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LANDSLIDE INVENTORY AND RISK REDUCTION OF THE NORTH AND CENTRAL PORTIONS OF WASCO COUNTY, OREGON

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

WEB MAP

Landslide inventory web map of a portion of Wasco County, Oregon
https://storymaps.arcgis.com/stories/c636418e140848cb962fa5e80a96e28b

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.
Geodatabase is Esri® v10.1 format. Metadata is embedded in the geodatabase and provided as xml.

Wasco_Landslide_Inventory.gdb
feature classes:
Deposits (polygons)
Scarp_Flanks (polygons)
Scarps (polylines)
Study Area (polygon)

1.0 REPORT SUMMARY

Landslides are common throughout Oregon due to the combination of high precipitation, steep slopes, landslide-prone geologic units, and frequent earthquakes. In June 2020, the Oregon Department of Geology and Mineral Industries (DOGAMI) received a grant from the Federal Emergency Management agency (FEMA) through the Risk MAP program as a Cooperating Technical Partner (CTP)(Cooperative Agreement EMS-2020-CA-00010) to perform regional landslide inventory mapping of the north and central portions of Wasco County, Oregon. A share of this funding was passed through to Wasco County Planning and Oregon Department of Land Conservation and Development (DLCD) to work on risk reduction activities. The purpose of this project was to provide detailed information about the landslide hazards in this area and perform continued landslide risk reduction. The main tasks included:

- Creating a detailed lidar-based landslide inventory following DOGAMI Special Paper 42 (Burns and Madin, 2009)
- Limited field checking landslides
- Identifying priority landslide risk reduction actions with the communities in Wasco County
- Writing this report and delivering maps and GIS data

We found 2,693 landslide deposits in the project area; 536 are deep landslides, 214 are rockfall deposits, 1,653 are debris flow deposits, and the rest of the landslides are shallow landslides or unclassified. In general, there are more large deep landslides in the northern portion of the project area where the Dalles geologic formation is located. The rockfalls are located mostly along steep basalt slopes adjacent to the rivers and streams such as Badger Creek, Tygh Creek, White River, Deschutes River, Mill Creek, and the Columbia River. Most of the debris flow deposits are in the steep channels of Tygh Valley and along the valley walls of many small drainages (such as Eightmile Creek) in the central-western portion of the project area.

Risk reduction strategies identified during the project include increasing public awareness, planning and zoning approaches, and emergency response considerations. The approach for landslide risk reduction in this project focused on community needs, as relayed by relevant community stakeholders, in combination with established recommendations from published reports. We began by compiling a list of recommendations from published reports. Next, we held three small group brainstorm meetings with communities in Wasco County to further develop the action items list. The action item lists from these three meetings were compiled into a master list. Finally, we held two more small group meetings to prioritize the list and establish pathways to success for these action items.

2.0 INTRODUCTION

Landslides are one of the most widespread and damaging natural hazards in Oregon. To continue reducing damage and losses from landslides, areas of landslide hazard must first be accurately located. The first step in landslide hazard assessment is to create an inventory of historic (<150 years old) and prehistoric (>150 years old) landslides. Landslide mapping in Wasco County has been performed in the past by student researchers, external consultants, and the Oregon Department of Geology and Mineral Industries (DOGAMI). However, none of these past studies used airborne lidar-derived high-resolution topographic data and geographic information system (GIS) data. Burns (2007) concluded that lidar data should be used for all future landslide studies. The lidar-derived topographic data provide a high-resolution view of the ground surface, which was not available in the past. The use of lidar-derived bare-earth digital elevation model (DEMs) was fundamental to the landslide mapping performed in this study.

The general term "landslide" refers to a range of mass movements including rockfalls, debris flows, earth slides, and other mass movements (Varnes, 1978). Different types of landslides have different frequencies of movements, different triggering conditions, and very different resulting hazards. All landslides can be classified into six types of movement: 1) falls, 2) topples, 3) slides, 4) spreads, 5) flows, and 6) complex. Most slope failures are complex combinations of these distinct types, but the generalized groupings provide a useful means for framing discussion of the type of hazard associated with the landslide, the landslide characteristics, identification methods, and potential mitigation alternatives (Burns and Madin, 2009).

2.1 Project Area

Wasco County is in north-central Oregon. The northern county boundary is the Columbia River, which is also the northern state boundary between Oregon and Washington. The Columbia River is entrenched in the Columbia River Gorge along the length of Wasco County. The western boundary of the county follows the eastern slopes of the High Cascades and includes the portions of Wasco with the most relief. The eastern boundary of the county mostly follows the Deschutes River southward from its terminus at the Columbia River. The Deschutes River is deeply incised into a canyon with relatively steep slopes (**Figure 1; Figure 2**). The county covers approximately 626.5 mi^2 (1623 km^2).

As of the 2010 census, the population was 25,213. There are several incorporated cities, including The Dalles, Mosier, Dufur, and Maupin, and many unincorporated communities such as Tygh Valley and Pine Grove. There are several dams in Wasco County, including the U.S Army Corps of Engineers Dalles Dam on the Columbia River (**Figure 2**). The Crow Creek Dam is located along South Fork Mill Creek and impounds the Crow Creek Reservoir, which is part of the drinking water system for several communities in Wasco County. There are two primary transportation routes in the county: Interstate 84 trends east-west along the Columbia River and Highway 97 trends north-south through the middle of the county.

This project studied 626.5 mi^2 (1,623 km^2) out of a total of 2,394 mi^2 (6,200 km^2) in Wasco County. There is landslide hazard in the project area as indicated both by historic landslides and by many prehistoric slides that have and could reactivate. The current Statewide Landslide Information Database for Oregon (SLIDO) release 4 has 135 mapped landslide polygons within or touching the Wasco project area (Franczyk and others, 2019). Many of these previously mapped landslides are indicated by overlapping polygons, the result of different authors mapping the same area. During the current effort, we reviewed all of these previously mapped landslides and made decisions on keeping or removing and reshaping.

There have been several notable historically active large deep landslides in Wasco County, including the Scenic Drive-Kelly Avenue Landslide in The Dalles, which moved significantly in the late 1970s and early to mid-1980s (Beaulieu, 1977; Sholin, 1982). Several other historically active landslides occurred in the Oregon Department of Transportation (ODOT) Quarry adjacent to the city of Mosier. These landslides happened in the 1980s (personal communications, Russel Frost, ODOT). In addition to the large deep landslides, rockfall has occurred countless times along the very steep basalt cliffs throughout the county, building up piles of past rockfall deposits or talus at the cliff bases.

Figure 1. Map of Wasco and neighboring counties in north-central Oregon and the project area (outlined in red).

