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LANDSLIDE HAZARD AND RISK STUDY OF TILLAMOOK COUNTY, OREGON

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WHAT'S IN THIS REPORT?

This report updates a landslide inventory, shallow and deep landslide susceptibility, and landslide risk for a portion of Tillamook County, Oregon. This information can help communities better reduce risk from landslides.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files. Geodatabase is Esri® version 10.1 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

O-13-20_TillamookLandslideandRiskStudy.gdb:

Datasets:

- Coseismic_Hazard_Data (feature dataset)
    - Landslide_Classes (shapefile)
    - Liquefaction_Classes (shapefile)
    - NEHRP_Classes (shapefile)
- Landslide_Inventory (feature dataset)
    - Deposits (polygons)
    - Historic_Landslide_Points (points)
    - Scarp_Flanks (polygons)
    - Scarps (polylines)
- Tillamook_Deep_Suscept (feature class, polygons)
- Tillamook_Shallow_Suscept (raster dataset)
- Tillamook_Study_Area (feature class, polygon)

EXECUTIVE SUMMARY

This study provides an updated geospatial inventory of landslide hazard data (including risk to properties and infrastructure) throughout Tillamook County, Oregon. These data are critically important for community planners, emergency managers, and the public at large.

Tillamook County has experienced hundreds of landslides in the past 50 years, many of which have been recorded in the Statewide Landslide Information Database for Oregon (SLIDO). However, no regional-scale landslide hazard study exists. Over 25,000 people reside in the study area portion of Tillamook County, with critical lifeline highway routes, including Highway 6 (Wilson River Highway) and U.S. Highway 101 (Oregon coast Highway) potentially at risk from landslides.

For this study we used existing protocols established by the Oregon Department of Geology and Mineral Industries (DOGAMI) for 1) making a landslide inventory; that is, mapping existing landslide deposits, 2) modeling deep and shallow landslide susceptibility in order to demonstrate where landslides may occur in the future, and 3) assessing landslide risk through exposure analysis and using the FEMA Hazus Multi-Hazard model. These established methods allow for a consistent scientific framework in which to perform the mapping, while also allowing for direct comparison to other areas in Oregon in order to understand the relative risk.

The study area is ~325 square miles (841 square kilometers), spans the length of the county, and includes numerous incorporated and unincorporated communities and transportation corridors. Results from our mapping and risk assessment indicate the following:

- There are 4,091 mapped landslides, and 605 located historic landslide points, covering 13% of the total study area.
- More than 1,700 residents live on existing debris flow fans; and more than 1,500 residents live on deep-seated landslides.
- Buildings with a value of approximately $207 million are located on existing deep landslides.

Our analyses indicate that the study area experiences moderate to high landslide hazard, which tends to be concentrated in several discrete communities and along certain key road corridors, notably in the northern portion of the study area, Neahkahnie, Nehalem, and Wheeler, and along U.S. Highway 101. The primary landslide hazard in the study area is exposure of existing structures and roadways to deep landslides and debris flow fans. Substantive risk reduction activities for this type of landslide hazard include controlling the input of water onto slopes within the moderate and deep landslide susceptibility zones and on existing deep landslides, and avoiding adding material (weight) to the tops of susceptible slopes or, conversely, removing material from the bottoms of slopes (by excavation or grading).

To assist the local communities, we recommend the following:

- increase private property owners' awareness of existing landslide hazards and encourage precautions through risk reduction efforts at the individual lot level,
- incorporate landslide hazard maps and risk reduction strategies into community- and county-level planning efforts, and
- create a landslide emergency response plan in order to best prepare and react in the case of a landslide occurrence.

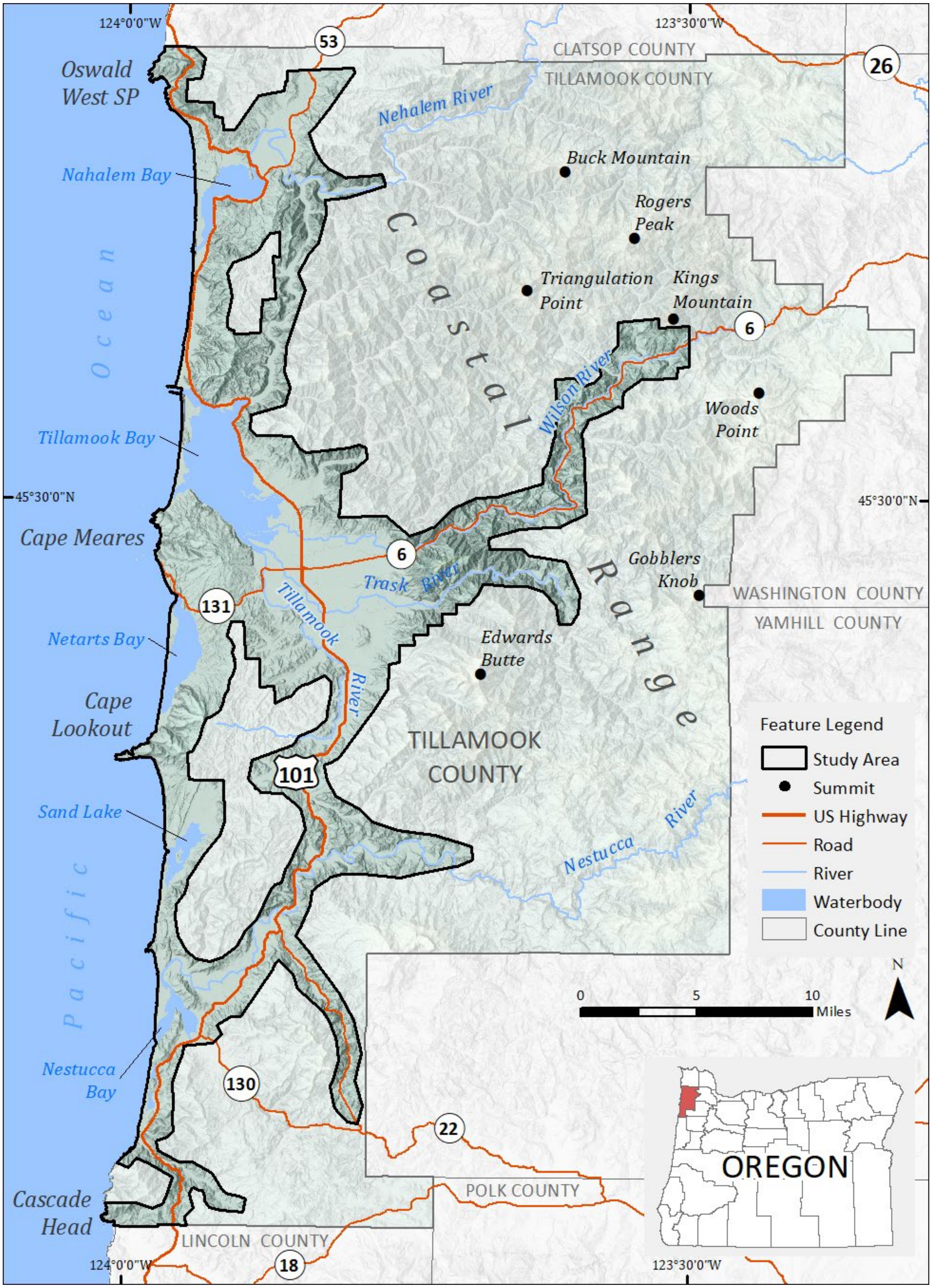
1.0 INTRODUCTION

Tillamook County has experienced many landslides in the last 150 years. Assessing landslide risk is the primary reason for this study. In our work, we use DOGAMI protocols established by Burns and Madin (2009), Burns and others (2012a), and Burns and Mickelson (2016). We also draw from the insights and results of Burns and others (2018).

1.1 Tillamook Landslide Hazard and Risk Study Area

The study area encompasses the most densely inhabited portions of Tillamook County, including Tillamook Bay and adjacent towns, as well as low-lying corridors along the coastline and in major river valleys (**Figure 1-1**). The study area extends to the Pacific Ocean in the west, Cape Falcon to the north, Cascade Head to the south, and east along Highway 6 to milepost ~25.5, about 5.5 miles west of the Tillamook County – Washington County line.

Figure 1-1. Map of the study area. SP is state park.

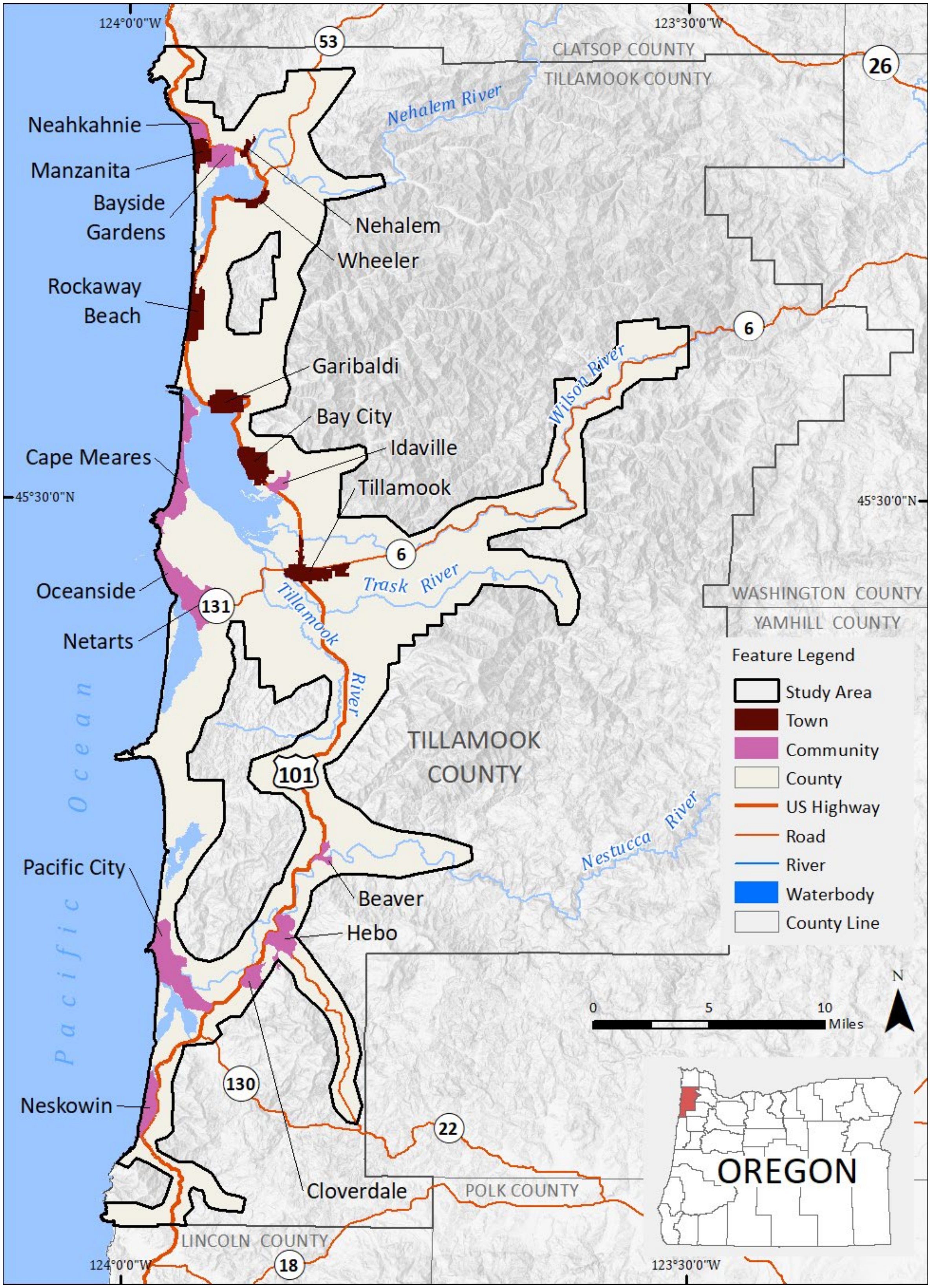


The population centers evaluated in this study include Tillamook, Manzanita, Garibaldi, Rockaway Beach, Wheeler, Bay City, and Nehalem, and the communities of Bayside Gardens, Beaver, Cape Meares, Cloverdale, Hebo, Idaville, Neahkahnie, Neskowin, Netarts, Oceanside, and Pacific City as well as unincorporated portions of Tillamook County (**Figure 1-2**). As of the 2010 census, 25,250 people live in Tillamook County (U.S. Census, 2010).

