Mapping of Potential Landslide Hazards along the River Corridors of King County, Washington

Technical Report

August 2016

Prepared
by
Department of Natural Resources and Parks
Water and Land Resources Division
River and Floodplain Management Section
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KING COUNTY FLOOD CONTROL DISTRICT

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This document was prepared under the supervision and direction of the undersigned, whose seals as licensed geologists affixed below:

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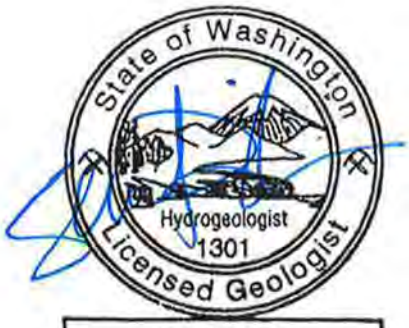

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Primary contributions to the technical work for this investigation were provided by King County Department of Natural Resources and Parks (DNRP) geologists licensed in the State of Washington. These staff include John Bethel in the River and Floodplain Management Section (RFMS), Water and Land Resources Division (WLR Division), and Sevin Bilir in the Science and Technical Support Section, WLR Division. Other WLR Division staff provided technical, inventory, mapping and field support (Fred Lott and Evelyn Conrado). Mapping information for this investigation was coordinated with the King County Department of Permitting and Environmental Review (DPER). Technical editing was provided by Jennifer Vanderhoof. Sevin Bilir served as the project manager. Jeanne Stypula, PE, was the project supervisor.

The King County Department of Natural Resources and Parks wishes to specifically acknowledge the Technical Review Committee members who provided expert advice and direction in the consideration of the mapping methodologies used in the preparation of the river corridor landslide hazard mapping. The Committee members are expert practitioners in Washington State in landslide science, geotechnical engineering, local geology and landslides, and landslide mapping, and include:

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Abbreviations and Acronyms

BNSF	Burlington Northern Santa Fe
DNR DGER	Department of Natural Resources Division of Geology and Earth Resources
DNRP	Department of Natural Resources and Parks
DPER	Department of Permitting and Environmental Review
DOT	Department of Transportation
DTM	Digital Terrain Model
FCD	Flood Control District
ft	feet
FOS	factor of safety
GIS	Geographic Information System
KC	King County
LiDAR	light detecting and ranging
km	kilometer/kilometers
m	meter/meters
Mt	Mount
NAD	North American Datum
NAVD	North American Vertical Datum
OR DOGAMI	Oregon Department of Geology and Mineral Industries
RFMS	River and Floodplain Management Section
RM	River Mile
Shannon & Wilson	Shannon & Wilson, Inc.
SI Units	International System of Units
USFS	United States Forest Service
USGS	United States Geological Survey
WA	Washington State
WLR Division	Water and Land Resource Division

EXECUTIVE SUMMARY

Areas subject to some type and magnitude of potential landslide hazard are widely distributed in King County, and since the early 1990s maps have been used in King County as a screening tool during land use development, permitting identification of areas of potential landslide hazard. However, the need to better understand the character and extent of the landslide threat in our communities was acutely highlighted after the SR 530 landslide event that occurred in 2014 near Oso, Washington. In continuing an effort to improve publicly available potential hazard information, an assessment of existing landslide data was initiated in 2014 by King County, and an approach to update available information about landslide hazards was developed.

The map prepared in the 1990s showed areas of undifferentiated landslide hazard in King County and was compiled by geologists using the resources then available. However, more recently developed data from technologies, such as light detection and ranging (LiDAR) imagery, improved methodologies for modeling types of landslide hazards, and new geologic maps are available and can be used to update landslide mapping. Given the age and quality of the County's existing landslide map and the demonstrated public safety risks associated with landslides, King County determined that its landslide maps should be updated and proposed a new landslide mapping effort using the newer data and updated geologic maps to more accurately locate and describe potential landslide hazards in King County.

This mapping project was conducted along major fluvial valleys in the county including the Cedar, Green, Sammamish, South Fork Skykomish, Snoqualmie, and White Rivers and Issaquah Creek utilizing funding from the King County Flood Control District. Although the study limits are predominately within unincorporated King County, the project also includes portions of 22 cities located within the major river corridor valleys. This approach to update landslide information began in 2014, and the map was completed in 2015.

This report includes a description of the methodologies used to map the following landslide types:

- Deep-seated landslides,
- Shallow debris slides,
- Depositional fans (Puget Lowland fans and alpine fans either more or less likely subject to debris flows),
- Rock fall, and
- Rock avalanches.

Evidence of long runout events were identified at multiple locations within the study limits. However, based on consultation with the Technical Review Committee and with local researchers with expertise in this field, it was determined that there is no feasible method for delineating runout areas on a landscape scale. Even at a site-specific scale and with significant information on local conditions, such predictions are problematic. Nonetheless, characteristics that might predispose a large landslide to have a long runout event were determined to include:

- Presence of an existing, ancient, deep-seated landslide,
- Recent or ongoing movement of or within the landslide,
- High groundwater table or emergent seepage in or around the landslide,

- Active erosion at the toe of the landslide,
- Presence of a water body immediately downslope from the landslide that could contribute additional water to debris in motion,
- Proximity to debris fields from adjacent failures that indicate past long runout events, and
- Larger failures on steeper, higher slopes.

King County retained Shannon & Wilson, Inc., (Shannon & Wilson) to map deep-seated landslides within the study limits. The report prepared by Shannon & Wilson included the mapping of 930 deep-seated landslides. Department of Natural Resources and Parks (DNRP) geologists conducted the mapping of other landslide types. A landscape scale slope stability model was used to generally identify slopes potentially subject to shallow debris slides, and LiDAR and topographic data were used to map depositional fans. A geographic information system (GIS)-based topographic analysis was used to map areas where rock fall could propagate downslope from a source. Finally, three rock avalanche deposits were identified within the study limits: two are located in the South Fork Skykomish River valley (Beckler Peak and Index Creek) and one is located in the Snoqualmie River valley, near Moon Valley Road NE (Mt. Si area).

Geotechnical reports, landslides studies and maps, permit applications, and field reports were obtained from city, county, state, and federal agencies, public utilities, and the University of Washington. Landslide data from the 314 documents referencing landslides within the study limits were cataloged in a spreadsheet inventory. A wide variety of data was extracted from the data sources, including landslide location, observations of water bodies, slide features, geomorphology, analyses completed, and any noted damage resulting from the landslide. The final product from this element of the project is a geodatabase with information on the location and attributes of areas of potential landslide hazard.

The final landslide GIS datasets, which together constitute the landslide map, include the following:

- Deep-seated landslides GIS datasets mapped by Shannon & Wilson. The supplied shapefiles include:
  - Entire landslide (polygon)
  - Top of headscarp (polyline)
  - Headscarp and flank scarps (polygon)
  - Landslide deposit/body (polygon)
  - Internal scarps, if present (polyline)
  - Toe along riverbank, if present (polyline)
  - Closed depressions, if present (polygon)
  - Ponded water, if present (polygon)
  - Watercourses, if present (polyline)
- Shallow debris slides GIS dataset is a vector shapefile showing areas subject to moderate and severe shallow debris landsliding potential hazards.
- Depositional fans GIS datasets are polygon shapefiles showing:
  - Lowland fans
  - Fans in alpine areas less likely subject to debris flows
  - Fans in alpine areas more likely subject to debris flows
- Rock fall potential GIS dataset is a polygon shapefile showing the CONEFALL output
- Rock avalanche GIS dataset is a polygon shapefile showing rock avalanche deposits.

A webtool has been prepared to provide easy access to river corridor landslide mapping and its supporting inventory of data. The webtool is located on this webpage:

http://www.kingcounty.gov/rivers-landslides. Mapped potential landslide hazards are also shown in the King County "iMap" interactive mapping webpage (http://www.kingcounty.gov/services/gis/Maps/imap.aspx). The webtool is intended to be used as an information source on the mapped locations and types of potential landslide hazards identified by this mapping project.

The map produced during this project identifies areas within the study limits that have been categorized as potential landslide hazard areas. The map does not purport to identify actual landslide hazards or existing landslide risks for specific properties, nor does it purport to show all areas of instability or potential instability within the study limits. Finally, the map does not include influences from climate change and seismic events.

1.0 INTRODUCTION AND BACKGROUND

Areas subject to some type and magnitude of potential landslide hazard are widely distributed in King County. The character of the hazard is strongly dependent on the style of potential landslide movement, and there is evidence and historical records of many different styles of landsliding in the county. Information about the extent and character of potential landslide hazards is important for informing capital planning, land-use review and emergency response planning. Landslide hazard information was first prepared by King County in the early 1990s. Under the Washington State Growth Management Act and the King County Comprehensive Plan, King County is required to protect the natural environment and public health and safety through the protection of environmentally critical areas which includes landslide hazard areas.

1.1 Previous Landslide Mapping

The original 1990s mapping of potential landslide areas was compiled by King County geologists using the resources then available, including stereo aerial photography, 1:24,000 United States Geological Survey (USGS) topographic mapping, and scattered geologic mapping. The 1990s map has been a valuable tool for screening land use applications for potential landslide hazards and for other county programs.

1.2 Project Background

Recent events in the Pacific Northwest region demonstrated the need to prepare updated landslide information. A major landslide, known as the "SR 530 landslide," occurred on March 22, 2014, on the North Fork Stillaguamish River near Oso, Washington, in Snohomish County. This tragedy, which resulted in 43 deaths, raised awareness across the Pacific Northwest, including King County, regarding the potential hazard posed by landslide events in this region. King County recognizes the importance of having updated information so as to improve the understanding about landslide hazards and to address risks to public health and safety. This report describes the technical methods used to develop updated landslide hazard mapping along the unincorporated and incorporated areas of the river corridors of King County.

New information and technologies provide an opportunity to improve landslide hazard mapping. These new tools dramatically improve the ability to recognize and characterize areas of landsliding. Chief among the new technologies is light detection and ranging (LiDAR) imaging. LiDAR entails using a laser rangefinder, mounted on an airplane, to scan the terrain below. The data collected can be used to create a high resolution digital terrain model (DTM) of the ground surface. This technique can create a detailed topographic representation of the ground surface even through relatively thick vegetation. The DTM can be used to create several products useful in landslide evaluation including detailed hillshade images of the ground surface, detailed contour maps, and high resolution mapping of hillslope inclination. In addition to the availability of LiDAR, many new geologic maps have been published by state and federal agencies in recent years that provide information on the location and geologic setting of landslides. The widespread use of geographic information system (GIS) software allows for easy access to a wide range of existing map and image data, creation and storage of new maps, and easy updating of maps and related information. The combination of these tools and resources allows for more accurate and detailed landslide identification and simplifies the process of updating maps as new information becomes available.

In the initial effort during 2014 to update information, a preliminary map of landslide areas was created based on visual inspection of LiDAR-generated shaded hillshade imagery and recent geologic mapping. This map provided information on some potential hazards but did not differentiate between different landslide processes. This preliminary map and its accompanying technical memorandum was an interim product completed in December 2014 and is now superseded by the mapping included in this report.

The mapping included in this report identifies the different landslide processes active in different parts of the county and considers a wide range of landslide processes including deep-seated landslides, shallow debris landslide susceptibility, depositional fans, potential rock fall locations, and rock avalanche deposits. Mapping methodologies were selected after researching current literature and review by the Technical Review Committee (see Acknowledgements). The updated mapping is appended to this report and available online at http://www.kingcounty.gov/rivers-landslides. This report describes all the background data and methods used to develop and prepare the Department of Natural Resources and Parks (DNRP) mapping of potential landslide hazard areas.

To support improvements in the review of land use proposals, the King County Department of Permitting and Environmental Review (DPER) prepared a landslide hazard mapping screening tool in a coordinated but separate mapping effort. The DPER mapping can be viewed at http://www.kingcounty.gov/depts/permitting-environmental-review/gis/LandslideMapping.aspx and this information is also on the King County iMap Interactive Mapping Tool at http://www.kingcounty.gov/services/gis/Maps/imap.aspx.

1.3 Study Limits

This project was funded by the King County Flood Control District (FCD) and is limited to identifying potential landslide hazards along the major river valleys (South Fork Skykomish, Snoqualmie, Cedar, Sammamish, Green, and White rivers) and the valley of Issaquah Creek. Mapping includes both incorporated and unincorporated areas within these river corridors (Figure 1). The Water and Land Resources Division (WLR Division) of DNRP serves as the service provider to the King County FCD and utilizes flood-related hazard information to develop river corridor capital planning and projects within unincorporated and incorporated areas of King County. While potential hazard mapping produced within the river corridor study limit is predominately within unincorporated King County, it also includes portions of 22 cities. The White River forms the boundary between King and Pierce counties. The Pierce County side of the White River was reviewed for the mapping where large landslides had the potential to affect King County land areas. The King County DPER completed a separate but coordinated mapping effort to identify areas needing geotechnical review during permitting activities. That study included all of those areas in unincorporated King County where development activities were likely.

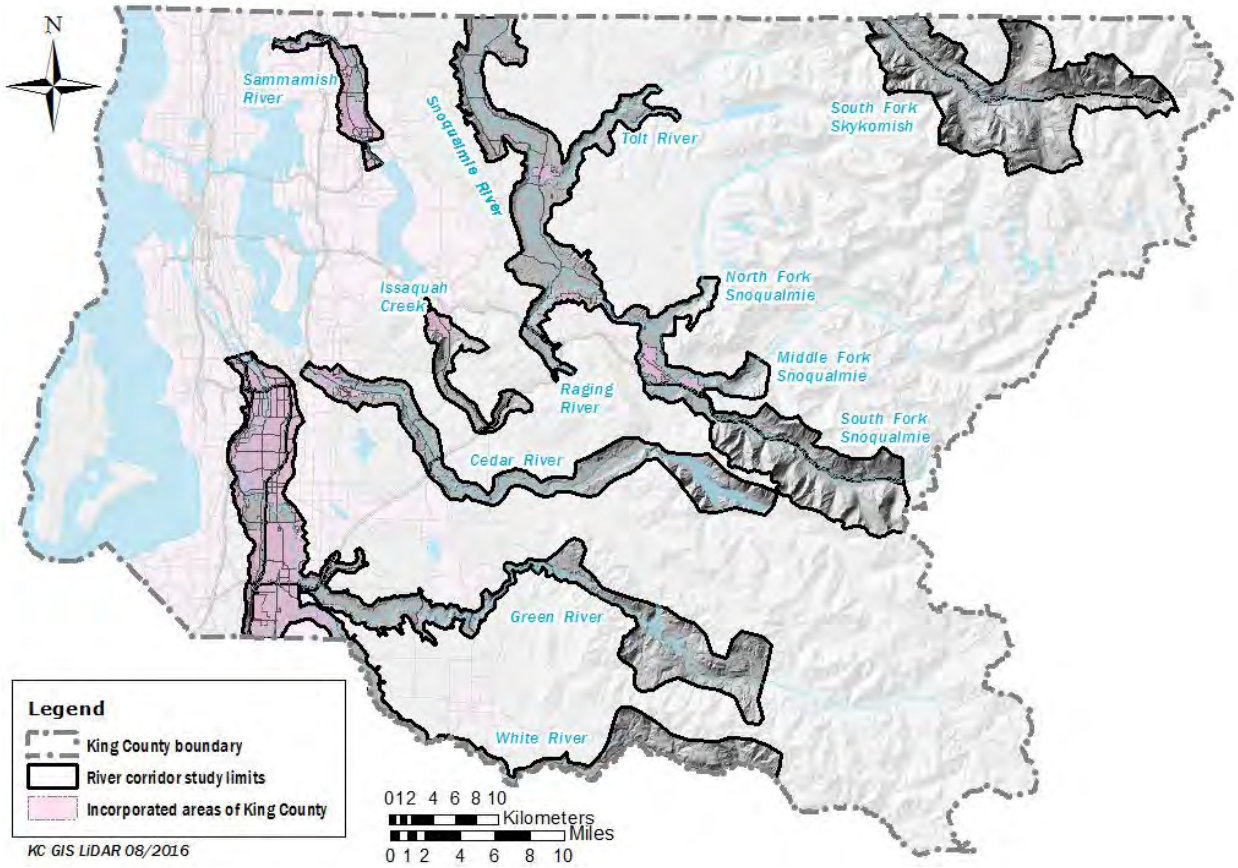

Figure 1. River corridor study limits.

1.4 Expert Review and Consultation

The majority of the landslide mapping was carried out by DNRP geologists. A Technical Review Committee (See Acknowledgements) was established and consulted on development of all mapping methodologies. Additional subject matter experts including faculty from regional universities, and staff from USGS and the Washington State Department of Natural Resources Division of Geology and Earth Resources (WA DNR DGER) were consulted on specific questions. A local geotechnical and environmental consulting firm, Shannon & Wilson, Inc. (Shannon & Wilson), was retained to participate in specific elements of landslide mapping.

1.5 Conventions Used in this Report

The primary units of measurement in this report are United States customary units; however, International System of Units (SI units) are also reported for convenience.

The terminology for naming the various landslide types described in this report will follow the Varnes classification (Varnes 1978; Cruden and Varnes 1996) as modified by Hungr et al. (2014). Italicized landslide descriptions throughout the text are simplified from Hungr et al. (2014).

Locations along rivers are generally identified using river miles (RM). Where rivers miles are used in this report, they refer to the system used by the King County DNRP WLR Division. Note that river

miles used in other reports may have different starting points or may be based on a centerline developed from other map sources and therefore may not be coincident with river miles used in this report.

Where the discussion refers to landslides on one side of the river (or river valley), the landslides are referred to as being either on the "right" or "left." In this report, this refers to the right or left hand of an observer looking downstream along the channel or valley.

Horizontal and vertical datum used in this report are the North American Datum (NAD) 1983 and the North American Vertical Datum (NAVD) 1988, respectively.

2.0 GEOLOGIC SETTING

King County includes portions of two physiographic provinces: the Cascade Mountains in the eastern third of the county and the Puget Lowland in the western two-thirds. For the purposes of this study, the general extent of these provinces is shown in Figure 2. These provinces have distinct topography, geology, and climate. As a result, they are subject to distinctly different types of landslide processes.

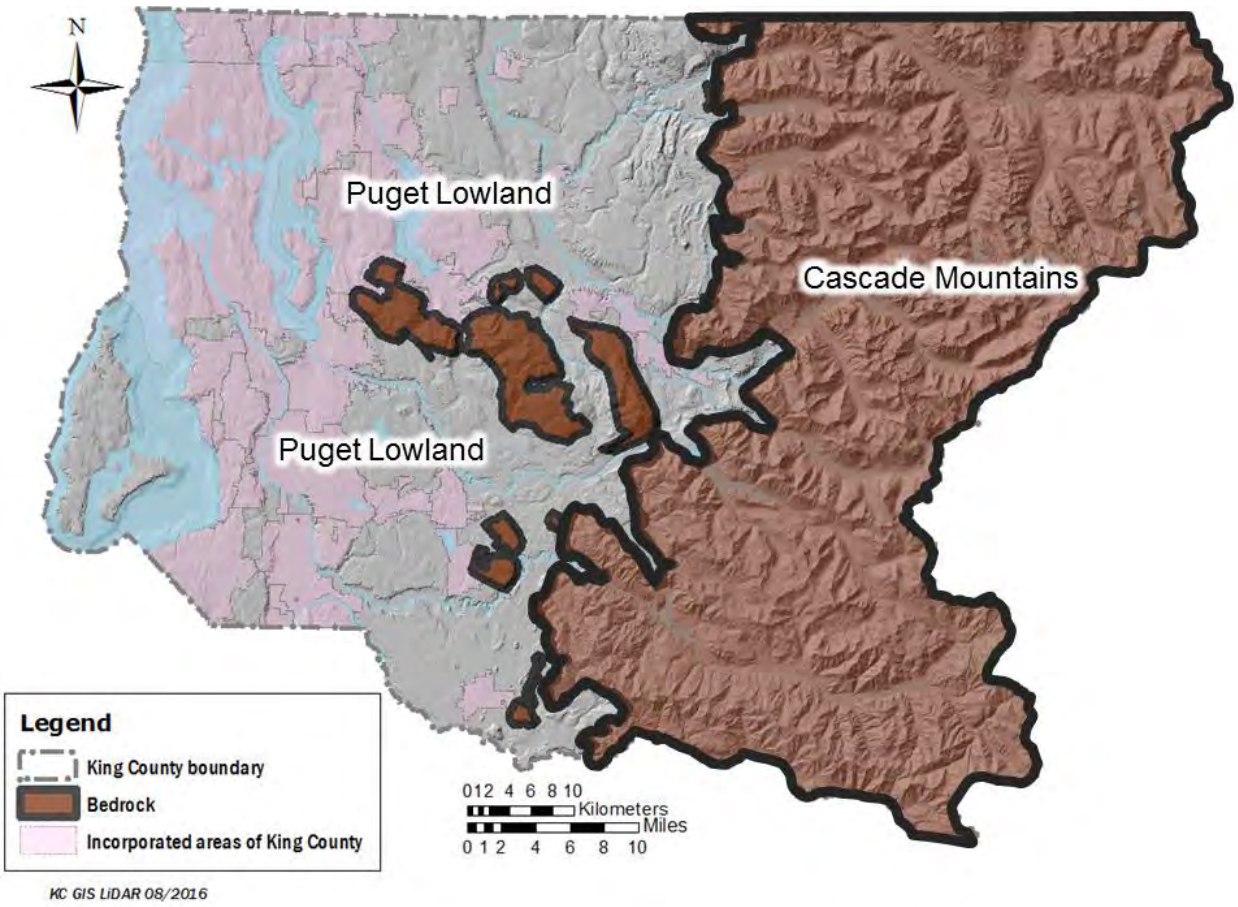

Figure 2. Physiographic provinces in King County.

Both the topography and geologic substrate in the Puget Lowland are products of repeated continental glaciations that have occurred over the last two million years. The last continental glacial advance, which reached a maximum approximately 17,000 calendar-years before present, deposited most of the surficial sediments present today and sculpted the landscape across the Puget Lowland. Following ice retreat, the glacially sculpted surface began to be eroded by non-glacial processes. This erosion did not occur uniformly across the landscape but was localized along coastal bluffs and river valley walls. Where fluvial or coastal erosion has created steep, high slopes in glacial sediments, these slopes are often subject to landsliding which has likely been the major agent of erosion along these valley walls and bluffs (Schulz 2005).

In the Cascade Mountains physiographic province of eastern King County, topography is steeper and higher than the Puget Lowland, precipitation is generally greater, and most slopes are

underlain by bedrock rather than glacial sediments. Although these areas are less populated than the Puget Lowland, there are communities present in the mountains, as well as critical transportation and utility corridors. Like the Puget Lowland, the Cascade Mountains province is also adjusting to the effects of recent glaciations. These glaciers originated locally, in the mountains, rather than flowing from the north as did the continental glaciers that affected the Puget Lowland. The combination of active tectonic uplift and glacial sculpting has created precipitous mountain topography that is subject to a variety of landslide processes.

3.0 LANDSLIDE ACTIVITY IN KING COUNTY

3.1 Types of Landslides in King County

The term "landslide" covers a range of geomorphic processes in which masses of soil, rock, or debris (a mixture of soil and rock) become detached and move downslope. This movement can happen quickly or slowly; displaced material can remain solid or move as a liquid. Landslides can range in size from a few cubic yards to millions of cubic yards. The detailed character of movement is referred to herein as the landslide style. The style of landsliding depends on the local geology, topography, and hydrology in the vicinity of the failure.

Table 1 is based on Hungr et al. (2014) but was modified to include only those landslide styles identified within King County.

Table 1: Landslide styles identified in King County and addressed in this report (Modified from Hungr et al. 2014).

Type of Movement	Style of Movement	
	Soil or debris	Rock
Fall		Rock fall
Slide	Rotational slide	Rock compound slide
	Shallow debris slide	
Spread	Liquefaction spread	
Flow	Debris flowslide	Rock avalanche
	Debris flow	
	Debris flood	
	Debris avalanche	

This report identifies five types of potential landslide hazards in King County. As noted below, some of these general hazard types include several distinct styles of landslide movement. The following is a list of these landslide hazards:

- Deep-seated landslides (including rotational slides, liquefaction spreads, debris flowslides, debris avalanches, and rock compound slides),
- Shallow debris slides,
- Depositional fans (including those produced by debris flows and debris floods),
- Rock fall, and
- Rock avalanches.

3.1.1 Deep-Seated Landslides

Where fluvial or coastal erosion has created steep, high slopes in glacial sediments, these slopes sometimes fail in large, deep-seated landslides. Bedrock slopes, weakened by weathering, fractured by tectonic movement or steepened by erosion can also fail through deep-seated landsliding. The

segregation of landslides into deep and shallow is somewhat arbitrary and different investigators have used different criteria to differentiate these landslides. For this project, the differentiation follows the criteria proposed by Burns and Madin (2009) that deep-seated landslides extend to a depth of more than 15 ft (4.6 m). In general, this corresponds to individual landslides which are large enough to be distinct on hillshade images generated from LiDAR data. For this report, deep-seated landslides may include features where the failure plane is more than 15 ft deep or where landslide debris accumulates to a depth of more than 15 ft. Virtually all deep-seated landslides in King County failed initially prior to European settlement although they may be subject to continuing movement in the present day. In King County, a variety of styles of landslide movement occur at a scale that may create deep-seated landslides. These styles of deep-seated landslides include rock compound slides, liquefaction spreads, rotational slides, debris flowslides, and debris avalanches. These specific types are defined below in italics based on Hungr et al. (2014).

3.1.1.1 Rock Compound Slide

Sliding of a mass of rock on a rupture surface of uneven curvature, so that motion is accompanied by significant internal distortion of the moving mass (Figure 3).

A number of occurrences of this style of landslide were identified during this project, mostly in relatively weak Tertiary bedrock in the foothills of the Cascade Mountains. Several of these landslides are quite large, like the one shown in Figure 3 with a total length of more than a mile (1.6 km). None of these landslides is known to be active although most are located in areas with little development where small movements might go unnoticed.