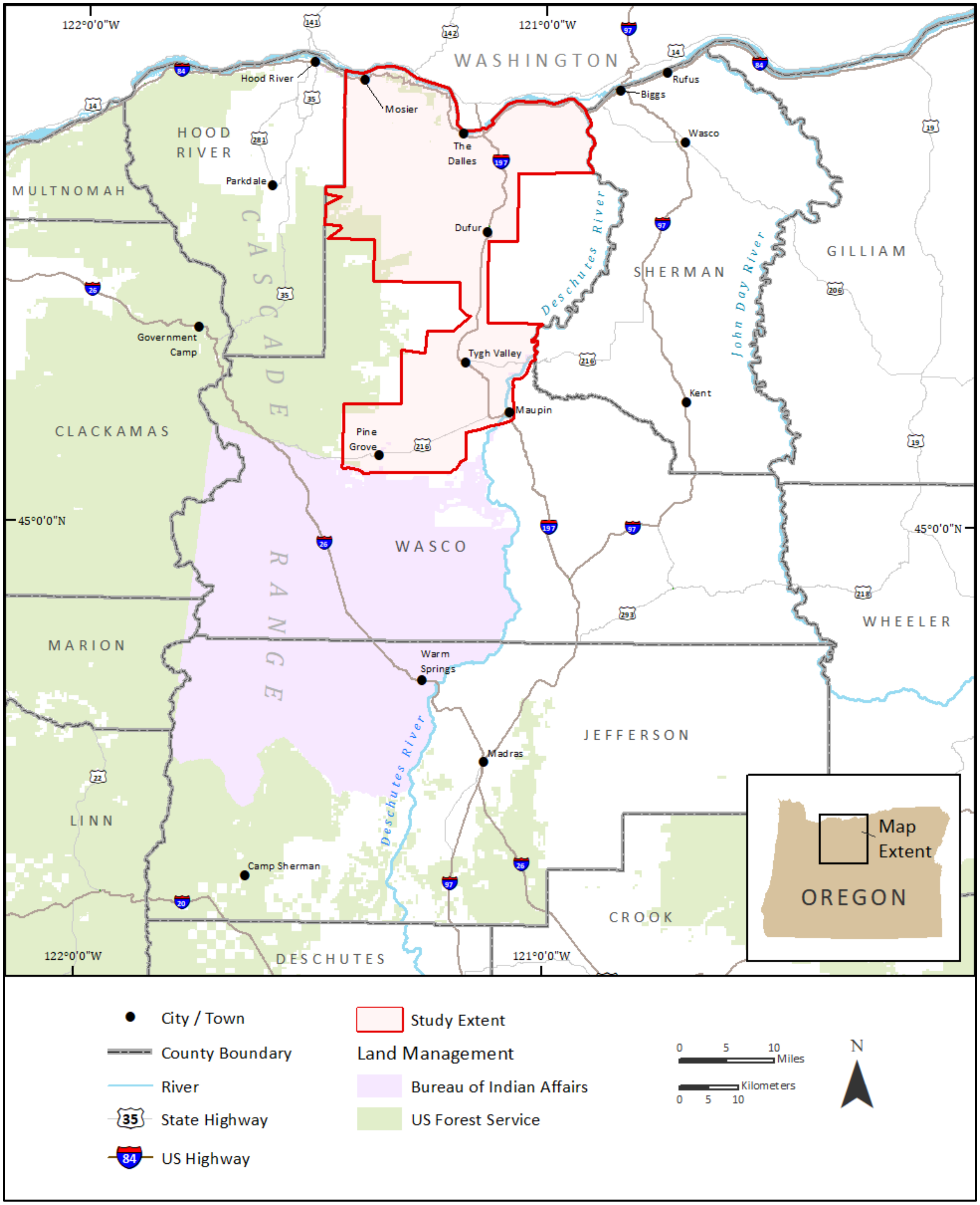
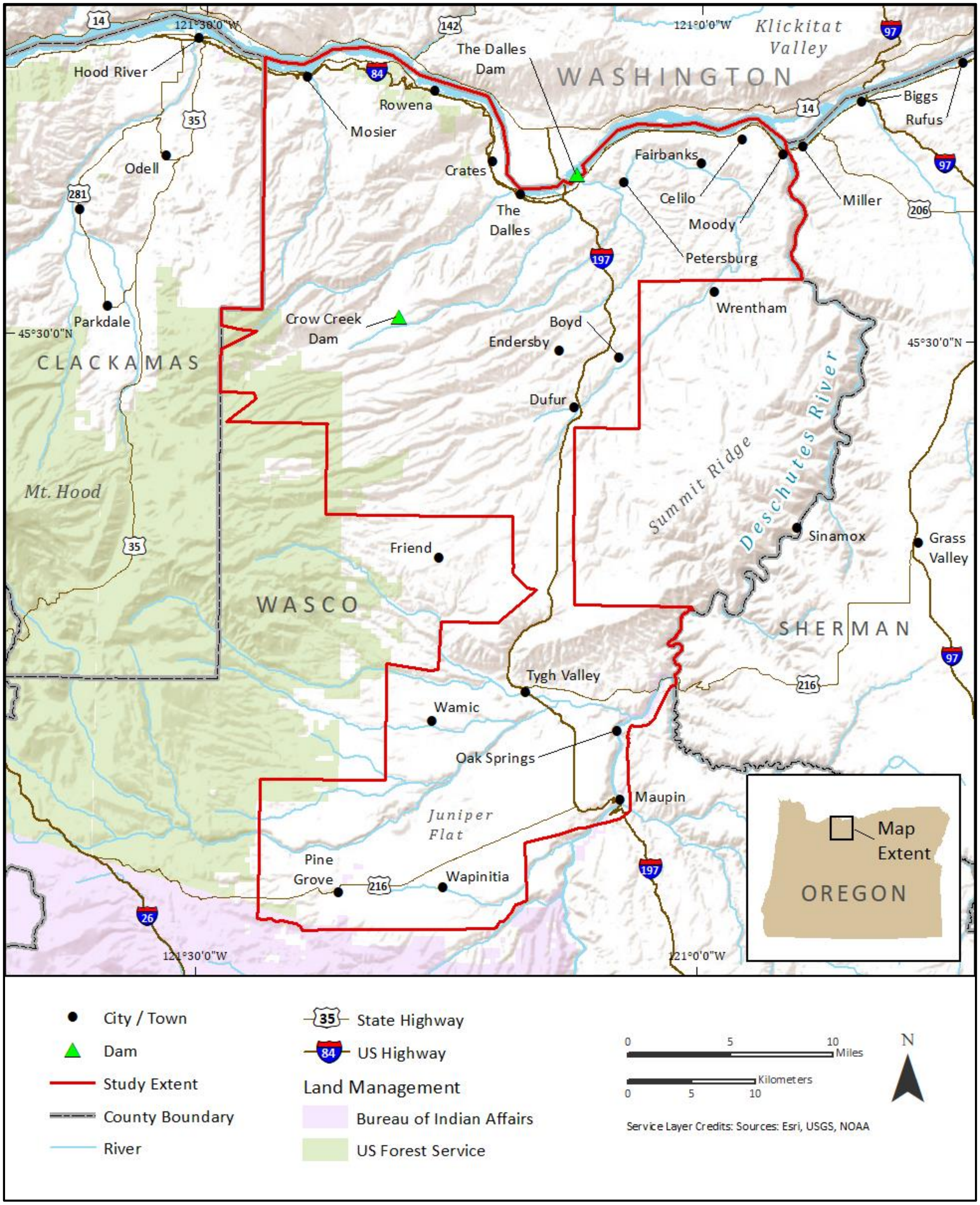


Figure 2. Map of the Wasco County landslide inventory project area (outlined in red).



2.2 Purpose

Recently, the Oregon Lidar Consortium collected high-resolution, high-accuracy lidar data to produce detailed DEMs for portions of Wasco County. The bare-earth lidar data provide a much better image of the surface geomorphology, allowing identification of features associated with landslides, such as concave slope depressions, vertical or steep scarps, shear zones located along the flanks of a landslide, and shortening features of landslides such as toes, transverse ridges, and snouts (Burns and Madin, 2009). Recognition of such features can be used to identify landslides with a high level of certainty and map landslide deposits accurately. In the past, landslide maps were created by using a combination of aerial photography and extensive field survey. The use of lidar-derived bare-earth DEMs is the key to the landslide mapping performed in this study. For example, we found several historically active large deep landslides in and around the community of Mosier that went unrecognized in Bulletin 91 (Beaulieu, 1977). The purpose of this project was to create a new modern landslide inventory and develop landslide risk reduction action items and pathways to accomplish those actions.

In 2020, DOGAMI was funded by the FEMA Cooperative Technical Partners (CTP) program to prepare a modern landslide inventory for portions of Wasco County, Oregon (**Figure 2**). Some of that funding was passed through DOGAMI to Wasco County and DLCD to continue working on landslide risk reduction using the new landslide inventory dataset produced as a deliverable for this project. The landslide risk reduction portion of the project was focused on brainstorm sessions with the communities to develop lists of needs and action items to reduce landslide risk. This report describes the methods and results of the landslide inventory mapping and the recommendations for landslide risk reduction.

For this study we identified and mapped existing landslides to provide users with an updated understanding of the landslide hazard in this area. This study provides a landslide inventory mapped following DOGAMI Special Paper 42, Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery [called DOGAMI SP-42 for the remainder of this paper] for the project area portion of Wasco County (**Figure 2**; Burns and Madin, 2009).

Throughout this report we use the engineering geology terms *hazard*, *susceptibility,* and *risk*. The term hazard is defined here as a possible source of danger and in this report we are specifically referring to landslides as a hazard. The term susceptibility is defined here as 'relative likelihood of a specified action or process' and in this report the process is landsliding. The term risk is defined here as the possibility of loss or injury. In this report risk is the overlap of the hazard with assets (such as infrastructure) and their vulnerability to the hazard.

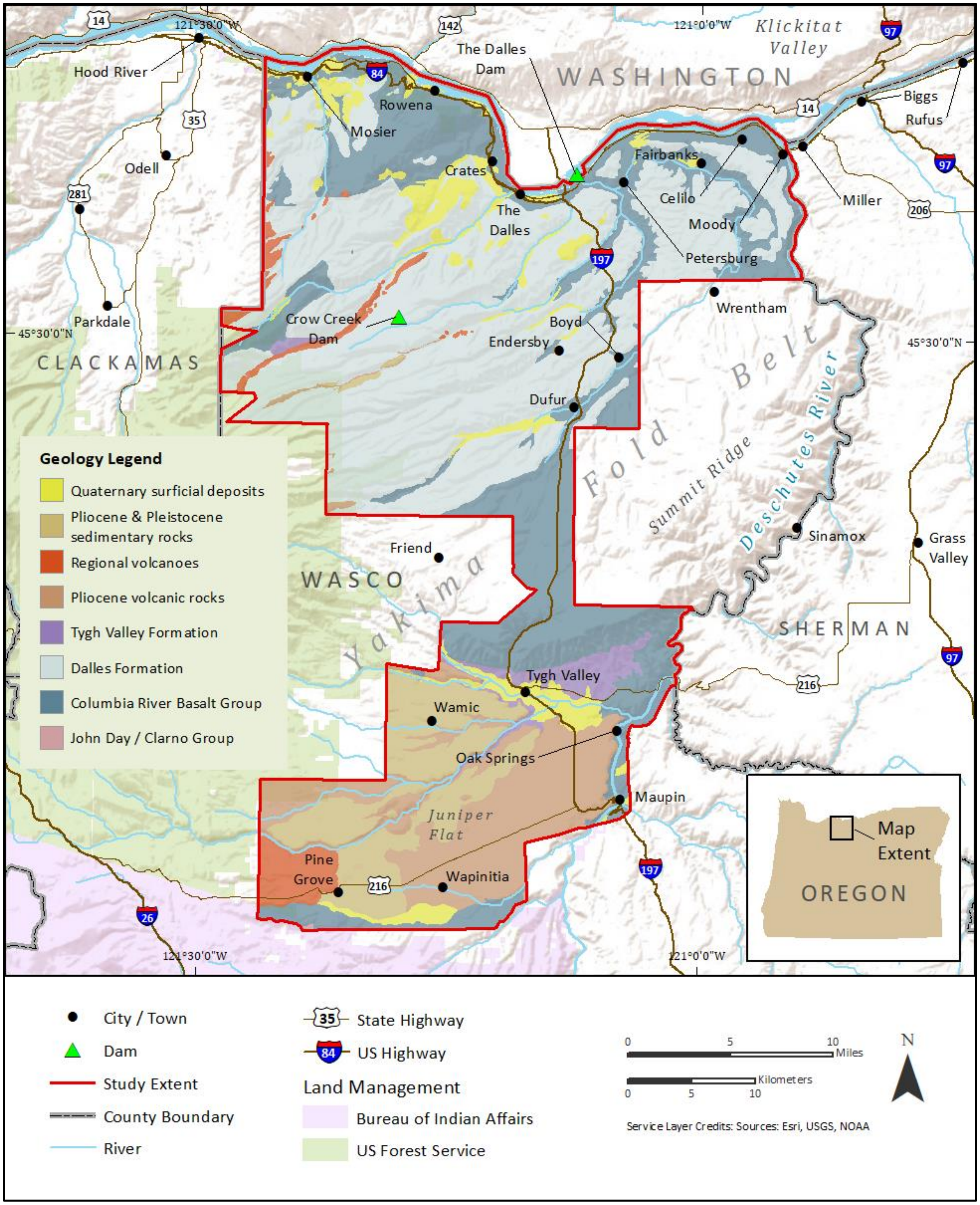
3.0 GEOLOGY

The study area lies along the eastern side of the Cascade Range in northern Oregon, ~28.5 mi (46 km) east of Mount Hood volcano. The Cascade Range is a north-south-trending volcanic arc stretching for ~800 mi (1,300 km) between northern California and southern British Columbia. Volcanoes making up the range are the observable magmatic expression of convergence along the Cascadia Subduction Zone, where the offshore Juan de Fuca tectonic plate is subducted beneath North America (Lux, 1982; Phillips and others, 1986; Verplanck and Duncan, 1987; Conrey and others, 2002; Sherrod, 2019).