The study area includes highway corridors along the North Wilson Highway (Oregon Highway 6), the Necanicum River Highway (Oregon Highway 53) northeast to the Clatsop County line, southeast along the Three Rivers Highway (Oregon Highway 22) to milepost 10, almost to the junction with Highway 130 and the Yamhill County line. The study area includes the entirety of U.S. Highway 101 within Tillamook County.

The study area includes seven major rivers draining the steep Coast Range and meeting the Pacific Ocean, including the Nehalem River draining into Nehalem Bay, the Miami, Kilchis, Wilson, and Tillamook Rivers flowing into the broad, extensive Tillamook Bay, and the Nestucca River flowing into Nestucca Bay. The area is characterized by a diverse array of landforms and geomorphology, including resistant coastal headlands, active and inactive sand dunes, estuaries, deltas, river valleys, marine terraces, coastal foothills and very steep highlands (Fillmore and Shipman, 2013). Tillamook County experiences some of the highest average annual precipitation in the state of Oregon (PRISM Climate Group, 2020). The coastal lowlands average 65–80 inches per year, with the headlands and highlands exceeding 130–160 inches per year. The summer is generally drier; the wettest months are November through March. The elevation within the study area ranges from sea level to 3,300 ft above sea level (asl) (1,005 m asl), with pronounced relief along the five coastal headlands in the study area (Cape Falcon, Cape Meares, Cape Lookout, Cape Kiwanda, and Cascade Head).

Figure 1-2. Map of risk reporting areas/communities in the study area.



The climate is dominated by the adjacent Pacific Ocean. Weather systems emanating from the west encounter the headlands and uplands of the Coast Range, resulting in precipitation, mostly rain, with mild temperatures dominating throughout the year (average annual low 40–46 °F; average annual high 50–56 °F).

The region is susceptible to small- to large-magnitude earthquakes from three primary sources: 1) the Cascadia subduction zone (CSZ), 2) intraplate, and 3) crustal faults. The CSZ is located approximately 50 miles to the west of the coast. The source for intraplate earthquakes is related to the subducting Juan de Fuca plate movement deep below the area. Shallow, crustal earthquakes occur from local geologic structures near the surface, with a few areas of potential sources in the greater mid- to northern Coast Range (Wells and others, 1994).

1.2 Purpose

The purpose of this project is to help communities in this region become more aware of and resilient to landslide hazards by providing the communities with accurate, detailed, and up-to-date information on the spatial distribution of these hazards, and those communities that may be at risk from landslide failures.

The main objectives of this study are to:

- compile existing data including previous geologic hazard reports and natural hazard mitigation plans,
- create a new geodatabase of landslide hazards including lidar-based landslide inventory and susceptibility (**Figure 1-3**), and
- perform exposure and Hazus–based risk analyses.

The body of this report describes the overall approach used to perform the mapping and analyses. Section 3.0 presents the overall study results determined to meet each of these objectives. 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 in this context is defined as a particular area being capable of slope failure or 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 (Burns and others, 2015).

1.3 Previous Studies

Following the winters of 1971 and 1972 when heavy rain and extensive flooding in coastal Clatsop and Tillamook Counties resulted in the area being declared a federal disaster, DOGAMI initiated a major study to evaluate coastal geologic hazards and environmental geology in both counties (Schlicker and others, 1972). A continuation of this work in the inland areas of Tillamook and Clatsop Counties also described geology and slope stability issues (Beaulieu, 1973). Several individual landslides are described, although their exact locations may not be defined.

Allan and Priest (2001) mapped erosion hazard zones for coastal Tillamook County. This work included detailed landslide mapping, which is included in the Statewide Landslide information Database for Oregon (SLIDO) and is used to inform the present study. Updated coastal erosion hazard mapping of the dune-backed beaches of Tillamook County was conducted in 2014 (Stimely and Allan, 2014) using the most current lidar data, sea level rise projections, and CSZ-induced subsidence estimates. More recently, Allan (2020) completed a geomorphic evaluation of beaches and dunes in Tillamook County using lidar data and photo interpretation.

A natural hazard risk assessment undertaken by Williams and others (2020) used the best available data for flooding, landsliding, liquefaction, earthquake damage (using Hazus Multi-Hazard) and detailed data of assets to perform an exposure analysis in order to quantify risk. Hazus Multi-Hazard (Hazus-MH) is a software program with standardized methods based on models to estimate potential wind, flood, and earthquake losses on a regional basis (FEMA, 2011).

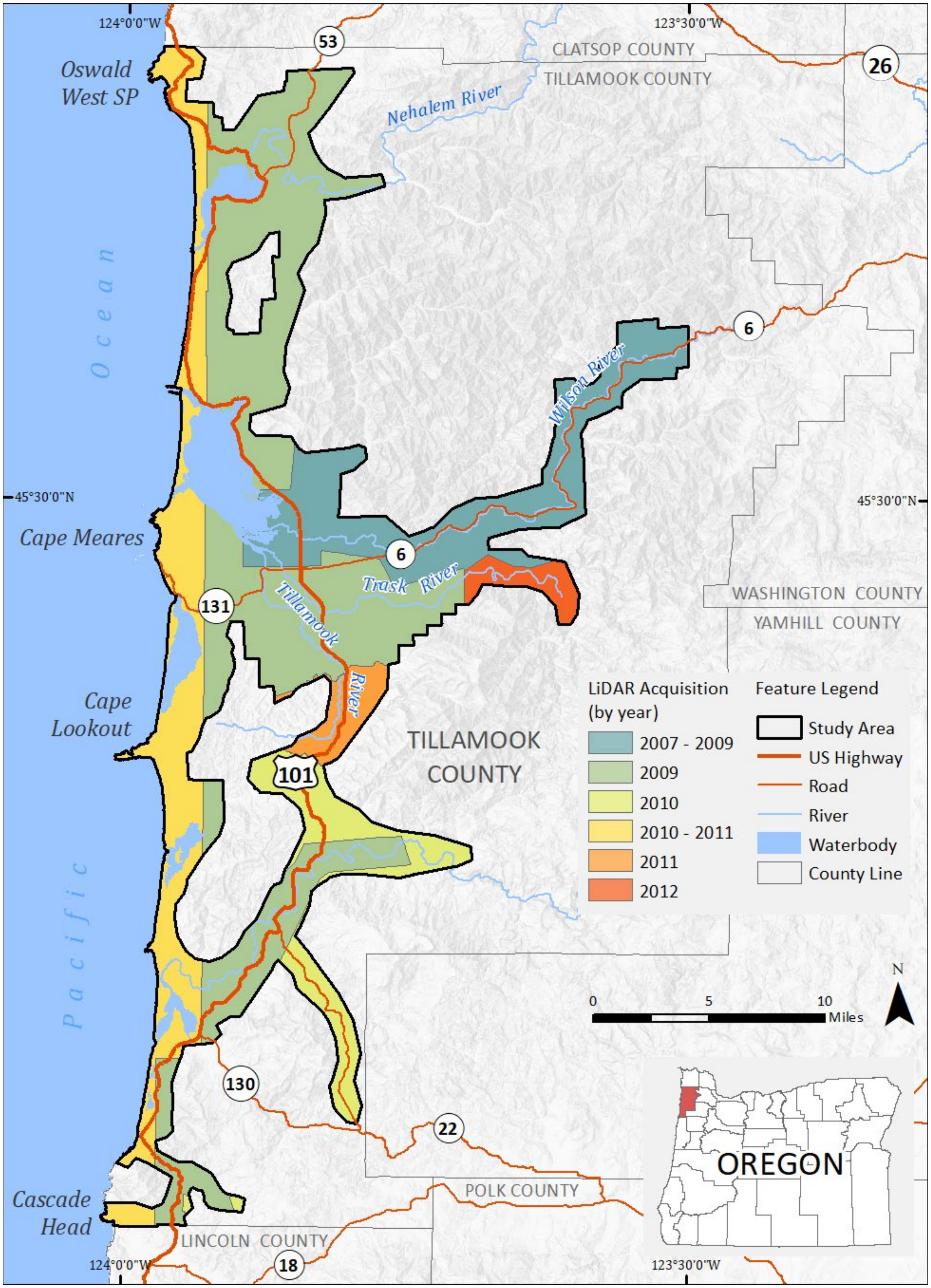
The most recent and detailed geologic studies were conducted by the U.S. Geological Survey in the 1990s: Wells and others (1994) and Snavely and others (1996) covered the majority of the study area. The most northern portion of the study area was mapped by Niem and others (1985).

Several site-specific landslide studies have been undertaken by staff at DOGAMI. Priest (1998) evaluated an active landslide named “The Capes” in the proximity of Netarts. Movement of the slide face was initiated due to significant toe erosion caused by the migration of the estuary mouth up against the landslide, enabling storm waves to erode the toe of the slide. Mitigation of the slide involving localized sheet piling was confined to a few discrete areas near the top of the bluff adjacent to several homes.

The active “Cape Meares Landslide” has been known since 1899 (Clarke, 1904). Several site-specific investigations have been conducted by ODOT and others (e.g., Machan, 2014). The landslide is impacted at the toe by periodic wave action. In the upper headscarp, retrogression and block failures have affected portions of the Cape Meares Loop Road. Over the years, the road had been periodically closed and was eventually closed indefinitely due to persistent large movement of the landslide block.

Schlicker and others (1972) identified several historical landslides, with descriptions, though in some cases lacking exact locations. Schlicker and others (1972) described an active Cape Meares landslide in 1971. Another nearby landslide, which has almost disappeared due to coastal erosion, occurred sometime in the 1930s or 1940s between Short Beach and Cape Meares Lighthouse, described as a 300 foot-wide slump, with remnant blocks visible (Schlicker and others, 1972).

Figure 1-3. Map displaying lidar data used in this study, with different acquisition years displayed.



1.4 Engineering Geology

We created bedrock and surficial engineering geologic maps of the study area as input datasets for the deep and shallow landslide susceptibility models described later in this report. Engineering geology maps are commonly based on geotechnical properties and engineering behavior derived from a standard lithostratigraphic geologic map (Dobbs and others, 2012). Such maps are commonly divided into bedrock engineering geology and surficial engineering geology (Keaton and DeGraff, 1996).