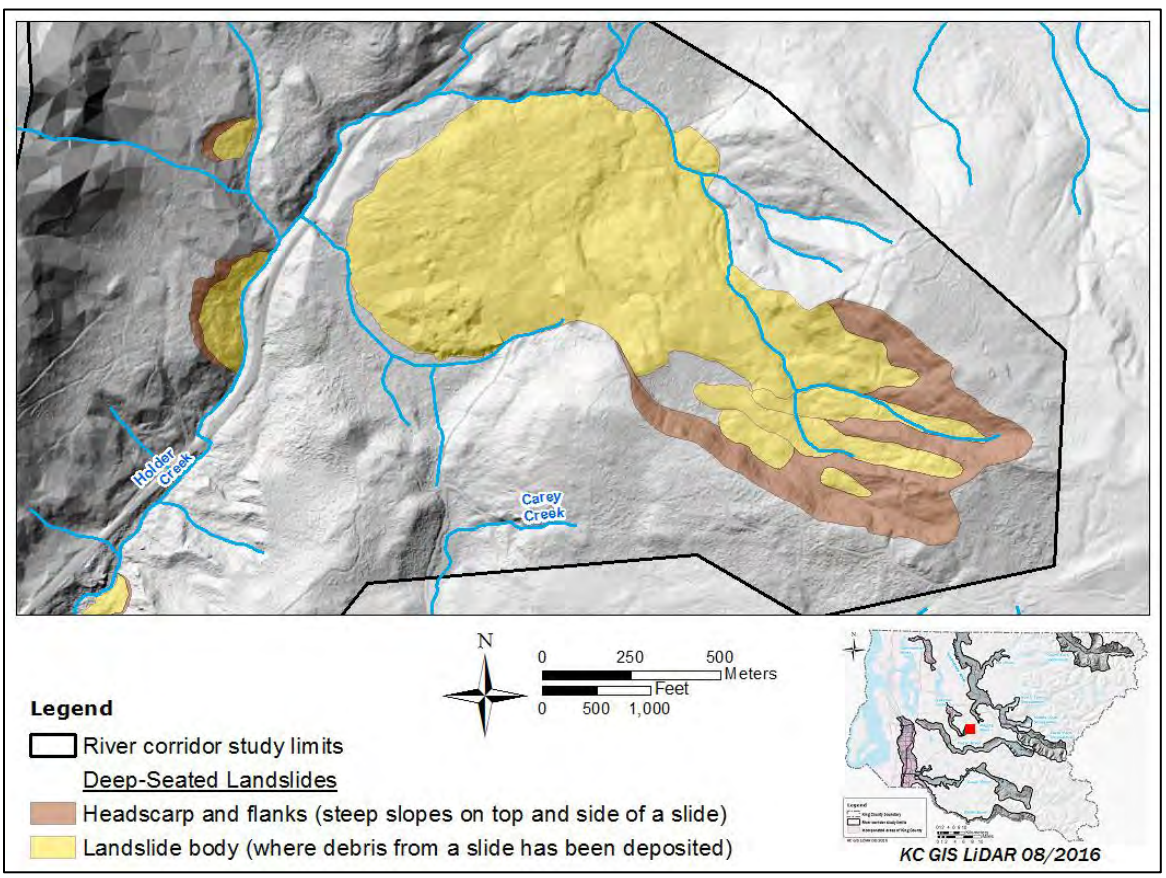

Figure 3. Rock compound slide, south of SR-18 near Tiger Mountain summit.

3.1.1.2 Liquefaction Spread

Rapid lateral spreading of a series of soil blocks, floating on a layer of saturated (loose) granular soil, liquefied by earthquake (Figure 4).

Only one landslide of this style is known to be present within the study limits. It is located on the Tolt River and identified by Dragovich et al. (2009) as part of the Tolt River Landslide Complex (Figure 4). Numerous small liquefaction spreads in other locations in other areas of King County were documented from the 1949, 1965, and 2001 earthquakes (Chleborad and Schuster 1998; Highland 2003) but were too small to be mapped for this project.

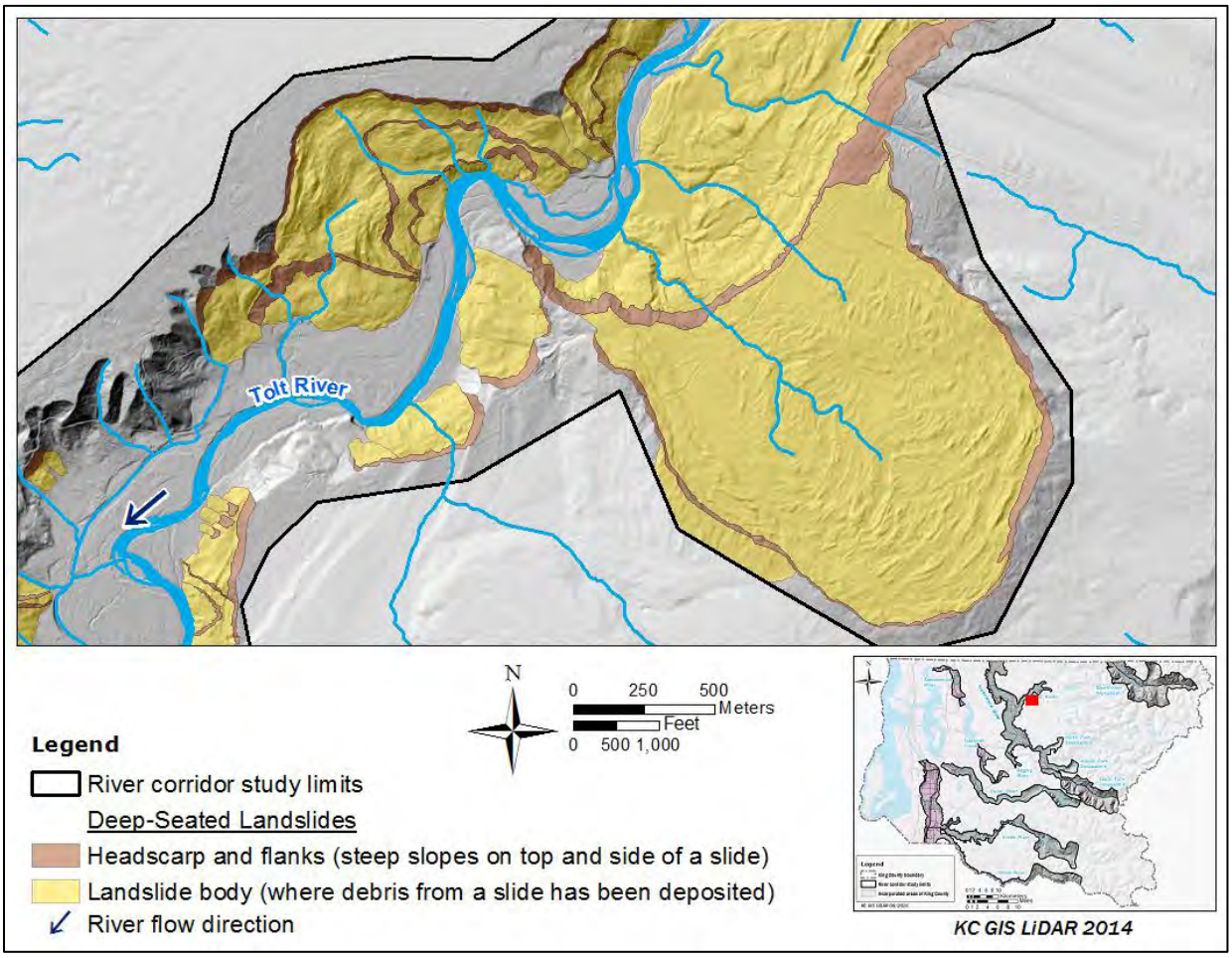

Figure 4. Liquefaction spread, RM 6.1 to 6.5, on the left valley wall of the Tolt River.

3.1.1.3 Rotational Slide

Sliding of a mass of soil on a rotational rupture surface. Little internal deformation. Prominent main scarp and back-tilted landslide head (Figure 5).

Rotational slides are also commonly called slumps. In rotational slides, the soil fails on a curved failure plane so that the debris rotates as it moves downslope. In this type of landslide, the soil fails through brittle or plastic deformation without becoming fluidized.

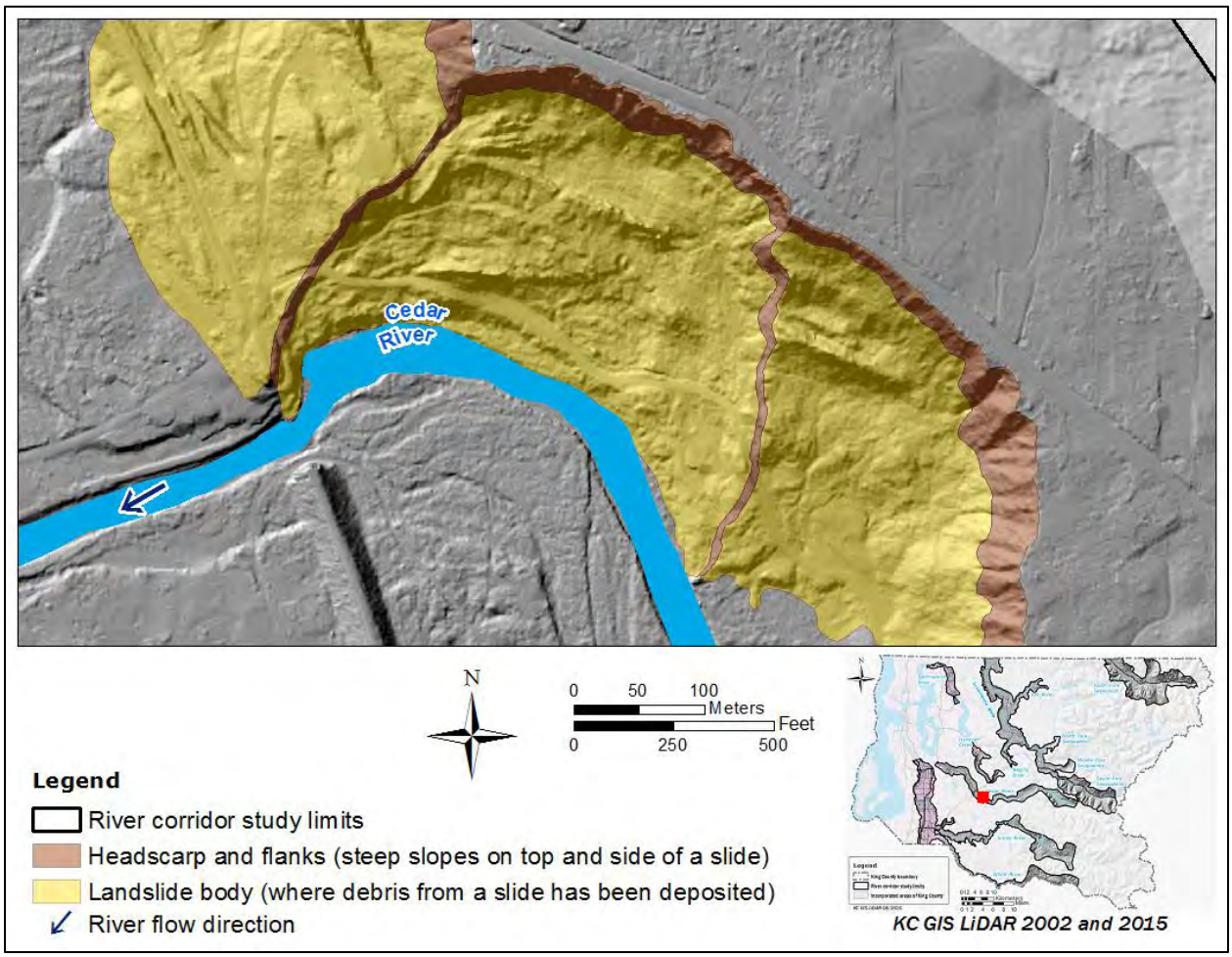

Figure 5. Rotational slide, RM 17.6 to 18.0, on the right valley wall of the Cedar River.

3.1.1.4 Debris Flowslide

Rapid flow of sorted or unsorted saturated granular material on moderate slopes, involving excess pore-pressure or liquefaction of material originating from the landslide source (Figure 6).

In a debris flowslide the debris that is displaced moves primarily in a fluid state. Figure 6 shows a series of flowslides located in the Cedar River Watershed. The ages of these landslides are unknown, but they are geologically very young as they overlap (and therefore post-date) the entire suite of river terraces present here. The exact trigger for this assemblage of large, closely spaced landslides is unclear. There are similar but smaller and less distinct features along the Snoqualmie River below Snoqualmie Falls, on the Raging River, and in the Middle Green River valley.

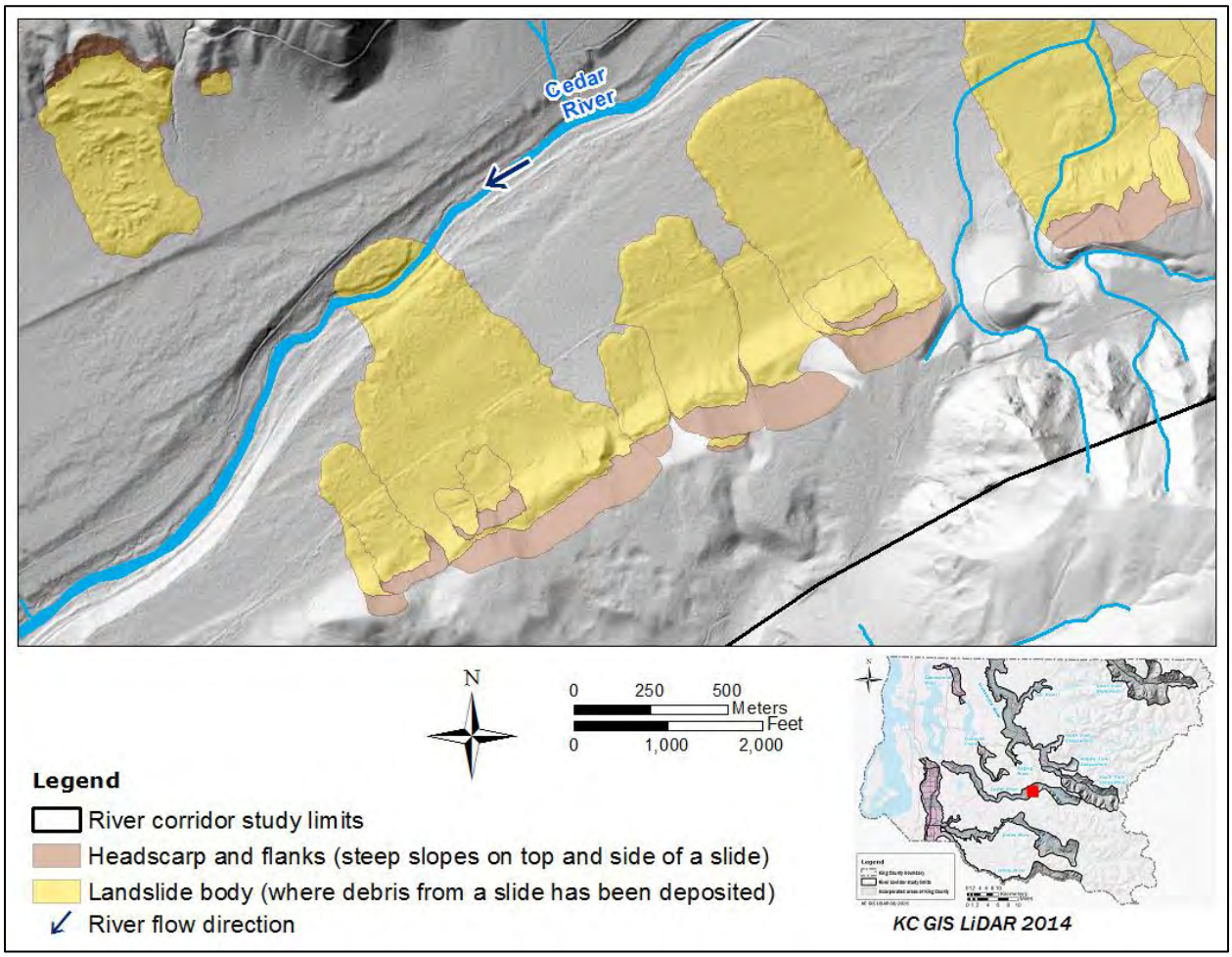

Figure 6. Debris flowslides, RM 31.2 to 32.4, on the left valley wall of the Cedar River.

3.1.1.5 Debris Avalanche

Rapid flow of partially or fully saturated debris on a steep slope, without confinement in an established channel. Occurs at all scales (Figure 7).

In a debris avalanche, the displaced debris moves as a flow but is less fluid than a debris flowslide. The 2001 Nisqually Earthquake-Cedar River landslide is an example of a recent debris avalanche in King County.

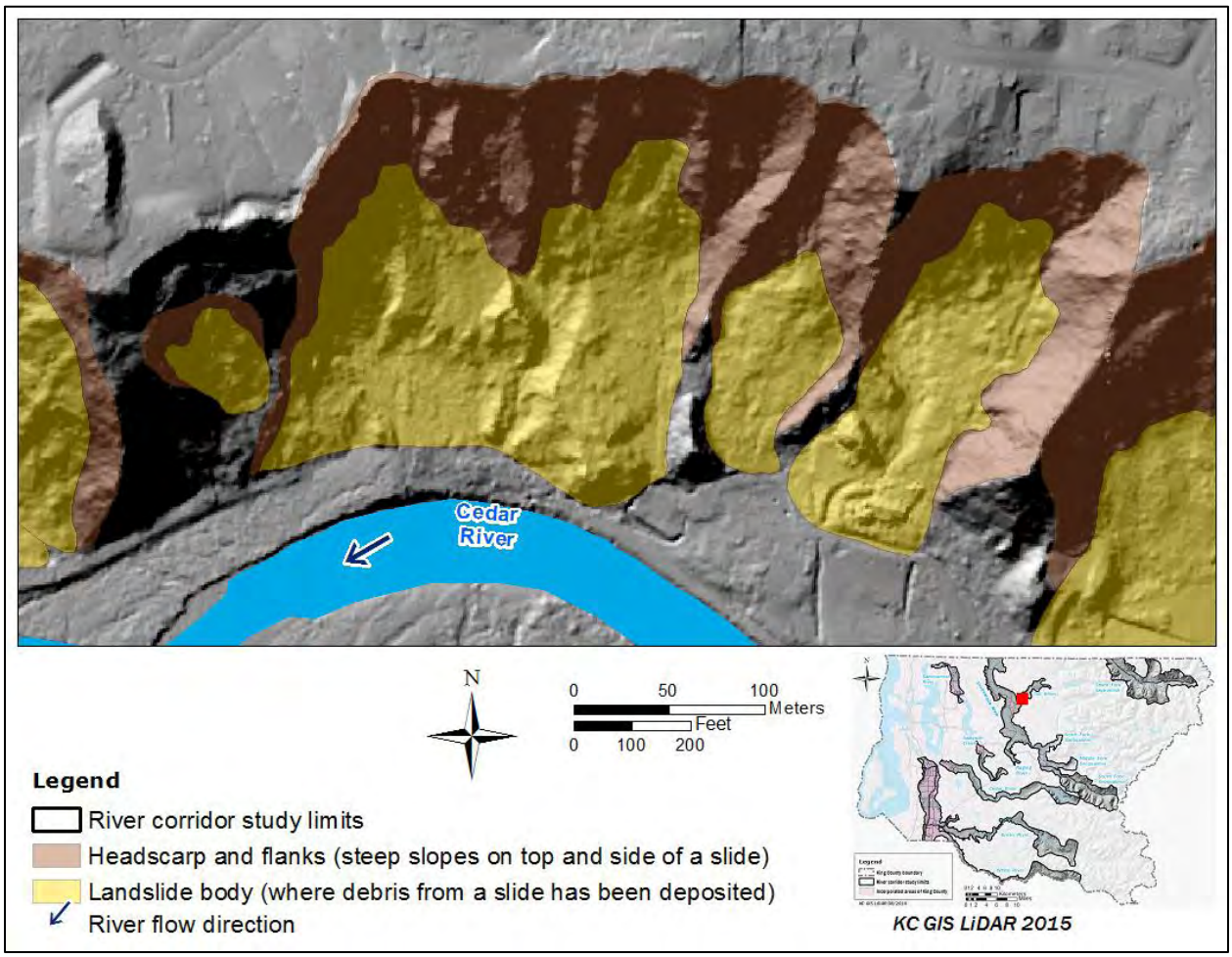

Figure 7. Debris avalanche, RM 5.0 to 5.3, on the right valley wall of the Cedar River. This is the site of the 2001 Nisqually Earthquake-Cedar River landslide.

Although described as discrete features, these various landslides represent endmembers with many actual failures exhibiting characteristics intermediate between two or more of these styles of deep-seated slides. Virtually all of the deep-seated landslides identified during this mapping project failed initially in prehistoric times. Although these are old features, the failed landslide debris in deep-seated landslides can be remobilized in response to unusually high precipitation, earthquakes, or as a result of human grading or drainage modifications.

As described above, there are a number of different styles of landslide movement that are grouped together as deep-seated landslides hazards. In addition, each identified deep-seated landslide on the landscape is typically a large and complex feature with different types of movement occurring in different areas of the slide. As a result, earth movement on or near deep-seated landslides can

manifest in various ways:

- Often the head scarps of deep-seated landslides are steep, unstable, and subject to secondary landslides, which expand the footprint of the original landslide upslope.
- The displaced landslide debris in the body of a deep-seated landslide may continue to move over time. If this movement does occur, it is often slow but over time can result in significant differential displacement.
- In some circumstances, when deep-seated landslides fail initially or are reactivated, landslide debris can travel long distances beyond the toe of slope and impact areas not obviously at risk (for example, the 2001 Nisqually Earthquake-Cedar River landslide).
- Movement of large landslides contiguous to rivers or major tributaries may form debris dams that can produce significant flood hazards, both up and downstream. When landslide debris blocks the active river channel, the resulting backwater can cause inundation of land upstream from the blockage. After the debris dam is breached, the release of impounded water can produce deep, fast flowing debris-laden water downstream.
- In many cases, the deep-seated landslides identified in this project have no known history of movement, and many such landslides have single-family residences, apartments, commercial structures and lifeline utilities constructed on them that show no evident adverse effects.

Because of their variability, it is not possible to generalize about the likelihood of future movement of deep-seated landslides, or the magnitude, timing, or speed of such movement should it occur. These landslides typically require thorough, site-specific technical investigations in order to address these issues.

3.1.2 Shallow Debris Slides

Shallow debris slides (also known as shallow landslides, infinite slope failures, and colluvial slides) are a common style of slope movement both in the Puget Lowland and Cascade Mountains. This style of landslide is defined below in italics based on Hungr et al. (2014).

> *Sliding of a mass of granular material on a shallow, planar surface parallel with the ground. Usually, the sliding mass is a veneer of colluvium or weathered soil sliding over a stronger substrate* (Figure 8).

Debris slides are characterized by failure of a relatively shallow layer of soil typically sliding on a surface of more competent material, either bedrock or dense glacial sediments. Debris slides are typically 3 to 6 ft (1 to 2 m) and translational (entailing linear movement of the failed soil without rotation). Shallow colluvial soils on slopes are formed through a variety of processes, including breaking up of the underlying in-place substrate (either bedrock or Quaternary sediments) by freeze/thaw, wetting/drying, bioturbation, and chemical weathering. Soils on steep slopes in King County vary significantly with respect to soil thickness, soil strength, and hydraulic properties; this variability presents the central challenge in assessing their stability across a landscape.

Figure 8. Shallow debris slide, Peasley Way S. Winter 2015. Photo courtesy King County (KC) Department of Transportation (DOT).

Shallow debris slides entail saturation and sliding of a thin layer of soil over the underlying dense glacial sediments or bedrock (Figure 8). These types of failures are typically too small and shallow to be discernable even with high resolution LiDAR imagery. They are widespread across the landscape and are common occurrences during periods of high rainfall in both mountain and lowland settings. Debris slides are often triggered by intense rainfall or, in developed areas, discharge of stormwater onto a steep slope. The potential for shallow debris slides is often increased by other human activities including vegetation removal (including logging) and inappropriate fill placement.

Although comparatively small in scale, shallow debris slides can occur on almost any steep slopes anywhere on the landscape. Because this type of landslide is shallow in depth and small in lateral extent, the debris often does not travel a long distance (unless it transitions into a debris flow as described in Section 3.1.3.1 Debris Flows). The debris in shallow debris slides is typically saturated, can move quickly, and often carries logs or entire trees. Impact and inundation by such debris can be highly destructive in the area of deposition.

3.1.3 Depositional Fans

Depositional fans are formed when sediment moving down a steep channel is deposited where the channel gradient abruptly decreases; for example, where a steep valley-wall tributary reaches the valley floor. Sediment can be carried down such a steep channel in flow-type landslides (debris flows, debris floods) or sediment can be carried in the water column by streamflow. Fans are subject to a range of hazards depending on which of the preceding processes are active.

Debris flows and debris floods are two styles of landslide movement that can contribute to the growth of depositional fans. Both of these entail landslide debris moving in a fluid state down a channel, often travelling a long distance from the point of origin (Table 1; Hungr et al. 2014). These failures occur in steep swales in both the Cascade Mountains and Puget Lowland. Debris flows and debris floods are defined below (italics based on Hungr et al. 2014).

3.1.3.1 Debris Flows

Surging flow of saturated debris in a steep channel. Strong entrainment of material and water occurs from the flow path (Figure 9).

Debris flows often begin as debris slides on steep slopes. If the debris has sufficiently high moisture content, it may liquefy as it is deformed and move downslope as flow. If it reaches a swale, it may continue down the swale as a slurry of water and sediment and accumulate additional water and sediment from the swale as it progresses downward (Figure 9). Frequently, logs and other organic detritus are also incorporated into the flow. As the swale reaches the base of slope there is often an abrupt decrease in the channel slope and sediment that had been entrained in the debris flow is deposited. Over time and with repeated debris flows from a given swale, sediment accumulates in a characteristic fan shape. Debris flows transport a wide range of sediment sizes up to and including large boulders (Figure 10 and Figure 11).

Figure 9. Recent debris flow track, Index Creek, South Fork Skykomish River basin. (Aerial photography, Feb. 12, 2015)

Figure 10. Debris flow deposit, Lowe Creek, South Fork Skykomish River basin. (Photo, Feb. 2016)

Figure 11. Puget Lowland debris flow deposit. This 2005 debris flow resulted from failure of a beaver dam on the upland, east side of the Snoqualmie Valley and deposited sediment on the valley in an area between Carnation and Fall City. Note scour on tree stems and transported boulder.

In the Puget Lowland, debris flows can also be initiated when there is a sudden high flow of water in a steep channel. One common circumstance where this occurs entails sudden breaching of a beaver-dammed impoundment that releases a flow many times larger than that generated by meteorological events (Figure 11 and Figure 12). This type of discharge often causes dramatic erosion and channel incision. Trees and organic detritus from adjacent slopes are often undermined and fall into the flow.

Figure 12. 2012 Debris flood on Deer Creek south of Duvall in the Snoqualmie Valley.

3.1.3.2 Debris Flood

Rapid flow of water, heavily charged with debris, in a steep channel.

Debris floods are differentiated from debris flows by having a higher water content. Debris floods move smaller-sized sediment, carry less organic debris, and pose less of a life/safety risk as compared with debris flows. Debris floods are transitional to conventional fluvial flooding. In Figure 12, a debris flood caused by a beaver dam failure in 2012 is visible flowing downslope through and around a home and flooding over the adjacent street.

3.1.3.3 Mud Flow

Rapid surging flow of saturated plastic soil in a steep channel, involving significantly greater water content relative to the source material. Strong entrainment of material and water from the flow path.

Some landslides that entail debris in a fluid state flowing in a channel may be more accurately categorized as mud flows. Lahars are a specific class of mud flows that result from failures on the flanks of volcanos. Lahars can be massive catastrophic events that can travel many tens of kilometers from their source areas. Lahars from Mt. Rainier have traveled down the White River valley, and lahar deposits from Mt. Rainier have been identified in Elliot Bay sediments. Assessment

of lahar hazards along the White River is the subject of a separate investigation and is not addressed in this report.

3.1.3.4 Fan Geomorphology

As described above, fans can form from a number of different geomorphic processes including debris flows and debris floods. Additionally, fans can form by fluvial deposition. The nature of the processes contributing to fan growth dictate the type of geomorphic activity and the potential geomorphic hazards on the fan surface. Debris flows are very fast moving, often incorporate logs and boulders, and may extend a long distance from the location of the original failure. Debris floods transport finer sediment (typically not boulders and cobbles) but can still carry logs and deposit multiple feet of sediment. Where fans are built entirely by fluvial processes, flooding and channel avulsion are common hazards. Floodwaters flowing over a fan surface can move rapidly and follow unexpected paths. Avulsions can lead to sudden and radical channel relocation, which could then undermine or isolate areas not previously at obvious risk. The channels on many fans are significantly incised below the ground surface, and in many cases, these fans may be relict features and human occupation of the fan surface may be at little risk. However, Kellerhals and Church (1990) caution that in some circumstances, logs and debris can obstruct a significantly incised channel and cause water and sediment to spill out onto the fan surface. Kellerhals and Church (1990), Wilford et al. (2004), and Millard et al. (2006) discuss site-specific assessment of hazards on fans. Regardless of the contributing process, actively growing alluvial fans are inherently dynamic geologic environments that can pose a range of challenges to human occupation.