The axis of the High Cascades in north-central Oregon is superimposed across the Yakima Fold Belt, a series of northeast-southwest-trending, asymmetric, locally overturned and faulted anticlinal ridges separated by broad synclinal valleys (Swanson and others, 1979, 1981; Anderson and Vogt, 1987; Watters, 1989; Reidel and Campbell, 1989; Tolan and Reidel, 1989; Anderson and others, 2013). Folds in the Yakima Fold Belt are generally east-west-trending across eastern Oregon and Washington, while across the Cascade Range, fold axes are more northeast in trend (Swanson and others, 1981; Bela, 1982; Reidel and others, 1989; Tolan and others, 2009). The High Cascades graben is segmented into three northward younging parts, including a southern segment between the Three Sisters and Mount Jefferson volcanoes, a central segment between Mount Jefferson and Mount Hood, and a northern segment between Mount Hood and Mount Adams volcano known as the Hood River graben (Conrey and others, 2002; Conrey and others, 2019). All segments of the graben are defined by significant offset along eastern boundary normal faults and asymmetric uplift of the western graben margin. Tilted fault blocks invariably dip eastward off the structural high. Development of the Hood River graben is related to a long history of regional clockwise tectonic rotation and northwest translation of crustal blocks along north-northwest-striking fault systems in the upper plate of the Cascadia Subduction Zone (McClaughry and others, 2022). The Yakima Fold Belt and the High Cascades graben are both active sources of crustal earthquakes in the region. Local crustal earthquakes are likely triggers of future (new) landslides and reactivations of portions of existing landslides within the project area.

The oldest rocks cropping out in the study area are part of the lower to middle Miocene Columbia River Basalt Group (CRBG), an extensive succession of tholeiitic basalt and basaltic andesite lava flows that cover more than 130,488 mi^2 (210,000 km^2) in parts of Washington, Oregon, and Idaho (**Figure 3**; Tolan and others, 1989; Reidel and Tolan, 2013). Members of the CRBG cropping out in the study area include the Pomona Member of the Saddle Mountains Basalt; Priest Rapids and Frenchman Springs members of the Wanapum Basalt; and Sentinel Bluffs, Winter Water, Ortley, and Grouse Creek members of the Grande Ronde Basalt. Generally thin (<6.6 ft [2 m]) and discontinuous horizons of fragmental sedimentary rock or paleosols are locally found separating individual lava flows. CRBG units commonly form distinctive bench and slope topography, resulting from differential erosion within and between flows. More easily erodible interflow zones are often marked by bands of trees, while more resistant flow interiors typically form continuous cliffs with grass-topped benches. Aggregate thickness of the CRBG in the study area is as much as 1,970 ft (600 m). Landslide hazards within the CRBG include rockfall and topple which are influenced by the spacing of joints and vertical cooling fractures (Beaulieu, 1977). Debris flows are also associated with CRBG because of the steep slopes and high relief. Large deep bedrock landslides also occur within the CRBG, especially in the northern portion of the study area along faults, joints, and interbeds (Beaulieu, 1977).

Figure 3. Generalized geologic map of the study area.



Regional CRBG units in this part of north-central Oregon are unconformably overlain by volcanic and sedimentary rocks of the upper Miocene and lower Pliocene Dalles Formation (**Figure 3**). They were chiefly erupted between ~8.8 and 5 Ma (McClaughry and others, 2020, 2021). The Dalles Formation was emplaced across a broad constructional volcanic highland along East Fork Hood River and in areas underlying present-day Mount Hood (McClaughry and others, 2020, 2021). In the eastern escarpment of the Hood River graben, along East Fork Hood River, the Dalles Formation is characterized by interlayered vent-proximal lava flows and domes, hypabyssal intrusions, block-and-ash flow deposits, and ash-flow tuff (McClaughry and others, 2020). Deposits mapped eastward to The Dalles and Dufur become increasingly rich in thick sections of block-and-ash-flow deposits, volcanogenic debris flow (lahar) deposits, hyperconcentrated flood-flow deposits, and ash-flow tuff, interbedded with horizons of fluvial conglomerate, sandstone, and siltstone (McClaughry and others, 2020, 2021). Intracanyon lava flows are nested into volcaniclastic rocks along several northeast-directed drainages between East Fork Hood River and Dufur. These lithologic associations indicate a transition from proximal volcanic-dominated highlands along East Fork Hood River on the west to a more distal broad volcaniclastic apron on the east, characterized by east-northeast-directed stream drainages. In the area of The Dalles, the Dalles Formation overlies the CRBG and is locally interbedded with fluvial conglomerate and sandstone. The Dalles Formation thins and pinches out to the south near Tygh Ridge; the formation thickens northward toward The Dalles where it reaches a maximum thickness of ~1,500 ft (457 m) (Piper, 1932). The Dalles Formation is deeply incised in the study area, yielding a distinctive and rugged finger-mesa and canyon topography. Landslides are a major hazard associated with the Dalles Formation. Most of the landslides are large deep rotational or translational slides, which are likely failing at or on the contact between the Dalles Formation and the underlying CRBG (Beaulieu, 1977).

A similar-aged series of Cascades-derived volcaniclastic sedimentary rocks and tuff, known as the Tygh Valley Formation, overlies the CRBG in the southern part of the study area. These rocks are mapped within the Tygh Valley syncline, a structural low between the shallow north-dipping backlimb of the Mutton Mountain anticline and the steeply south-dipping forelimb of the asymmetric Tygh Ridge anticline (Johnson, 2011).

The Dalles Formation and CRBG are unconformably overlain across the central part of the study area between East Fork Hood River, Dufur, and the Columbia River by less extensive Pliocene volcanic and volcaniclastic sedimentary rocks that partially fill paleochannels carved into older units. Pliocene units in this part of the study area include a basalt, tuff breccia, welded and nonwelded ash-flow tuffs, and dacite lava flows erupted from source volcanic vents within the Hood River graben along the East Fork Hood River. A suite of Pliocene rhyolite, andesite and basalt, plus thin to massive volcaniclastic and sedimentary deposits also crops out above the Tygh Valley Formation in Tygh Valley (Johnson, 2011). These units are locally overlain by latest Pliocene or earliest Pleistocene sand and gravel.

Pliocene and older rocks are locally disconformably overlain between East Fork Hood River and The Dalles in the north and between the Laughlin Hills and Tygh Valley in the south by a series of upper Quaternary olivine-phyric basalt, basaltic andesite, and andesite lava flows erupted from small volcanoes located along the eastern escarpment of the Hood River graben. Scott and Gardner (2017) and McClaughry and others (2020) referred to these lava flows and corresponding vents surrounding Mount Hood as products of regional Quaternary volcanoes. In the Mount Hood region, Quaternary volcanic rocks crop out over a 99-mi-wide (160 km) area between the forearc Boring Volcanic Field in the Portland Basin, through the Cascade Range, and eastward to the backarc Simcoe Mountains (Washington State)(Hildreth, 2007).

During the Pleistocene, cataclysmic glacial lake outburst floods (Missoula Floods) swept periodically across eastern Washington and down the Columbia River Gorge. These events likely repeated nearly 100 times between approximately 19,000 and 13,000 years ago (Benito and O'Connor, 2003). Along the Columbia River Gorge where the floods had the greatest velocity, the canyon walls were eroded and over-steepened by the catastrophic stripping of the Missoula Floods (McClaughry and others, 2012). The water and sediment from the Missoula Floods also traveled upstream into the side channels/rivers perpendicular to the Columbia River. Missoula Flood deposits are found at elevations of ~850 ft (260 m) along Brown Creek, 700 ft (213 m) along Mill Creek, and 600 ft (183 m) along Chenoweth Creek (Benito and O'Connor, 2003; McClaughry and others, 2012). O'Connor and others (2020) found erratics deposited up Fifteen Mile Creek by the floods at an elevation of 1,120 ft (341 m) along Fifteenmile Creek in the area south of The Dalles. We therefore assume a maximum flood inundation elevation of 1,120 ft (341 m) was reached, but likely only a couple times out of the nearly 100 events. However, repeated flood inundation elevation of 900 ft (274 m) was likely reached many times, as evident from the more extensive deposits at this elevation. Mapped landslide deposits in the northern part of the study area are often coincident with mapped Missoula Flood deposits and scour features.

4.0 METHODS

This section describes the methods followed to produce the landslide inventory and the recommendations for landslide risk reduction.

4.1 Landslide Inventory

Prior to mapping landslides, we reviewed existing landslide publications using SLIDO-4 (Franczyk and others, 2019) as well as the latest geologic maps of the area using the Oregon Geologic Data Compilation (Franczyk and others, 2020). We also reviewed Beaulieu (1977), Geologic Hazards of Parts of Hood River, Sherman, and Wasco counties, Oregon; and Sholin (1982), Landslide Hazards in The Dalles, Wasco County, Oregon.