In general, we followed the methods of Burns and others (2012a) and Burns and Mickelson (2016) to create the surficial and bedrock engineering geology maps. A brief geologic history of the study area is provided below. For additional information on the bedrock and surficial geology, see Wells and others (1994), Snavely and others (1996), Niem and others (1985), and the Oregon Geologic Data Compilation (OGDC, release 6 [Smith and Roe, 2015]).

The Tillamook study area is in the northern Oregon Coast Range, dominated by Eocene Tillamook Volcanics overlying Miocene-aged sedimentary rocks, crossing a broad, northeast-plunging structural arch (Wells and others, 1994). The associated uplift of the Coast Range exposes the core of the arch in the study area, which consists of marine mudstone and sandstone interbedded with volcanic units from late Eocene to Miocene age (5 to 40 million years old). North of Tillamook Bay and the Wilson River, basalt flow sequences of the Tillamook Volcanics form the highland and steep mountainous terrain. To the south, widespread diabase sills interfinger deep marine strata of the Tyee and Yamhill Formations (Wells and others, 1994). These contacts are complex. The coastal headlands of Arch Cape, Cape Lookout, and Cascade Head are resistant peninsulas of basalt flows. Wells and others (1994) mapped portions of these headlands as the Grande Ronde unit of the Columbia River Basalt group.

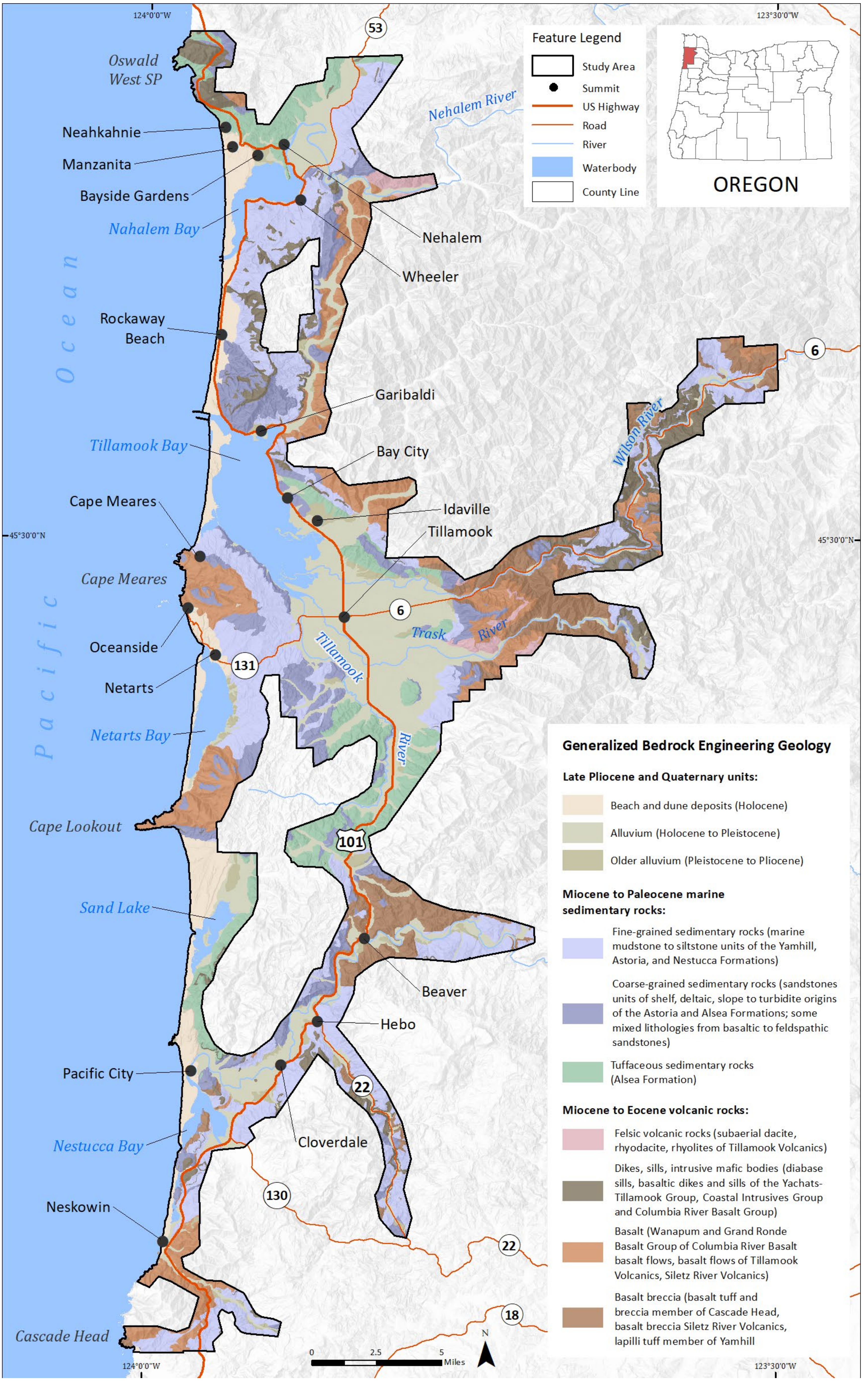
Within the Oregon Geologic Data Compilation (OGDC, version 6), there are over 80 unique geologic map units within the study area. We simplified the geologic units into 10 bedrock engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 1-4**). These groups are:

Late Pliocene and Quaternary units:
- Beach and Dune Deposits (Holocene)
- Alluvium (Holocene to Pleistocene)
- Older alluvium (Pleistocene to Pliocene)

Miocene to Paleocene marine sedimentary rocks:
- Fine-grained sedimentary rocks (marine mudstone to siltstone units of the Yamhill, Astoria and Nestucca Formations)
- Coarse-grained marine sedimentary rocks (sandstones units of shelf, deltaic, slope to turbidite origin of the Astoria and Alsea Formations; some mixed lithologies from basaltic to feldspathic sandstones)
- Tuffaceous sedimentary rocks (Alsea Formation)

Miocene to Eocene volcanic rocks:
- Felsic volcanic rocks (subaerial dacite, rhyodacite, rhyolites of Tillamook Volcanics)
- Dikes, sills, intrusive mafic bodies (diabase sills, basaltic dikes and sills of the Yachats-Tillamook Group, Coastal Intrusives Group and Columbia River Basalt Group)
- Basalt (Wanapum and Grand Ronde Basalt Group of Columbia River Basalt flows, basalt flows of Tillamook Volcanics, Siletz River Volcanics)
- Basalt breccia (basalt tuff and breccia member of Cascade Head, basalt breccia Siletz River Volcanics, lapilli tuff member of Yamhill Formation)

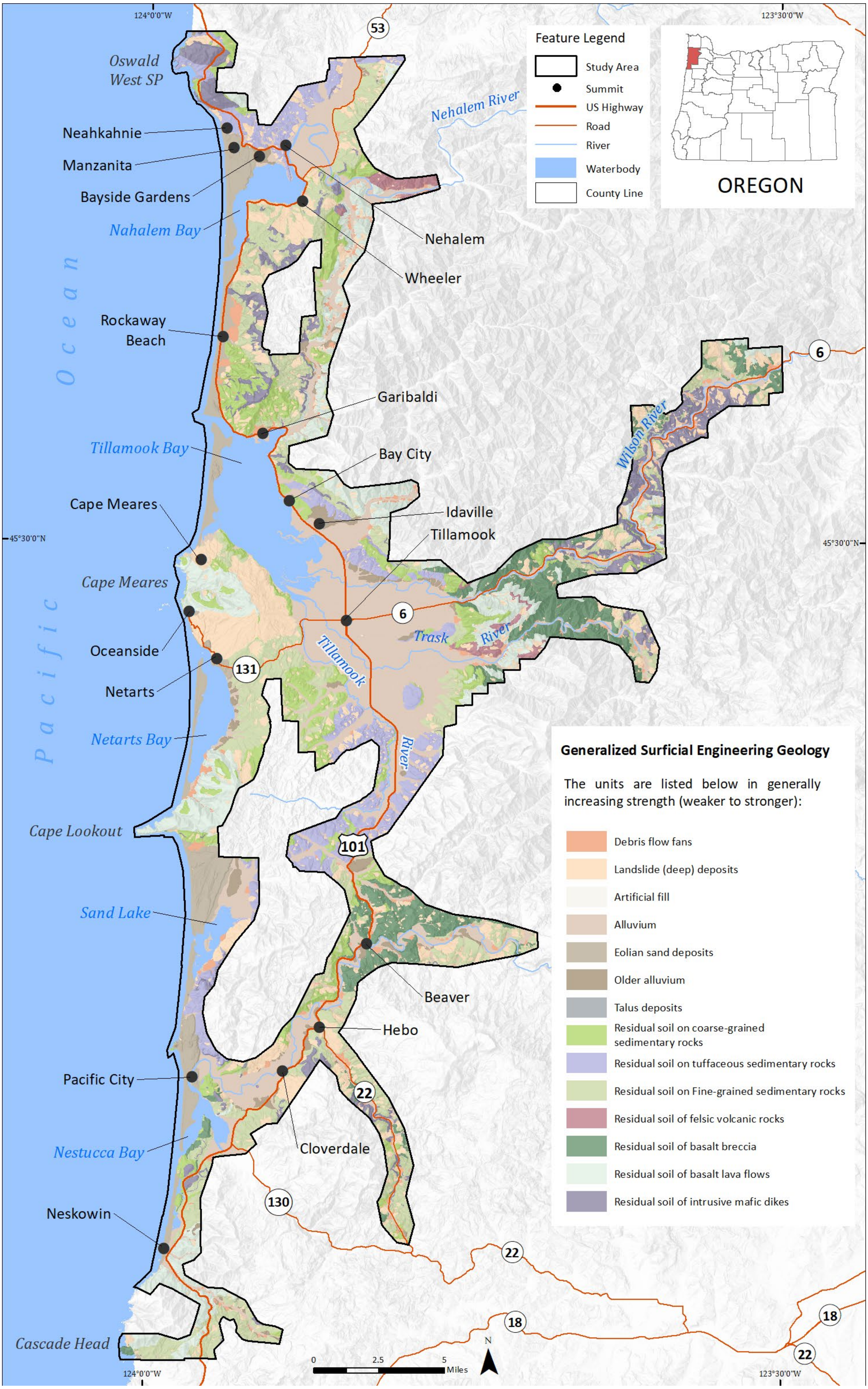
Figure 1-4. Generalized bedrock engineering geologic map, based on work of Wells and others (1994), Snavely (1996), and Niem and others (1985).



We simplified the surficial geologic units in the study area into 14 surficial engineering geologic units on the basis of similar geologic and geotechnical properties (**Figure 1-5**). The surficial engineering geologic map takes into consideration descriptions of soils and materials at the surface, based on the work of Wells and others (1994), Snavely and others (1996), Niem and others (1985), and Fillmore and Shipman (2013). The units are listed below in generally increasing strength (weaker to stronger):

- Debris flow fans
- Landslide (deep) deposits
- Artificial fill
- Alluvium
- Eolian sand deposits
- Older alluvium
- Talus deposits
- Residual soil on coarse-grained sedimentary rocks
- Residual soil on tuffaceous sedimentary rocks
- Residual soil on fine-grained sedimentary rocks
- Residual soil of felsic volcanic rocks
- Residual soil of basalt breccia
- Residual soil of basalt lava flows
- Residual soil of intrusive mafic dikes

Figure 1-5. Map of generalized surficial engineering geology in the study area of Tillamook County.