3.1.4 Rock Fall

Rock fall is a type of landslide that occurs in bedrock where single or multiple rocks are dislodged and fall from steep cliff faces. Rock fall is defined below in italics based on Hungr et al. (2014).

> *Detachment, fall, rolling, and bouncing of rock fragments. May occur singly or in clusters, but there is little dynamic interaction between the most mobile moving fragments* (Figure 13 and Figure 14).

In a typical alpine setting, cliffs are located on the upper slopes of a mountain with a talus below, extending to the base of the mountain (Figure 13). The talus is composed of rocks that have fallen from the cliff face and accumulate at their angle of repose below the cliff. The talus marks the limit of most rock fall from the cliff, but as described by Evans and Hungr (1993), a few boulders that fall from the cliff travel beyond the toe of the talus and it is these outliers that can pose a hazard to adjacent development (Figure 14). Rock fall can be triggered by earthquakes, freeze-thaw cycles, or severe weather. Chleborad and Schuster (1998) describe rock fall on Mt. Si as having occurred during the 1945, 1949, and 1965 earthquakes. Tumbling boulders falling from a cliff face are fast moving and pose a serious threat to anything in their path.

Figure 13. Talus below McClellan Butte.

Figure 14. Isolated boulder next to Moon Valley Rd. NE below the west face of Mt. Si near the North Fork Snoqualmie River.

3.1.5 Rock Avalanches

Rock avalanche is a style of landslide characterized by the simultaneous failure of an entire bedrock hillslope and with the dislodged mass cascading to the valley below. Rock avalanche is defined below in italics based on Hungr et al. (2014).

Extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall.

Although no rock avalanches have occurred in King County in historical times, fields of angular boulders at the base of steep mountainsides are clear evidence of prehistoric failures. The largest of the three prehistoric rock avalanche deposits found within the study limit is the Beckler Peak rock avalanche, identified by Tabor et al. (1993).

Rock avalanches move at extremely high speeds and are potentially massive in size. They can extend farther from the base of slope and cover a much larger area compared with individual rock fall. Rock avalanche deposits in King County pre-date European settlement, but rock avalanches have occurred in recent times elsewhere in the region. For example, the 1965 Hope Slide in British Columbia is a rock avalanche and remains the largest landslide in Canadian history (Mathews and McTaggert 1969).

Deposits from past rock avalanches were identified and mapped as a part of this project, but it is not clear that existing rock avalanche deposits are good predictors of likely future rock avalanches locations.

3.2 Influences on Landsliding

Typically, landslide movement is the result of a convergence of a number of contributing factors. Some or all of these factors may be natural, including an episode of intense rainfall, seasonally wet conditions, coastal or riverine toe erosion, or seismic shaking. Often, however, human actions trigger or contribute to the movement. In a 2000 study prepared for the City of Seattle, Shannon & Wilson found that of the 1,326 landslides they cataloged in the City of Seattle, 84 percent had some human contribution, 13 percent were entirely natural in origin, and the origin of 3 percent was unknown (Laprade et al. 2000).

3.2.1 Human Activities

Human activities have a major role contributing to or triggering landslides. In a survey following a severe storm in January 1990, Miller (1991) identified 57 incidents of damage from landsliding in unincorporated King County. Out of these incidents, 79 percent appeared to have some human contribution. Of the landslides with some human contribution, 2 percent were ascribed to vegetation alterations, 24 percent to drainage issues, 44 percent to grading, and in the remaining 28 percent the character of the contribution was unclear. Johnson (1989) discusses construction of the I-5 freeway through Seattle and describes landsliding initiated by deep excavations conducted as a part of that project.

3.2.2 Seismicity

In recent decades, the character and magnitude of the seismic risk in the Pacific Northwest has become increasingly clear (Koehler et al. 2012). The Puget Lowland could be subject to shaking as a result of an earthquake along the Cascadia Subduction Zone, movement on surface faults like the

Seattle Fault, or on intra-crustal faults like those responsible for the 1949 and 1965 earthquakes. Abundant evidence exists to document the strong correlation between earthquakes and landsliding in this region. Geologic studies relate landslide deposits, many of which were massive, to dated earthquake events in the Olympic and Cascade Mountains, and in Lake Washington and Lake Sammamish (Schuster et al. 1992; Jacoby et al. 1992; Karlin and Abella 1992; Pringle et al. 1998; Logan et al. 1998; and Logan and Walsh 1995). Chleborad and Schuster (1998) researched historical records to identify ground failure, including landslides associated with the 1949 and 1965 earthquakes in the Puget Lowland. They identified 45 landslides in King County related to these events including slides, slumps, and rock falls. Highland (2003) investigated landslide damage from the 2001 Nisqually Earthquake and identified four "significant" earthquake-induced landslides in King County.

Allstadt and Vidale (2012) modelled landsliding that might result as a consequence of a magnitude 7 earthquake occurring on the Seattle Fault. In their scenario, if the earthquake occurred when soil moisture was high, more than 8,000 buildings in the City of Seattle could be at risk from the resulting landslides. Developing such a scenario entails numerous assumptions and simplifications and, as a consequence, the results should not be viewed as a specific prediction. Nonetheless, this study clearly suggests the extent to which landsliding is likely to contribute to overall impacts associated with the next major earthquake in this region. Evidence from geologic and recorded history and projections based on current knowledge all point to the likelihood that widespread landsliding will likely accompany a major earthquake in the Pacific Northwest. Although landsliding clearly warrants independent consideration as a geologic hazard, the likelihood of widespread, seismically induced landsliding should also be included as a critical element in earthquake hazard planning in this region.

3.2.3 Climate Change

Climate change is likely to have several substantial effects on slope stability in unincorporated King County and result in increased landslides, most notably along coastal bluffs and along river corridors. Severe weather (rain and wind), flood events, and fires are all likely to increase in intensity, duration and frequency in the future as a result of climate change. Increased summer temperatures and drought conditions can lead to an increase in wildfires, increasing the occurrences of landslides on steep unstable slopes.

Larger and more frequent storm events, which are projected to occur under climate change conditions, increase the occurrences of landslides resulting from increased soil saturation. More frequent and larger rain events and more intense storms are likely to include significantly increased flooding in Pacific Northwest rivers (Raymond et al. 2014), and an increase in flooding would likely lead to increased channel migration and bank and cliff erosion, which may also increase occurrences of landslides along steep slopes along river valleys. Although not likely a concern in the river corridors of unincorporated King County, sea level rise can accelerate erosion at the base of coastal bluffs especially during high tides and storm surges. Such erosion can further reduce the stability of these often marginally stable landforms.

4.0 METHODOLOGIES FOR MAPPING HAZARDS

Tools for evaluating and identifying potential landslide hazards are continuously evolving. During the course of this project, an effort was made to identify and utilize appropriate methodologies for the various types of landslide hazards identified in the study limits. This section presents the methodologies used to map the following landslide types:

- Deep-seated landslides,
- Shallow debris slides,
- Depositional fans (Puget Lowland fans and alpine fans either more or less likely subject to debris flows),
- Rock fall, and
- Rock avalanches.

Different mapping methodologies were utilized for each of the landslide hazard types listed above. The methods were identified based on literature review and vetted in consultation with the Technical Review Committee.

4.1 Map Resources

The advent of LiDAR and the data and imagery derived from it have revolutionized landslide mapping over the last decade. The topographic data generated from LiDAR shows the ground surface topography at a resolution unattainable with any other mapping technology. Remote detection of subtle yet important topographic features, even where covered by mature forest, is possible by visual inspection of LiDAR-derived hillshade images (Figure 15).

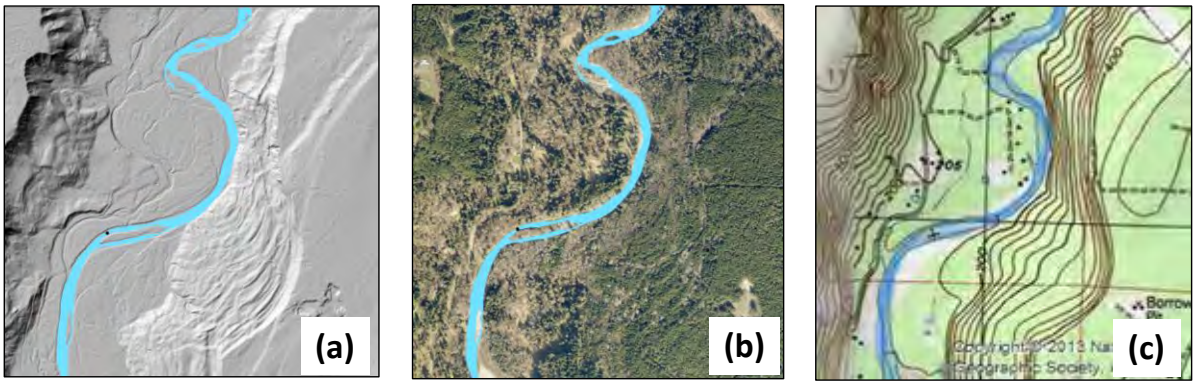

Figure 15. Tolt Valley RM 3.5 to 4.6 topographic detail for comparison using (a) LiDAR, (b) aerial photography, and (c) USGS topographic mapping.

LiDAR data from the King County GIS Center was used for mapping landslides for this report. The shaded-relief was generated from a digital ground elevation model by calculating the intensity of simulated sunlight reflected from calculated ground-slope angles. This particular model, which has a resolution of approximately 6 ft per pixel, was made primarily from a mosaic of LiDAR data that was collected over King County and southwest Snohomish County from 2001 through 2004 by various agencies, including the Puget Sound LiDAR Consortium and King County. Supplements and

revisions made from LiDAR data collected for specific areas since 2001 are included in that mosaic as data is made available. Even newer data is being added in an ongoing effort to ensure that every part of the geographic extent is represented by the best and most current data available for that location.

In addition to LiDAR imagery, geologic maps prepared by the USGS and by the WA DNR DGER were utilized for this DNRP mapping (see Map References in Section 8.0 - References).

4.2 Deep-Seated Landslides

As described in Section 3.1.1, deep-seated landslides are those landslides that extend to a depth of more than 15 ft. Another characteristic all these landslides share is they are typically large enough to identify and map based on their topographic expression in LiDAR imagery. Deep-seated landslides include:

- Rock compound slides,
- Lateral spreads,
- Rotational slides,
- Debris flowslides, and
- Debris avalanches.

King County retained Shannon & Wilson to map deep-seated landslides within the study limits using the procedure in the Oregon State Department of Geology and Mineral Industries (OR DOGAMI) Special Paper 42 (Burns and Madin 2009). The report prepared by Shannon & Wilson to present the mapping of 930 deep-seated landslides is included as Appendix A.

Many of the features of deep-seated landslides share similar topographic characteristics including steep, often arcuate head scarps defining the upslope limit of the slide and a distinct deposit of displaced debris downslope. The debris was often identifiable by its lobate form and hummocky upper surface. These features varied in their topographic distinctness from features that appeared sharp and unambiguous (Figure 16) to features that were muted and subtle (Figure 17). It is likely that some features mapped as landslides based on their topographic character may have formed in other ways and it is also likely that some prehistoric deep-seated landslides present in the study limits were not identified because they were not distinguishable with the available imaging.

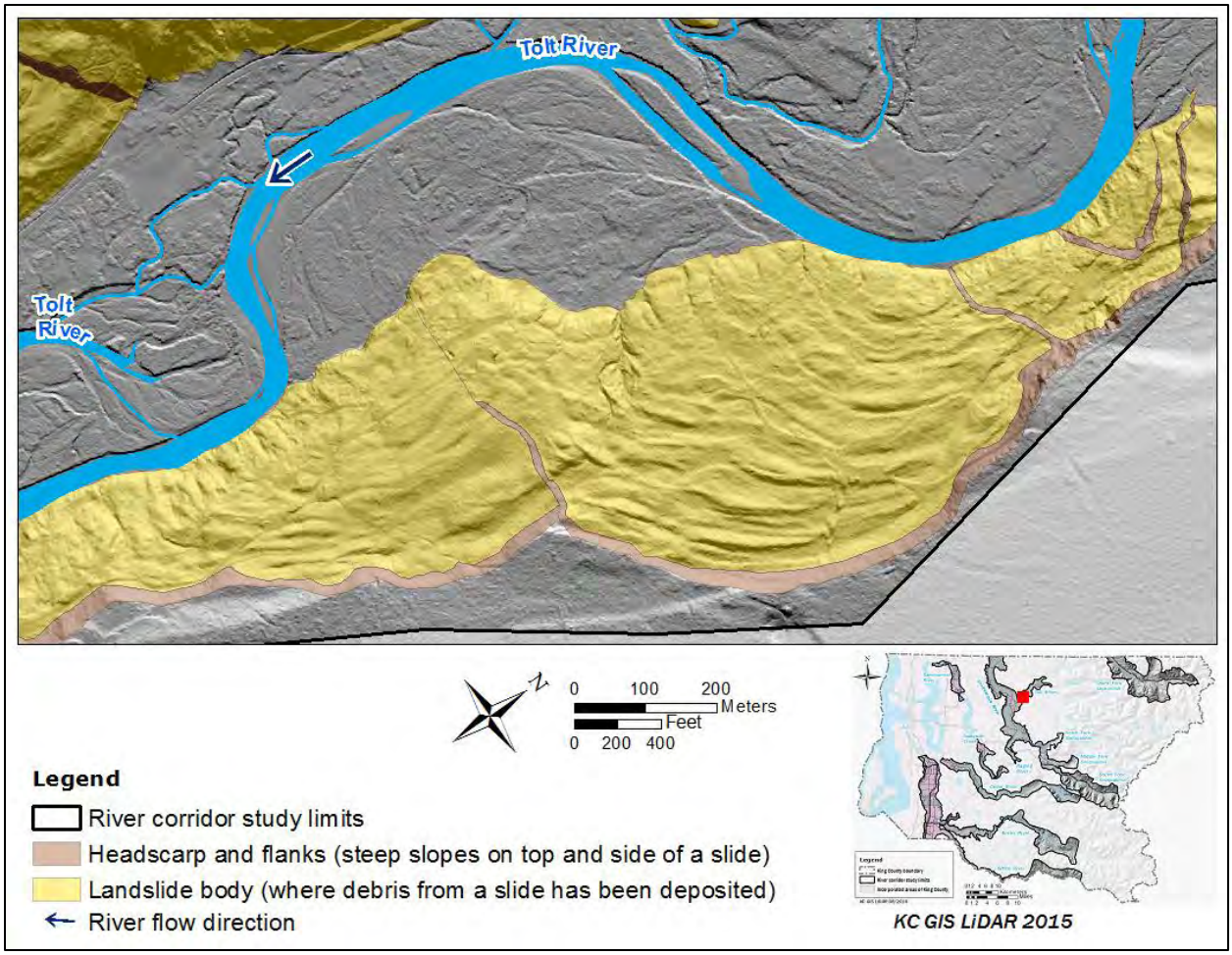

Figure 16. Example of a sharply defined slump, Tolt River valley, between RM 5 to RM 3.

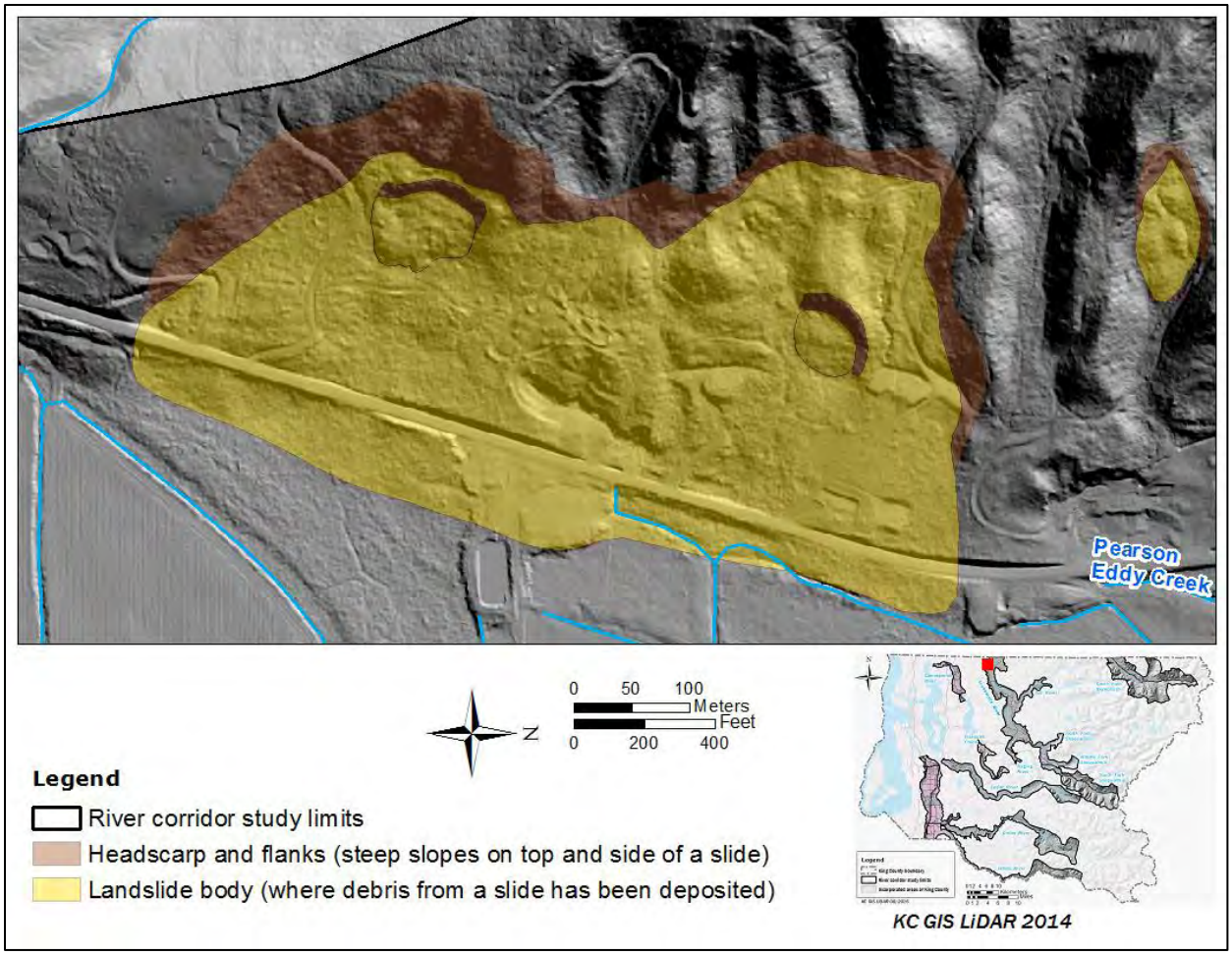

Figure 17. Example of a landslide with subdued topographic expression, Duvall area, Snoqualmie River valley.

Figure 18 shows examples of landslide features identified by Shannon & Wilson following the OR DOGAMI method. Shannon & Wilson (2015) mapped the following separate features of each deep-seated landslide:

- Entire slump, in outline
- Top of headscarp
- Headscarp and flank scarps
- Slump deposit/body
- Internal scarps, if present
- Toe along riverbank, if present
- Closed depressions, if present
- Ponded water, if present
- Watercourses, if present

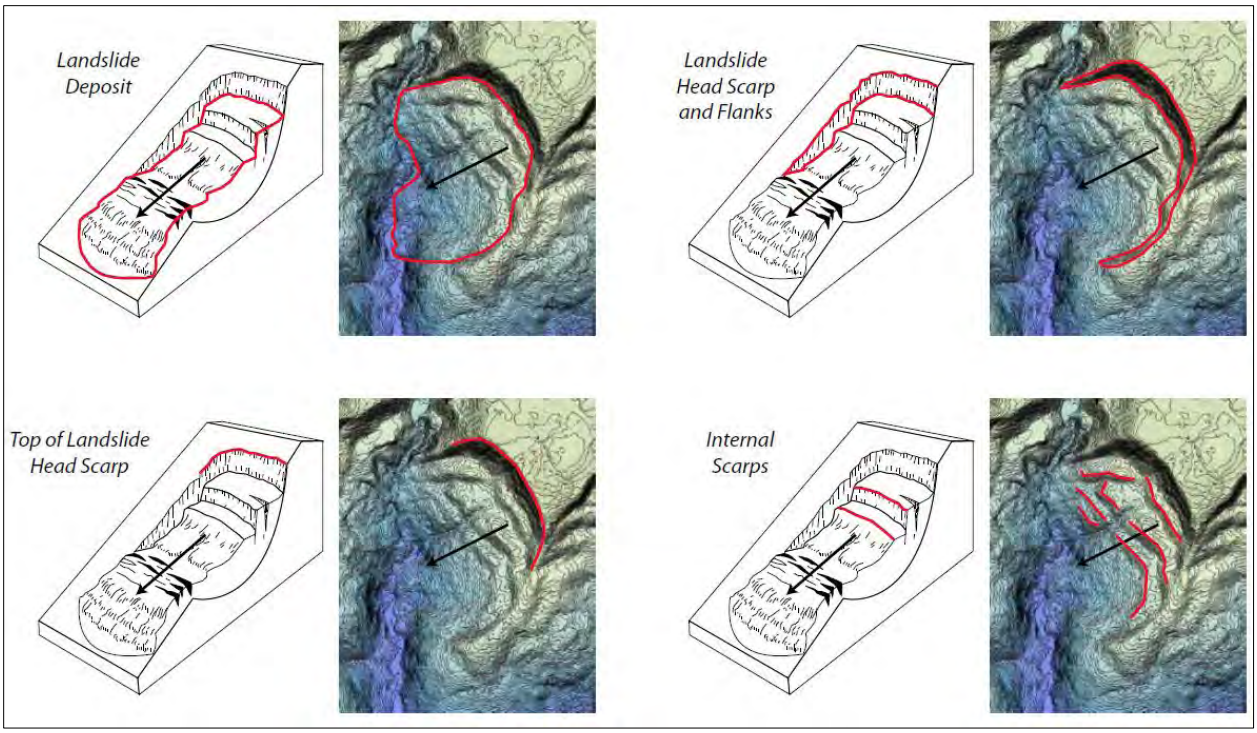

Figure 18. Examples of slide features identified using the OR DOGAMI protocol for inventory mapping of landslide deposits from LiDAR imagery (Burns and Madin 2009).

A numerical confidence rating method set by the OR DOGAMI method (e.g., headscarp and slide morphology) was used to assign ratings to each mapped landslide. Twenty attributes, i.e., relative age of landslide, LiDAR source and date, and whether the slide appeared natural or human modified, of each landslide were documented.

Under certain circumstances during initial failure or reactivation, runout from deep-seated landslides can travel long distances beyond the toe of slope and impact areas not obviously at risk (for example, the 2014 SR 530 landslide and the 2001 Nisqually Earthquake-Cedar River landslide). Evidence of long runout events were identified at multiple locations within the study limits (Figure 19).

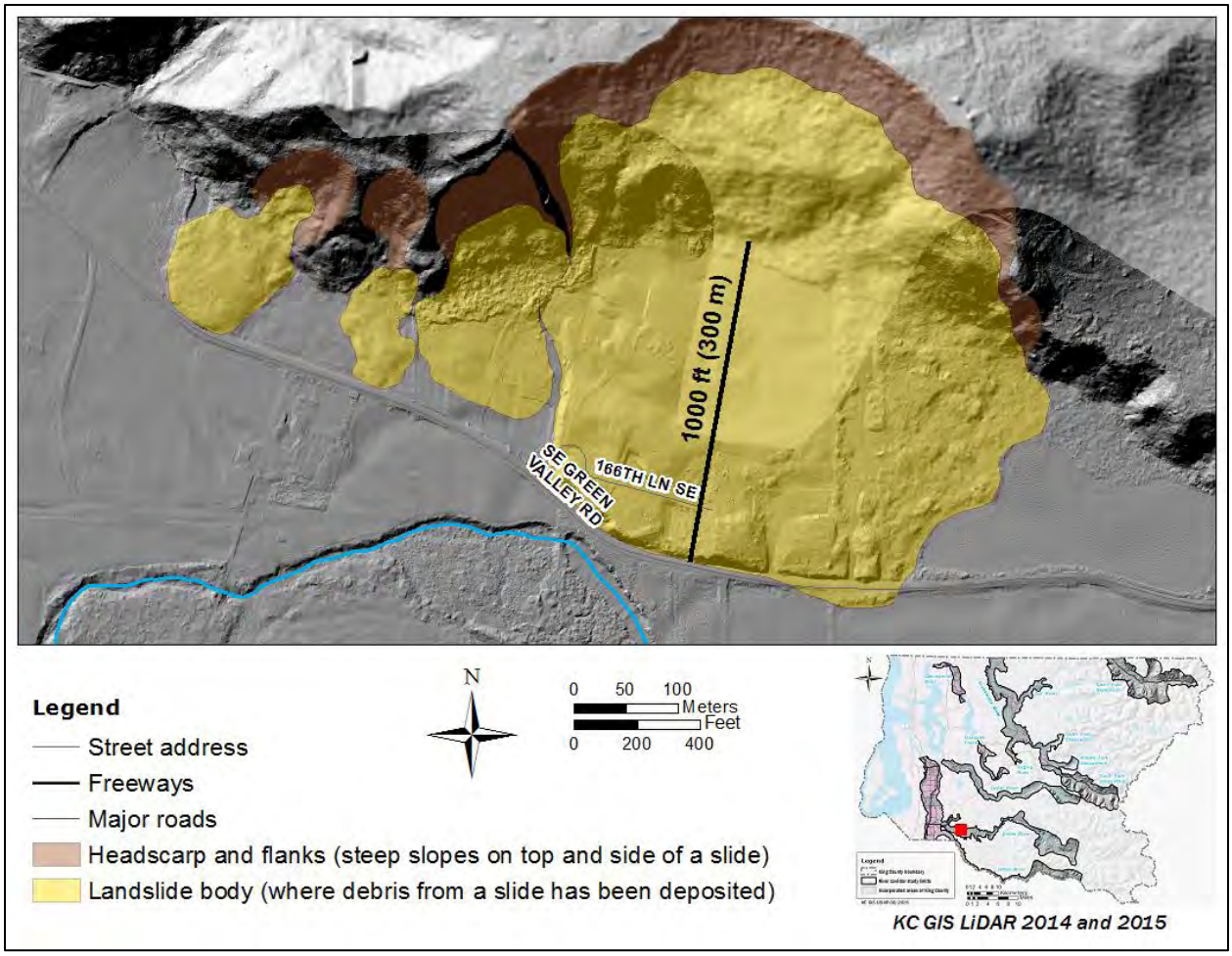

Figure 19. Apparent long-runout landslide in the Green River valley.

Based on consultation with the Technical Review Committee and with local researchers with expertise in this field, it was determined that there is no feasible method for predicting the extent of such runout events on a landscape scale. Even at a site specific scale and with significant information on local conditions, such predictions are problematic, as noted by Iverson et al. (2015): "A strong dependence of landslide mobility on nuanced differences in initial conditions, which themselves depend on geological and meteorological contingencies, has wide implications. It poses a significant challenge for quantitative landslide hazard evaluation, which differs fundamentally from landslide hazard recognition."