Next, we acquired landslide polygons mapped as part of several recent and ongoing local geologic mapping efforts in Wasco County, including:

- Johnson, 2011 - Dextral shear and north-directed crustal shortening defines the transition between extensional and contractional provinces in north-central Oregon.
- McClaughry and others, 2021 - Geologic Map of the Dufur Area, Wasco County, Oregon.
- McClaughry and others, 2012 - Digital Geologic Map of the Hood River Valley, Hood River and Wasco Counties.
- McClaughry and others, 2023 - Geologic Map of the Mill Creek Area, Hood River and Wasco Counties, Oregon (includes Brown Creek, Ketchum Reservoir, and Fivemile Butte and northern part of the Flag Point 7.5' quadrangles).
- O'Connor, J.E., Unpublished – Geologic Map of The Dalles 1x2 degree Quadrangle, Wasco County, Oregon.

We extracted landslide and fan deposits within our study area from the projects listed above and used them as a starting place for our mapping. Some polygons from these geologic studies needed editing before they met the mapping criteria described in DOGAMI SP-42. Much of the editing consisted of dividing large polygons mapped as Quaternary landslide deposits into individual landslides. We also added many more landslides.

To create the detailed landslide inventory for this project, we performed two primary tasks: lidar-based landslide mapping and attributing, and field inspection. The methodology for these tasks is described in detail in DOGAMI SP-42 (Burns and Madin, 2009). To capture some additional information for the historic landslides (e.g., dates of movement, event details), we interviewed ODOT engineering geologist Russel Frost (personal communication, 2022). We also looked at readily available georeferenced serial air photos ranging from 1995 to 2020. If we noted movement at a particular landslide, we included the date range in the *date_range* attribute field. The final landslide data are compiled in a geodatabase that is provided as part of this report.

4.2 Landslide Risk Reduction

The approach for landslide risk reduction in this project focused on community needs, as relayed by relevant community stakeholders, in combination with established recommendations from published reports.

To develop recommendations for continued landslide risk reduction in Wasco County, we began by compiling a list of recommendations from published reports, including:

- Calhoun and others, 2020 - Landslide Hazard and Risk Study of Tillamook County, Oregon.
- Sears and others, 2019 - Preparing for Landslide Hazards, A Land Use Guide for Oregon Communities.
- Washington Geological Survey and Oregon Department of Geology and Mineral Industries – A Homeowner's Guide to Landslides.

Next, we held three small group brainstorming meetings with communities in Wasco County to further develop the action items list. These initial community brainstorm meetings included the following:

- City of Mosier staff
- City of The Dalles staff, Wasco County staff, several unincorporated communities
- Wasco County staff, Grant County staff, other unincorporated communities

Although this report refers to landslide mapping completed in Wasco County, participants in the risk reduction discussions also included representatives of Grant County, where another landslide mapping project was underway.

The action item lists from these three meetings were compiled into a master list. This master list was shared back to the communities. Finally, we held two more small group meetings to prioritize the list and establish pathways to success for these action items. The full list is provided in the Results section of this report.

Several themes emerged from the community stakeholder meetings that overlap with previously published recommendations for landslide risk reduction. These themes are awareness, planning and regulation, and emergency response.

5.0 RESULTS

We found 2,693 landslide deposits in the project area; 536 are deep landslides, 214 are rockfall deposits, 1,653 are debris flow deposits, and the rest of the landslides are shallow landslides or unclassified (**Figure 4**). Instead of creating a static map plate for the entire project area, we created an interactive online map that can be accessed here:
https://storymaps.arcgis.com/stories/c636418e140848cb962fa5e80a96e28b.

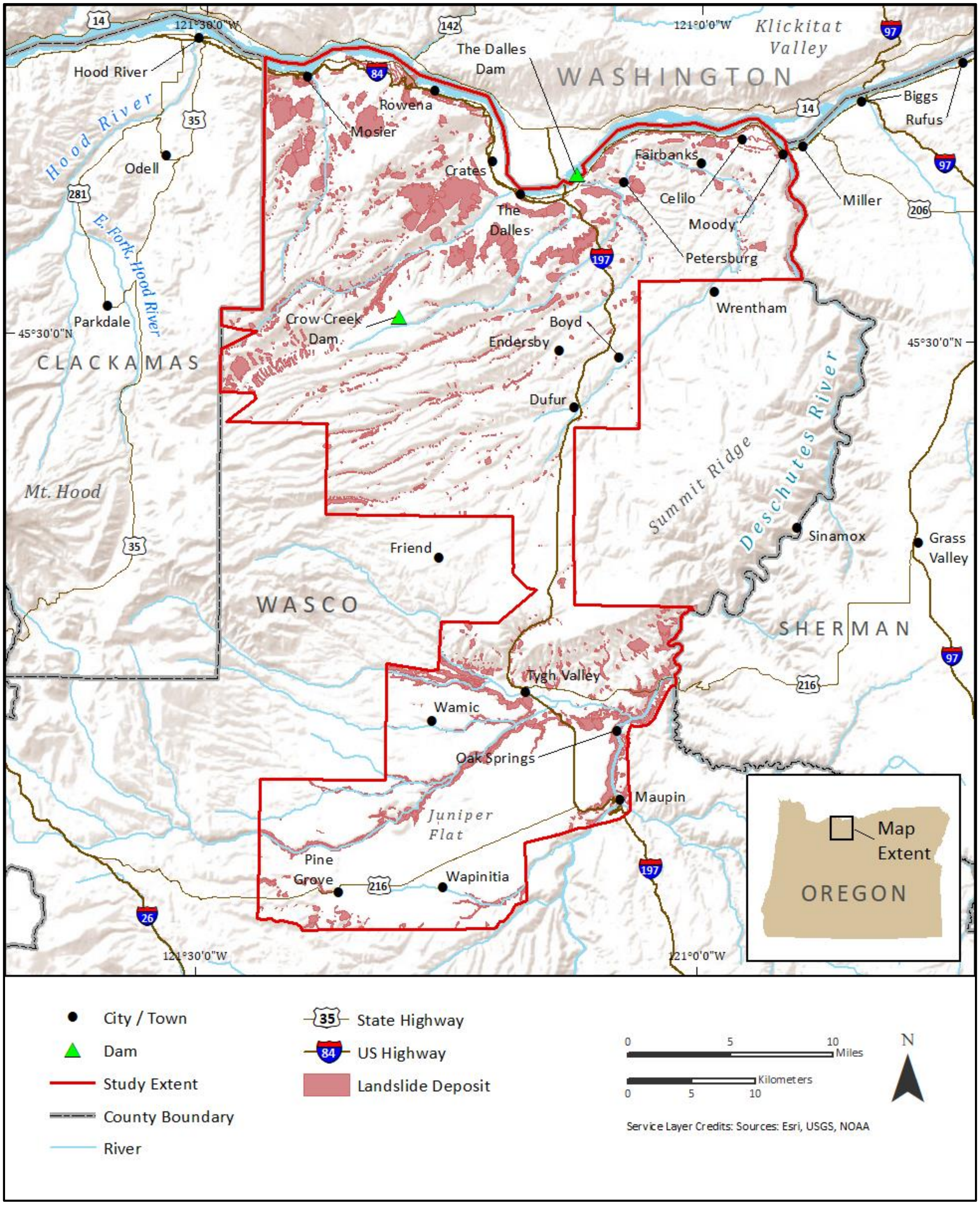
In general, there are more large deep landslides in the northern portion of the project area where the Dalles Formation deposits are located. The rockfall areas are located mostly along the steep basalt valley or gorge cliffs/slopes adjacent to the rivers and streams such as Badger Creek, Tygh Creek, White River, Deschutes River, Mill Creek, and the Columbia River. Most of the debris flow deposits and associated steep channels are located in Tygh Valley and along the valley walls of many small drainages (such as Eightmile Creek) in the central-western portion of the project area.

Some of the deep landslides — for example the Government Flat landslide (located east-southeast of The Dalles) — are very large, up to approximately 2.5 miles^2 (6.5 km^2) (**Plate 1**). We found all mapped landslide deposits cover a total area of 60.5 miles^2 (157 km^2) which is approximately 10% of the 626.5 miles^2 (1623 km^2) project area. Debris flow deposits occurred on a mean slope of 9.5°. General direction of movement was recorded at all landslides except rockfall. In general, the landslides appear to trend/move toward the northwest (337.5°) or the southeast (135°).

Most of the debris flow fans and rockfall talus in the project area were mapped as historic (less than 150 years old) indicating these two processes are active in the project area. Most of the 668 deep landslides were mapped as prehistoric (greater than 150 years old) indicating less recent activity in this group of landslides. However, the deep landslides that have been active within the past 150 years (classified as historic in our work) were destructive. For example, the Scenic Drive-Kelly Avenue landslide and the E 14th Street-Union Street landslide in The Dalles damaged a school and church, many residential structures, and infrastructure such as roads, sewer, sidewalks, water lines, and a reservoir (Sholin, 1982; **Plate 1**). The most recent significant movement of these deep landslides in The Dalles is estimated to have happened in the late 1970s and early to mid-1980s (Sholin, 1982; Beaulieu, 1977; Beaulieu, 1985).

The city of Mosier also has several active/historic large deep landslides in the southwestern portion (**Plate 2**). Besides many historic rockfall areas, two notable historic landslides occurred within the ODOT quarry directly southwest of the city of Moiser (**Plate 2**). Fortunately, only the quarry was affected.

Figure 4. Landslide inventory overview map of the project area. To view the landslide inventory in detail, visit the interactive web map located at https://storymaps.arcgis.com/stories/c636418e140848cb962fa5e80a96e28b.