1.5 Landslides

The Federal Emergency Management Agency (FEMA) issued 73 major disaster declarations for Oregon during the period 1953–2019 (https://www.fema.gov/disasters/disaster-declarations). Most of these disasters were related to storm events that caused flooding that commonly included landslides. During this time, 17 declared disasters affected Tillamook County (FEMA Disaster Declarations Summary):

- 1964 – FEMA DR-184, Heavy Rains and Flooding
- 1971 – FEMA DR-301, Storms and Flooding
- 1972 – FEMA DR-319, Severe Storms and Flooding
- 1974 – FEMA DR-413, Severe Storms, Snowmelt, and Flooding
- 1990 – FEMA DR-853, Severe Storms and Flooding
- 1994 – FEMA DR-1036, The El Nino (The Salmon Industry)
- 1996 – FEMA DR-1099, High Winds, Severe Storms and Flooding
- 1996 – FEMA DR-1107, Severe Storms and High Winds
- 2004 – FEMA DR-1510, Severe Winter Storms
- 2006 – FEMA DR-1632, Severe Storms, Flooding, Landslides, and Mudslides
- 2006 – FEMA DR-1672, Severe Storms, Flooding, Landslides and Mudslides
- 2006 – FEMA DR-1683, Severe Winter Storm and Flooding
- 2007 – FEMA DR-1733, Severe Storms, Flooding, Landslides, and Mudslides
- 2009 – FEMA DR-1824, Severe Winter Storm, Record and Near Record Snow
- 2011 – FEMA DR-1956, Severe Winter Storm, Flooding, Mudslides, Landslides, and Debris Flows
- 2012 – FEMA DR-4055, Severe Winter Storm, Flooding, Landslides, and Mudslides
- 2016 – FEMA DR-4258, Severe Winter Storms, Straight-line Winds, Flooding, Landslides, and Mudslides

The winters of 1996 and 1997 where particularly impactful from landslides and 9,582 landslides (Hofmeister, 2000) were recorded across Oregon (FEMA Disaster Declarations 1099, 1107, 1149, and 1160). The increase in declared disasters in recent decades is likely due to a combination of 1) improved reporting, recording, and communications because of the onset of digital technology during this time period, and 2) development in areas with relatively higher landslide hazards. Not all of the above declared disasters for Tillamook County included landslides or were located in the immediate study area for this project.

There are hundreds of historic (<150 years ago) and prehistoric (>150 years ago) landslides in the study area. It is important to note that not all landslides that occurred within the study area have been recorded or are accessible. For this study, we mapped the landslides following the method outlined by Burns and Madin (2009).

The combination of FEMA declared disasters, hundreds of prehistoric landslides, and hundreds of historic landslides provides evidence of a moderate to high level of landslide hazard and risk in the study area. Therefore, these data attest to the importance of landslide risk reduction.

2.0 METHODS

To evaluate the landslide hazard and risk for the study area, we performed three primary tasks: 1) compiled and created landslide hazard data including landslide inventory and susceptibility, 2) compiled and used existing asset data from Williams and others (2020) including critical facilities, generalized land occupancy (land use/zoning), buildings, and population distribution data, and 3) performed risk analysis including exposure and Hazus-based risk analysis. **Table 2-1** summarizes the hazard and asset datasets needed for the risk analyses and where in this report the results of the analyses can be found.

Table 2-1. Input datasets and results.

Dataset	Source	Results
Building footprints and value; critical facilities; population distribution	Williams and others (2020)	**Table 3-4** **Table 3-5**
Landslide inventory and susceptibility	this study	**Figure 3-1** **Figure 3-2** **Figure 3-3** **Figure 3-4**

2.1 Landslide Hazard Evaluation Methods

First, we compiled the detailed lidar-based landslide inventory. Lidar data are from laser imaging of the ground surface from an airplane. The data provide high-accuracy elevation imagery of the ground surface without vegetation and buildings. The use of lidar makes mapping landslide scarps and morphology much more straightforward (Burns, 2007). After our lidar analyses, we updated the historic point landslide inventory within the study area by using aerial photos and records. Because both datasets are landslide inventories but derived from different sources, we will refer to the lidar-based polygon inventory as the *SP-42 inventory* (after Burns and Madin, 2009) and the historic point inventory as the *historic landslide point inventory* throughout this paper. Next, we used models to create shallow and deep landslide susceptibility maps. The methods we used to perform these steps are described in detail below and are consistent with approaches developed by DOGAMI elsewhere in Oregon.

2.1.1 Landslide inventories

We mapped and digitized the SP-42 inventory dataset by using lidar analysis and field checking, following the methodology of Burns and Madin (2009), to create the landslide inventory at a recommended use scale of 1:8,000.

We created the historic landslide point inventory dataset by compiling two existing datasets: 1) SLIDO-3.2 (Burns, 2014) and 2) locally held historic landslide records. We then added landslide points by using orthorectified, high-resolution satellite imagery from the National Agricultural Imagery Program (NAIP), which is serially collected every 5 years. We identified landslides in the imagery and reported the timing of the landslide occurrence as within the range of NAIP collections (e.g., 2000–2005). The final version of this dataset is included with this publication and is referred to as *historic landslide points*.

Many of these records were from a post-1996 storm season damage survey carried out by FEMA and the Oregon Office of Emergency Management (FEMA, 1996). Other records were compiled by DOGAMI in the aftermath of the 1996 and 1997 winter storms (Hofmeister, 2000). Other historic landslide points were recorded by ODOT for failures along their roadways. Prior to this study, there were 504 identified historic landslide points.

2.1.2 Shallow landslide susceptibility

We created the shallow landslide susceptibility map by following the shallow landslide susceptibility mapping methodology of Burns and others (2012a). The main components of the method include:

1) using a landslide inventory,
2) calculating regional slope stability factor of safety (FOS),
3) removing isolated small elevation changes (to reduce overprediction),
4) creating buffers to add susceptible areas missed in a grid-type analysis (to reduce underprediction), and
5) combining the four components into final susceptibility hazard zones.

The first component was taken directly from the landslide inventory created as part of this project. The calculation of the FOS requires several input datasets. One is a map of the surficial geology with geo-technical material properties. As discussed in section 1.4, we created a new surficial engineering geology map for this study. We created a table of material properties, based in part on local geotechnical reports and in part on existing, generalized statewide values (Burns and others, 2012a, **Table 2-2**), for each of the primary surficial engineering geologic units in the study area. A recent dissertation (Korte, 2018), conducted lab and field geotechnical studies on a nearby watershed in the Coast Range, Drift Creek watershed, about 10 miles to the south of this study area. Korte (2018), tested physical properties of the Nestucca, Yamhill, Alsea, Tyee, and Siletz River volcanic formations. These were incorporated into the geotechnical material properties table.

Other geotechnical reports submitted to the County of Tillamook were used to gather information on geologic units not found in Korte (2018) such as alluvium, older alluvium, and residual soils on basalt (Professional Service Industries, Inc., 2006; PBS Engineering and Environmental, 2014).

To calculate the FOS (component 2), we estimated new material properties from these local geotechnical reports and from past studies in the northern Willamette Valley including Clackamas, Multnomah County, and City of Portland (Burns and others, 2013, 2018), for geologic units that were not measured locally.

After we acquired the material property values either directly from past studies or through correlations for each surficial geologic unit, we averaged each set of values by geologic unit. DOGAMI staff then reviewed these ranges of values and averaged values in order to decide the final material properties to be used for this study. These properties are listed in **Table 2-2** and were used to calculate the two slope thresholds that separate the three FOS ranges. The ranges are 1) values >1.5 (generally considered stable), 2) values between 1.25 and 1.5 (generally considered potentially unstable), and 3) values <1.25 (generally considered potentially unstable and unstable below 1.0).

Table 2-2. Summary of geotechnical material properties for primary surficial geologic engineering units in the study area, based on Burns and Mickelson (2016).

Engineering Geologic Unit	Angle of internal friction (degrees)	Cohesion (lb/ft^2)	Unit Weight (saturated lb/ft^3)	Threshold for Stable Slopes (degrees)	Threshold for Potentially Unstable Slopes (degrees)	Source
Residual soil of felsic volcanic rocks	28	500	115	20	24	IMS-57
Residual soil of basalt breccia	28	500	115	20	24	SP-46
Older Alluvium/Terrace	34	0	115	11.5	13.5	IMS-60
Alluvium	30	0	115	9.5	11.5	IMS-60
Artificial fill	30	0	115	9.5	11.5	IMS-60
Eolian sand deposits	32	0	115	10.5	12.5	IMS-57
Residual soil on tuffaceous sedimentary rocks	30	200	115	14.5	16.5	IMS-57
Residual soil of basalt lava flows	28	500	115	20	24	IMS-57
Residual soil on fine-grained sedimentary rocks	30	200	115	14.5	16.5	IMS-57
Residual soil of intrusive mafic dikes	28	500	115	20	24	IMS-60
Residual soil on coarse-grained sedimentary rocks	40	0	115	14	16.5	IMS-57
Deep landslide deposits	28	0	115	9	10.5	IMS-60
Talus deposits	30	150	115	13	15.5	IMS-57
Debris flow fans	28	0	115	9	10.5	IMS-57

*Slope angle thresholds are the boundaries calculated for three FOS ranges: 1) values >1.5 (generally considered stable), 2) values between 1.25 and 1.5 (generally considered potentially unstable), and 3) values <1.25 (generally considered potentially unstable and unstable below 1.0). Sources include IMS-57 (Burns and others, 2017), IMS-60 (Calhoun and others, 2018), and SP-46 (Burns and others, 2015).

To remove isolated small elevation changes (to reduce overprediction—component 3) and to add susceptible areas missed in a grid-type analysis (to reduce underprediction—component 4), we created buffers as described in detail by Burns and others (2012a). When the FOS class map is prepared using a slope map with such high resolution, many areas with shallow landslide susceptibility are falsely classified as having moderate or high susceptibility (overprediction). This occurs because many fine-scale topographic features are represented in the lidar DEM that do not have sufficient vertical or lateral extent to pose a significant shallow landslide hazard. This could include features like road ditches. One disadvantage of a slope stability analysis using a raster or grid-type infinite slope equation is that the analysis looks at each raster cell independently. The FOS is calculated in the same way regardless of where the cell falls on a slope or where it sits in relation to important topographic features or changes. Because the location of a cell can have an important impact on the landslide susceptibility, DOGAMI developed these two buffers to help reduce underprediction.

2.1.3 Deep landslide susceptibility

We created the deep landslide susceptibility map by following the methodology of Burns and Mickelson (2016). Deep landslides were defined by Burns and Madin (2009) as having a failure surface greater than 15 feet in depth. The main components of the method include:

1) using a landslide inventory
2) creating buffers (hazard zone expansion areas)
3) combining the following four factors to determine the moderate susceptibility zone:
    a. susceptible geologic units
    b. susceptible geologic contacts
    c. susceptible slope angles for each engineering geology unit polygon
    d. susceptible direction of movement for each engineering geology unit polygon
4) combining components 1–3 into final susceptibility hazard zones

For each component and factor, we made separate GIS data layers. The first component is taken directly from the landslide inventory created as part of this project. Because many deep landslides move repeatedly over hundreds or thousands of years and, commonly, the continued movement is through retrogressive failure or upslope failure of the head scarp, we applied a buffer (expanded the hazard zone) to all mapped deep landslide deposits.