Similar reservations are expressed in Hungr et al. (2014), referring to large debris avalanches: "Such hazard scenarios depend on unique sets of circumstances and are extremely difficult to anticipate and prevent."

In discussions with both the Technical Review Committee and local researchers, a set of characteristics was identified that may predispose an area to a long runout event:

- Presence of an existing, ancient, deep-seated landslide (with disturbed, potentially contractive soil)
- Recent or ongoing movement of or within this landslide

- High groundwater table or emergent seepage in or around the landslide
- Active erosion (fluvial, coastal, anthropogenic) at the toe of the landslide
- Presence of a water body (e.g., a river channel) immediately downslope from the landslide that could contribute additional water to debris in motion
- Proximity to debris fields from adjacent failures (indicating past long runout events)
- Larger failures on steeper, higher slopes.

This set of characteristics does not, however, yield sufficient specificity to permit mapping specific areas at risk of such occurrences.

4.3 Shallow Debris Slides

The stability of slopes with respect to shallow debris failures is often evaluated using a simple limit equilibrium analysis known as the infinite slope model. This model assumes that the slope is planar, and that the failure surface, the shallow groundwater surface, and the ground surface are all parallel. This model ignores edge effects and assumes that all resistance to sliding is a result of the shear strength of the soil along the basal failure plane. The infinite slope model is the only commonly used quantitative slope stability model applicable across an entire landscape. In its simplest form the model is based on the following equation:

$$FOS = \frac{C + [\rho_s - (\rho_w\, m)]\, g\, z_s \cos\theta \tan\phi}{\rho_s\, g\, z_s \sin\theta}$$

Where:

FOS:	Factor of safety
C:	Cohesion
ρs:	Bulk density of saturated soil
ρw:	Density of water
m:	Saturated soil thickness / Total soil thickness
g:	Acceleration of gravity
zs:	Total soil thickness
θ:	Slope angle
φ:	Internal angle of friction

Colluvial soil cover on slopes is heterogeneous with respect to the parameters that control slope stability including slope angle, cohesion, apparent cohesion (due to root strength), friction angle, soil depth, and hydraulic properties (which control soil moisture). As a result, soil stability across slopes is also variable. There is little site-specific information of most of these factors on a landscape scale within King County. The only parameter in the infinite slope equation that is known with good accuracy across the landscape is slope angle.

Because many of the input parameters vary significantly across the landscape, application of an infinite slope model on a landscape scale provides a broad approximation of slope stability, and as such will inevitably misidentify some stable slopes as unstable and some unstable slopes as stable due to the inherent uncertainty of the application of a landscape-scale analysis. Stability assessments, especially as they relate to land development, road construction, or utility

installations or any other evaluation with site-specific public health and safety consequences should be based on a site-specific evaluation by a qualified professional.

Harp et al. (2006) used an infinite slope model to assess the stability of slopes in the City of Seattle, and compared the results to the distribution of landslides in the Seattle Landslide Database[1]. They used soil strength parameters from Shannon & Wilson (Laprade et al. 2000) keyed to geologic units from available geologic mapping. Soil depth was held constant over the entire city. Harp et al. (2006) found good correlation between the factor of safety (FOS) derived from the infinite slope model and the distribution of landslides from the City of Seattle database. They also found, however, that the correlation was almost as good assuming uniform soil properties, with the only variable being slope angle.

The OR DOGAMI has adopted a version of the infinite slope model equation as a standard method for evaluating shallow debris landslide susceptibility (Burns et al. 2012). The WA DNR DGER is considering adoption of a similar protocol for this state.

For this DNRP mapping project, an infinite slope analysis was used to generally identify slopes potentially subject to shallow debris slides. Soil strength parameters were estimated by measuring the inclination of 45 valley-wall slopes in the study limits that were relatively straight in profile (Figure 20). The distribution of slope angles showed a strong peak at about 35°. It was assumed that this angle represented an equilibrium (FOS ≈ 1) inclination for typical slopes under conditions of extreme rainfall and soil saturation. Using that assumption, and also making reasonable assumptions for soil thickness and depth of saturation, it was possible to use the infinite slope equation to back calculate a range of cohesion/friction-angle values that would yield a unit FOS. A soil cohesion value of 125 pound/square foot (6kPa) and a friction angle of 33° were selected from this range to use in the global infinite slope analysis.

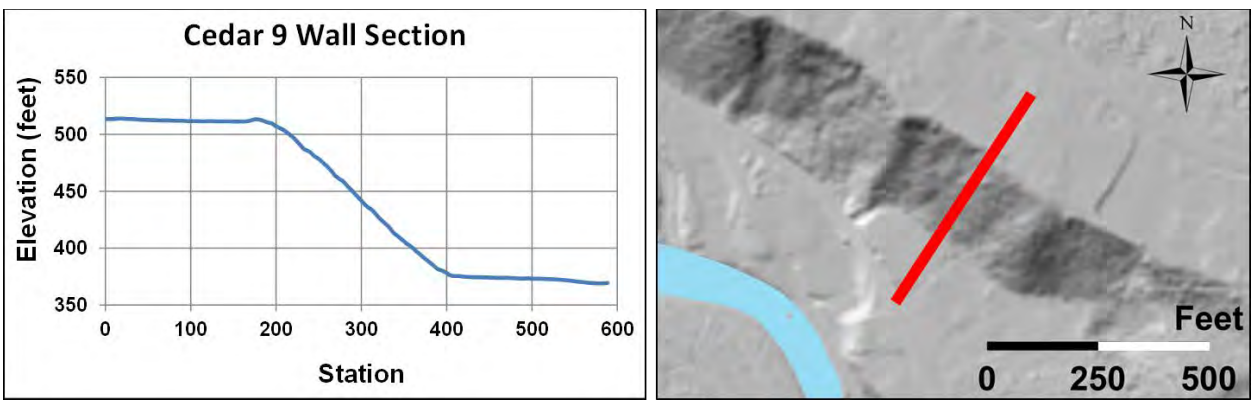

Figure 20. Typical valley wall section as shown on the Cedar River at RM 16.3. The valley wall in this section is inclined at approximately 34°.

Using these values and following the OR DOGAMI protocol (Burns et al. 2012), slopes of 24° to 28° (44 to 54 percent) were identified as having a FOS between 1.25 and 1.5 and having a moderate hazard of being subject to shallow debris slides. Slopes steeper than 28° (54 percent) were identified as having a FOS of less than 1.25 and having a severe hazard of being subject to shallow debris slides. These slope angles are in general agreement with values reported in the literature for

[1] The Seattle Landslide Database is Appendix E in Laprade, W.T., Kirkland, T.E., Nashem, W.D., and Robertson, C.A. 2000. Seattle Landslide Study: Internal Report W-7992-01. Shannon & Wilson, Inc., Seattle, WA. 164 p.

slopes vulnerable to shallow debris slides (e.g., Jakob 2000). Figure 21 shows two examples of how the resulting map looks for selected areas along the Cedar River (Figure 21(a)) and along the Snoqualmie River (Figure 21(b)).

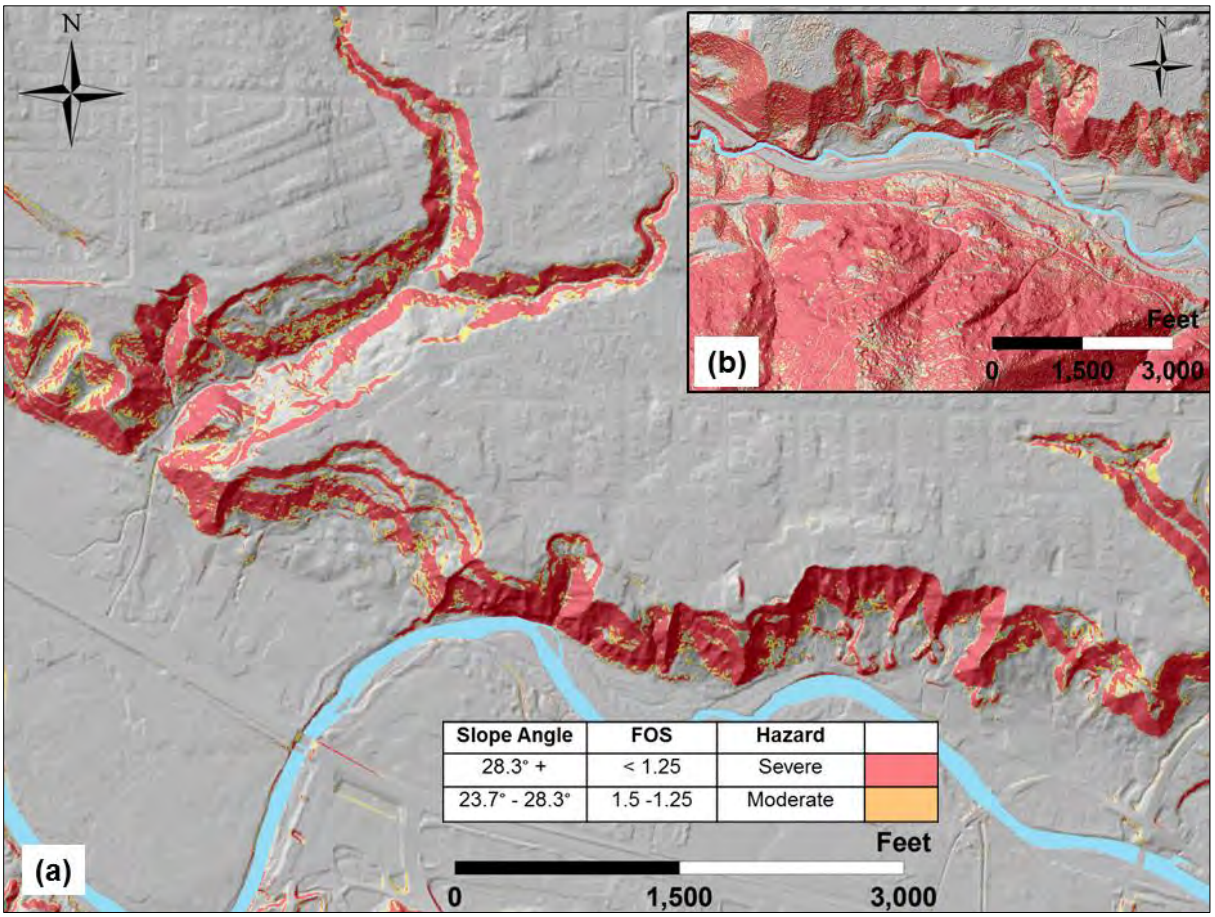

Figure 21. Examples of shallow debris landslide potential in (a) the Cedar River basin and (b) the Snoqualmie River basin.

4.4 Depositional Fans

This section addresses methodologies used to map depositional fans and to differentiate within the fans located in alpine areas within the study limits those that are either more or less likely subject to debris flows. Figure 22 summarizes the methodology followed and shows the decision making criteria for identifying all fans (Section 4.4.1), addressing large alluvial fans (Section 4.4.2), mapping all fans in Puget Lowland areas (Section 4.4.3), and mapping alpine fans that are either more or less likely subject to debris flows (Section 4.4.4).

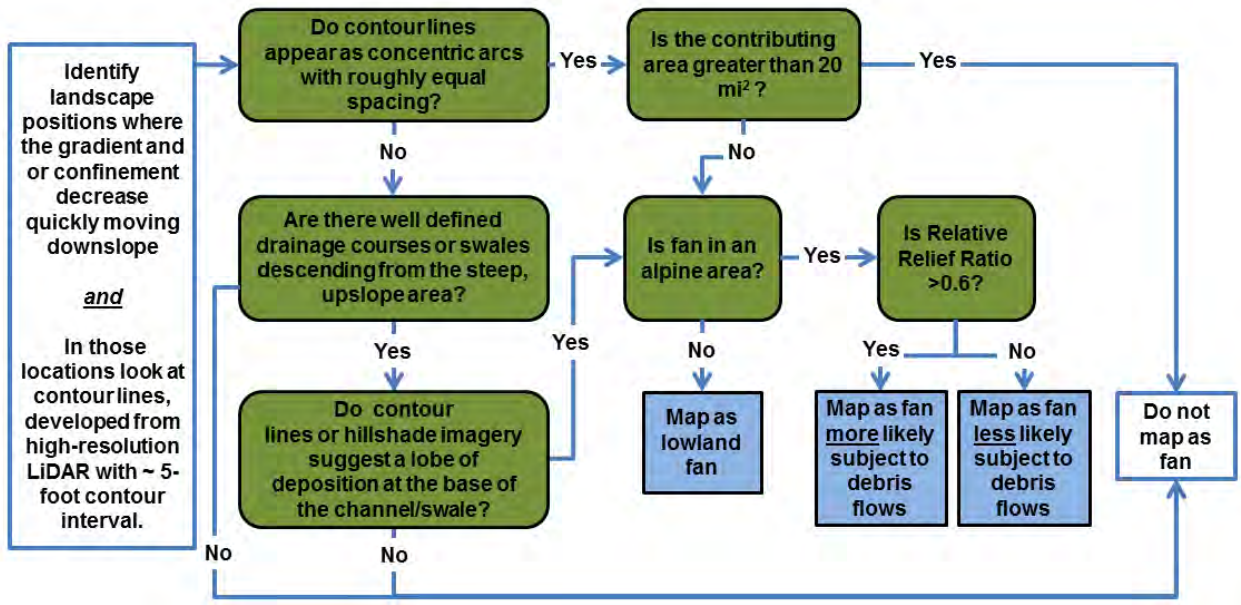

Figure 22. Flow chart showing criteria used for mapping fans in alpine areas likely subject to debris flows.

4.4.1 Identifying Fans

A depositional fan is physical evidence of the extent of past debris deposition, and these features often are indicators of future inundation. These depositional fans tend to be relatively low-gradient and are not readily apparent from hillshade imagery (Figure 23(a)). However, LiDAR data provides digital terrain information that can be used to generate more detailed elevation data and closely spaced contour lines. Although fans appear fan-shaped in plan view (which is how they got their name), in three dimensions, fans are actually truncated cones, and the conical shape is most clearly evident when looking at closely spaced (5-foot) contour interval lines derived from high resolution, LiDAR-derived topography (Figure 23(b)). Contour lines appear as concentric arcs often with roughly equal spacing in plan view (indicating the sides of the cone are of roughly constant slope).

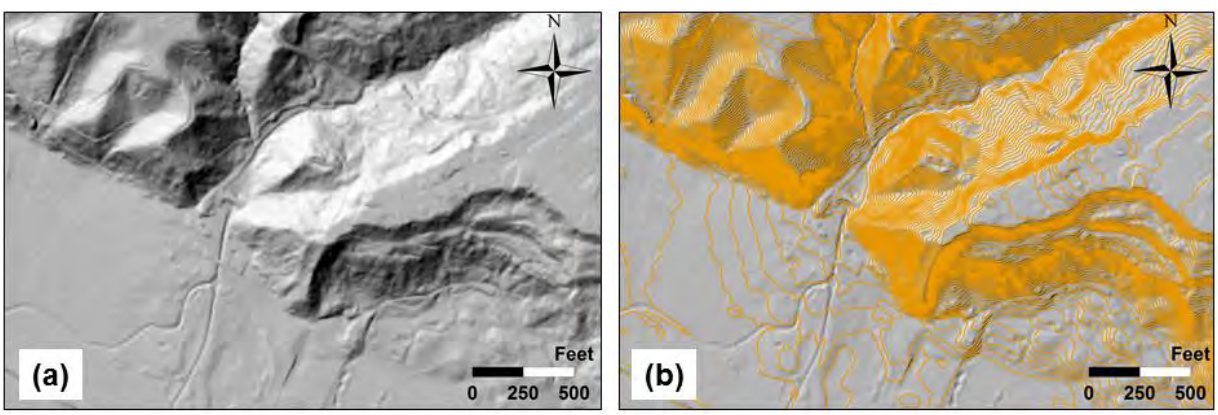

Figure 23. Maplewood Creek fan on the Cedar River near RM 3.5. Fan is shown (a) using LiDAR hillshade imagery and (b) more clearly identified when utilizing 5-foot contour interval lines.

Another distinguishing characteristic of both alluvial and debris fans is that they form where

sediment deposition occurs where there is an abrupt change in gradient from a steep source area upslope to a lower gradient receiving area below. Fans may have a wide range of slope angles depending on the nature of the sediment transport onto the fan. The lowest-gradient fans are formed by large streams where the fan gradient is roughly equal to the gradient of the channel that created it. The steepest fans are a result of debris deposition by debris flows, raveling, or rock fall. Fans often merge laterally into one another where deposition from multiple sources overlap.

Most fans are associated with a topographically distinct drainage channel that joins the fan at its apex. Fans created by rock fall or raveling may not have a contributing channel. It is common for the channel to be significantly incised into the fan where it crosses the fan surface. This sort of incision may indicate that the fan is a relict feature from some prior climatic/landscape regime (immediate post-glacial time, for example). As noted in Kellerhals and Church (1990), however, under some circumstances, streams can be diverted out of relatively deeply incised ravines and potentially impact other areas of the fan surface. In this report, all fans including those with incised channels are mapped unless the magnitude of the incision precludes all plausible channel relocation.

4.4.2 Rationale for Excluding Large Fans

Certain fans were not included in the potential landslide hazard areas of this mapping project. As the contributing area upslope from a fan increases, the slope of the contributing channel and the slope of the fan surface typically decrease. Fans created by rivers are typically a result of only fluvial processes and have no direct contribution from mass-wasting. Four large riverine fans in King County clearly fall in this category and, as such, have been excluded from a map describing hazards associated with mass-wasting.

In King County, basins with a contributing area of more than 20 mi^2 (52 km^2) appear to capture this group of riverine-only features. By excluding those basins from the further analysis, landslide-related fan features on fans created by fluvial processes will not mistakenly be included or identified as landslide features. In King County, this will exclude fan features formed by the mainstems of the Tolt, Raging, Middle and South Fork Snoqualmie, and White Rivers. Figure 24 shows a riverine fan located in the City of Auburn.

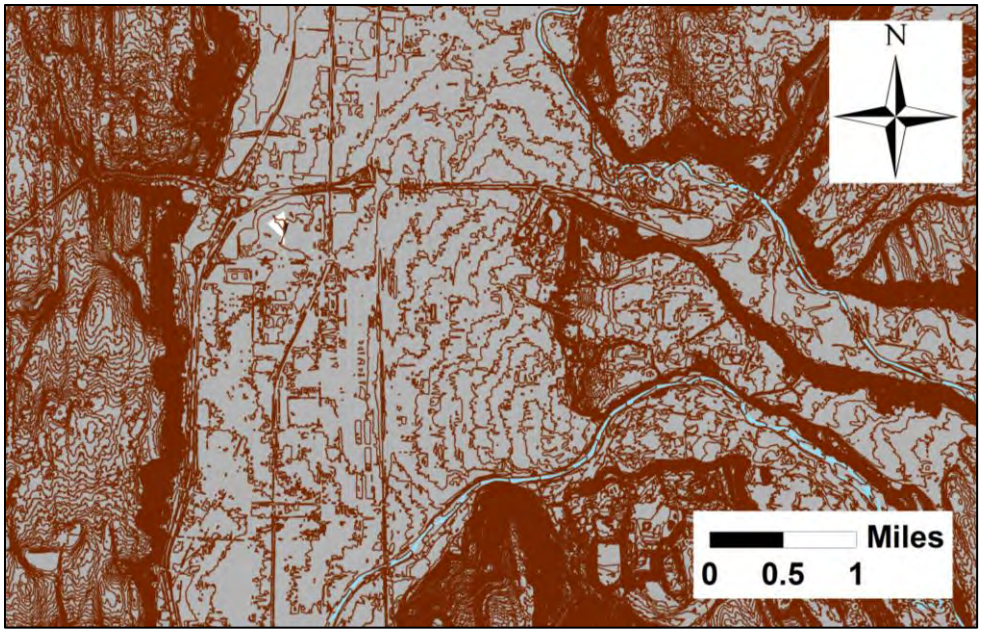

Figure 24. The White and Green Rivers fan near the City of Auburn, clearly seen using 5-foot contour lines.

Some smaller low-gradient fans included in the landslide mapping study limits are also likely formed entirely by fluvial action. All of these smaller fans have been mapped as potential landslide hazards. Other site-specific scale evaluations outside of this report's mapping may determine that some of these smaller fans are not associated with mass-wasting processes. Note that even if these low-gradient fans are determined not to be subject to landslide-related hazards, in-stream sediment accumulation, channel migration, and sudden channel avulsion may still pose a threat to public health and safety as different types of flood fluvial hazards.

4.4.3 Alpine Fans and Debris Flows

Of the various geomorphic processes that contribute to the growth of fans, the most dangerous is likely debris flow (Kellerhals and Church 1990). Research in British Columbia has identified a simple landscape metric that identifies alpine drainage[2] basins that are more likely to produce debris flows (Wilford et al. 2009). This metric is known as the Relative Relief Ratio (used here) or the Melton Ratio (Figure 25). The ratio increases with the elevation range[3] of the basin and decreases with the square root of the basin area. The ratio will therefore be greatest for small basins that span a large elevation change. Research in British Columbia has shown that basins with a Relative Relief Ratio of 0.6 or more are more likely to produce debris flows, and that fans with a Relative Relief Ratio less than 0.6 are more likely to produce debris floods or normal fluvial flooding (Wilford et al. 2009).

[2] Alpine drainage basins are located in mountain settings and underlain primarily by bedrock.
[3] The elevation range is measured from the high point in the basin to the apex of the fan at the bottom of the basin.

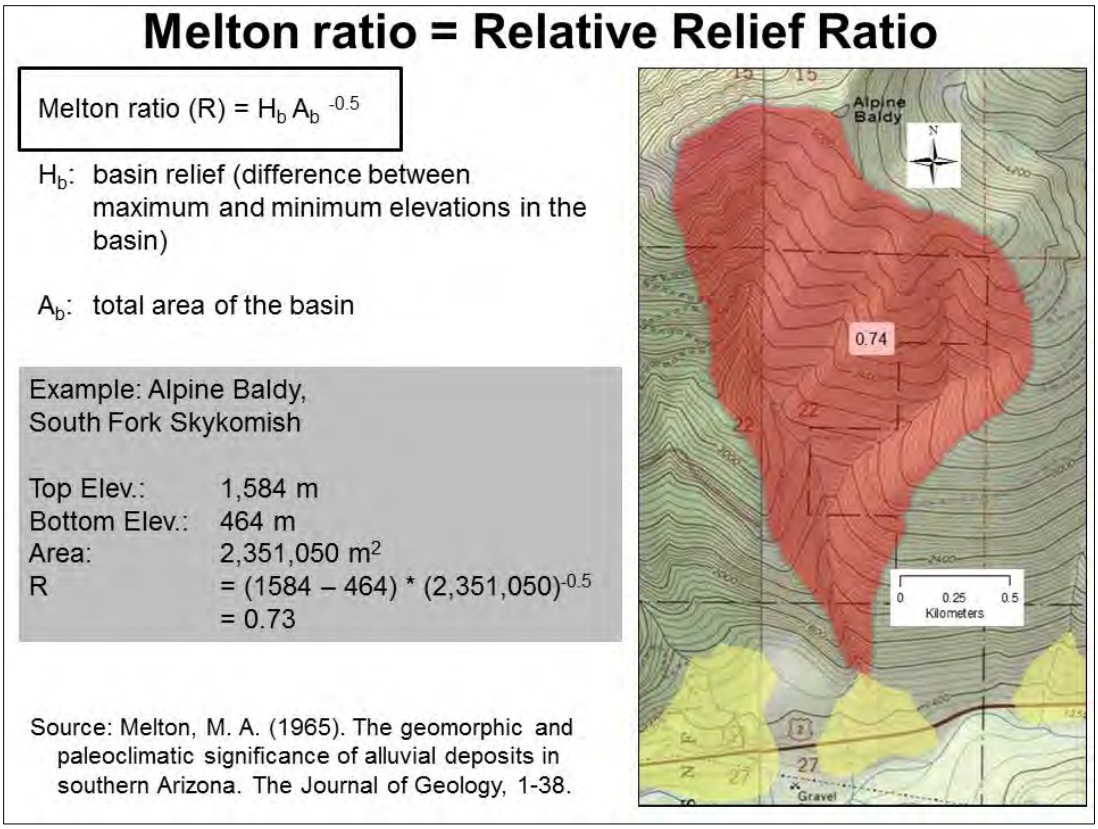

Figure 25. Relative Relief Ratio.

This relationship has not been verified for the alpine drainage basins of the Washington Cascades, but during fieldwork for this project, recent debris flow deposits were observed in basins with a ratio of more than 0.6, and none for basins with a lower ratio. For alpine basins, in the study limits (Figure 26), this metric was used to discriminate between basins more likely to produce debris flows from those less likely to produce debris flows.

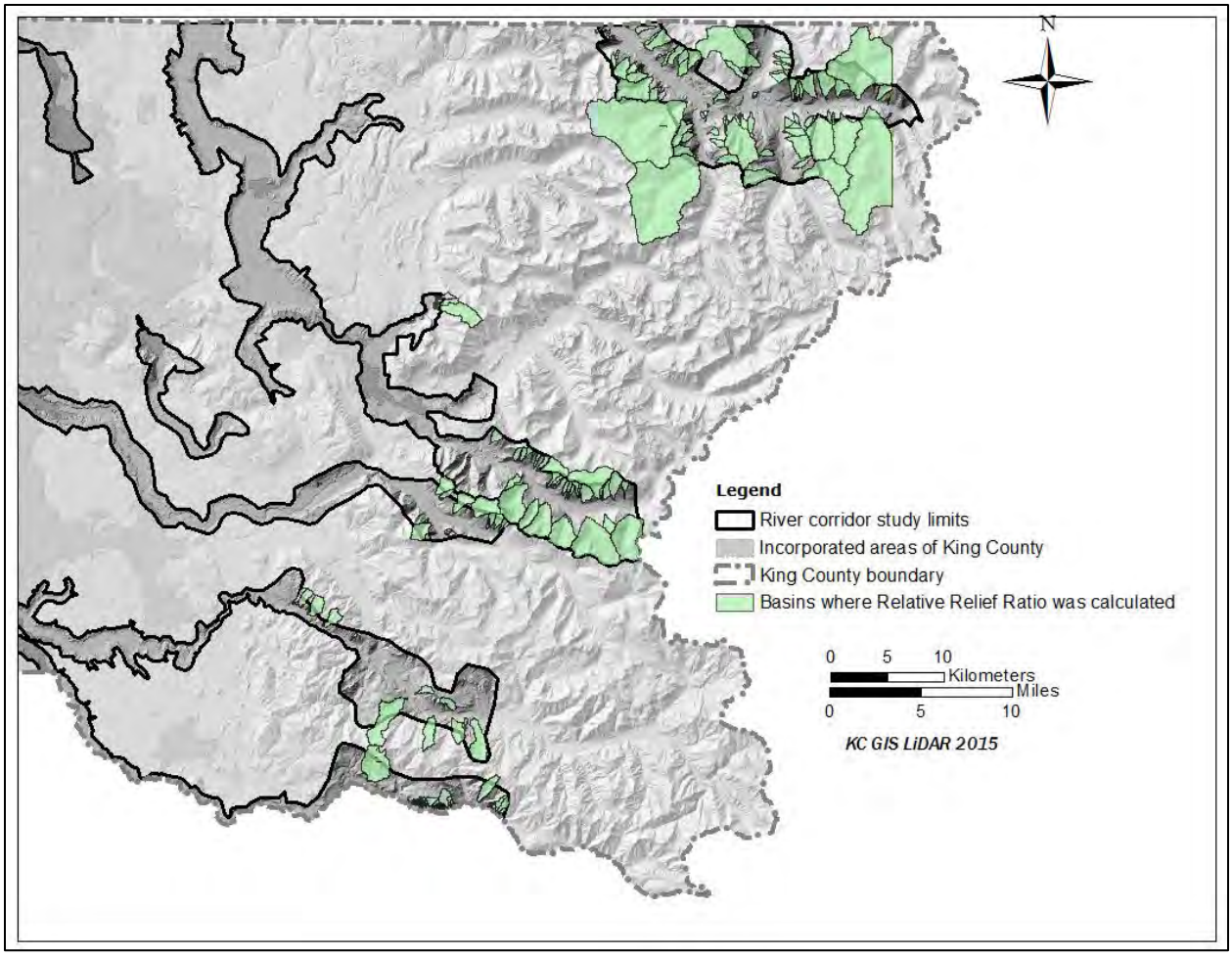

Figure 26. Contributing basins in alpine areas for which Relative Relief Ratios were calculated.