5.1 Relationship of Geology to Landslides

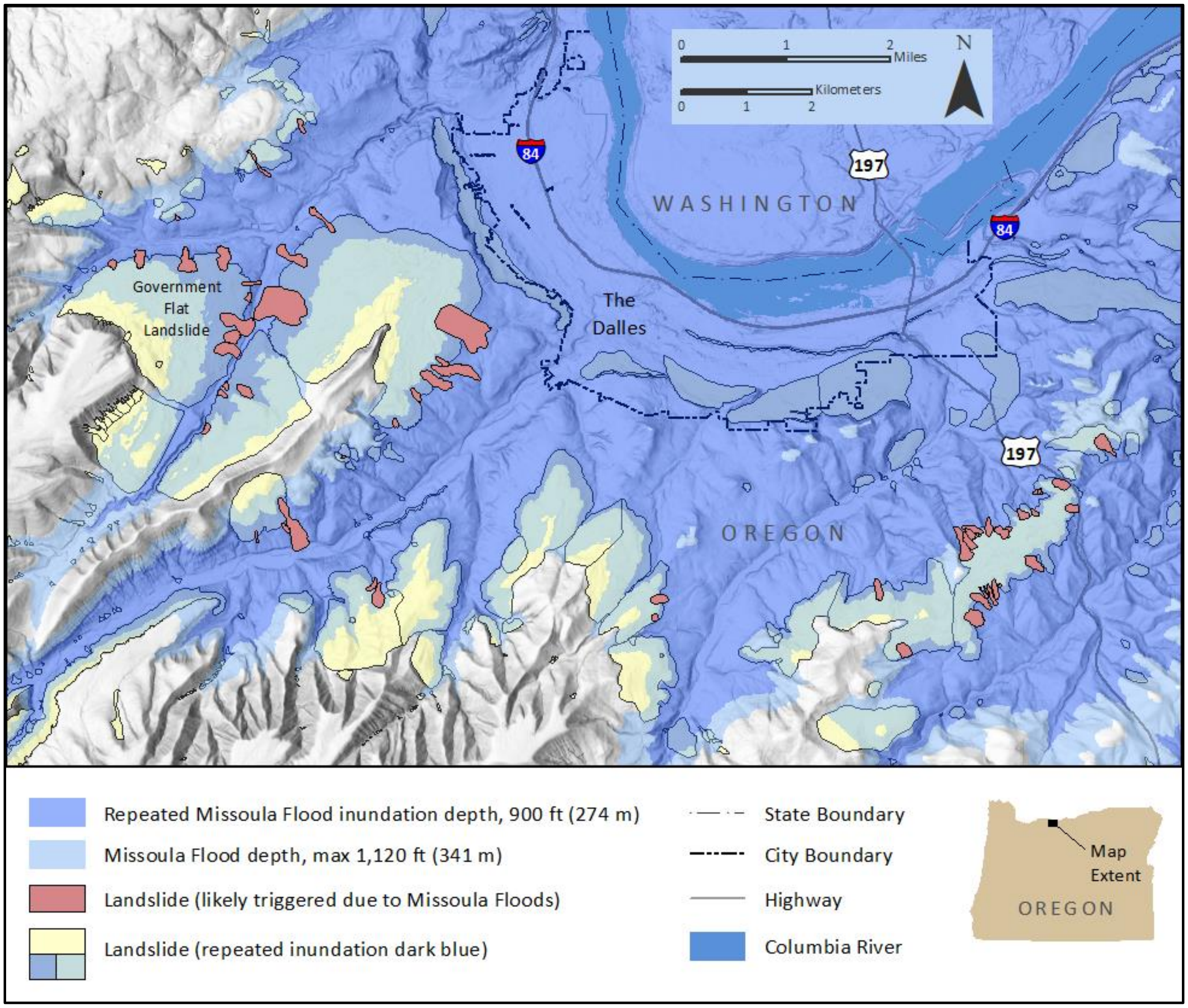
The majority of landslide deposits in the study area between The Dalles and Tygh Valley are rotational or translational slides or shallow earthflow landslides that occur along major drainages, originating on sparsely vegetated, moderate to steep slopes underlain by weakly consolidated rocks of the Dalles Formation or from flow contacts within the CRBG (Beaulieu, 1977). Many of these slides can be attributed to the combined influences of readjustment of canyons to filling by lava flows, parallel topographic slope and bedding dip due to Yakima folding, undercutting by streams, heavy precipitation, groundwater conditions, earthquakes, and rock type (Beaulieu, 1977). The generally weakly consolidated nature of the Dalles Formation makes this unit especially prone to landslides on both gentle and steep slopes. Future landslides should be expected in this unit, particularly in areas of changing land use where infrastructure development (e.g., drain fields, septic tanks, modified runoff, and irrigation) may alter local groundwater conditions (Beaulieu, 1977).

Between Dufur and East Fork Hood River, a majority of mapped landslide deposits are earthflows and debris flows that occur along major southwest- to northeast-trending drainages associated with Pliocene and younger intracanyon lava flows inset into sparsely vegetated, moderate to steep slopes underlain by the weakly consolidated rocks of the Dalles Formation.

Large translational-spreading landslides (e.g., the Government Flat landslide) south of The Dalles appear to have been completely or partially inundated by Missoula Flood waters (**Figure 5**; Beaulieu, 1977; Benito and O'Connor, 2003; McClaughry and others, 2012, O'Connor and others, 2020). The Missoula Floods inundated this area south of The Dalles to an assumed maximum flood inundation elevation of 1,120 ft (341 m) (likely reached only a couple times out of the nearly 100 events) and repeatedly inundated to an elevation of 900 ft (274 m)(likely many more times). Each time the water inundated and receded, a process called rapid drawdown occurred, which is known to cause slope instabilities (Turner and Schuster, 1996). Rapid drawdown is the removal of water from a waterbody (usually a lake or reservoir) at a rate faster than the rate of drainage of the geologic materials composing the slopes of the reservoir. This results in undrained or saturated materials on a slope that are very susceptible to failure or landsliding. This repeated process likely caused many of the large translational-spreading landslides in this region to occur or reactivate (**Figure 5**).

Interestingly, along the toes/lower margins of these large translational-spreading landslides, there are many (40+) smaller flow-type landslides that spatially overlap the repeated Missoula Floodwater inundation elevation of 900 ft (274 m)(**Figure 5**). This repeated rapid drawdown process likely caused most of these smaller flow-type landslides along the lower margins of the large translational-spreading landslides.

Figure 5. Map showing the maximum Missoula Flood inundation elevation of 1,120 ft (341 m) in light blue. The repeated Missoula Flood inundation elevation of 900 ft (274 m) is shown in dark blue. The large translational-spreading landslides (yellow) spatially correlate to the maximum Missoula Flood inundation, and the smaller flow-type landslides (red) spatially correlate to the repeated Missoula Flood inundation.



Deep landslide complexes are common along the Columbia River Gorge where canyon walls have been over-steepened by long-lived river erosion and more punctuated catastrophic stripping by the Missoula Floods (**Figure 4**Error! Reference source not found.; **Figure 5**; McClaughry and others, 2012). Several l arge deep landslides along the Columbia River Gorge (e.g., in Mosier and Rowena) were likely influenced by the floods scouring away the material that was contributing to the resisting forces holding those hillslopes in place. Along the Oregon side of the Columbia River Gorge, large deep landslides occur in areas coincident with major northwest-trending oblique strike-slip faults that are associated with broad, north-northeast-trending folds. Landslide deposits along the Columbia River Gorge (e.g., Mosier and Rowena) occur in a stacked succession of CRBG lavas that are locally unconformably overlain by conglomerate of the Troutdale Formation and the Basalt of Hood River (McClaughry and others, 2012). The distribution of slope failures in this part of the study area are likely related to bedding that dips northwest toward the Columbia River and thin sedimentary interbeds within the CRBG. Landsliding may also be occurring in this region along brecciated and clay-altered fault breccia along thrust fault zones, and unconformable contacts between the CRBG and the overlying Troutdale Formation and the Basalt of Hood River.

5.2 Existing and Potential Future Risk Reduction Strategies

The city of The Dalles has dealt with landslides in the past. The Scenic Drive-Kelly Avenue landslide moved repeatedly throughout the late 1970s and mid-1980s, damaging roads, sewers, water lines and sidewalks, as well as several homes and churches and a school (Beaulieu, 1977; Sholin, 1982). In response, the city instituted a mitigation program in which several wells were installed to “dewater” the base of the Kelly Avenue landslide area; those wells remain in operation today. The city has also implemented several other mitigation efforts in the last several decades to address known deep and shallow landslides, including installation of retaining walls and establishment of future development requirements in defined hazard zones created by consultant Fujitani, Hilts & Associates in 1991. The city instated a “hazard overlay zone” within which an engineering geological report or geotechnical report is required to build, to mitigate further landslide movement (personal communication, Dave Anderson, The Dalles Public Works Director, 2022).

During this project, potential future risk reduction strategies were developed during three conversations/brainstorm sessions with representatives from the cities of Mosier, The Dalles, and John Day and Wasco and Grant counties. These participants represented the entire study area, including the Columbia Gorge and the Tygh Valley. These conversations were held in July 2021, February 2022, and March 2022. The ideas provided in this report were written nearly verbatim from the notes taken during these conversations and combined with similar ideas from other group discussions with Wasco County stakeholders. Each idea was grouped with a tag to assist in sorting and prioritizing these strategies.

The final list of landslide risk reduction action items is below in three broad categories as identified by meeting participants: First Priority, High Priority, and Long Term.

First Priority

- Mapping: Create and use modern lidar-based landslide maps. This was completed for a large portion of Wasco County as part of this project.