Next, we used four factors to determine the moderate zone. The first factor, geologic units, has a relatively widespread correlation with surficial processes. For example, it is very common that certain rock formations or soil types are more or are less prone to landslides. This is generally due to the properties of the rock or soil, such as the material strength or bedding planes.

The second factor, geologic contacts, accounts for a phenomenon we have noted, especially since we began mapping landslide inventories using lidar (Burns and Mickelson, 2016). Many landslides occur along a contact, particularly when sedimentary or volcaniclastic rock is in contact with hard intrusive or volcanic rock. For example, large, deep landslides are located along resistant intrusive or volcanic rocks and marine sedimentary rocks.

The third factor, slope angle, is very commonly correlated with landslide susceptibility. Most landslide susceptibility maps use slope as the primary factor or as at least one of the factors to predict future landslide locations. With regard to shallow landslides, it is very common to see more shallow landslides associated with steeper slopes. Deep landslides appear to have a less direct correlation with slope steepness, which is one reason to include the other three factors (geologic units, geologic contacts, and direction of movement).

Finally, the fourth factor is the direction of movement, which is recorded as an attribute for every landslide in our landslide inventory. A standard factor to examine during site-specific evaluations is the local bedding dip and dip direction because deep landslides tend to fail along those bedding planes and in the direction of the dip, especially where slope and dip are in the same direction. Unfortunately, we do not have extensive dip and dip direction measurements in the study area. Therefore we used the recorded direction of movement from the landslide inventory database as a proxy for dip direction or preferred direction of movement, and, where available, we included dip and dip direction measurements from digitized geologic maps (Wells and others, 1994).

We added together the four GIS data layers made from each of these factors to delineate the line between the moderate and low hazard zones (**Figure 3-4**). We then combined the four component GIS layers to create the deep landslide susceptibility map with low, moderate, and high hazard zones.

2.2 Asset Data Compilation and Creation Methods

A recent study (Williams and others, 2020) focused in Tillamook County compiled asset data by synthesizing assessor data, U.S. Census information, Hazus-MH general building stock information, and building footprint data. Combined, these data resulted in a single dataset of building points and their associated building characteristics. We leveraged the recently created, high-precision data to use for risk analysis for the landslide hazard data created for this study.

2.2.1 Population

Permanent population (resident) figures are needed to estimate losses from disasters. However, it is challenging to map population because people tend to travel on yearly, seasonal, monthly, daily, and hourly bases, especially in Tillamook County, where 7–12% of residential buildings are likely vacation rentals (Williams and others, 2020).

In the study area, U.S. Census population data are organized in spatial units called census block groups. Block groups are statistical divisions of census tracts and generally contain between 600 and 3,000 people. Blocks can be as small as 125 acres (50 hectares) and are typically bounded by streets, roads, or creeks. In urban areas census blocks are small, usually defined by one city block, while in rural areas with fewer roads, census blocks are larger and can be bound by other geographic and geomorphic features. Within each block group the census provides no information on the spatial distribution of population; instead it defines one population number per block group. To estimate the size and distribution of permanent population for most of the study area, Williams and others (2020) distributed the population per census block among residential buildings and pro-rated based on square footage. Finally, it is important to note that the census block population does not include visitors or non-permanent populations.

2.2.2 Buildings

Williams and others (2020) compiled data for all buildings larger than 500 square feet (152 square meters) as determined from existing building footprints or tax assessor data. They converted building footprints to points and migrated them into a user-defined facility (UDF) database with standard field names and attribute domains. With such detailed building data, a particular damage function can be applied to each building, providing more detail in Hazus-MH. Both tax lot data and assessor data were incorporated and formatted to be incorporated into the building inventory database, and subsequently, into the UDF points. We used this building geodatabase for analysis in this study.

2.2.3 Critical facilities

Critical facilities are typically defined as emergency facilities such as hospitals, fire stations, police stations, and school buildings (FEMA, http://www.fema.gov/national-flood-insurance-program-2/critical-facility). We started with the definitions and data created for the DOGAMI Statewide Seismic Needs Assessment (SSNA; Lewis, 2007) to identify the critical facilities. These data, updated by Williams and others (2020), are used in this study. The critical facilities included in this project include school buildings, police stations, fire stations, emergency operations, military facilities, and hospitals. We extracted critical facilities as points from the SSNA. These points were buffered into polygons, which were used to complete the exposure analysis.

2.3 Risk Analysis Methods

When landslides affect assets, landslides become natural hazards. Natural hazard risk assessment is the characterization of the overlap of natural hazards and assets. Risk analysis can range from simple to complicated. In this project we selected two types of regional risk analysis: 1) hazard and asset exposure and 2) Hazus-MH analysis. Hazus-MH is a multi-hazard (MH) analysis program that estimates physical, economic, and social impacts of a disaster (FEMA, 2011). In order to understand better the risk, we also collected historic landslide data for the study area and estimated actual historic losses.

2.3.1 Exposure analysis

A building, or other asset, is considered to be exposed to a hazard if it is located within that particular hazard area. To find which community assets fell in which hazard zones, we performed exposure analysis with Esri® ArcGIS® software. We determined exposure through a series of spatial and tabular queries between hazards and assets. We then summarized the results by community (**Table 2-3**). Landslide hazard datasets used in the exposure analysis are:

- shallow landslides (inventory polygons; see section 3.1)
- deep landslides (inventory polygons; see section 3.1)
- debris flow fans (inventory polygons; see section 3.1)
- shallow landslide susceptibility (low, moderate, and high – see section 3.2)
- deep landslide susceptibility (low, moderate, and high – see section 3.3)

Asset data (section 2.2) used in the exposure analysis are:

- population
- buildings and land in three generalized use classes: residential, commercial, and public
    - buildings reported by count, count percent of total, and value (dollars)
- critical facilities buildings: fire stations, police stations, hospitals, military facilities, emergency response and school buildings
    - buildings reported by count, count percent of total, and value (dollars)

For example, we superimposed the buildings layer for the study area on the deep-landslide inventory layer to determine which buildings are exposed to that type of hazard, as demonstrated in **Figure 2-1**. The result of this analysis is both a map of the community assets exposed to the hazard and a table with the corresponding numbers of community assets exposed (full results in Appendix A).

Figure 2-1. Exposure examples from Cape Meares: generalized land use (left), deep landslide deposits (center), and exposure of assets to deep landslides (right).

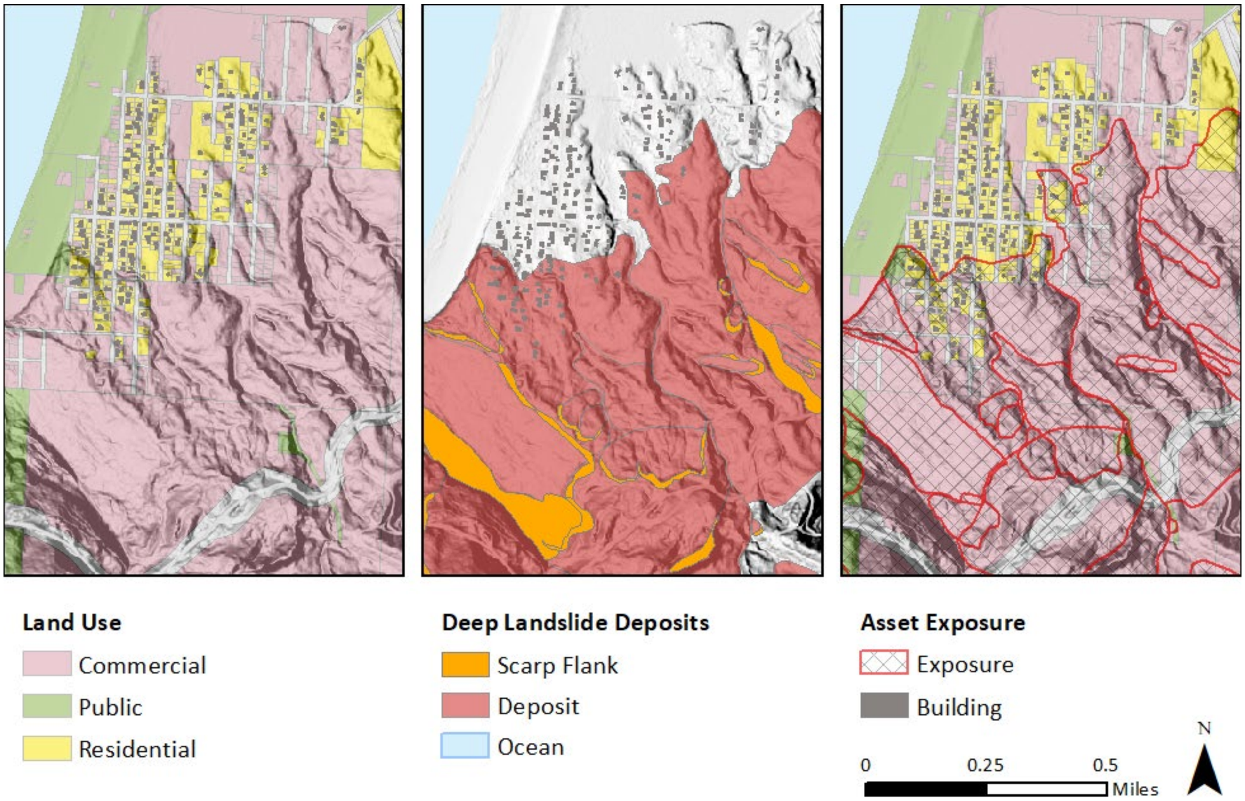


Table 2-3. Communities for exposure reporting. Community extents are shown in Figure 1-2.

Community	Area (mi^2)
Bay City	1.93
Bayside Gardens	0.99
Beaver	0.39
Cape Meares	2.76
Cloverdale	0.8
Garibaldi	1.33
Hebo	1.63
Idaville	0.49
Manzanita	0.82
Neahkahnie	0.65
Nehalem	0.27
Neskowin	0.96
Netarts	2.6
Oceanside	1.04
Pacific City	1.21
Rockaway Beach	1.57
Tillamook	1.79
Tillamook County Unincorporated	302
Wheeler	0.51
Total area	323.74

2.3.2 Hazus-MH analysis

We performed risk analysis with Hazus-MH, a risk modeling software package developed by FEMA (2011). Hazus requires a specific landslide susceptibility map, which is different than either the shallow or deep landslide susceptibility maps created as part of this project. The Hazus landslide susceptibility map (created for input into the Hazus earthquake module only) follows a specific method outlined in the Hazus technical manual (FEMA, 2011). We created both "dry" and "wet" Hazus landslide susceptibility maps for the study area, in which we used the surficial and bedrock engineering geologic information from **Figure 1-4** and **Figure 1-5** (**Table 2-4**).

Table 2-4. Landslide susceptibility of geologic groups (Hazus-MH 2.0, Table 4-15 [FEMA, 2011]).