Examples of fans along the Snoqualmie River and the Relative Relief Ratio calculated for each basin are shown in Figure 27. In this figure, topography is displayed using a gradation of colors, grading from brown at higher elevations along peaks to greens and blues at lower elevations in the floodplain for the Snoqualmie River. Fans are differentiated in colors: dark orange-colored fans show those that are more likely subject to debris flows, and light orange-colored fans illustrate fans that are less likely subject to debris flows.

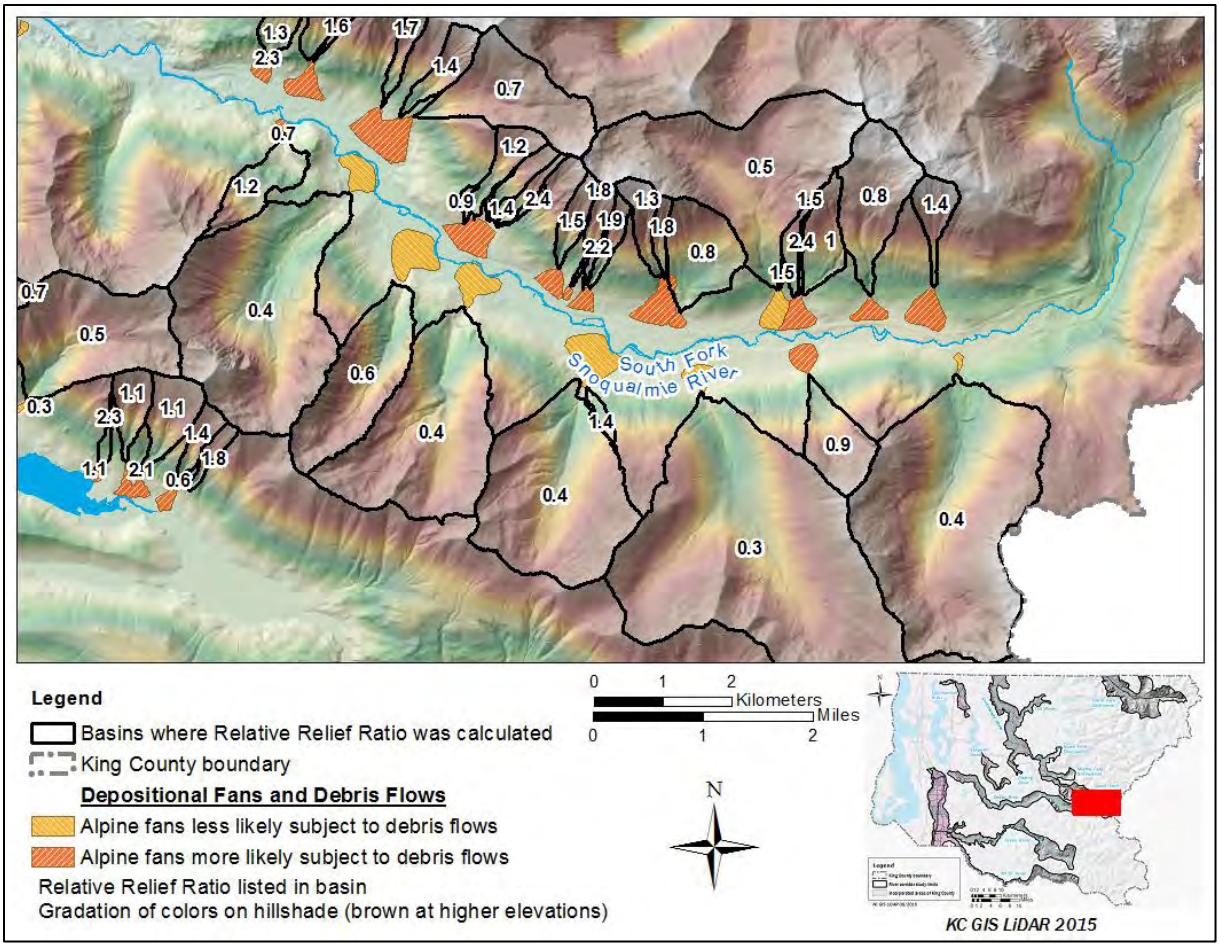

Figure 27. Relative Relief Ratios for contributing basins along Snoqualmie River.

4.4.4 Puget Lowland Fans

Debris flows and related flow phenomena also occur and contribute to debris fans in the Puget Lowland. The Relative Relief Ratio was developed for and is applicable to alpine drainage basins underlain by bedrock, and it is therefore not applicable to the geology or topography typical of basins in the Puget Lowland. No other simple metric was identified in the literature that could be used to screen these basins and identify those most likely to be inundated by such flows.

A review of sites with known recent debris flows or debris floods in the Puget Lowland areas of King County suggests that they share some characteristics in common:

- All of the recent incidents reviewed entailed discharge from ravines with steep side slopes, typically greater than 60 percent slopes;
- All discharged onto well-defined, preexisting fans, and these flows were often initiated by a sudden release of water, and in a number of recent cases this has been the result of failure of an upstream beaver dam;
- Where the channel gradient above the fan was steep, in excess of a 15 percent slope, the discharge was in the form of a debris flow; and
- Where the channel gradient was less than a 15 percent slope, the discharge took the form of a debris flood.

These observations are based on a small number of recent incidents, but these incidents number too few to develop robust screening criteria. However, further monitoring of these events might yield criteria that could be used to identify Puget Lowland ravines that may be subject to debris flows.

Based on the characteristics above, DNRP geologists used LiDAR imagery and closely spaced contour lines to map depositional fans in the Puget Lowland areas.

4.5 Rock Fall

Evans and Hungr (1993) describe an approach to assessing the limits of rock fall hazard, based on work in the Canadian Rockies. They reported that the maximum travel distance for the distal-most boulders from a cliff face was defined by a vertical angle, projected from the base-of-cliff/top-of-talus at an angle of 27.5° (Figure 28) to lower slopes. Jaboyedoff and Labiouse (2011) describe a software program called CONEFALL (Figure 29) that implements this approach in a GIS environment to map areas where rock fall could propagate downslope from a source. In Figure 29, the example shows an image of a steep slope in Les Cretaux, Switzerland, where a talus slope, fan, and boulders were mapped and coincided within the modeled boundaries using CONEFALL.

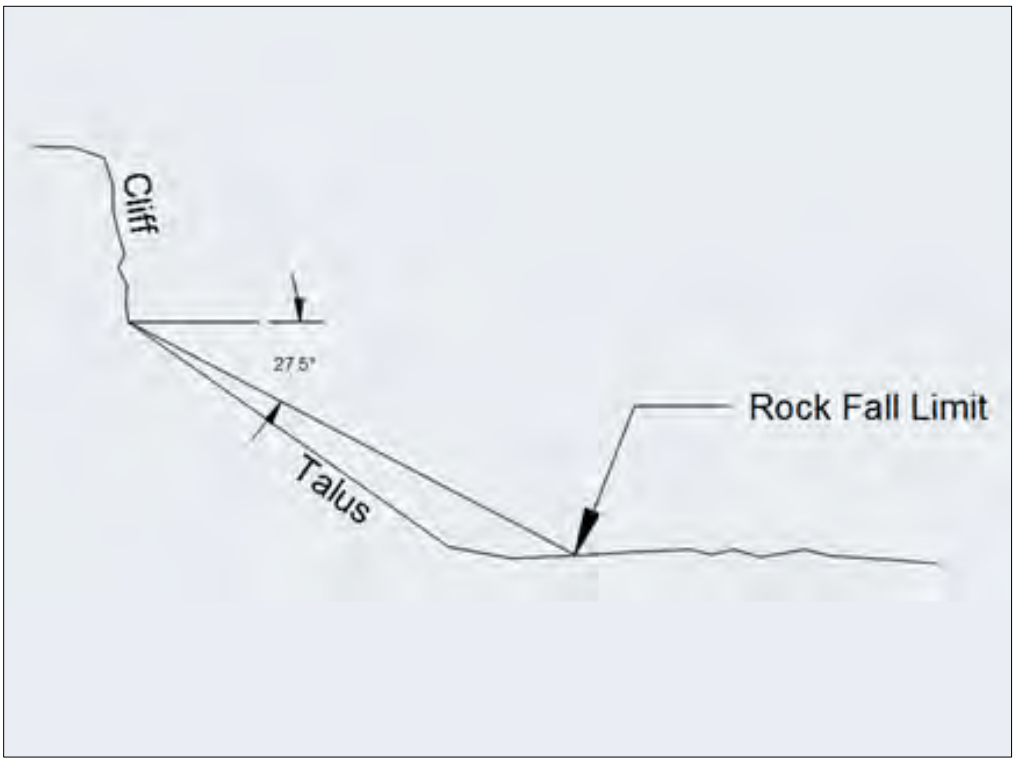

Figure 28. Shadow angle, based on Evans and Hungr (1993).

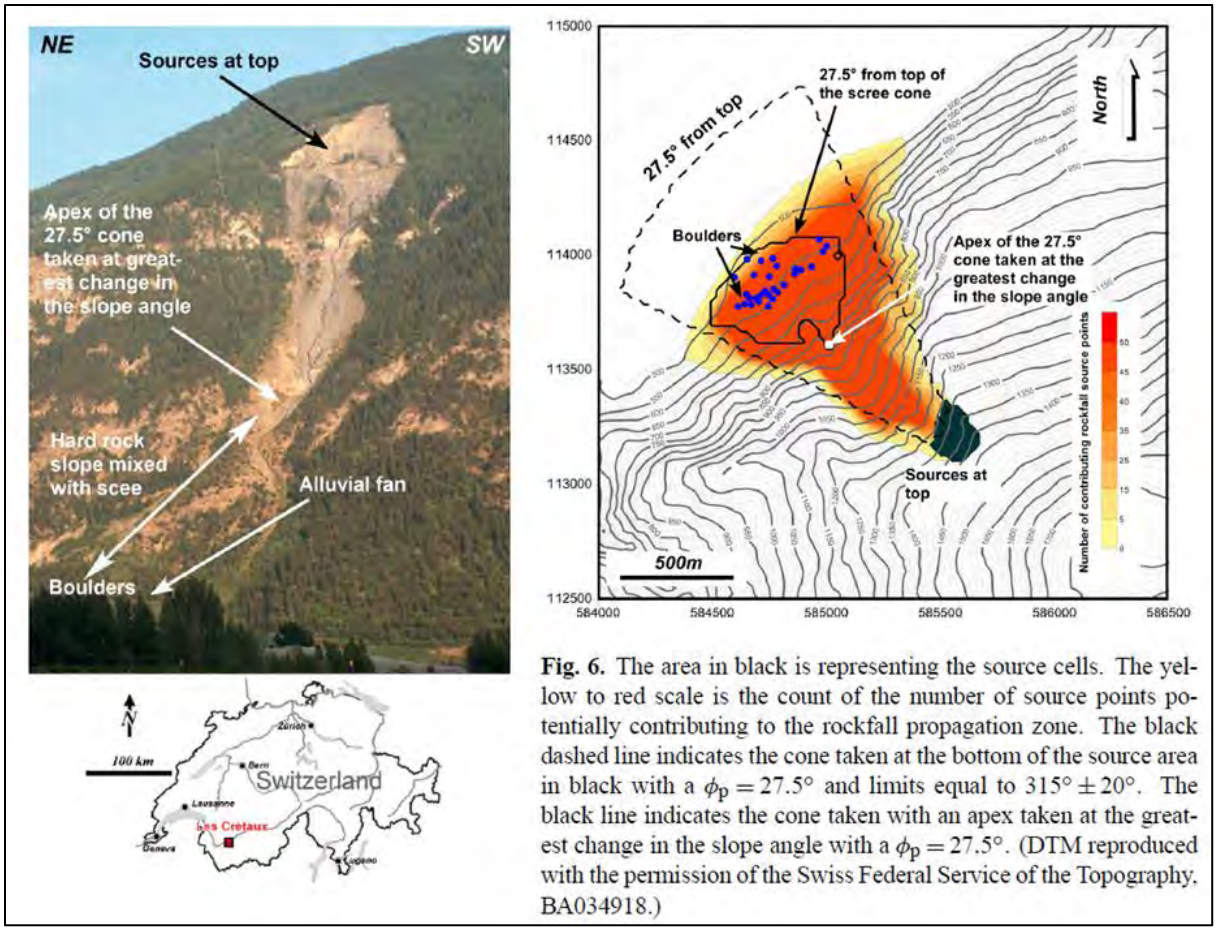

Fig. 6. The area in black is representing the source cells. The yellow to red scale is the count of the number of source points potentially contributing to the rockfall propagation zone. The black dashed line indicates the cone taken at the bottom of the source area in black with a $\phi_p = 27.5°$ and limits equal to $315° \pm 20°$. The black line indicates the cone taken with an apex taken at the greatest change in the slope angle with a $\phi_p = 27.5°$. (DTM reproduced with the permission of the Swiss Federal Service of the Topography, BA034918.)

Figure 29. CONEFALL method used to map rock fall potential. From Jaboyedoff and Labiouse (2011).

For the DNRP landslide mapping project, the CONEFALL program with a shadow angle of 27.5° was used. As a starting point for the CONEFALL program, it is necessary to identify cliff-faces and, in particular, to delineate the line representing the base-of-cliff/top-of-talus. Within the study limits, these lines were mapped based on professional judgement using a variety of tools in a GIS environment including vertical orthophotography, oblique photography, and slope mapping. Slopes inclined at more than 200 percent were often found to correlate well with cliff faces.

An example of the output from CONEFALL for the Mt. Si area is shown in Figure 30, where boulders are mostly mapped within the CONEFALL modeled area near the base of Mt. Si. It is important to note that the CONEFALL model is based entirely on topography and the integrity of the bedrock is not considered in this model.

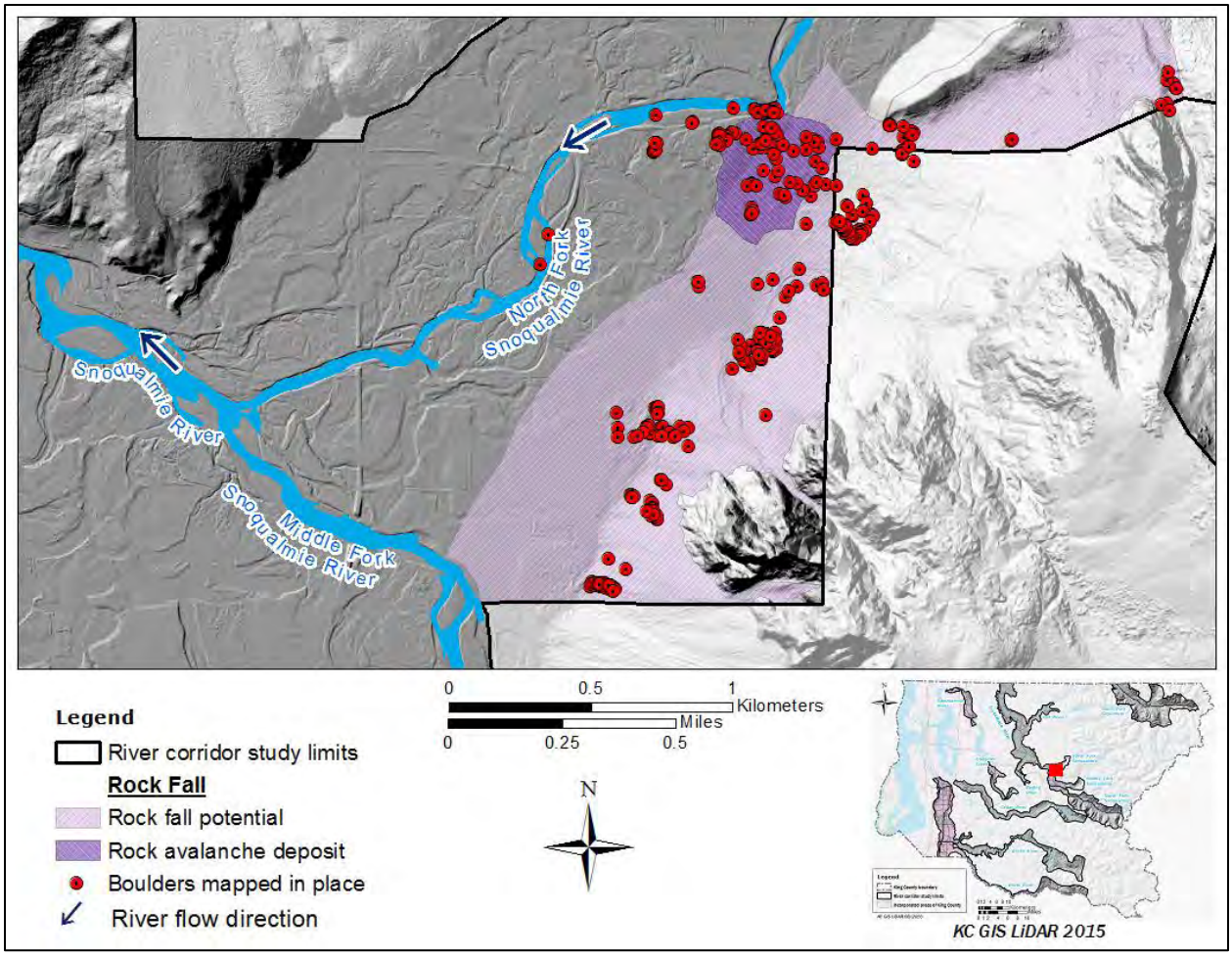

Figure 30. Example of results using CONEFALL in the Mt. Si area.

4.6 Rock Avalanche Deposits

Three rock avalanche deposits were identified within the study limits. Two were mapped in the South Fork Skykomish River valley (Beckler Peak and Index Creek) and one in the Snoqualmie River valley, near Moon Valley Road NE (Mt. Si area).

The Beckler Peak rock avalanche had previously been mapped by Tabor et al. (1993). Tabor et al.'s map extents were modified based on examination of more recent, and greater accuracy LiDAR imagery and field investigations (Figure 31).

The rock avalanche in the vicinity of Moon Valley Road NE (Mt. Si area) was mapped by Shannon & Wilson (1993a and 1993b) and the limits were modified based on examination of LiDAR imagery. This mapped deposit is shown in Figure 31 and correlates well with the cluster of boulders mapped in place in the Snoqualmie River valley.

One additional rock avalanche deposit in the Index Creek area of the South Fork Skykomish River valley was identified and mapped as a part of this project based on LiDAR hillshade imagery and interpretation of orthophotography.

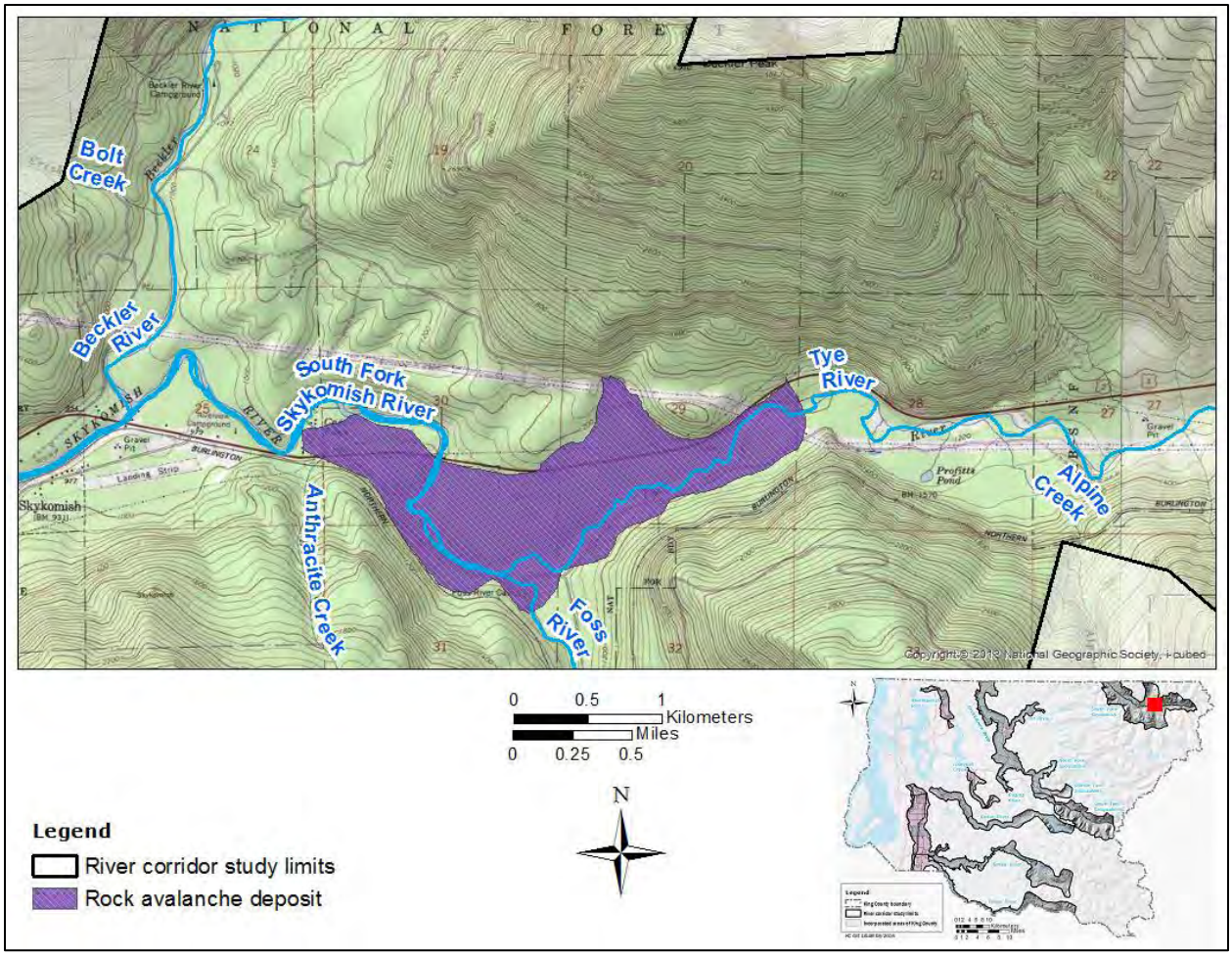

Figure 31. Beckler Peak rock avalanche deposit mapped in the South Fork Skykomish River valley: the purple tint shows the extent of the deposits which originated on the south face of Beckler Peak and filled the lower Tye and upper South Fork Skykomish River valleys.

Due to the lack of detailed information on significant variables including rock strength, zones of weakness, and joint patterns, predictions of future sites of rock avalanches were not feasible.

4.7 Fieldwork Supporting this Project

During the course of this project, King County DNRP geologists visited selected locations to verify the presence of landslide features initially identified using LiDAR imagery. Features visited included depositional fans in both alpine and lowland settings, rotational slides, flow slides, rock compound slides, sites with rock fall and rock avalanche deposits, and sites of recent shallow debris slides.

In addition to these field visits, field verification was also accomplished on the basis of past observation of active and relict landslide features by DNRP geologists and through the review of geotechnical reports submitted to King County.

5.0 PRODUCTS

5.1 Landslide Map

The final landslide GIS datasets for landslides described in Section 3.1 Types of Landslides in King County, were completed as follows:

- Deep-seated landslides GIS datasets provided by Shannon & Wilson contained extensive information in attached attribute tables. Content and type of specific shapefiles are:
  - Entire landslide (polygon)
  - Top of headscarp (polyline)
  - Headscarp and flank scarps (polygon)
  - Landslide deposit/body (polygon)
  - Internal scarps, if present (polyline)
  - Toe along riverbank, if present (polyline)
  - Closed depressions, if present (polygon)
  - Ponded water, if present (polygon)
  - Watercourses, if present (polyline)
- Shallow debris slides GIS dataset is a vector shapefile containing moderate and severe shallow debris landsliding potential hazards.
- Depositional fans GIS datasets are polygon shapefiles having the following content:
  - Lowland fans
  - Fans in alpine areas less likely subject to debris flows
  - Fans in alpine areas more likely subject to debris flows
- Rock fall potential GIS dataset is a polygon shapefile of the CONEFALL output
- Rock avalanche GIS dataset is a polygon shapefile.

These GIS datasets are available through the King County GIS Center[4]. A hard copy of the maps resulting from the GIS datasets is not provided as part of this document.

5.2 Landslides Inventory

It is common knowledge to landslide practitioners that where a landslide has occurred in the past, it may happen again. Having an inventory of these locations would support activities related to planning for hazards, evaluating risks, assisting with permitting process, and informing on vulnerable infrastructures.

An inventory of historical landslides was completed for the study limits. Historical landslides are landslides that are known to have occurred either from observation, studies, or monitoring. This section will present the sources, types, results, and uses of data reviewed.

5.2.1 Sources and Type of Data Reviewed

Geotechnical reports, landslides studies and maps, permit applications, and field reports are commonly stored by city, county, and federal agencies. Five divisions or sections within King County were contacted to inquire about landslide-related data (Table 2). Additionally, 11 cities, two Washington State agencies, three local public utilities, the United States Forest Service (USFS),

[4] King County GIS Center can be reached at http://www.kingcounty.gov/operations/GIS.aspx

Burlington Northern Santa Fe Railway (BNSF), and the University of Washington were also queried (Table 2).

Table 2: Sources, types and status of data reviewed for inventory.