High Priority

- Geotechnical Analysis: Use new landslide mapping to determine where codes require certain landslide mitigation such as site-specific geotechnical analysis or evaluation; use landslide mapping to determine whether a geologic impact study is needed for a development proposal.
- Geotechnical Analysis: Ensure all new construction is reviewed against landslide mapping to determine if mitigation actions need to be considered.
- Geotechnical Analysis: Determine when to require geotechnical evaluations using a clear and objective method.
- Land Use Codes: Scale the requirements for geotechnical review based on the level of risk. Establish a risk assessment matrix for development. For example, the city of Salem scores risk using environmental factors and activity levels to rank susceptibility to landslides. The scores determine the level of geotechnical review required. For example, construction of an outbuilding may require less detailed site assessment than would a residence or an essential building like a hospital. Landslide risk scores in the Salem code also incorporate environmental factors based on mapped earthquake-induced landslide hazard zones and

water-induced landslide hazard zones using published DOGAMI Interpretive Map Series: https://library.municode.com/or/salem/codes/code_of_ordinances?nodeId=TITXUNDECO_UDC_CH810LAHA.

- Land Use Codes: Use questions about construction methods — cut and fill earth work in particular — to determine what level of study is required.
- Land Use Codes: Define how and when geotechnical analysis requirements apply.
- Land Use Codes: Update codes (land use, stormwater, building, grading and erosion control) to include grading and tree removal restrictions in existing landslide areas and on already developed lots.
- Land Use Code: Require revegetation as part of conditions of approval for new construction on landslide hazard areas.
- Land Use Code: For existing structures on landslides; consider grading and fill restrictions to avoid reactivating landslides. It might be helpful to include specific guidance; for example, the threshold for amount of grading (e.g., >4 ft cut/fill requires a geotechnical analysis), or, use existing thresholds in engineering guidelines. Perhaps take into account population density and parcel size (e.g., agricultural land use) when determining thresholds or grading code language.
- Land Use Code: For existing structures on landslides, develop guidelines for surface water management in order to slow water movement on the surface and allow slow infiltration of stormwater into the soil. This limits concentration of flows and accumulation of infiltrated water in landslide areas. Examples and illustrations may be helpful to illustrate code language and to make recommendations.
- Land Use Permitting: For new construction, use site-specific engineering reports to develop conditions of approval and specific mitigation strategies for the particular site.
- Awareness: Communicate with the public before new mapping is made available to help people understand the large increase in mapped landslides.
- Awareness: For existing structures on landslides, provide information to property owners about how landslides can be reactivated and how to reduce the risk.
- Awareness: Communicate with private property owners about the multiple layers of planning and building rules.
- Awareness: In communication with the public about landslide hazards, combine information about the hazard with information about how to address risk from the hazard.
- Resources to Property Owners: Provide resources and access to funding to property owners to help them understand the risk and then make decisions for themselves.
- Advice to Property Owners: Provide advice to property owners with existing structures located on landslides to help them reduce risk. For example, share maps so they can see the location of the hazard compared to their structure; possibly advise that they contract for a geotechnical report so they know what to do to mitigate the risk. For example, would controlling water or building a retaining wall best mitigate future movement?
- City and County Staff Capacity: Provide guidelines for geotechnical reports to ensure that they are complete. Support staff capacity to review geotechnical reports through in-house training and/or using other resources such as another department's skillset, or another county's knowledge.
- City and County Staff Capacity: Increase capacity of local staff to provide technical information to citizens; develop relationships between local planners and DOGAMI staff so that calling on

the experts to answer questions about landslide mapping and technical aspects of risk reduction is part of the service provided to citizens.

- City and County Staff Capacity: Increase capacity of local staff to address administrative aspects of risk reduction activities, such as the drafting of ordinances or ordinance updates.
- Self-Certification: Develop method of self-certification of landslide risk reduction efforts, similar to wildfire defensible space self-certification: https://oregonexplorer.info/data_files/OE_topic/wildfire/documents/pdf/guide_0106.pdf.

Long Term

- Insurance: Establish definitions to help insurance companies protect structures by establishing a set of parameters for rating risk at the structure level.
- State level: State building codes could include precautions for landslide areas.

6.0 CONCLUSIONS AND DISCUSSION

Although we cannot predict when and where the next landslide events will occur in Wasco County, we are able to provide a detailed map of areas impacted by historic and prehistoric landslides. We conclude that the geology in Wasco County is a fundamental factor in the location, type, and distribution of landslide deposits. We mapped 2,693 landslides deposits in the study area.

This study area has a landslide density of ~9%. Compared to other areas that used a similar approach to landslide mapping, the Wasco County study area has a relatively low to moderate landslide hazard (**Table 1**). Some of these previous studies are centered in mountainous, entirely steep terrain, making a direct comparison to another study area's mean landslide density slightly misleading, as the hazard locally can have a considerable range.

Table 1. Landslide density reported from past studies in Oregon.

Study	Percent Landslide Coverage	Relative Overall Hazard Classification Concluded
North Fork Siuslaw Watershed (Burns and others, 2012)	37%	High
Astoria (Burns and Mickelson, 2013)	27%	High
Coastal Curry County (Burns and others, 2014)	25%	High
Clatskanie (Mickelson and Burns, 2012)	25%	High
Bull Run Watershed (Burns and others, 2015)	15%	Moderate to High
Tillamook (Calhoun and others, 2020)	13%	Moderate to High
Eugene-Springfield (Calhoun and others, 2018)	6%	Low to Moderate

Risk reduction strategies may vary depending on the type of landslide hazard present. Large, deep landslides are commonly harder and more expensive to mitigate because a single deep landslide may affect multiple landowners, including private, city, county, state, and federal landowners. Mitigation may require cooperating effort from public and private entities (e.g., city, county, and private landowners) because the slides can span entire neighborhoods, such as the Scenic Drive-Kelly Avenue landslide described in the Results section.

6.1 Landslide Risk Reduction Priorities and Pathways

Broad consensus holds that the first priority identified by participating stakeholders was improved landslide mapping; having the updated landslide maps was the primary risk mitigation tool participants wanted. This report fulfills the landslide mapping request and summarizes risk reduction options. The group had different secondary and tertiary priorities; however, awareness action items were among the top priorities for all stakeholders. The following three topics were at the top of stakeholders' prioritized lists:

- Geotechnical Analysis
- Public Information
- Land Use Codes

The primary purpose of this study is to help communities in the study area become more resilient to landslide hazards by providing new detailed hazard maps and establishing action items for future risk reduction. The action item list above is a beginning point, and if actions from it are implemented at the local level, this will result in landslide risk reduction.

It is also important for the public to be notified during times of increased landslide potential. Oregon currently has a landslide warning system operated in partnership by the NOAA National Weather Service (NWS), DOGAMI, ODOT, and Oregon Emergency Management (Burns and Franczyk, 2021). NWS initiates the system by sending out landslide watches, and the state agencies help citizens become aware of the heightened potential for landslides. In the future, this information could be streamlined to the local municipalities via RSS feeds and live web pages. During these periods of increased landslide potential, the public could then access hazard maps to find locations where this potential is most likely.

Because awareness, planning, and emergency response of local landslide hazards are crucial to understanding, risk reduction, and response, we have added additional details in the following sections.

6.2 Awareness

One of the main purposes of this report and the data provided is to help city staff communicating with residents and landowners in the study area to become aware of the parts they can play in readiness for hazardous events and risk reduction. Once the hazard is better understood, residents and landowners can work on risk reduction. To increase awareness, we will post this report and add the data to the SLIDO interactive web map on the DOGAMI website. Helpful brochures can be linked from DOGAMI websites and/or distributed to help educate landowners of activities that individuals can take to reduce landslide risk. These brochures include the "Homeowners Guide to Landslides" (https://www.oregongeology.org/Landslide/ger_homeowners_guide_landslides.pdf) and the DOGAMI fact sheet "Landslide Hazards in Oregon" (https://www.oregongeology.org/pubs/fs/landslide-factsheet.pdf).

City, county, neighborhood, and other local community leaders can implement awareness campaigns to educate neighborhoods, businesses, and individual homeowners about the locations of local hazards and how to reduce risk. For example, homeowners can unintentionally increase their own risk through discharge of stormwater onto slopes that are susceptible to landslides. Landslides resulting from this type of discharge were observed after the 1996 events (Burns and others, 1998). Just knowing which slopes are susceptible can provide the impetus to switch from unknowingly increasing risk to actively reducing risk through cost-effective methods such as extending stormwater discharge pipes beyond the high hazard zone.

When development exists on land now identified as a large deep landslide, neighborhood-scale educational efforts may be warranted. A public awareness campaign could be undertaken to educate homeowners and landowners about the landslide hazard and risk in their areas and to prioritize future risk reduction actions. Residents on mapped landslides could participate in a neighborhood risk reduction program where all affected entities help reduce the overall risk.

6.3 Planning and Regulation

Planning is an effective method to work on risk reduction and can be initiated in a variety of ways using the maps and data produced in this project. Two types of long-term planning that engage leaders, residents, and landowners include 1) focusing on future development and 2) focusing on existing infrastructure.

A recent joint publication from DLCD and DOGAMI entitled "Preparing for Landslides: A Land Use Guide for Oregon Communities" (Sears and others, 2019) identified various land use tools and strategies to help communities reduce potential losses from landslides. Data generated as part of this current study are essential to developing long-term planning, including expansion of urban growth boundaries. Another long-term planning tool is adopting the results from this current study into local comprehensive plans, which most cities and counties use to identify community goals. Some planning could result in the avoidance of proposed development in high hazard areas, creation of mitigation requirements, and even public buyouts in very high or life-threatening hazard areas. Additional planning can focus on maintenance of road-related grading, repeated asphalt overlays, or expanding roadways. Keeping specific records of maintenance practices is a good way to track risk reduction effects.

Stormwater runoff routing, a process good to reduce risk where infrastructure already exists on landslides, must be done carefully so that water is not directed onto or into unstable slope areas. Planning of the public stormwater system, for example, should include location of culvert outlets in order to evaluate potential impact of any discharge onto landslide hazard areas. Planning staff could implement private landowner education in order to promote awareness and to gain landowner partnership in the control of stormwater.