		Slope Angle, degrees					
	Geologic Group	**0–15**	**10–15**	**15–20**	**20–30**	**30–40**	**>40**
	(a) Dry (groundwater below level of sliding)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' = 300 psf, ϕ' = 35°)	none	none	I	II	IV	VI
B	Weakly Cemented Rocks (sandy soils and poorly cemented sandstone, c' = 0, ϕ' = 35°)	none	III	IV	V	VI	VII
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' = 0, ϕ' = 20°)	V	VI	VII	IX	IX	IX
	(b) Wet (groundwater level at ground surface)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' = 300 psf, ϕ' = 35°)	none	III	VI	VII	VIII	VIII
B	Weakly Cemented Rocks (sandy soils and poorly cemented sandstone, c' = 0, ϕ' = 35°)	V	VIII	IX	IX	IX	X
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' = 0, ϕ' = 20°)	VII	IX	X	X	X	X

The symbol c' is cohesion and ϕ' angle is friction angle, both of which are measures of soil strength; the roman numerals I-X indicate least landslide prone to most landslide prone for each geologic group at different slope angles.

Hazus software can be used to model a variety of earthquake, flood, and wind probabilistic hazards and/or hazard event scenarios. Hazus Multi-Hazard (MH) can use building inventory data with the user-defined facility (UDF) mode. This mode makes loss estimations for individual buildings relative to their "cost," which is then aggregated to the community level to report loss ratios.

The damage functions within Hazus-MH are based on observations of previous disasters (FEMA, 2011). "Estimates of loss are made by intersecting building locations with natural hazard layers and applying damage functions based on the hazard severity and building characteristics" (Williams and others, 2020, p. 7). Although Hazus has limitations, we chose to use Hazus as part of our risk analysis because it is a standardized methodology with widely and publicly available risk analysis program built with empirical data from and for the United States.

The goal for the Hazus analysis was to estimate damage and losses from earthquakes coming from the Cascadia subduction zone, both with and without earthquake-induced landslides, so that we could examine the difference in damage and losses caused by just the earthquake-induced landslides. We subtracted the earthquake-without-landslides model results from the earthquake-with-landslides model results so that earthquake-induced landslide damage and losses results could be examined separately. We also analyzed landslides in dry and wet conditions (see **Table 2-4**) for each scenario to simulate the differences between an earthquake occurring when it is generally dry (summer) versus when it is wet (winter).

For the Cascadia subduction zone (CSZ) magnitude 9.0 earthquake scenario, Madin and Burns (2013) obtained synthetic bedrock ground motions from Dr. Arthur Frankel (U.S. Geological Survey, written communication, 2012); we used the same bedrock ground motion data for this project. We used the surficial engineering geology map from this study, created for the shallow landslide susceptibility, as the basis to create a seismic site class map, which was then used to amplify the bedrock ground motions for the CSZ.

These choices resulted in three different Hazus analyses (Appendix B):

- M9 Cascadia subduction zone
  - No landslides
  - Landslides dry
  - Landslides wet

In order to examine the coseismic landslide damage and loss only, we subtracted the "No landslides" results from the dry and wet landslide results.

2.3.3 Annualized loss

To better understand the landslide risk, we used the historic landslide point inventory in conjunction with previous research related to landslide losses in Oregon (Burns and others, 2017). There are limited records of landslides in this study area, but landslide location points gathered from ODOT and damage survey reports from FEMA and OEM after the February 1996 storms and associated disasters (FEMA, 1996; Hofmeister, 2000) are recorded as historic landslide points in SLIDO. We identified other landslides by using aerial imagery. One restriction is the lack of available aerial imagery before 1995, confining historic point identification to the last 25 years only. We identified in the date attribute table "pre-1995" for all visible landslides preceding the 1995 aerial imagery series.

Some records (~260 of 605 historic points) from ODOT, FEMA and OEM include comments related to frequency of occurrence, brief damage summaries, or cost estimates within the attribute table of the historic landslide points file. From these damage estimates, there is a range from $20,746 to $89,159 in annual road damage and repairs alone within the study area.

The best available estimates for cost per landslide in the state of Oregon, gathered from a recent landslide study for western Multnomah County and the City of Portland (Burns and others, 2018), included dozens of landslides of a range of sizes and amounts of damage. When a permit is required to repair landslide damage, the City of Portland has a record of the monetary damage done to private infrastructure from landslide impact. A compilation of permits for landslide repairs, as well as loss estimates made immediately post-1996 on damage to public entity infrastructure, allowed an average landslide cost to be calculated from both public and private landslide loss data. The range of losses per landslide from these sources is $67,500 to $144,000 (Burns and others, 2017).

Our assumption is that damage from landslides in other places has similar economic loss impacts as calculated in the Burns and others (2017) study. We acknowledge that different landslide types in different geologic units may cause different amounts and types of damage and that differences in housing and property values may cause differences in damage and losses amounts. However, given the limited scope of this project, we were unable to factor in these differences.

A total of 605 landslide points from pre-1995 to 2016 are included. There are very likely other landslides that have occurred in the past 150 years in the area that were not observed, recorded, or captured here.

3.0 RESULTS

We produced four detailed hazard maps from the data collected and analyzed in this study. **Figure 3-1** is a landslide inventory, **Figure 3-2** shows shallow landslide susceptibility, **Figure 3-3** shows debris flow fans and historic landslide points, and **Figure 3-4** shows deep landslide susceptibility. We combined the hazard maps with asset data to complete a landslide risk analysis. The data are available through a downloadable GIS database, as well as the Statewide Landslide Information Database of Oregon (SLIDO), a streaming web service.

3.1 Landslide Inventory Findings

Before the use of lidar to map existing landslides in the study area, 506 landslides areas (polygons) were mapped and included in SLIDO-4.0 (Franczyk and others, 2019). In contrast, our new mapping resulted in 4,091 landslides in the study area. The combined surface area of these landslides covers approximately 43.7 square miles (113 square kilometers), or about 13.3 percent of the study area (327 square miles; 847 square kilometers; **Figure 3-1**). These landslides range in size from 660 square feet (61 square meters) to 2.7 square miles (7 square kilometers). Of the 4,091 SP-42 inventory landslides, ~650 are classified as shallow and ~2,470 are deep. The other 971 landslides are mostly debris flow fans (957) and rock fall talus. Inventories for each community are summarized in **Table 3-1**.

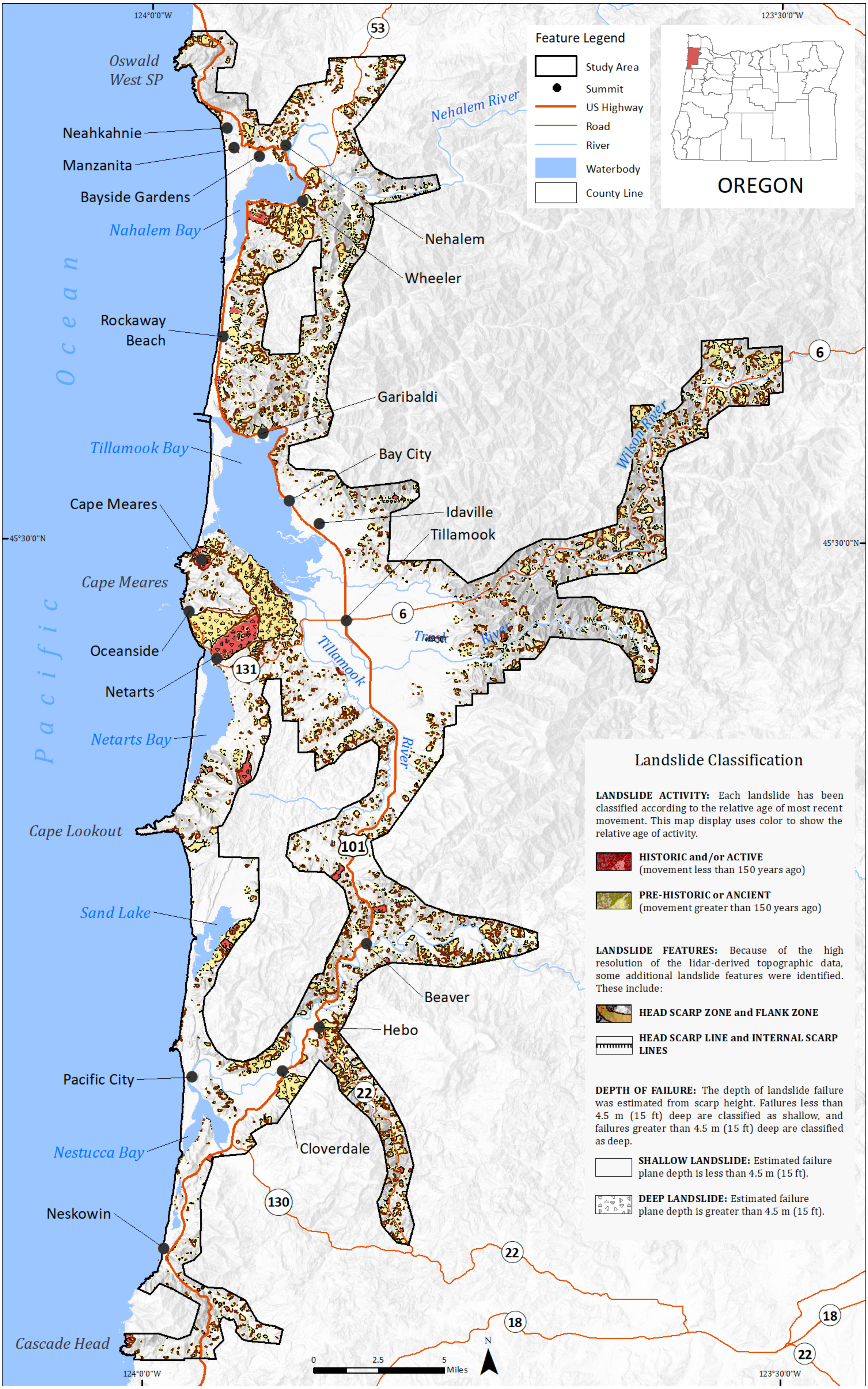
The updated historic landslide point inventory contains 605 landslide records from an undetermined historic time to 2016 within the study area. Through the process of compiling existing records and identifying landslide occurrences in aerial photos, we mapped a further 145 historic points in the vicinity of the study area. These 145 points will be included in SLIDO, but will not be counted in the analysis or results herein. The historic landslide point dataset is displayed in **Figure 3-3** and inventories for each community are shown in **Table 3-1**.

Table 3-1. Summary of landslide inventories for each community.

Communities	Landslide Count	Historic Points Count
Bay City	3	4
Bayside Gardens	6	4
Beaver	8	0
Cape Meares	25	8
Cloverdale	4	5
Garibaldi	14	5
Hebo	16	1
Idaville	1	0
Manzanita	2	0
Neahkahnie	9	9
Nehalem	14	4
Neskowin	6	2
Netarts	28	1
Oceanside	9	4
Pacific City	35	3
Rockaway Beach	24	17
Tillamook	0	0
Tillamook County Unincorporated	3,955	513
Wheeler	19	25
Total	4,178	605

Note: Some landslides overlap community boundaries, so totals will not equal total landslides in study area.

Figure 3-1. Landslide inventory map of study area within Tillamook County.