Agencies/Cities	Has Data	DNRP Received Data	Location of data provided with respect to study limits		Type of data shared with DNRP				Number of Documents Reviewed by DNRP	Number of Entries into Inventory
			Inside	Outside	Lists	Reports	Photos	GIS		
INCORPORATED AREAS										
Auburn	X	X	X	X		X			53	3
Bothell	X	X						X	1	0
Issaquah	X	X	X	X		X			123	9
Kenmore	X	X	X	X		X			2	0
Kent	X	X		X		X			1	0
Renton	X	X	X			X		X	50	4
Seatac									0	0
Snoqualmie									0	0
Skykomish									0	0
Tukwila	X	X						X	2	0
Woodinville	X								0	0
GOVERNMENT AGENCIES										
KC Archives	X	X	X	X			X		53	10
KC DNRP WLRD Stormwater Services	X	X	X	X	X	X			510	18
KC DNRP WLRD River & Floodplain Management*	X	X	X	X		X			1	4
KC DOT Roads Services Division	X	X	X	X	X	X			2182	37
KC DPER*	X	X	X	X		X			130	12
SPU Cedar River Watershed	X	X	X	X*				X	1	145
SPU Tolt River Watershed	X								0	0
TPU Green River Watershed									0	0
United States Forest Service	X	X						X	1	0
Washington State DNR DGER	X	X	X	X		X		X	107	7
Washington State DOT	X	X	X	X				X	1	51
OTHER										
Burlington Northern Santa Fe Railway	X								0	0
GeoMapNW, University of Washington	X	X	X	X		X		X	295	14
Northshore Utility District	X	X		X		X			1	0
TOTAL									**3514**	**314**

Acronyms

DNR DGER = Department Natural Resources, Division of Geology and Earth Resources
DNRP = Department of Natural Resources and Parks
DOT = Department of Transportation
DPER = Department of Permitting and Environmental Review
KC = King County
SPU = Seattle Public Utilities (City of Seattle)
TPU = Tacoma Public Utilities
WLRD = Water and Land Resources Division

Note:

King County DPER file review for parts of Snoqualmie and Cedar River only
* data exists, review not complete or conducted

Documents came in the form of formal and field reports (hard copy and electronic), electronic lists, photographs (hard copy and microfliche), and ArcGIS® electronic map files (GIS) (Table 2). The most common form of data was received as geotechnical reports. The King County Archives Division (a service of the Records and Licensing Services in the Department of Executive Services) provided records in the form of historical photographs (stored as microfliche) that had been taken following landslide events (Figure 32). KC DOT Road Services Division keeps an inventory of monitoring locations of landslides along county roads (KC DOT, Personal communication 2016). GeoMapNW (University of Washington) provided a collection of technical reports and boring logs to WA DNR DGER. GeoMapNW identified whether a report or borehole log indicated landslide activity. This landslide data was especially useful in combination with the WA DNR DGER files, where there were repeat records of the same landslides.

Figure 32. Example of a photograph reviewed. Landslide at Jones Road, date unknown (Photo source: KC Archives).

Some agencies that did not share data were in the process of collecting information and may be able to share in the future. Obtaining information from the BNSF Railway Company was not possible within the timeframe of completing this report.

5.2.2 Attribute Table

Landslide data from the 314 documents referencing landslides within the study limits were cataloged in a spreadsheet inventory. Table 3 shows the wide variety of data extracted from the data sources, including landslide location, observations of water bodies, slide features, geomorphology, analyses completed, and any noted damage resulting from the landslide. The final GIS dataset is a point shapefile having extensive information in the attribute tables.

Table 3: Information included in landslide inventory.

General Types of Data Collected	Column Headings in Attribute Table
Data source	Data source
Location	Latitude
	Longitude
	Street Address
	Author
Report	Report
	Report title
	Report date
	Site map
Exploration	Subsurface logs
	Photographs
	Exploration year
	Test pits
	Borings
	Groundwater wells
	Inclinometers
	Movement monitoring
Geomorphology	Type of movement
	Defined scarp
	Defined toe
	Head scarp height (ft)
	Slope setting
	Visible landslide features
	Faults
Lab Analysis	Strength testing
	Textural analysis
Failure Description	Style of Failure
	Evidence of historic movement
	Age of latest historic movement
	Evidence of ongoing movement
Trigger	Trigger
Human Contributing Factors	Human Contributing Factors
Water	Groundwater found in exploration
	Springs present
	Natural stream course crosses site
	Natural stream course adjoins site
	Constructed stormwater discharge to site
	Natural impoundment on or upslope
Field Observations	Structures observed
	Roads observed
Damage	Structure damage
	Road damage
	Utility damage
	Road closure

5.3 Landslide Mapping Webtool

A webpage has been prepared to provide information on the landslide mapping products. The webpage includes information about the types of landslides mapped in King County, the mapping methodologies used and where to find the products, such as the map, this report and a publically accessible GIS map on the internet. Figure 33 shows the webpage with links to the main King County iMAP page, informational pages on landslides, and a webtool.

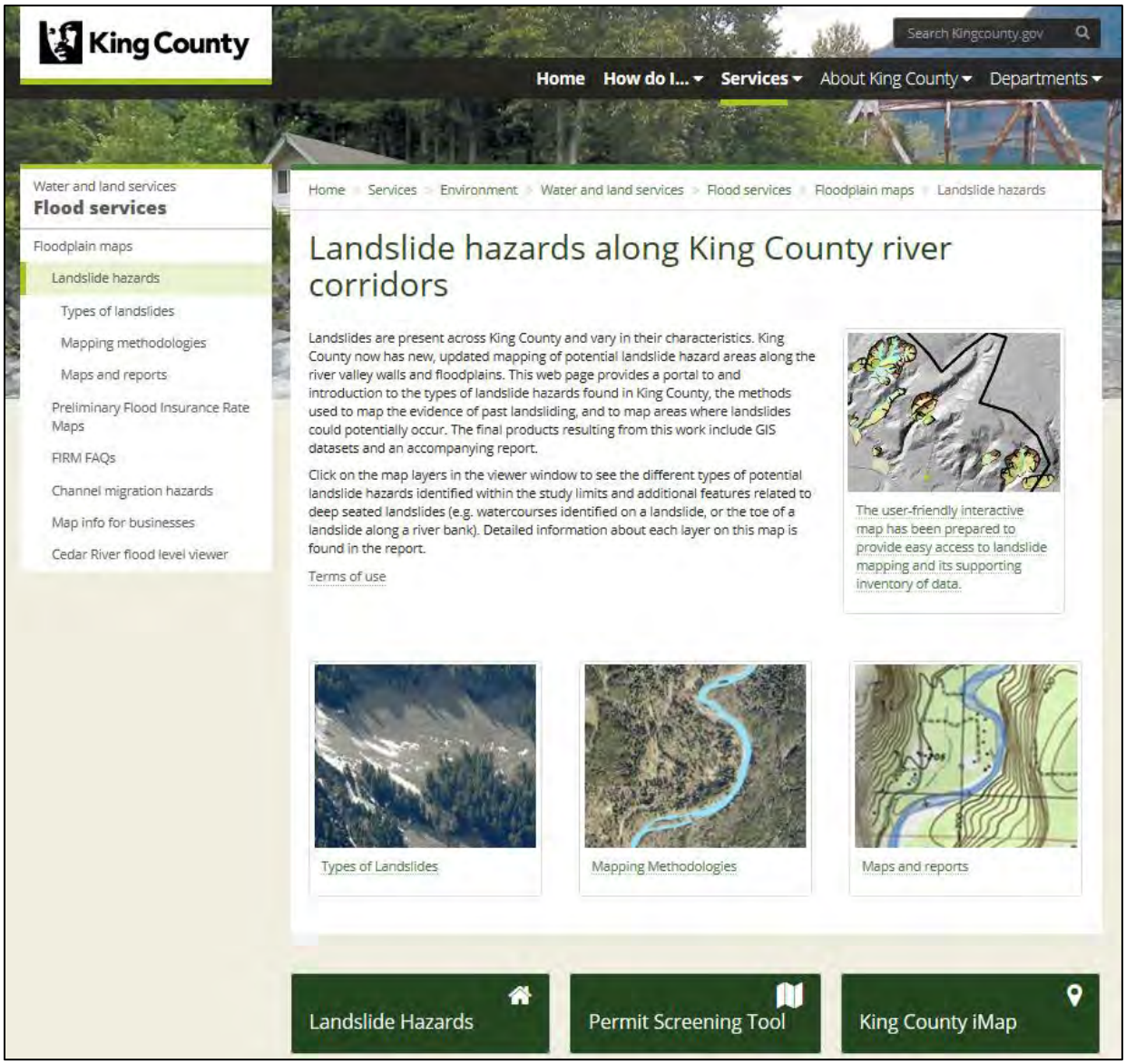

Figure 33. User-friendly webpage designed to be informative about DNRP landslide hazards mapping along river corridors.

A user-friendly webtool has been prepared to provide easy access to landslide mapping and its supporting inventory of data. The webtool is intended to be used as an information source on the mapped locations and types of potential landslide hazards identified by this mapping project. The landslide datasets described in Section 3.1 Types of Landslides in King County and the Landslides Inventory described in Section 5.2 are all available for viewing and clickable as "layers," meaning as

much or as little of the embedded information can be selected to view.

Figure 34 shows an example of a deep-seated landslide along the Cedar River displayed on the interactive mapping webtool. The webtool includes a legend along the right hand side of the page where the landslide datasets may be made visible. For deep-seated landslides, the details of features recognizable on the landslide body are also visible, including where watercourses travel across or adjacent to the landslide. In addition, where the toe of a deep-seated landslide is located at the edge of a river channel it is marked by a thick red line indicating an area of possible bank erosion that could remove toe support and destabilize the adjacent landslide feature.

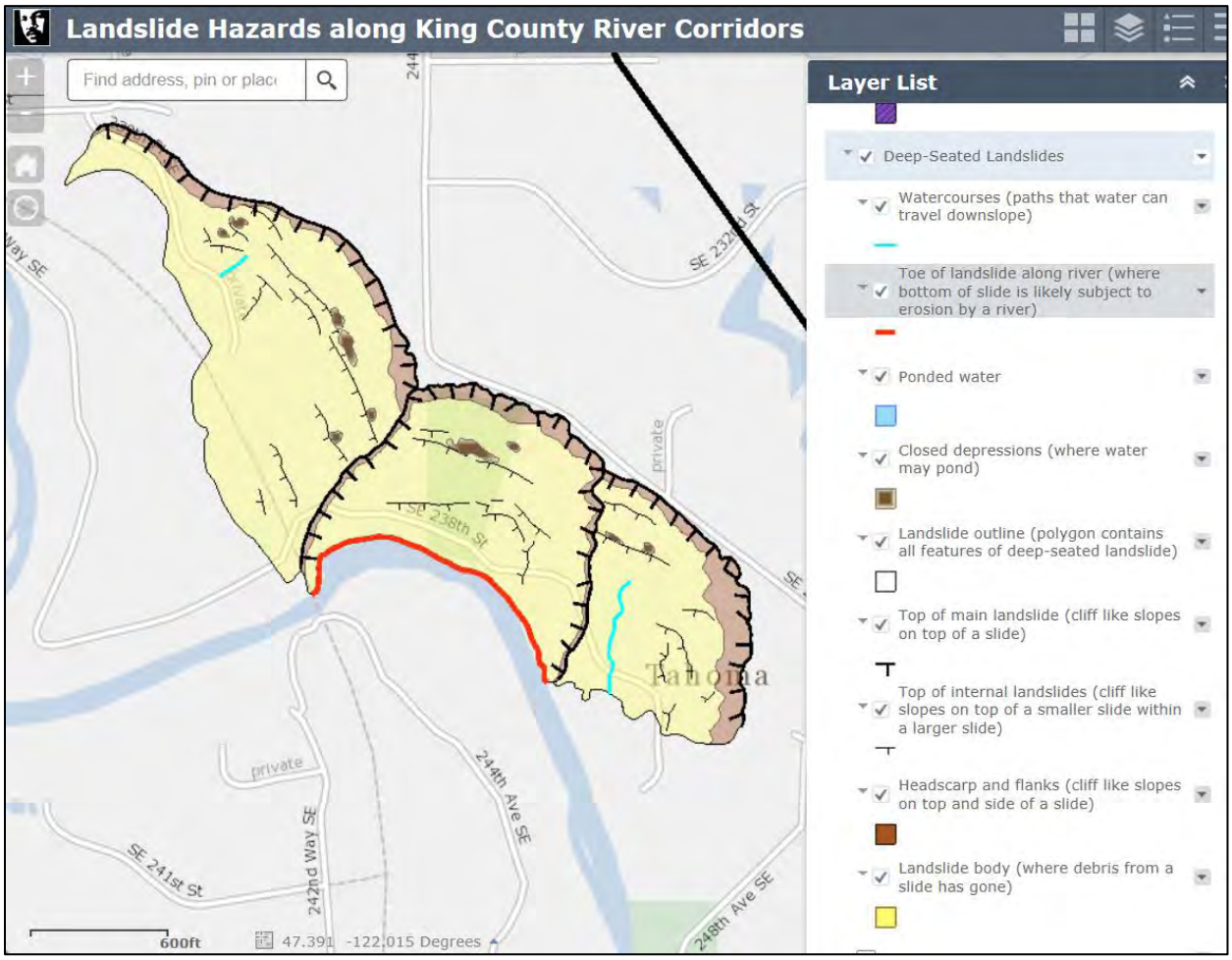

Figure 34. Example of webtool showing deep-seated landslides along the Cedar River.

Figure 35 shows landslide attribute data accessible via the webpage. In this example, layers for rock fall, rock avalanche deposits, and fans are visible. The green squares indicate locations where a landslide was referenced in a document in the inventory. Clicking on the green square opens a window showing the attribute data associated with a given slide, and it also provides links to any related scanned images or reports.

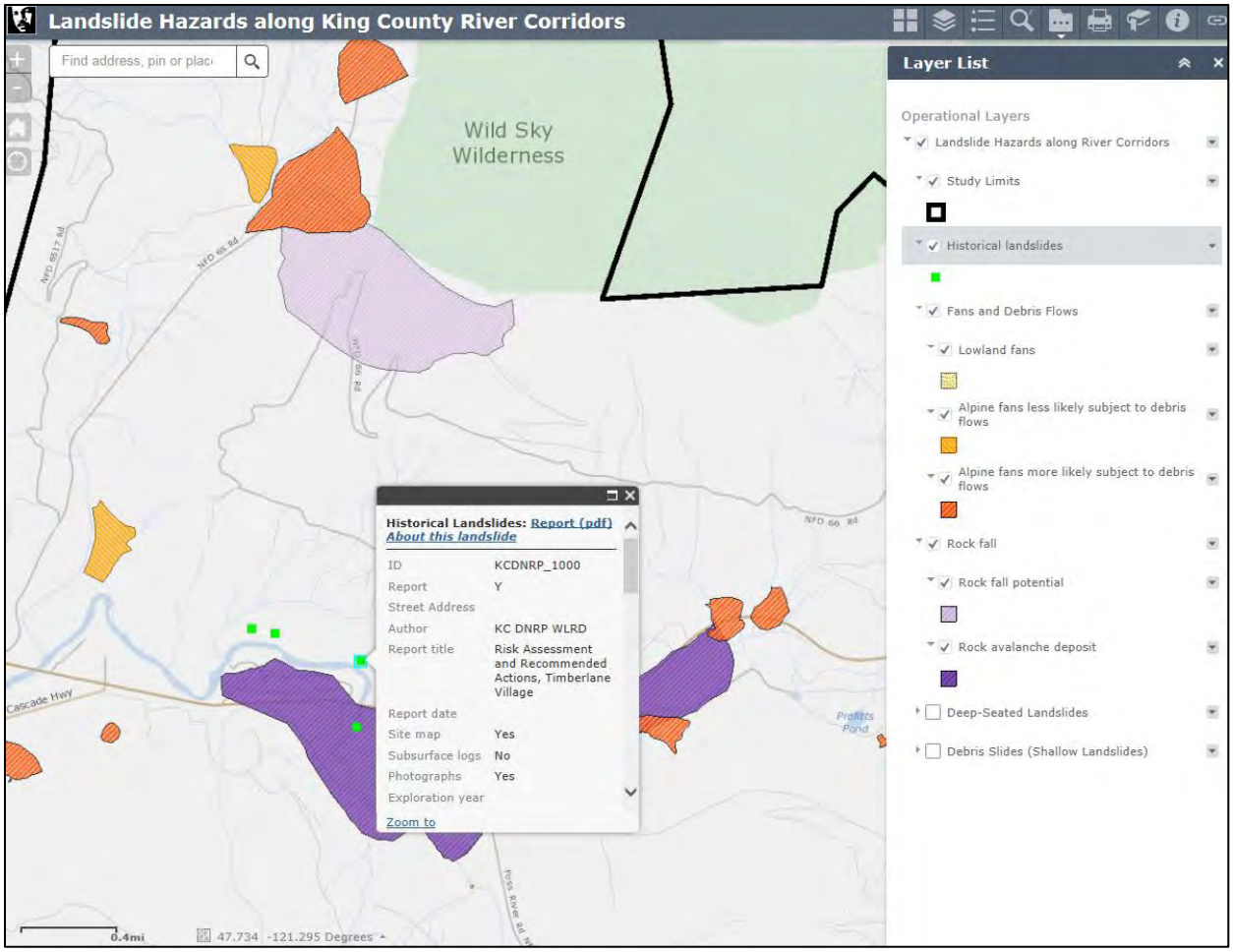

Figure 35. Example of landslide map data webtool showing rock fall, rock avalanche deposits, fans and historical landslide inventory in the South Fork Skykomish River corridor.

6.0 FUTURE CONSIDERATIONS

In the future it is likely that improved imagery will become available, improved mapping techniques will be developed, and additional landsliding will occur. All of these point to the potential for refining the present landslide hazard mapping in the future. An ongoing program to update the present mapping would better define the extent, character and timing of potential landslide hazards throughout the study area. Climate change may also influence the occurrence of landslides in the future. It is likely that increasing rainfall duration, frequency, and intensity will lead to an increase in landsliding on the valley walls of the river corridors in King County.

A program to maintain and update the existing mapping would include adding new landslide events to the existing inventory, refining existing mapping as new imagery becomes available, and monitoring developments in landslide science to identify new mapping approaches that would better characterize landslide hazards in the county. Compiling the present mapping in a GIS environment simplifies the process of making such refinements in the future.

7.0 DISCLAIMER

The map produced during this project ('Map") identifies areas within the study limits that have been categorized as potential landslide hazard areas. The map does not purport to identify actual landslide hazards or existing landslide risks for specific properties. The Map does not purport to show all areas of instability or potential instability within the study limits. The Map does not include influences from climate change and seismic events.

This mapping project included a classification of landslides by type (deep-seated landslides, potential shallow debris landsliding, depositional fans, potential rock fall, and rock avalanche deposits) and the identification of historically active landslides within the study limits. Mapping methodologies were researched and geological and geotechnical information was incorporated as available.

Landscape scale models were applied to areas across the study limits for potential rock fall and shallow debris landsliding. Mapping deep-seated landslides, depositional fans and rock avalanche deposits were based entirely on interpretation of LiDAR imagery, reports, and published geologic mapping. Features too small or indistinct to be visible were not included. LiDAR imagery across the study limits has been assembled from a variety of sources collected at different times and resolutions. Additional geologic and geotechnical information may exist, but the information relied upon for this report is limited to the 314 sources previously described. Landslide delineation methods used to prepare this map are subject to changes in the future, as such methods are improved. This mapping identifies areas potentially subject to the various landslide processes described herein, but does not address the probability or timing of such an occurrence. Potential runout areas have not been evaluated and are not shown in this map. For further information about the LiDAR data, contact the King County GIS Center.

An inventory of historically active landslides was populated with data collected from several internal and external entities. Additional information that may exist but was not received by the date of this document was not used. Until additional funds become available to update the map and inventory, these and future events will not be included.

These mapping methods, as applied within the extents of the study limits, were reviewed by a committee of geological professionals (the Technical Review Committee). Mapping results were peer reviewed by King County staff. Some mapped landslides were verified by field inspection.

Funding for the preparation of this mapping project along the major rivers (South Fork Skykomish, Snoqualmie, Green, White, Sammamish and Cedar Rivers) and Issaquah Creek was provided by the King County Flood Control District.

The information included on the Map has been compiled by King County staff from a variety of sources and is subject to change without notice. King County makes no representations or warranties, express or implied, as to accuracy, completeness, timeliness, or rights to the use of such information. King County shall not be liable for information provided to the County from other entities. King County shall not be liable for any errors, omissions, or inaccuracies in such information regardless of their cause, and King County shall not be liable for any decision made, action taken, or action not taken by the user in reliance upon such information. This document is not intended for use as a survey product. King County shall not be liable for any general, special, indirect, incidental, or consequential damages including, but not limited to, lost revenues or lost

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Appendix A: DEEP-SEATED LANDSLIDES MAPPING BY SHANNON & WILSON, INC.

Slumps Identification for the
King County Flood Control District
Landslide Project
King County Water and
Land Resources Division
King County, Washington

December 30, 2015

SHANNON & WILSON, INC.

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Submitted To:
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21-1-21859-031

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SLUMPS IDENTIFICATION FOR THE KING COUNTY FLOOD CONTROL DISTRICT LANDSLIDE PROJECT
KING COUNTY WATER AND LAND RESOURCES DIVISION
KING COUNTY, WASHINGTON

1.0 OVERVIEW

This report summarizes Shannon & Wilson, Inc.'s (Shannon & Wilson's) deliverables and describes the methods we used for mapping slumps and slump-related features within the study area for the King County (KC) Flood Control District (FCD) Landslide Project area (Figure 1). The KC FCD study area includes river floodplain areas within unincorporated and incorporated portions of KC, but does not include Vashon and Maury Islands.

2.0 DELIVERABLES

Shannon & Wilson's deliverables for this project include:

- Nine georeferenced ArcGIS 10.2 shapefiles that delineate slumps and slump-related features in the FCD Landslide Project area (Appendix A, Electronic Deliverables).
- This summary report.

Table 1 lists slump features and shapefile geometry types for each of the nine shapefiles. Tabular attributes for each shapefile are detailed in Tables 2 and 3.

3.0 METHODS

Mr. Stephen Newman of Shannon & Wilson mapped slumps (i.e., landslides greater than 15 feet deep) in the FCD project area in modified accordance with Oregon Department of Geology and Mineral Industries Special Paper 42 (Burns and Madin, 2009). Mr. Newman used professional judgment to identify, delineate, and characterize slumps and slump-related features in ArcGIS, using the KC standard coordinate system NAD 1983 HARN State Plane WA North. Mapping decisions were based primarily on observations of geomorphic indicators in Light Detection and Ranging- (LiDAR-) derived rasters, color orthophotos, black and white aerial photos, and other georeferenced base maps. Slope-steepness rasters and hillshade rasters were generated from the raw bare-earth LiDAR data using the Spatial Analyst and 3D Analyst ArcGIS extensions. Three hillshade rasters were generated for each watershed, using three different sun-illumination angles, to facilitate identification of landslides on slopes of varying aspects.

3.1 Data Sources

KC delivered the following ArcGIS base layers to Shannon & Wilson:

- A polygon shapefile of the KC FCD Landslide Project mapping boundaries (Figure 1).
- A polygon shapefile of the slumps mapped during the KC FCD Phase 1 preliminary landslide-mapping campaign.
- Raw, bare-earth, LiDAR-derived digital elevation models (DEMs) in raster format, buffered 500 feet beyond the limits of the KC FCD study-area boundaries. The LiDAR DEMs have a pixel depth of 32 bits per pixel, and pixel dimensions of 6 feet by 6 feet.
- Color orthophotos acquired in the year 2000 in raster format, buffered 500 feet beyond the limits of the KC FCD study-area boundaries. The provided rasters are three-band RGB raster. Each band has a pixel depth of 8 bits per pixel, and pixel dimensions of 4 feet by 4 feet.
- Color orthophotos acquired in the year 2012 in raster format, buffered 500 feet beyond the limits of the KC FCD study-area boundaries. The provided rasters are three-band RGB raster. Each band has a pixel depth of 8 bits per pixel, and pixel dimensions of 1 foot by 1 foot.
- Orthorectified, black-and-white aerial photos for western KC, acquired in the year 1936 in raster format, buffered 500 feet beyond the limits of the KC FCD study-area boundaries. The rasters were mosaicked together from scanned 3-foot by 3-foot prints.
- An example map and example attribute tables.

Shannon & Wilson downloaded the following layers from online geographic information system databases hosted by KC and the Washington State Department of Natural Resources (DNR):

- A 1:100,000-scale map of landslide and mass wasting features, identified in ArcMap as "DNR_LandslideMapping_100k." The complete 1:100,000-scale landslide source data can be downloaded at: http://www.dnr.wa.gov/Publications/ger_portal_surface_geology_100k.zip
- A 1:24,000-scale map of landslide and mass wasting features, identified in ArcMap as "DNR_LandslideMapping_24k." The complete 1:24,000-scale landslide source data can be downloaded at: http://www.dnr.wa.gov/Publications/ger_portal_surface_geology_24k.zip
- A 1:24,000-scale map of surficial geologic units, identified in ArcMap as "DNR_GeologicUnits_24K," containing information defining the extent, age,

lithologic type, and formation of geologic units for selected areas of Washington State.

- A polyline shapefile showing streams and rivers in KC.
- A polygon shapefile showing streams, rivers, and water bodies in KC.
- A polyline shapefile showing forest roads in KC.
- A polyline shapefile showing trails in KC.

3.2 Slump Geomorphic Indicators

Geomorphic indicators of slumps, after Varnes (1978), include:

- A headscarp.
- Flank scarps or lateral-release surfaces.
- A deposit located downslope from the headscarp, typically characterized by distinct breaks in slope along its lateral margins and toe.
- Hummocky topography on the deposit surface.
- Transverse ridges, tension cracks, fissures, and trenches on the deposit surface.
- Tension cracks behind (i.e., uphill from) the headscarp.
- Minor scarps within the deposit mass.
- Radial cracks.
- A concave zone of depletion and a convex zone of accumulation.

After initial failure, displaced debris may move downslope as a deformed but semi-coherent solid producing the characteristic topographic signature of a slump (Figure 2). In other cases, the displaced material has sufficient moisture content, and undergoes sufficient deformation that it moves downslope as a viscous flow and produces a different but also characteristic topographic flow form (Figure 3). The landslides mapped in this project include both of these end members, as well as a continuum of landslides showing intermediate behavior.

3.3 Polygon Slump Features

A discrete polygon was traced around the spatial extent of each of the following slump and slump-related features in ArcGIS:

- The slump deposit.
- The slump headscarp and flank scarps.

- The composite outline of the slump deposit, headscarp, and flank scarps (slump outline).
- Closed depressions within the footprint of the slump outline.
- Bodies of standing water within the footprint of the slump outline.

3.4 Polyline Slump Features

A discrete polyline was traced along each of the following slump-related features in ArcGIS:

- The top of the slump headscarp.
- The top of minor scarps within the slump deposit.
- The course of incised rills and streams that lie within the footprint of the slump outline.
- The toe of the slump deposit, where coincident with a riverbank.

3.5 Relative Ages of Slumps

We assigned a relative age to each slump. Relative ages fell into three categories: (a) "Pre-historic" (greater than 150 years old), (b) "Historic" (less than 150 years old), and (3) "Unknown" (age was difficult to estimate). We estimated the relative age of each slump based on the following geomorphic characteristics, after McCalpin (1974) and Burns and Madin (2009):

- Sharpness of geomorphic slump indicators.
- Relative erosional scouring of the slump topography.
- Infilling of marginal and internal depressions by sediment from slope wash and mass-movement processes.
- Drainage-induced incision and dissection of slump deposits.

3.6 Confidence Ratings

We assigned numerical confidence ratings to each of the following geomorphic indicators for each mapped slump, using a scale from 0 to 10:

1. Slump headscarp.
2. Slump deposit and toe.
3. Slump morphology (e.g., irregular or hummocky surface).
4. Other slump features (internal scarps, sag ponds, closed depressions, compression ridges, radial cracks, etc; rating assigned collectively and only once).