Connecting landslide inventory maps and data to regulations such as development codes and ordinances can be very effective for long-term planning. Such regulations use landslide hazard maps to identify areas for proposed development and to limit or prevent grading or other activities that may increase landslide risk in high hazard areas. Examples of regulation code are provided by Sears and others (2019). These regulations typically have requirements to perform site-specific geotechnical analysis and mitigation design. Regulations can also reduce grading-related landslides. For example, relatively shallow grading activities can unintentionally cause slope failures, especially in conditions where existing landslides may be only marginally stable. Placing debris or soil in the wrong location, for example near the heads of existing landslides, can also unknowingly cause slope failure simply by adding more weight to the slope.

Developing appropriate regulations or conditions of approval to apply in landslide hazard areas involves determining when more stringent conditions apply based on the use proposed, determining who can conduct a geotechnical analysis, and determining how a local planner can ensure that such an analysis contains all the needed information.

Risk reduction measures may include these aspects of site development:

- Limit grading, excavation, or filling.
- Minimize or eliminate irrigation.

- Intercept and collect surface water on and above the area to reduce natural water infiltration.
- Collect surface water runoff from within the area from impervious surfaces — for example, roof downspouts, streets, and driveways — and discharge into a suitable receptacle.
- Minimize any onsite storm water retention and infiltration within the area.
- Require detailed site-specific evaluation prior to development or grading.

Care should be taken when developing land use codes, that they provide clear and objective standards with respect to needed housing for compliance with Senate Bill 1051 which amended Oregon Revised Statute (ORS) 197.307(4): https://library.municode.com/or/salem/codes/code_of_ordinances?nodeId=TITXUNDECO_UDC_CH810LAHA.

6.4 Emergency Response

Finally, we recommend that neighborhoods and communities create landslide emergency response plans before a landslide disaster. One component of the plan could include identifying local engineering geologists and geotechnical engineers and establishing working relationships with them so they can be asked to evaluate landslides or areas during and directly after the next disaster. Their evaluations would help determine the necessary actions immediately following a disaster. For example, they would determine if a neighborhood should be evacuated or if the area is stable enough to perform an emergency response.

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STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
RUARRI J. DAY-STIRRAT, STATE GEOLOGIST
www.oregongeology.org

Landslide Inventory Map of The Dalles, Oregon

2023

Open File Report O-23-02

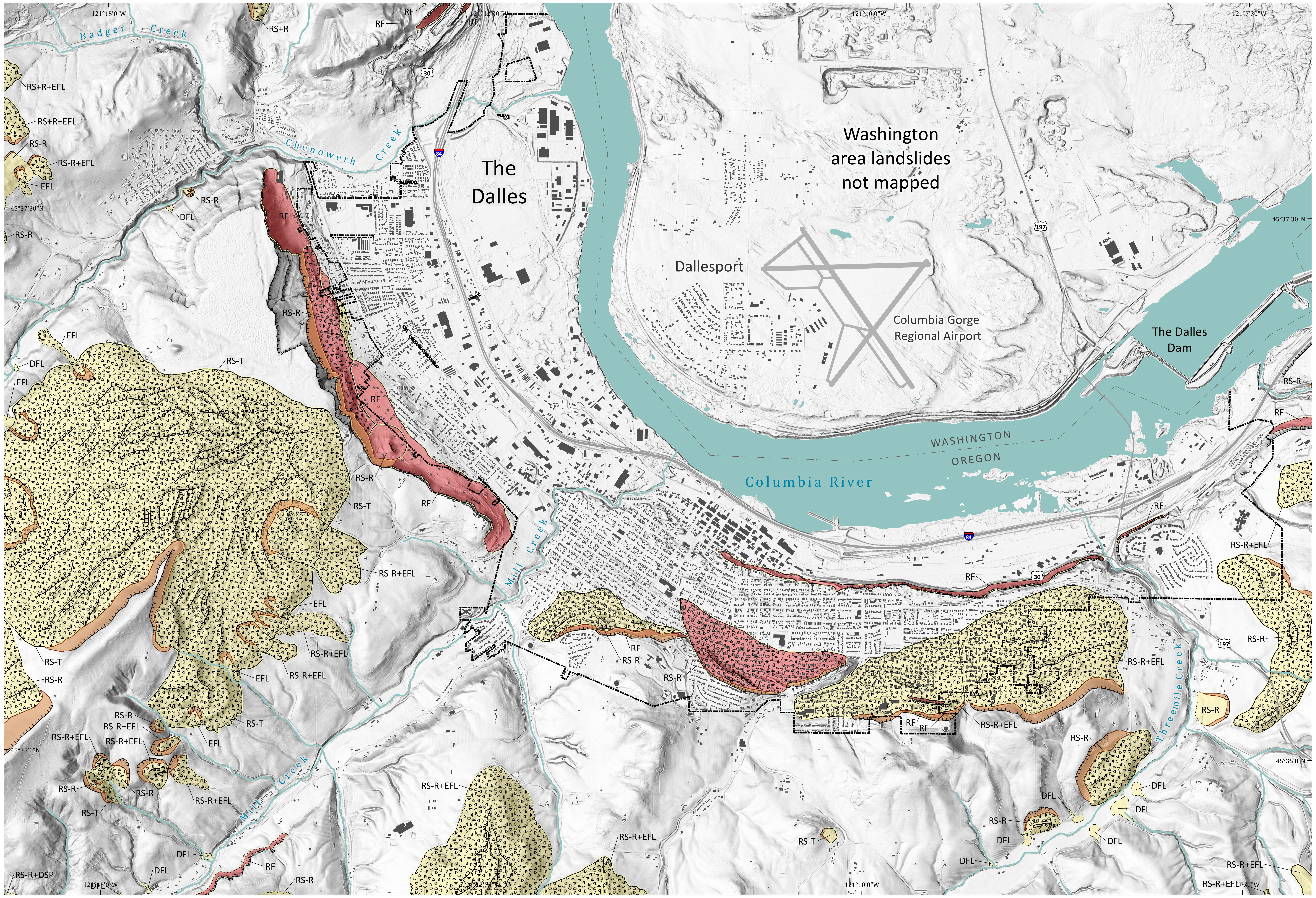
Landslide Inventory and Risk Reduction of the North and Central Portions of Wasco County, Oregon

by William J. Burns[1], Nancy Calhoun[1], Jon Franczyk[1], Jason D. McClaughry[2], and Katherine Daniel[3]

[1]Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Suite 965, Portland, OR 97232
[2]Oregon Department of Geology and Mineral Industries, Baker County Courthouse, 1995 3rd Street, Suite 130, Baker City, OR 97814
[3]Oregon Department of Land Conservation and Development, 635 Capitol Street NE Suite 150, Salem, OR 97301

Funding for this project was provided in part by FEMA grant number EMS-2020-CA-00010.

PLATE 1



INTRODUCTION

The Oregon Department of Geology and Mineral Industries (DOGAMI) partnered with Federal Emergency Management Agency (FEMA) to better understand the landslide hazards in the Wasco County, Oregon study area. The goal of the partnership was to create detailed landslide inventories. The text below explains how this was done.

EXPLANATION

This map is an inventory of existing landslides in the study area. The landslide inventory is one of the essential data layers used to delineate regional landslide susceptibility. This landslide inventory is not regulatory, and revisions can happen when new information regarding landslides is found or when new landslides occur. Therefore, it is possible that landslides within the mapped area were not identified or occurred after the map was prepared.

This inventory map was prepared by following the Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery developed by Burns and Madin (2009). The three primary tasks included compilation of previously mapped landslides (including review of the Statewide Landslide Information Layer for Oregon Release 4 [Franczyk and others, 2019]), lidar-based morphologic mapping of landslide features, and review of aerial photographs. Landslides identified by these methods were digitally compiled into a GIS database at varying scales. While the protocol recommends data use at a map scale of 1:8,000, and the geodatabase contains data at 1:8,000 or better, for representation the data have been visualized on the map plate at 1:32,000. Each landslide was also attributed with classifications for activity, depth of failure, movement type, and confidence of interpretation. The landslide data are displayed on top of a base map that consists of an aerial photograph (orthorectified) overlaid on the lidar-derived hillshade image.

This landslide inventory map is intended to provide users with basic information regarding landslides within the study area. The geologic, terrain, and climatic conditions that led to landslides in the past may provide clues to the locations and conditions of future landslides.It is intended that this map will provide useful information to develop regional landslide susceptibility maps, to guide site-specific investigations for future developments, and to assist in regional planning and mitigation of existing landslides.

LANDSLIDE CLASSIFICATION

We have classified each landslide shown on this map according to a number of specific characteristics identified at the time the data were recorded in the GIS database. The classification scheme was developed by the Oregon Department of Geology and Mineral Industries (Burns and Madin, 2009). Several significant landslide characteristics recorded in the database are portrayed with symbology on this map. The specific characteristics shown for each landslide are the activity of landsliding, landslide features, deep or shallow failure, confidence of landslide interpretation, and type of landslide movement. These landslide characteristics are determined primarily on the basis of geomorphic features, or landforms, observed for each landslide. The symbology we use to display these characteristics on the map is explained below.

LANDSLIDE ACTIVITY: Each landslide has been classified according to the relative age of most recent movement. This map display uses color to show the relative age of activity.

HISTORIC and/or ACTIVE (movement less than 150 years ago): The landslide appears to have moved within historic time or is currently moving (active).

PRE-HISTORIC or ANCIENT (movement greater than 150 years ago): Landslide features are slightly eroded and there is no evidence of historic movement. In some cases, the observed landslide features have been greatly eroded and/or covered with deposits that result in smoothed and subdued morphology.

LANDSLIDE FEATURES: Because of the high resolution of the lidar-derived topographic data, some additional landslide features were identified. These include:

HEAD SCARP ZONE and FLANK ZONE: The head scarp or upper most scarp, which in many cases exposes the primary failure plane (surface of rupture), and flanks or shear zones.