3.2 Shallow Landslide Susceptibility Findings

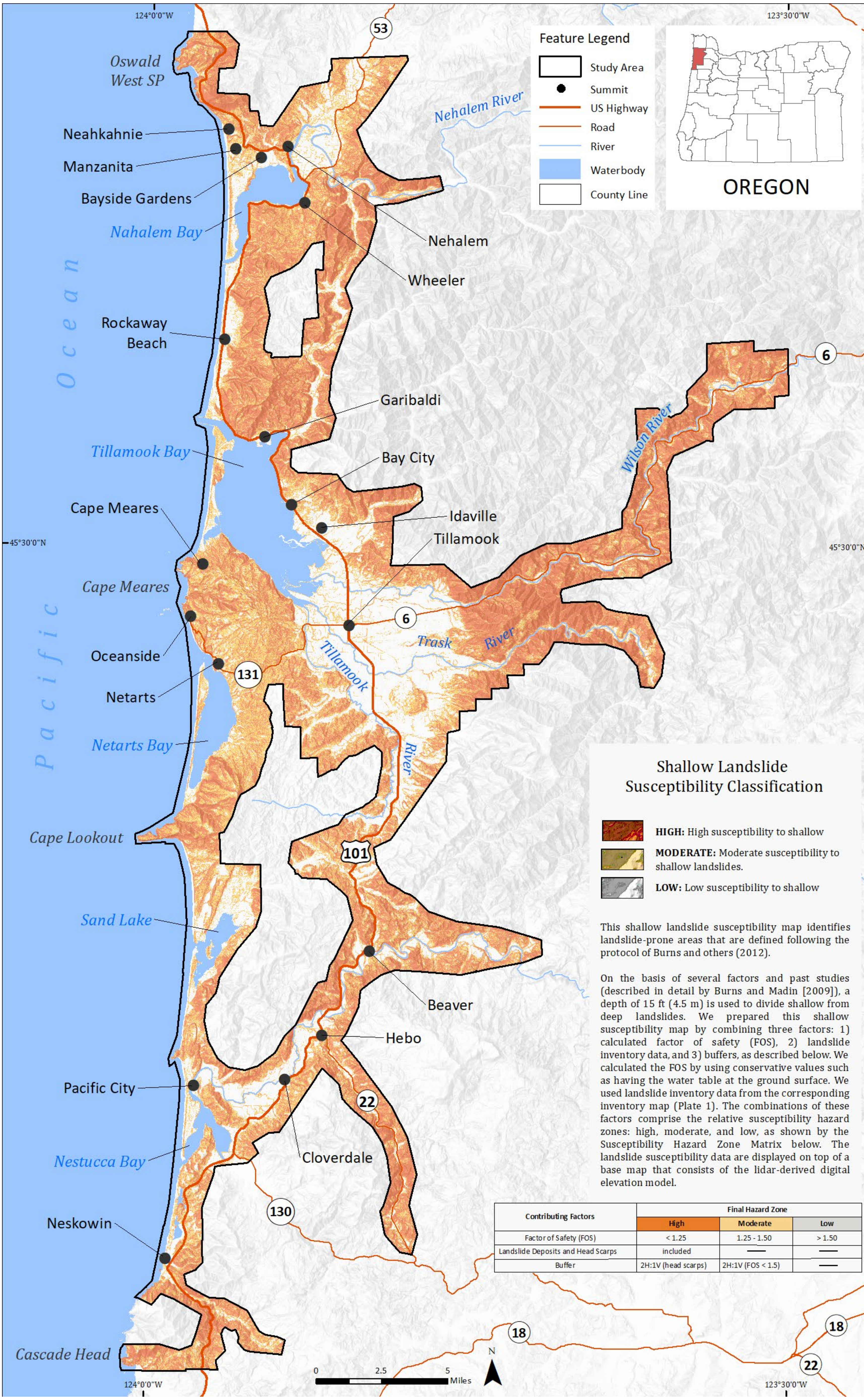
We classified the entire study area into zones of low, moderate, and high susceptibility to shallow landslides. Approximately 31% of the study area is classified as within a water body but also within a geographic boundary of a jurisdiction or low, 25% as moderate, and 43% as high susceptibility (**Table 3-2**). It is important to remember that the shallow landslide susceptibility map is not a scenario. We produced the susceptibility map by setting the groundwater table level to the ground surface throughout the study area. This worst-case scenario (ground water at the surface) would be unlikely to occur everywhere at the same time.

Table 3-2. Summary of shallow landslide susceptibility by community.

		Percentage by Zone		
Community	**Water**	**Low**	**Moderate**	**High**
Bay City	24	33	30	13
Bayside Gardens	2	53	28	17
Beaver	4	54	27	15
Cape Meares	10	23	38	29
Cloverdale	0	11	47	42
Garibaldi	29	18	19	33
Hebo	1	25	36	38
Idaville	0	81	15	4
Manzanita	0	39	45	16
Neahkahnie	1	12	44	43
Nehalem	1	22	48	29
Neskowin	11	42	30	16
Netarts	1	15	54	30
Oceanside	0	11	41	48
Pacific City	4	26	33	37
Rockaway Beach	0	63	27	10
Tillamook	4	84	10	2
Tillamook County Unincorporated	9	21	25	45
Wheeler	2	9	49	39

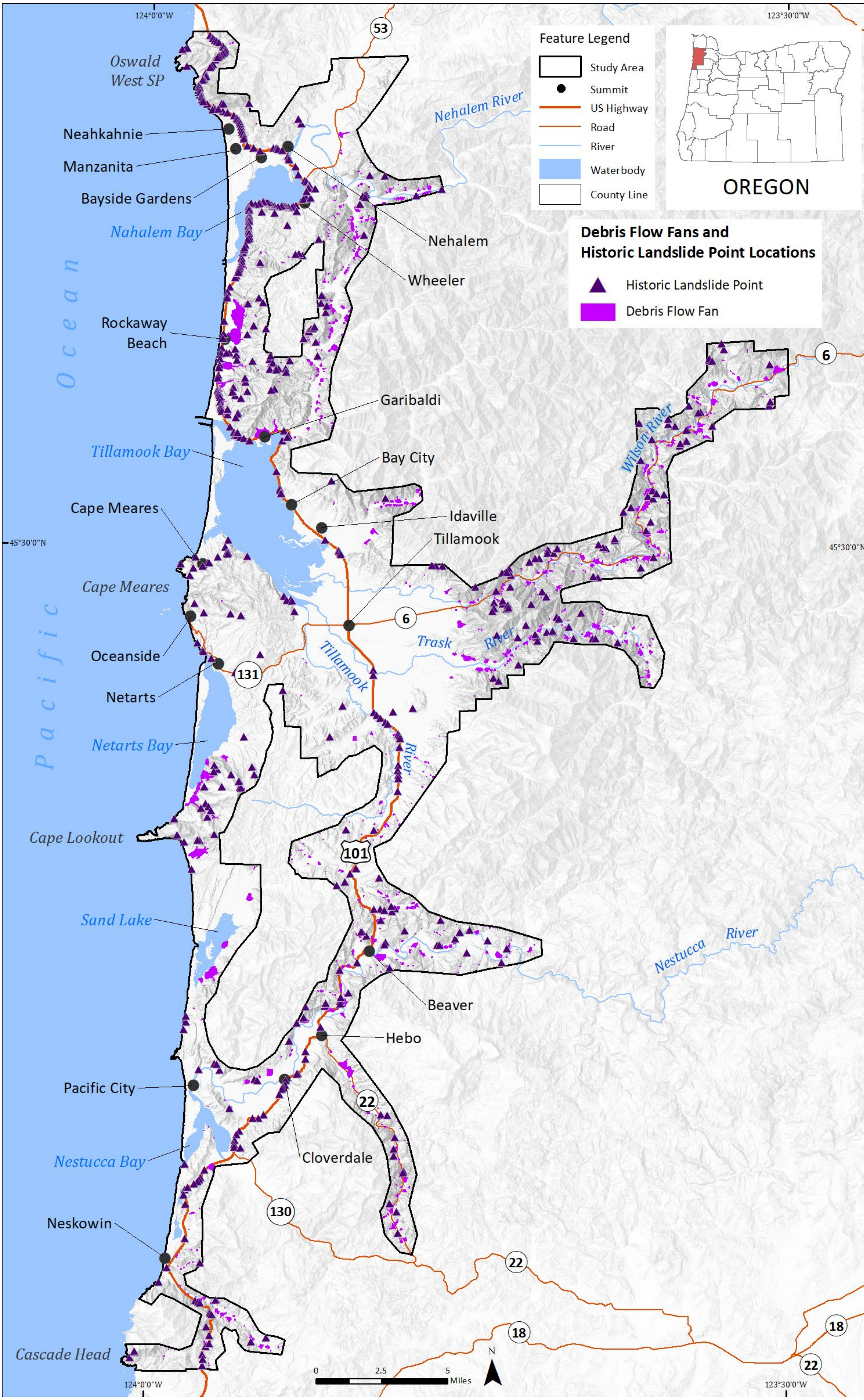
Although we did not model susceptibility to channelized debris flow transport and deposition, we did map 957 existing debris flow fans as part of the landslide inventory (**Figure 3-3**). Areas identified as highly susceptible to shallow landsliding are likely to be highly susceptible for initiation of debris flows, due to the weakness of the material and high slope angles (Highland and Bobrowsky, 2008). A possible method to identify whether or not a particular drainage is susceptible to debris flows is the presence of a fan at the mouth of the drainage developed by past debris flow events. The fan is usually formed by a sequence of debris flows depositing material where channel gradient is reduced and channel confinement is lost (Highland and Bobrowsky, 2008).

Figure 3-2. Shallow landslide susceptibility map.



Contributing Factors	Final Hazard Zone		
	High	Moderate	Low
Factor of Safety (FOS)	< 1.25	1.25 - 1.50	> 1.50
Landslide Deposits and Head Scarps	included	—	—
Buffer	2H:1V (head scarps)	2H:1V (FOS < 1.5)	—

Figure 3-3. Map of channelized debris flow fans and historic landslide point locations in the study area.