Numerical confidence ratings are a function of how clearly identifiable a feature is, and how morphological distinguishable a feature is from its surrounding terrain. For example:

- A concave headscarp identified on a smooth, low-curvature, convex slope is morphologically distinguishable, and receives a relatively higher confidence rating than a low-curvature, convex headscarp identified on a hummocky slope.
- A hummocky slump deposit identified on a smooth floodplain is morphologically distinct, and receives a relatively higher confidence rating than a poorly resolvable slump deposit mapped in an area of poor LiDAR resolution.
- A steep embayed headscarp with distinguishable lateral boundaries on a steep, laterally continuous valley sidewall receives a higher confidence rating than a steep, planar headscarp with diffuse or indistinguishable lateral boundaries on a similar slope.

For each slump, we cumulatively summed the four numerical confidence ratings listed above, and derived a categorical confidence rating based on the sum. A categorical confidence rating of "High" corresponds to a cumulative numerical confidence total of greater than or equal to 30, a confidence rating of "Moderate" corresponds to a total of less than 30 and greater than 10, and a confidence rating of "Low" corresponds to a total of less than or equal to 10. Figures 4 through 6 show examples of slumps assigned Low, Moderate, and High confidence ratings, respectively.

3.7 Cartographic Measurements

The following cartographic measurements were calculated in ArcGIS for each polygon slump feature, using the "Calculate Geometry" built-in tool:

- Polygon area (square feet).
- Polygon centroid X coordinate (feet).
- Polygon centroid Y coordinate (feet).
- Polygon perimeter length (feet).

The following cartographic measurements were calculated in ArcGIS for each polyline slump feature, using the "Calculate Geometry" built-in tool:

- Polyline midpoint X coordinate (feet).
- Polyline midpoint Y coordinate (feet).
- Polyline length (feet).
- Parent vs. non-parent, as per sample table.

3.8 Slump Identifications (IDs), Parent Slumps, and Parent IDs

We assigned a boolean classification to each slump based on whether or not the slump is a "parent" slump, in accordance with the example map and data template included in the project scope. This attribute, termed "isParent" in the attribute tables for shapefiles Nos. 1 through 6, is assigned a value of "Y" if the slump is a parent slump, and a value of "N" if the slump is not a parent slump. A parent slump is defined as any slump that has spawned one or more "child" slumps, i.e., at some point in time after formation of the parent slump, a subsequent slump occurred within or initiated within the parent slump. By default, standalone slumps are also parent slumps. A child slump is a parent slump only if it has one or more children. The only slumps assigned an "isParent" value of "N" are child slumps that do not have one or more child slumps of their own.

We assigned each slump a unique integer ID, termed "lsID" in the attribute tables for shapefiles Nos. 1 through 6. An additional attribute, termed "parentID," references the lsID of each slump's parent. For parent slumps that do not themselves have parents, i.e., standalone slumps, the parentID is simply the value of the slump's own lsID. For slumps that do have parents, the parentID is the value of the parent slump's lsID. Shapefiles Nos. 7 through 9 also have a parentID attribute; for a given feature in these three shapefiles, the parentID value corresponds to the lsID of the slump that encloses the feature.

3.9 Slope Setting

We assigned a slope setting classification of "Modified" or "Natural" to each slump. Slope setting is "Natural" by default. Geomorphic or optical evidence of human earthworks within the slump outline, including roads, building pads, excavations, quarries, and other grading, triggered a classification of "Modified."

3.10 Mapping Quality Control

We consulted preexisting landslide inventory maps only after completing an initial round of Phase-2 slump mapping, as a quality control reference. These maps include the KC FCD Phase 1 landslide inventory map and two DNR landslide inventory maps. We identified and mapped additional landslides following consultation of these maps.

4.0 LIMITATIONS

Slump and slump-related features identification in the KC FCD Landslide Project area is subject to the following limitations:

- Shannon & Wilson cannot guarantee the accuracy of the input data and base layers used to map slumps and slump-related features.

- KC did not provide optical imagery for the entire KC FCD Landslide Project area.
- The quality of orthorectification of the 1936 aerial photographs varied, especially along the mosaicked margins of the scanned photos.
- Landslides were not field checked.
- Despite efforts by Shannon & Wilson that are standard practice in Western Washington, it is likely that we missed or overlooked some landslides.
- Human activities such as large-scale earthworks or landslide mitigation can mask the geomorphic evidence of past slumping. Identification of landslides in such areas is difficult at best.
- The DOGAMI slump-mapping method (Burns and Madin, 2009) is a deposit-centric method, meaning that if no slump deposit is present, the slump is not mapped. Even slumps with clearly identifiable headscarps are not mapped if the deposits have been completely eroded away by fluvial or other erosional processes.
- The DOGAMI slump-mapping method (Burns and Madin, 2009) is not a completely objective mapping method. The professional experience of the mapper plays a large role in the initial identification of each slump. Personal judgment plays a large role in assigning confidence ratings and relative ages to each slump.
- The LiDAR DEM provided by KC for the Snoqualmie River Watershed lacked data over an area of about 1.7 square miles, centered at the following coordinates: 1,375,820 feet N, 197,870 feet E (coordinates in NAD 1983 HARN State Plane WA North). We downloaded replacement LiDAR data for this missing patch from the Puget Sound LiDAR Consortium.
- LiDAR DEMs and derivative base maps exhibit variable spatial resolution and quality due to the spatial variation of laser return-pulse density, and due to post-processing limitations. Low pulse-return density is often due to reduced flight coverage during the LiDAR acquisition phase, or due to dense vegetation cover, which prevents adequate laser penetration to, and reflection from, the ground surface. Because modern forestry practices prohibit removal of trees from steep, landslide-prone slopes, some landslides remain densely forested, exacerbating the problem of poor pulse-return density. Accurate and thorough landslide mapping is not always practical in areas with moderate or poor LiDAR resolution. Landslides that are identified in such areas may receive lower confidence ratings due to the mapper's reduced ability to resolve some geomorphic slump indicators. An example of moderate LiDAR spatial resolution occurs in the uppermost end of the Raging River valley (Figure 7; see also landslides lsID=237 and lsID=524). An example of poor LiDAR spatial resolution occurs along the Beckler River, in the upper Skykomish River watershed (Figure 8; see also terrain near landslide lsID=112).

Shannon & Wilson has prepared the enclosed Appendix B, “Important Information About Your Geotechnical/Environmental Proposal,” to assist you and others in understanding the use and limitations of our reports.

SHANNON & WILSON, INC.

Stephen D. Newman
Geology Staff

William T. Laprade, L.E.G.
Senior Vice President

WTL:CAR/sdn

5.0 REFERENCES

Burns, W. J., and Madin, I. P., 2009, Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (LiDAR) Imagery: Oregon Department of Geology and Mineral Industries Special Paper 42 [CD].

McCalpin, J., 1974, Preliminary age classification of landslides for inventory mapping: 21st Annual Symposium on Engineering Geology and Soils Engineering, Proceedings: Moscow, Idaho, University of Idaho, p. 99-111.

Varnes, D. J., 1978, Slope movement types and processes, *in* Schuster, R. L., and Krizek, R. J., eds., Landslides - Analysis and Control: Washington, D.C., Transportation Research Board Special Report 176, p. 11-33.

TABLE 1
SHAPEFILE FEATURE TYPES AND GEOMETRY TYPES

Shapefile No.	Shapefile Name	Feature Description	Shapefile Geometry Type
1	fc01_SlumpOutline.shp	Outline of entire slump (outer edge of following four layers)	Polygon
2	fc02_TopOfHeadscarp.shp	Top of headscarp	Line
3	fc03_HeadScarpFlanks.shp	Headscarp and flank scarps	Polygon
4	fc04_LandslideDeposit.shp	Slump deposit/body	Polygon
5	fc05_InternalScarps.shp	Internal scarps, if present	Line
6	fc06_ToeAlongRiverBank.shp	Toe along riverbank, if present	Line
7	fc07_ClosedDepressions.shp	Closed depressions, if present	Polygon
8	fc08_StandingWater.shp	Standing water, if present	Polygon
9	fc09_DrainageCourses.shp	Drainage courses, if present	Line

TABLE 2
TABULAR ATTRIBUTES FOR SHAPEFILES NOS. 1 THROUGH 6

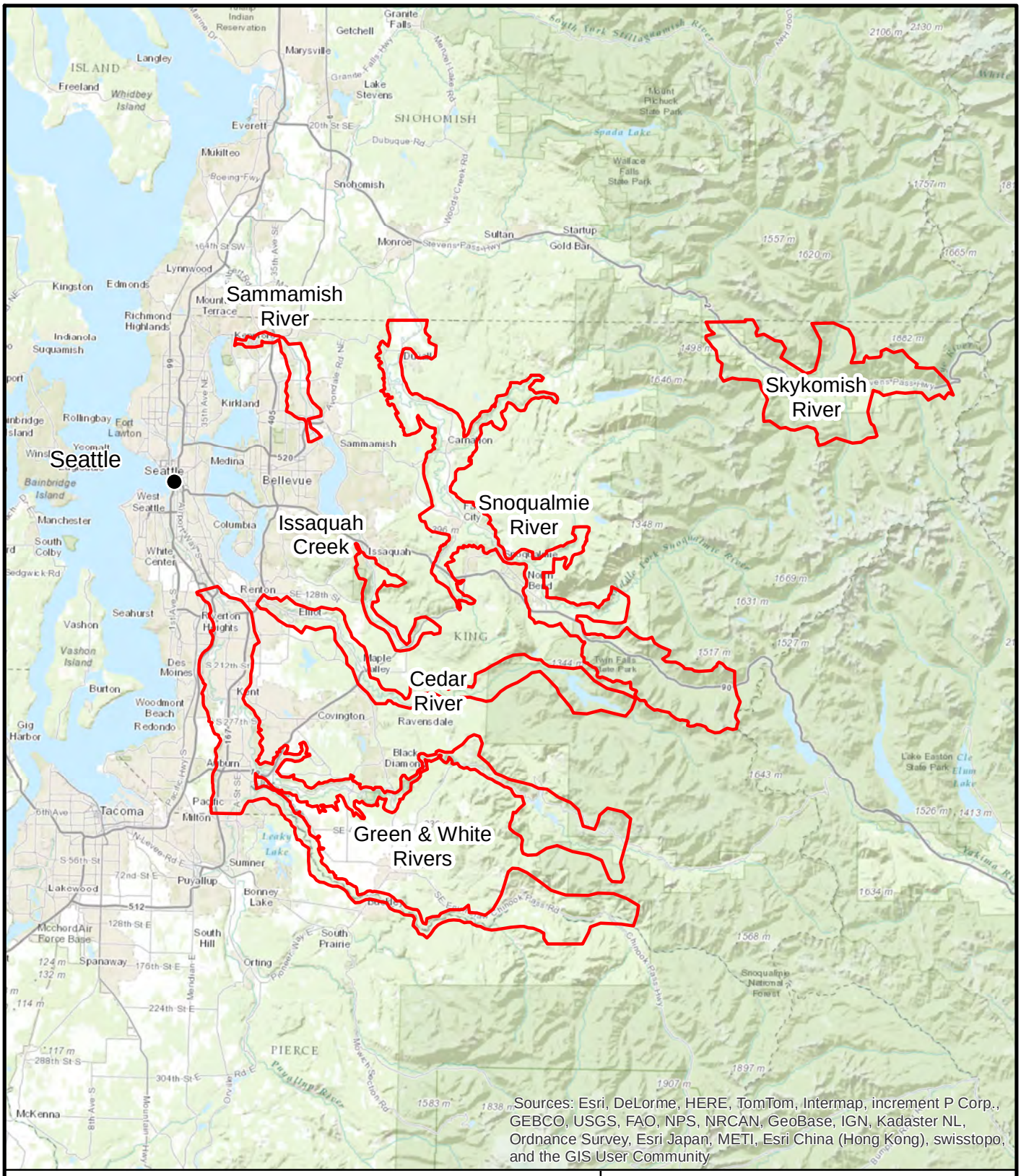
Attribute Name	Type	Attribute Description and/or Values	Units
OBJECTID	Integer	Unique ID feature	
lsID	Integer	Unique ID of slump; for each slump, this value is internally consistent between shapefiles #1 through #6, and is equal to the OBJECTID of the 'fc04_LandslideDeposit.shp' feature for each slump	N/A
areaSqFt	Floating Point	Area of (polygon) feature	Square Feet
centroidX / midpointX	Floating Point	X coordinate of polygon centroid / X coordinate of polyline midpoint	Feet
centroidY / midpointY	Floating Point	Y coordinate of polygon centroid / Y coordinate of polyline midpoint	Feet
perimFt	Floating Point	Perimeter length (of polygon)	Feet
lengthFt	Floating Point	Length (of polyline)	Feet
feature	Text	Description (Slump Outline / Top of Headscarp / Headscarp and Flank / Body / Internal Scarp / Toe Along Riverbank)	N/A
isParent	Text	Answers if this feature is a parent slump (Yes / No)	N/A
parentID	Integer	lsID of parent slump	N/A
slopeSetting	Text	Answers if the slump terrain has been modified by humans (Natural / Modified)	N/A
relativeAge	Text	Relative age of slump (Historic [less than 150 years old] / Pre-historic [greater than 150 years old] / Unknown)	N/A
interpAuthor	Text	Initials of geologist that drew the feature (SDN)	N/A
lidarSource	Text	LiDAR data source (KCWLRD)	N/A
lidarDate	Date	Date of LiDAR delivery to author (July 13, 2015)	N/A
headscarp	Integer	Confidence level of headscarp identification (on a scale from 0 [not identifiable] to 10 [clearly identifiable]	N/A
toeDeposit	Integer	Confidence level of toe and deposit identification (on a scale from 0 [not identifiable] to 10 [clearly identifiable]	N/A
morphology	Integer	Confidence level of general slump-morphology identification (on a scale from 0 [not identifiable] to 10 [clearly identifiable]	N/A
otherFeatures	Integer	Confidence level of identification of internal scarps, sag ponds, closed depressions, compression ridges, radial cracks (on a scale from 0 [not identifiable] to 10 [clearly identifiable]	N/A
totalConfidence	Integer	Cumulative sum of previous four features' confidence levels (ranges from 0 to 40)	N/A
confidenceRating	Text	Categorical confidence rating; dependent on value of totalConfidence (High [greater than or equal to 30] / Moderate [less than 30 and greater than 10] / Low [less than or equal to 10])	N/A

Notes:
ID = identification
KCWLRD = King County Water & Land Resources Division
LiDAR = Light Detection and Ranging
N/A = Not applicable
SDN = Stephen Newman

TABLE 3
TABULAR ATTRIBUTES FOR SHAPEFILES NOS. 7 THROUGH 9

Attribute Name	Type	Attribute Description and/or Values	Units
OBJECTID	Integer	Unique ID of feature	N/A
areaSqFt	Floating Point	Area of (polygon) feature	Square feet
centroidX / midpointX	Floating Point	X coordinate of polygon centroid / X coordinate of polyline midpoint	Feet
centroidY / midpointY	Floating Point	Y coordinate of polygon centroid / Y coordinate of polyline midpoint	Feet
perimFt	Floating Point	Perimeter length (of polygon)	Feet
lengthFt	Floating Point	Length (of polyline)	Feet
feature	Text	Description (Closed Depression / Standing Water / Drainage Course)	N/A
parentID	Integer	lsID of slump outline that encloses this feature	N/A
featureSetting	Text	Answers if the feature has been modified by humans (Natural / Modified)	N/A
relativeAge	Text	Relative age of slump (Historic [less than 150 years old] / Pre-historic [greater than 150 years old] / Unknown)	N/A
interpAuthor	Text	Initials of geologist that drew the feature (SDN)	N/A
lidarSource	Text	LiDAR data source (KCWLRD)	N/A
lidarDate	Date	Date of LiDAR delivery to author (July 13, 2015)	N/A

Notes:
ID = identification
KCWLRD = King County Water & Land Resources Division
LiDAR = Light Detection and Ranging
N/A = Not applicable
SDN = Stephen Newman



LEGEND

KCFCD Landslide Project mapping limits

N
W E
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0 5 10
Miles

Slumps Identification for the KCFCD Landslide Project
King County Water & Land Resources Division
King County, Washington

KCFCD LANDSLIDE PROJECT AREA

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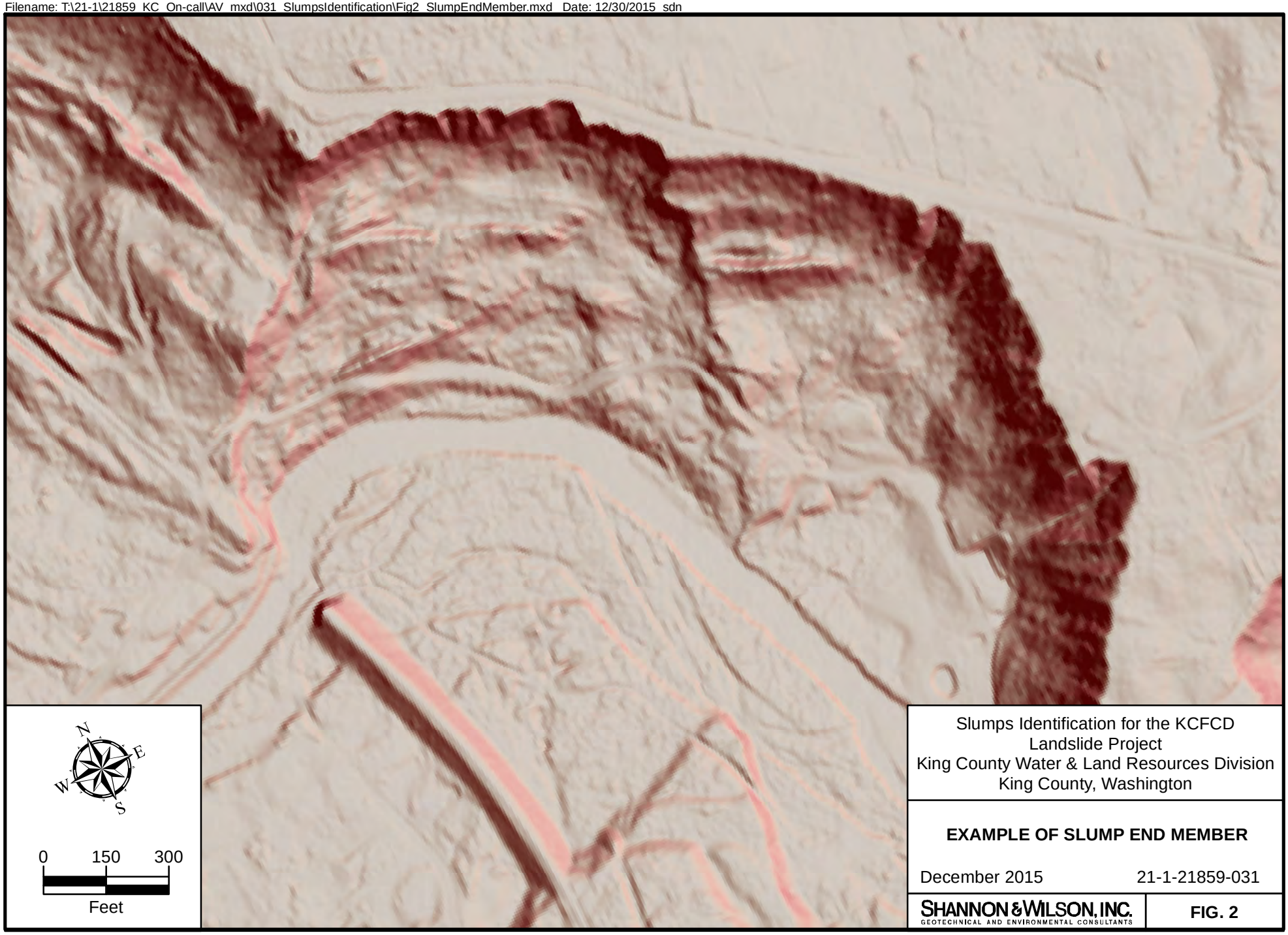
FIG. 1

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig1_ProjectArea.mxd Date: 12/30/2015 sdn

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig2_SlumpEndMember.mxd Date: 12/30/2015 sdn



Slumps Identification for the KCFCD
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King County Water & Land Resources Division
King County, Washington

EXAMPLE OF SLUMP END MEMBER

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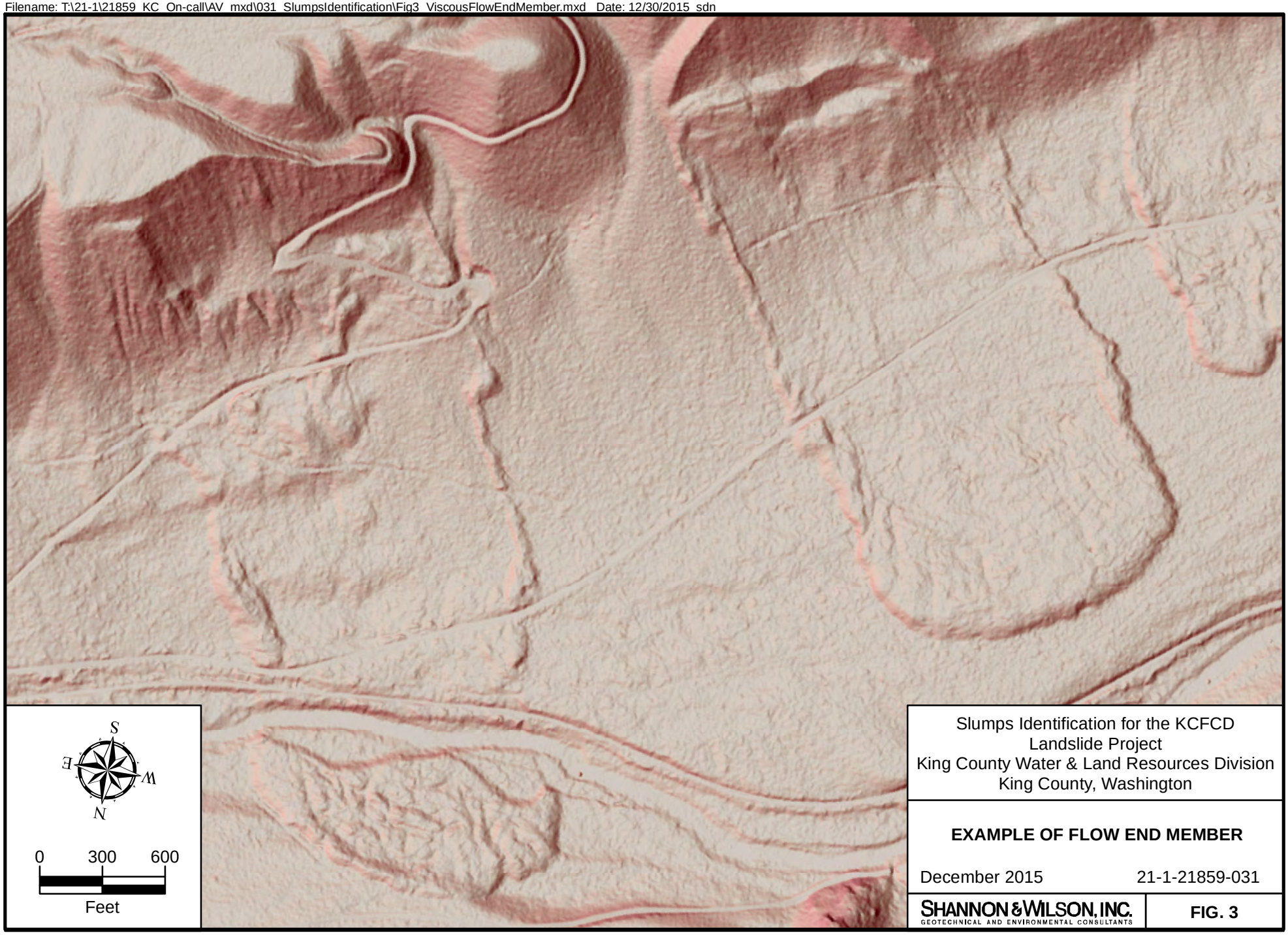
FIG. 2

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig3_ViscousFlowEndMember.mxd Date: 12/30/2015 sdn



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King County Water & Land Resources Division
King County, Washington

EXAMPLE OF FLOW END MEMBER

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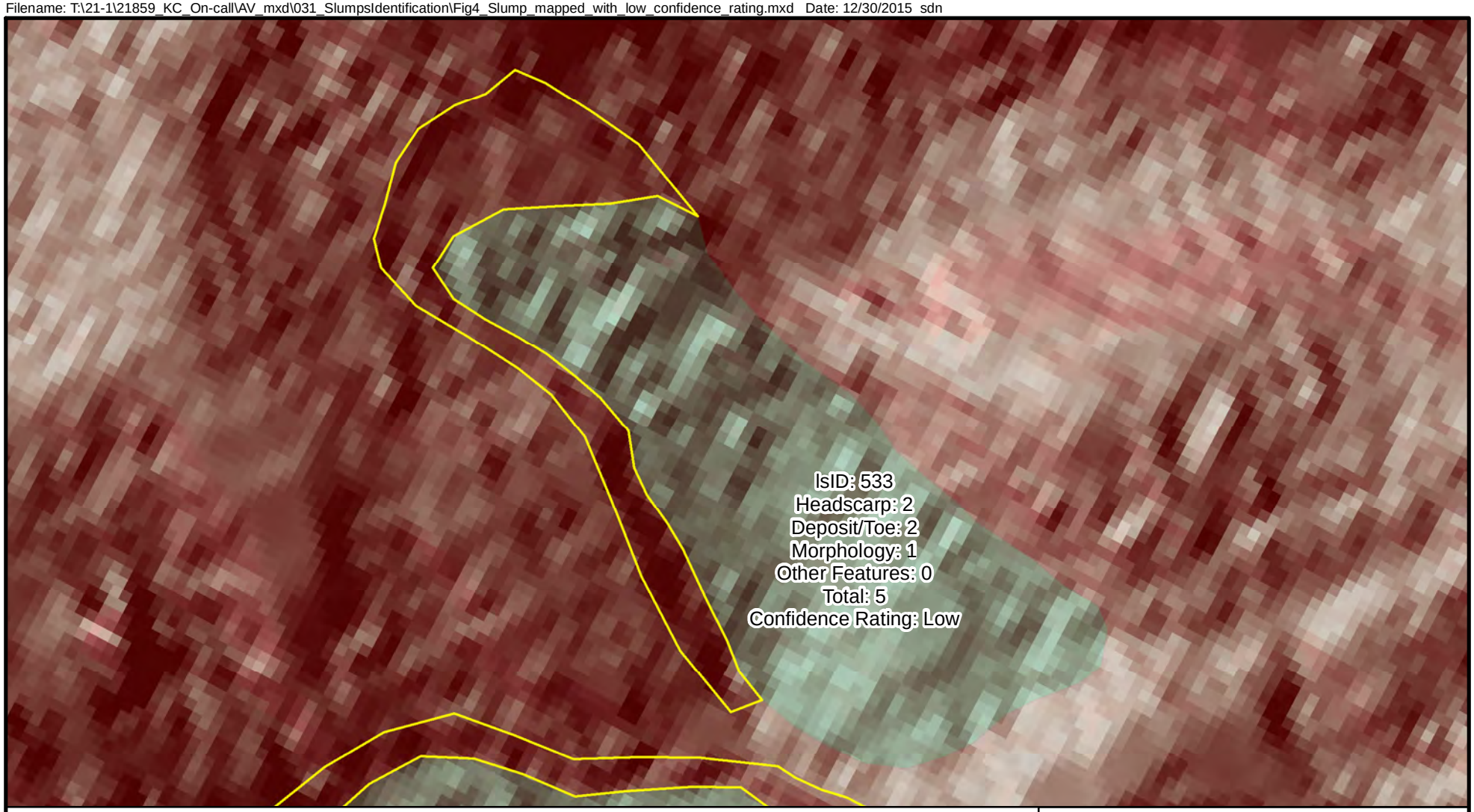
FIG. 3