HEAD SCARP LINE and INTERNAL SCARP LINES: Upper most extent of the head scarp and internal scarps within the body of the landslide. Hatching is in the down-dropped direction.

DEPTH OF FAILURE: The depth of landslide failure was estimated from scarp height. Failures less than 4.5 m (15 ft) deep are classified as shallow, and failures greater than 4.5 m (15 ft) deep are classified as deep.

SHALLOW LANDSLIDE: Estimated failure plane depth is less than 4.5 m (15 ft).

DEEP LANDSLIDE: Estimated failure plane depth is greater than 4.5 m (15 ft).

CONFIDENCE OF INTERPRETATION

HIGH CONFIDENCE (≥ 30 points)

MODERATE CONFIDENCE (20 – 30 points)

LOW CONFIDENCE (≤ 20 points)

Landslide Feature	Points
Head scarp	0-10
Flanks	0-10
Toe	0-10
Internal scarps, sag ponds, compression ridges, etc.	0-10*

* Applied only once so that total points do not exceed 40.

EFL EFL - Earth Flow - Abbreviation for type of slope movement. The table below displays movement types (Varnes, 1978). Generalized diagrams (some modeled from Highland, 2004) showing types of movement are shown in the next column.

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Type of Movement	Type of Material		
	Rock	Debris	Soil
Fall	**RF** rock fall	**DF** debris fall	**EF** earth fall
Topple	**RT** rock topple	**DT** debris topple	**ET** earth topple
Slide-rotational	**RS-R** rock slide-rotational	**DS-R** debris slide-rotational	**ES-R** earth slide-rotational
Slide-translational	**RS-T** rock slide-translational	**DS-T** debris slide-translational	**ES-T** earth slide-translational
Lateral spread	**RSP** rock spread	**DSP** debris spread	**ESP** earth spread
Flow	**RFL** rock flow	**DFL** debris flow	**EFL** earth flow
Complex	**C** complex or combinations of two or more types (for example, ES-R + EFL)		

Source Data:
Oregon Lidar Consortium, 2015 and US Army Corp Engineers, 2010 for Brown Creek (45121-E3), Lyle (45121-F3), Petersburg (45121-E1), The Dalles North (45121-F2), and The Dalles South (45121-E2) quadrangles. Water features from the National Hydrology Dataset (NHD), 2017 and transportation from Oregon Department of Transportation (ODOT), 2015.

Projection:
Oregon Statewide Lambert Conformal Conic, Unit: International Feet, Horizontal Datum: NAD 1983 2011.

Software:
Esri® ArcMap® 10.7.1

Digital Cartography:
Jon J. Franczyk

APPROXIMATE MEAN DECLINATION, 2015

SCALE 1:20,000

0 0.5 1 Miles

0 0.5 1 Kilometers

State Boundary
City Boundary
Highway
Stream
Building
Waterbody

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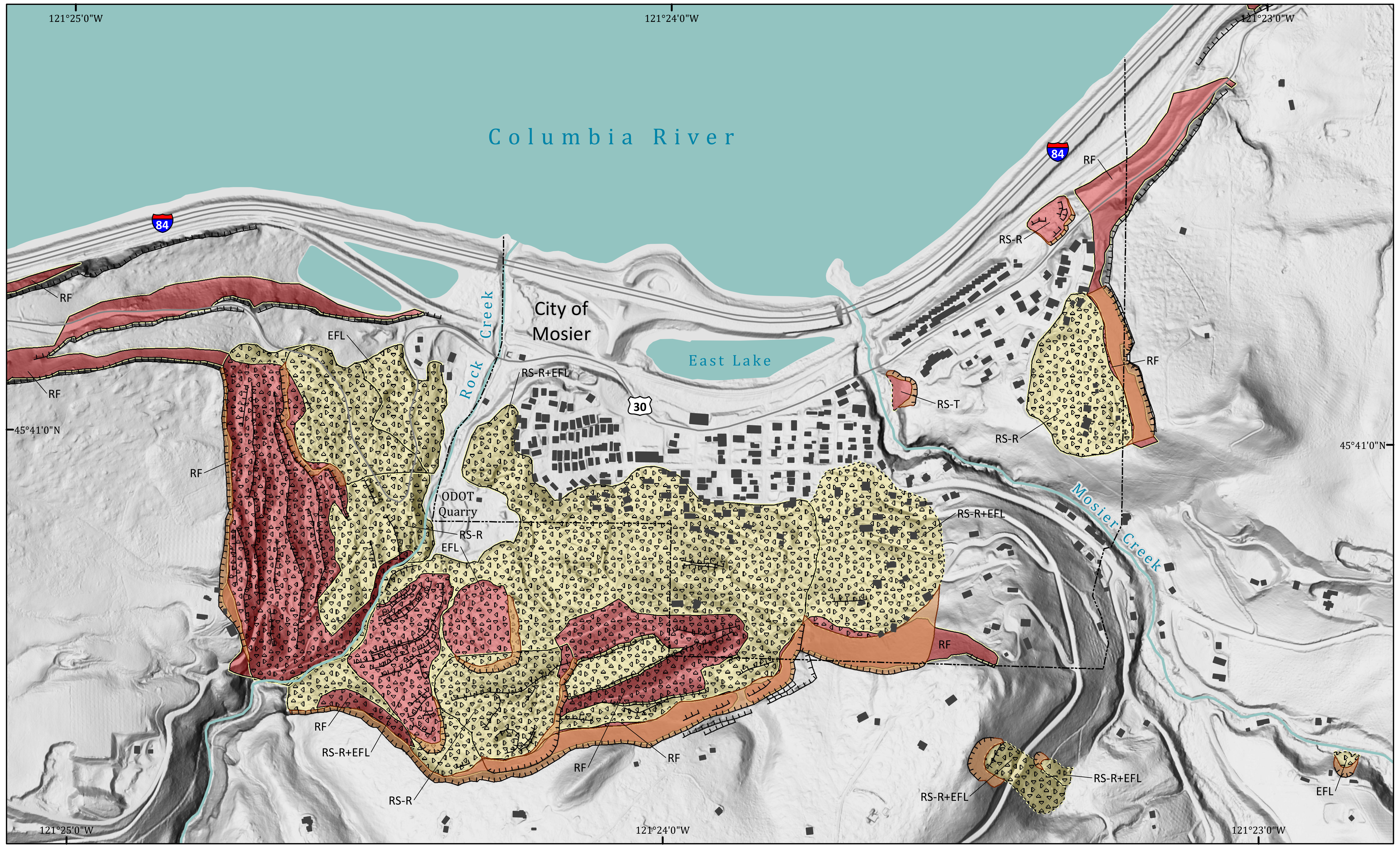
PLATE 2



Source Data:
Oregon Lidar Consortium, 2015 and US Army Corp Engineers, 2010 for White Salmon (45121-F4) and Lyle (45121-F3) quadrangles. Water features from the National Hydrology Dataset (NHD), 2017 and transportation from Oregon Department of Transportation (ODOT), 2015.

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Oregon Statewide Lambert Conformal Conic, Unit: International Feet, Horizontal Datum: NAD 1983 2011.

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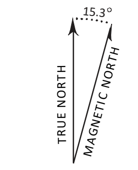


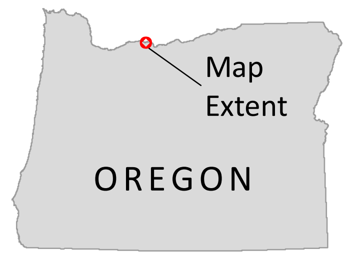
APPROXIMATE MEAN DECLINATION, 2015

SCALE 1:8,000

0 0.25 0.5 Miles

0 0.25 0.5 Kilometers

City Boundary
Highway
Stream
Building
Waterbody



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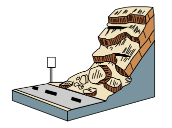
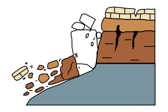
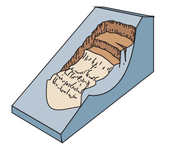


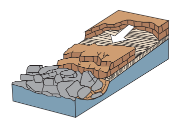
Falls are near-vertical rapid movements of masses of materials, such as rocks or boulders. The rock debris sometimes accumulates as talus at the base of a cliff.



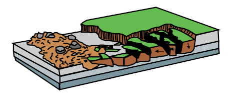
Topples are distinguished by forward rotation about some pivotal point, below or low in the mass.



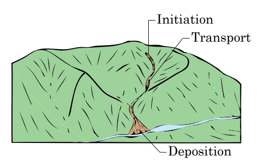
Slides are downslope movements of soil or rock on a surface of rupture (failure
- Rotational slides move along a surface of rupture that is curved and concave.



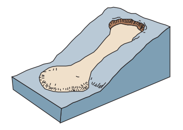
- Translational slides displace along a planar or undulating surface of rupture, sliding out over the original ground surface.



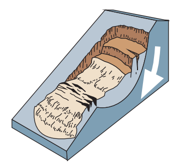
Spreads are commonly triggered by earthquakes, which can cause liquefaction of an underlying layer and extension and subsidence of otherwise cohesive materials overlying liquefied layers.



Channelized Debris Flows commonly start on steep, concave slopes as small slides or earth flows into channels. As this mixture of landslide debris and water flows down the channel, the mixture picks up more debris, water, and speed, and deposits in a fan at the outlet of the channel.



Earth Flows commonly have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head.



Complex Landslides are combinations of two or more types. An example of a common complex landslide is a rotational slide + earth flow, which usually exhibits rotational slide features in the upper region and earth flow features near the toe.

(Block Diagrams from Highland, 2004)

REFERENCES

Franczyk, J.J., Burns, W.J., Calhoun, N.C., 2019. Statewide Landslide Information Database for Oregon, release 4 (SLIDO-4.0), Oregon Department of Geology and Mineral Industries, Digital Data Series, https://www.oregongeology.org/slido/index.htm

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