources (currently available geotechnical reports, LiDAR elevation data, PRISM climate data) to characterize a representative sample of glacial deep-seated landslides.

d) Use the representative sample to develop statistical models to characterize the level of landslide activity based on topographic, stratigraphic, land cover, and climatic attributes. Use these models to provide quantified estimates of the likelihood for landslide movement and for the change in likelihood associated with a proposed forest practice.

e) Collect data with all ongoing and future landslide risk assessments to test and improve these statistical models.

f) Explore soil-water-budget models to better estimate changes in evapotranspiration associated with timber harvest. It was recommended above that these changes initially be estimated as a function of mean-annual precipitation. Better estimates may be feasible using meteorological time-series.

g) Use the data collected and models developed to constrain the range of landslide characteristics and their relationship to levels of landslide activity. This will guide selection of characteristic landslide settings for application of detailed physical models seeking to answer the two critical questions. Results from these detailed models will provide hypotheses to be tested with long-term field monitoring and paired basin treatment experiments.

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 research, but collects and synthesizes existing work and applies it to the problem at hand, and makes recommendations for a) developing tools to use the results of the research reported on in the literature review and b) future research.