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig4_Slump_mapped_with_low_confidence_rating.mxd Date: 12/30/2015 sdn



LEGEND

Head & Flank Scarps

Slump Deposit

0 80 160

Feet

Slumps Identification for the KCFCD
Landslide Project
King County Water & Land Resources Division
King County, Washington

SLUMP MAPPED WITH LOW CONFIDENCE RATING

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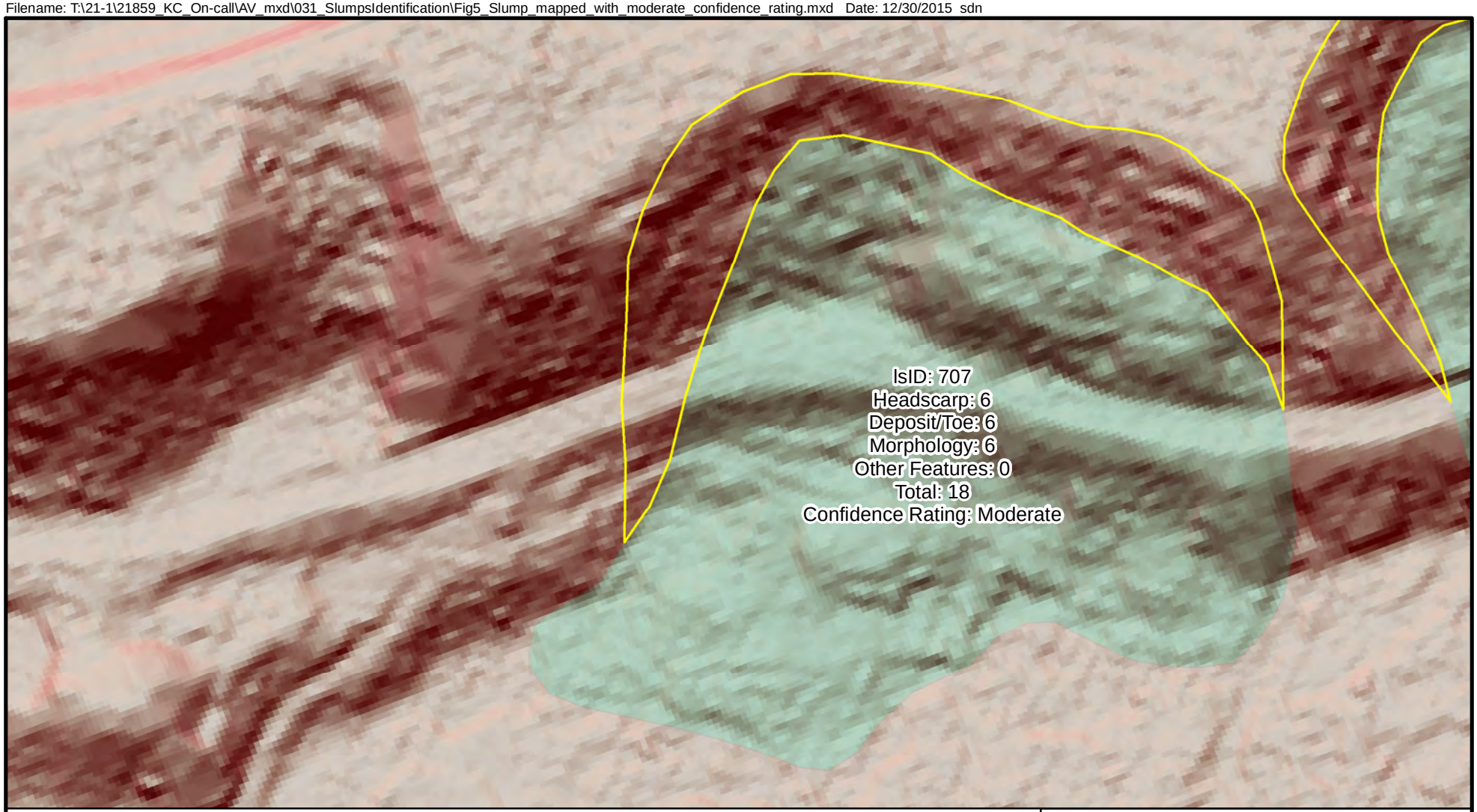
FIG. 4

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig5_Slump_mapped_with_moderate_confidence_rating.mxd Date: 12/30/2015 sdn



LEGEND

Head & Flank Scarps

Slump Deposit

0 150 300

Feet

Slumps Identification for the KCFCD Landslide Project
King County Water & Land Resources Division
King County, Washington

SLUMP MAPPED WITH MODERATE CONFIDENCE RATING

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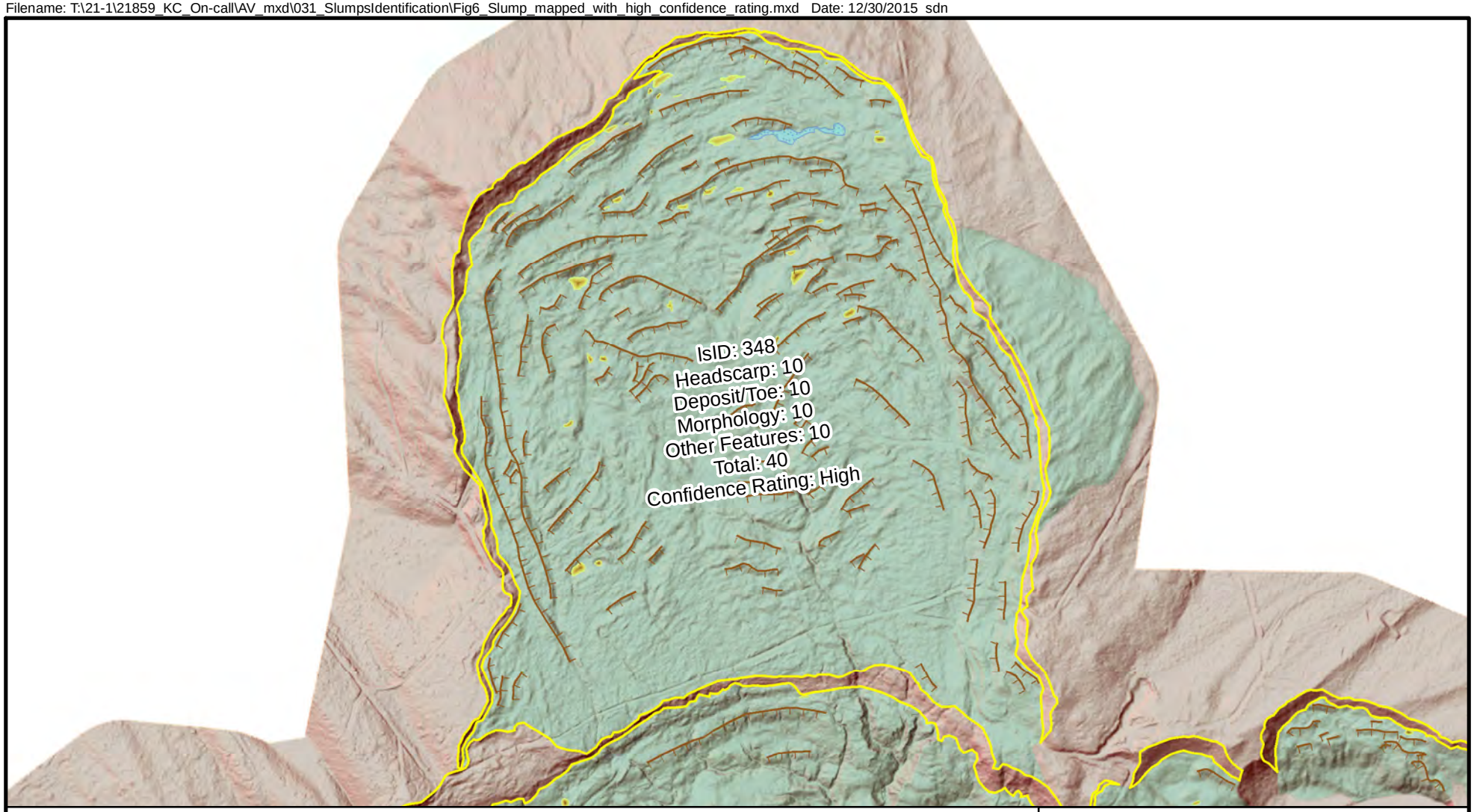
FIG. 5

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig6_Slump_mapped_with_high_confidence_rating.mxd Date: 12/30/2015 sdn



LEGEND

- Head & Flank Scarps
- Slump Deposit
- Internal Scarps
- Closed Depressions
- Standing Water

N S E W

0 1,000 2,000
Feet

Slumps Identification for the KCFCD
Landslide Project
King County Water & Land Resources Division
King County, Washington

SLUMP MAPPED WITH HIGH CONFIDENCE RATING

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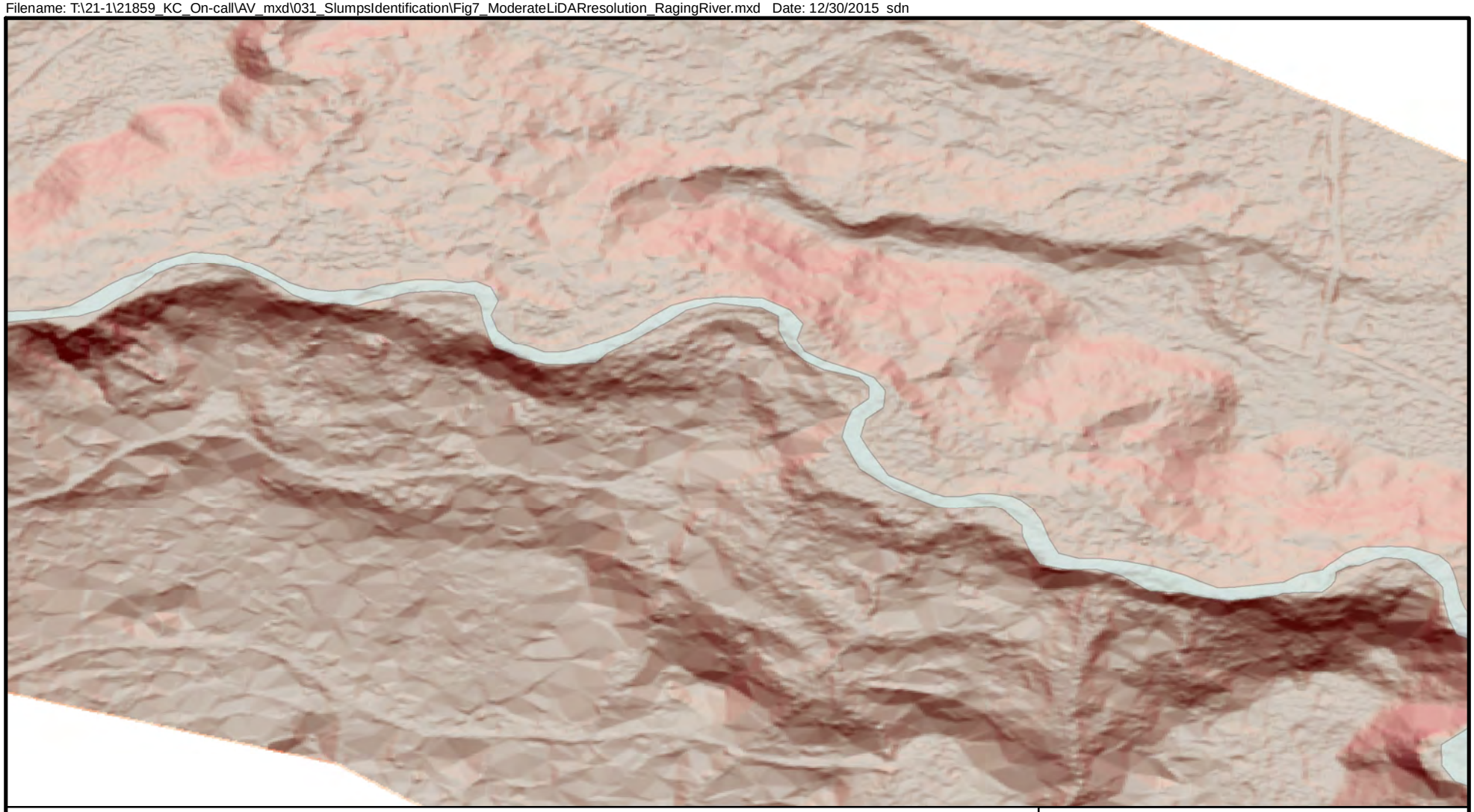
FIG. 6

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig7_ModerateLiDARresolution_RagingRiver.mxd Date: 12/30/2015 sdn



LEGEND

Raging River

N
W E
S

0 500 1,000
Feet

Slumps Identification for the KCFCD
Landslide Project
King County Water & Land Resources Division
King County, Washington

LIDAR HILLSHADE WITH MODERATE SPATIAL RESOLUTION - RAGING RIVER

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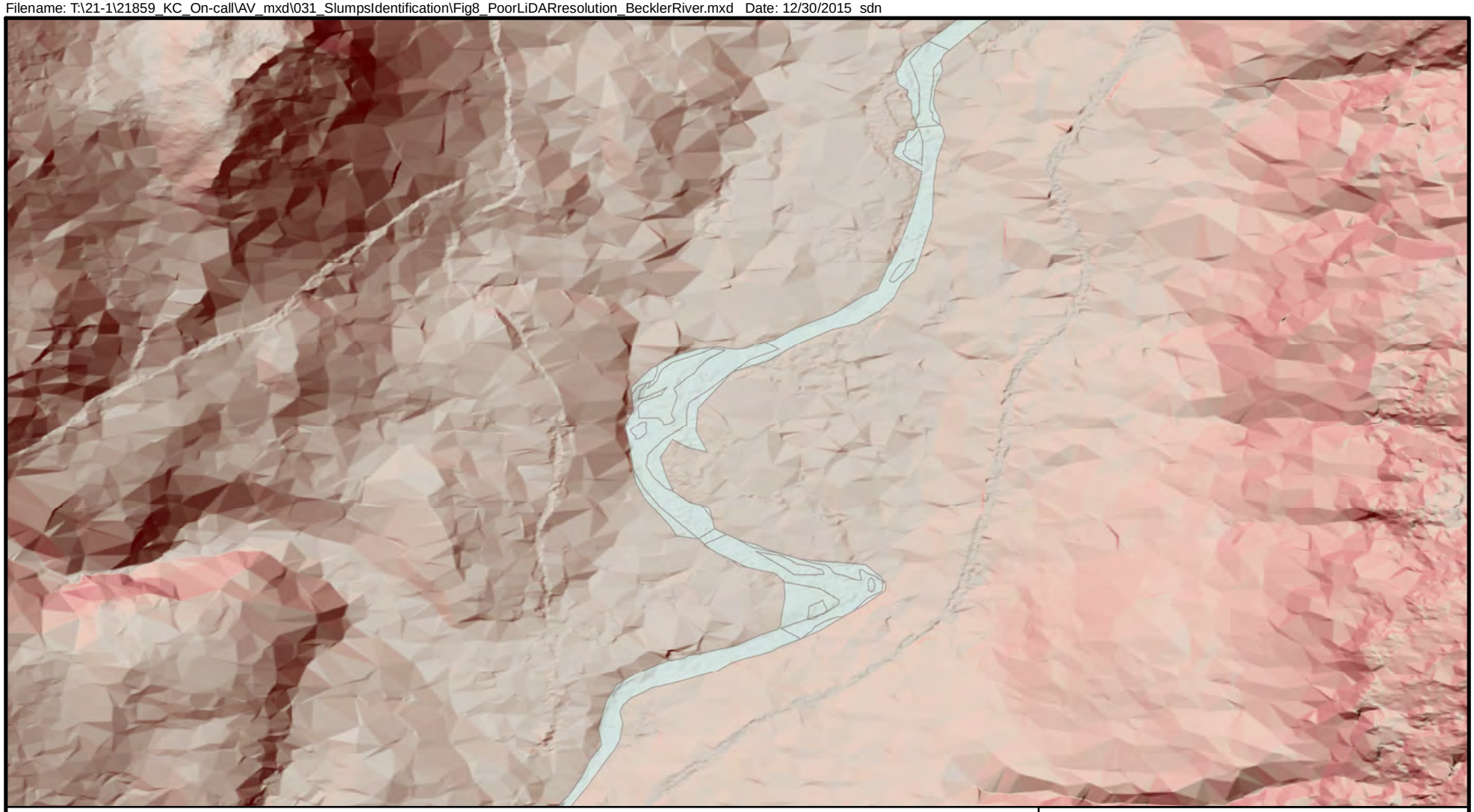
FIG. 7

Filename: T:\21-1\21859_KC_On-call\AV_mxd\031_SlumpsIdentification\Fig8_PoorLiDARresolution_BecklerRiver.mxd Date: 12/30/2015 sdn



LEGEND

Beckler River

N
W E
S

0 1,000 2,000
Feet

Slumps Identification for the KCFCD
Landslide Project
King County Water & Land Resources Division
King County, Washington

LIDAR HILLSHADE WITH POOR SPATIAL RESOLUTION - BECKLER RIVER

December 2015 21-1-21859-031

SHANNON & WILSON, INC.
GEOTECHNICAL AND ENVIRONMENTAL CONSULTANTS

FIG. 8

APPENDIX A

ELECTRONIC DELIVERABLES

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ELECTRONIC DELIVERABLES

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APPENDIX B

INPORTANT INFORMATION ABOUT YOUR GEOTECHNICAL/ENVIRONMENTAL REPORT

IMPORTANT INFORMATION ABOUT YOUR GEOTECHNICAL/ENVIRONMENTAL REPORT

CONSULTING SERVICES ARE PERFORMED FOR SPECIFIC PURPOSES AND FOR SPECIFIC CLIENTS.

Consultants prepare reports to meet the specific needs of specific individuals. A report prepared for a civil engineer may not be adequate for a construction contractor or even another civil engineer. Unless indicated otherwise, your consultant prepared your report expressly for you and expressly for the purposes you indicated. No one other than you should apply this report for its intended purpose without first conferring with the consultant. No party should apply this report for any purpose other than that originally contemplated without first conferring with the consultant.

THE CONSULTANT'S REPORT IS BASED ON PROJECT-SPECIFIC FACTORS.

A geotechnical/environmental report is based on a subsurface exploration plan designed to consider a unique set of project-specific factors. Depending on the project, these may include: the general nature of the structure and property involved; its size and configuration; its historical use and practice; the location of the structure on the site and its orientation; other improvements such as access roads, parking lots, and underground utilities; and the additional risk created by scope-of-service limitations imposed by the client. To help avoid costly problems, ask the consultant to evaluate how any factors that change subsequent to the date of the report may affect the recommendations. Unless your consultant indicates otherwise, your report should not be used: (1) when the nature of the proposed project is changed (for example, if an office building will be erected instead of a parking garage, or if a refrigerated warehouse will be built instead of an unrefrigerated one, or chemicals are discovered on or near the site); (2) when the size, elevation, or configuration of the proposed project is altered; (3) when the location or orientation of the proposed project is modified; (4) when there is a change of ownership; or (5) for application to an adjacent site. Consultants cannot accept responsibility for problems that may occur if they are not consulted after factors which were considered in the development of the report have changed.

SUBSURFACE CONDITIONS CAN CHANGE.

Subsurface conditions may be affected as a result of natural processes or human activity. Because a geotechnical/environmental report is based on conditions that existed at the time of subsurface exploration, construction decisions should not be based on a report whose adequacy may have been affected by time. Ask the consultant to advise if additional tests are desirable before construction starts; for example, groundwater conditions commonly vary seasonally.

Construction operations at or adjacent to the site and natural events such as floods, earthquakes, or groundwater fluctuations may also affect subsurface conditions and, thus, the continuing adequacy of a geotechnical/environmental report. The consultant should be kept apprised of any such events, and should be consulted to determine if additional tests are necessary.

MOST RECOMMENDATIONS ARE PROFESSIONAL JUDGMENTS.

Site exploration and testing identifies actual surface and subsurface conditions only at those points where samples are taken. The data were extrapolated by your consultant, who then applied judgment to render an opinion about overall subsurface conditions. The actual interface between materials may be far more gradual or abrupt than your report indicates. Actual conditions in areas not sampled may differ from those predicted in your report. While nothing can be done to prevent such situations, you and your consultant can work together to help reduce their impacts. Retaining your consultant to observe subsurface construction operations can be particularly beneficial in this respect.

A REPORT'S CONCLUSIONS ARE PRELIMINARY.

The conclusions contained in your consultant's report are preliminary because they must be based on the assumption that conditions revealed through selective exploratory sampling are indicative of actual conditions throughout a site. Actual subsurface conditions can be discerned only during earthwork; therefore, you should retain your consultant to observe actual conditions and to provide conclusions. Only the consultant who prepared the report is fully familiar with the background information needed to determine whether or not the report's recommendations based on those conclusions are valid and whether or not the contractor is abiding by applicable recommendations. The consultant who developed your report cannot assume responsibility or liability for the adequacy of the report's recommendations if another party is retained to observe construction.

THE CONSULTANT'S REPORT IS SUBJECT TO MISINTERPRETATION.

Costly problems can occur when other design professionals develop their plans based on misinterpretation of a geotechnical/environmental report. To help avoid these problems, the consultant should be retained to work with other project design professionals to explain relevant geotechnical, geological, hydrogeological, and environmental findings, and to review the adequacy of their plans and specifications relative to these issues.

BORING LOGS AND/OR MONITORING WELL DATA SHOULD NOT BE SEPARATED FROM THE REPORT.

Final boring logs developed by the consultant are based upon interpretation of field logs (assembled by site personnel), field test results, and laboratory and/or office evaluation of field samples and data. Only final boring logs and data are customarily included in geotechnical/environmental reports. These final logs should not, under any circumstances, be redrawn for inclusion in architectural or other design drawings, because drafters may commit errors or omissions in the transfer process.

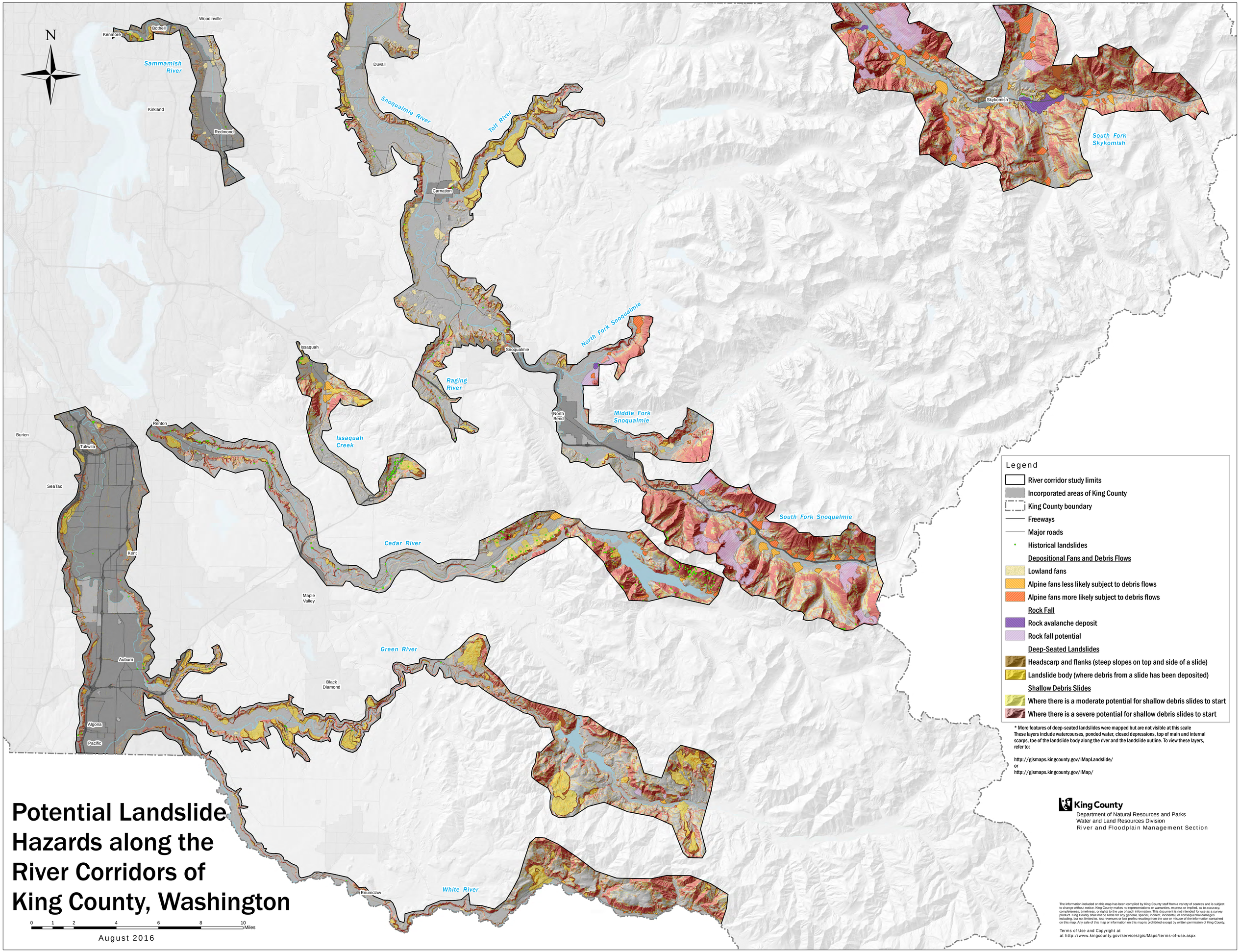
To reduce the likelihood of boring log or monitoring well misinterpretation, contractors should be given ready access to the complete geotechnical engineering/environmental report prepared or authorized for their use. If access is provided only to the report prepared for you, you should advise contractors of the report's limitations, assuming that a contractor was not one of the specific persons for whom the report was prepared, and that developing construction cost estimates was not one of the specific purposes for which it was prepared. While a contractor may gain important knowledge from a report prepared for another party, the contractor should discuss the report with your consultant and perform the additional or alternative work believed necessary to obtain the data specifically appropriate for construction cost estimating purposes. Some clients hold the mistaken impression that simply disclaiming responsibility for the accuracy of subsurface information always insulates them from attendant liability. Providing the best available information to contractors helps prevent costly construction problems and the adversarial attitudes that aggravate them to a disproportionate scale.

READ RESPONSIBILITY CLAUSES CLOSELY.

Because geotechnical/environmental engineering is based extensively on judgment and opinion, it is far less exact than other design disciplines. This situation has resulted in wholly unwarranted claims being lodged against consultants. To help prevent this problem, consultants have developed a number of clauses for use in their contracts, reports and other documents. These responsibility clauses are not exculpatory clauses designed to transfer the consultant's liabilities to other parties; rather, they are definitive clauses that identify where the consultant's responsibilities begin and end. Their use helps all parties involved recognize their individual responsibilities and take appropriate action. Some of these definitive clauses are likely to appear in your report, and you are encouraged to read them closely. Your consultant will be pleased to give full and frank answers to your questions.

The preceding paragraphs are based on information provided by the
ASFE/Association of Engineering Firms Practicing in the Geosciences, Silver Spring, Maryland

Appendix B: POTENTIAL LANDSLIDE HAZARDS ALONG RIVER CORRIDORS



Potential Landslide Hazards along the River Corridors of King County, Washington

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