3.3 Deep Landslide Susceptibility Findings

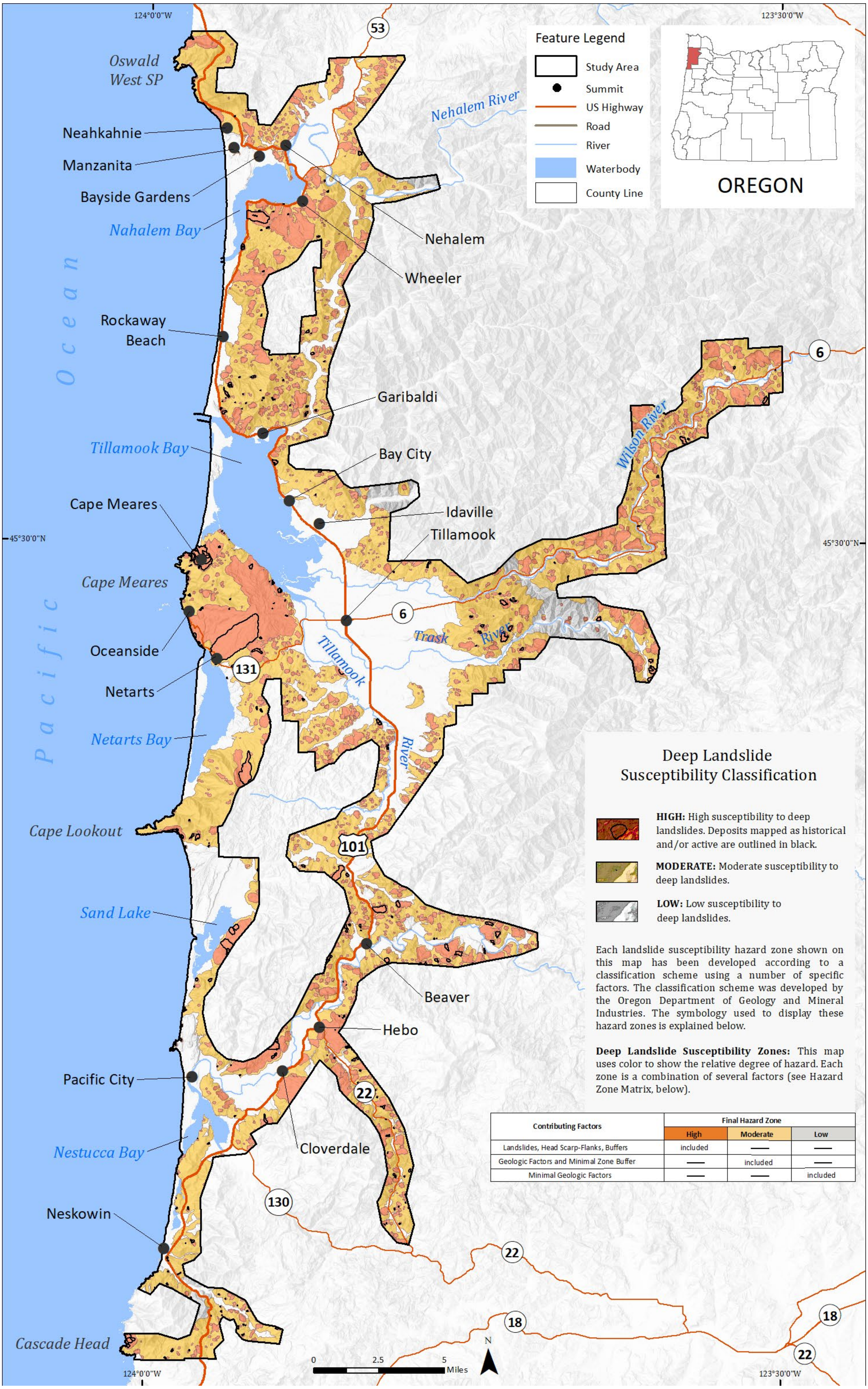
We classified the entire study area into areas of low, moderate, and high susceptibility to deep landslides. Approximately 30% of the study area is classified as low, 41% as moderate, and 16% as having high susceptibility (**Table 3-3**; **Figure 3-4**). As previously mentioned, we noted that some historic deep landslides occurred within existing prehistoric landslides. It is important to remember that the susceptibility map is a conservative approach that can be thought of as a worst-case scenario. This is because we included all deep landslides that have been mapped in the high susceptibility zone. However, we do not expect all deep landslides to be active at the same time throughout the study area.

As with shallow landslide susceptibility, we calculated the area covered by deep landslide susceptibility for each community (**Table 3-3**).

Table 3-3. Summary of deep landslide susceptibility by community.

Community	% Low	% Moderate	% High
Bay City	56.4	19.4	0.2
Bayside Gardens	80.6	11.2	6.2
Beaver	76.1	19.7	0.0
Cape Meares	48.8	15.5	25.0
Cloverdale	3.5	29.6	66.8
Garibaldi	29.1	35.3	6.3
Hebo	8.2	41.9	49.3
Idaville	90.2	9.1	0.7
Manzanita	98.4	1.2	0.2
Neahkahnie	7.2	72.9	18.6
Nehalem	44.4	37.4	17.3
Neskowin	59.5	25.3	0.4
Netarts	19.4	34.3	45.7
Oceanside	0.0	30.8	68.4
Pacific City	58.3	30.5	7.1
Rockaway Beach	87.4	10.7	1.2
Tillamook	96.4	0.0	0.0
Tillamook County Unincorporated	28.4	42.5	16.3
Wheeler	2.7	41.2	53.8
Total	**29.9**	**41.1**	**16.5**

Figure 3-4. Map of deep landslide susceptibility model.



3.4 Risk Analysis and Loss Estimation Results

We performed two types of risk analysis: 1) hazard and asset exposure and 2) Hazus-MH earthquake-triggered landslide risk analysis.

3.4.1 Exposure analysis results

We performed hazard and community asset exposure analysis on the nine hazard datasets/zones:

- shallow landslides (inventory polygons),
- deep landslides (inventory polygons),
- debris flow fans (inventory polygons),
- shallow landslide susceptibility (low, moderate, and high), and
- deep landslide susceptibility (low, moderate, and high)

and three asset datasets:

- buildings,
- critical facilities, and
- permanent population.

Tables showing the full results of this analysis are provided in Appendix A.

Table 3-4 is a summary of the exposure of select assets to the three landslide types. We found that about 3,300 people and approximately $334M in building value are located on existing landslides.

Table 3-4. Summary of the exposure of select assets to three existing landslide types.

Landslide Type	Permanent Population	Buildings	Building Value	Critical Facilities
Shallow landslides	15	23	$2.4M	0
Deep landslides	1,562	1,854	$207M	4
Debris flow fans	1,735	1,997	$125M	5

M is million.

Table 3-5 is a summary of exposure of select assets to the six landslide susceptibility classes from the deep and shallow susceptibility maps. We found approximately $1.1B in building value are located in the combined shallow and deep high susceptibility zones. More than 5,000 people live in the shallow landslide high susceptibility hazard zone, and more than 1,650 people live in the deep landslide high susceptibility zone.

Table 3-5. Summary of exposure of select assets to shallow and deep landslide susceptibility zones.

Susceptibility Zone	Susceptibility Class	Permanent Population	Buildings	Building Value	Critical Facilities
Shallow	Low	12,489	11,842	$1,000M	57
	Moderate	7,199	8,982	$895M	26
	High	5,004	5,934	$877M	22
Deep	Low	18,780	19,898	$2,010M	91
	Moderate	4,233	4,865	$536M	10
	High	1,677	1,995	$226M	4

M is million.

The amount of exposure is dispersed across the county and may be seen in more detail in Appendix A. The exposure from deep landslides could affect a large proportion of buildings in Cloverdale (40%), Hebo (38%), Oceanside (56%), and Wheeler (65%). Shallow high susceptibility exposes over one fifth of buildings in the communities of Hebo, Garibaldi, Netarts, Nehalem, Neahkahnie, Cloverdale, and Wheeler.

3.4.2 Hazus-MH analysis results

To examine the estimated damage and losses from future landslides triggered by an earthquake, we performed three different Hazus analyses (Appendix B):

Subduction Zone M9.0 earthquake scenario: Cascadia Fault

- No landslides
- Dry scenario landslides
- Wet scenario landslides

The results show that in a subduction zone event the earthquake-induced landslide hazard alone would result in economic loss to buildings of approximately $882M.

An important omission is the exclusion of tsunami damage from this analysis. No tsunami-inundation was considered in the Cascadia earthquake scenario of Hazus-MH for this report, because 1) this will be included in a much more detailed study for Tillamook County by Allan and others (in press), 2) in less detail, this was recently undertaken by Williams and others (2020), and 3) the intent of this analysis is to highlight the effect of the landslide hazard in an earthquake. Allan and others (in press) provide evaluations of both the earthquake and tsunami damage for three tsunami scenarios, focusing on the resident and temporary population. Williams and others (2020) simulated damage and loss estimates from one tsunami scenario and earthquake shaking in a Cascadia subduction zone earthquake using Hazus-MH.

Total economic loss values are likely either over- or underestimates due to the low quality of some of the stock Hazus asset data, especially the critical facilities and infrastructure data. However, loss ratios are likely to be better estimates than the absolute numbers.

The analysis estimates damage by landslides alone triggered in a Cascadia event will result in ~ 1,795 buildings being moderately damaged, and ~625 completely damaged, with more than 700 residents needing shelter (Appendix B).

As can be seen in **Table 3-6**, Neahkahnie may experience $8M of seismically induced losses from landslide impacts alone, with many communities experiencing ~1$M to ~$15M in losses damage just from landslides. Damage solely from seismically induced landslides in the study area may exceed $147M, which is 20% of the overall expected earthquake damage without landslides (excluding tsunami impacts).

Table 3-6. Summary of Hazus analysis results for the Cascadia Subduction Zone M9.0 earthquake scenario: building dollar values only. Other results are included in Appendix B.

	Total Building Value	Cascadia- No Landslides		Cascadia–With Landslides (Dry Scenario)		Cascadia–With Landslides (Wet Scenario)		Landslide Only (Wet Scenario)	
Community	**(Assessor Value=Cost $)**	**Loss ($)**	**Loss Ratio (%)**	**Loss ($)**	**Loss Ratio (%)**	**Loss ($)**	**Loss Ratio (%)**	**Difference in Losses ($)**	**% of Total Losses from Landslides**
Bay City	75,006,281	22,239,866	29.7	22,959,910	30.6	25,193,671	33.6	2,953,805	11.7
Bayside Gardens	80,058,421	16,230,344	20.3	17,701,191	22.1	19,996,734	25.0	3,766,390	18.8
Beaver	8,198,597	4,254,536	51.9	4,375,300	53.4	4,504,326	54.9	249,790	5.5
Cape Meares	24,119,799	3,942,115	16.3	4,701,589	19.5	5,442,381	22.6	1,500,266	27.6
Cloverdale	23,126,161	3,847,96	16.6	4,359,928	18.9	5,265,974	22.8	1,418,010	26.9
Garibaldi	64,338,054	22,531,956	35.0	23,037,793	35.8	24,729,360	38.4	2,197,404	8.9
Hebo	8,288,218	2,562,769	30.9	2,717,857	32.8	2,923,675	35.3	360,906	12.3
Idaville	12,455,492	4,000,478	32.1	4,120,897	33.1	4,401,974	35.3	401,496	9.1
Manzanita	257,326,425	45,533,181	17.7	54,480,517	21.2	62,623,432	24.3	17,090,251	27.3
Neahkahnie	90,181,480	5,288,475	5.9	9,331,679	10.3	13,327,438	14.8	8,038,963	60.3
Nehalem	25,706,362	8,807,311	34.3	9,444,984	36.7	10,145,441	39.5	1,338,130	13.2
Neskowin	139,571,079	18,939,898	13.6	22,037,932	15.8	28,677,009	20.5	9,737,111	34.0
Netarts	92,203,741	17,383,453	18.9	20,544,943	22.3	23,548,034	25.5	6,164,581	26.2
Oceanside	123,768,190	18,374,790	14.8	23,849,828	19.3	28,708,531	23.2	10,333,741	36.0
Pacific City	218,029,020	37,057,598	17.0	43,035,262	19.7	51,044,604	23.4	13,987,006	27.4
Rockaway Beach	210,225,627	51,931,980	24.7	55,936,718	26.6	62,368,595	29.7	10,436,615	16.7
Tillamook	324,291,697	153,632,976	47.4	159,156,666	49.1	164,009,396	50.6	10,376,420	6.3
Tillamook County Unincorporated	967,517,611	290,241,464	30.0	308,624,242	31.9	335,122,514	34.6	44,881,050	13.4
Wheeler	30,516,156	7,610,541	24.9	8,605,770	28.2	9,530,716	31.2	1,920,175	20.1
TOTAL	2,774,928,411	734,411,695	26.5	799,023,006	28.8	881,563,805	31.8	147,152,110	16.7

* “Landslides (Wet) Only” is the difference between “Cascadia – No Landslide” and “Cascadia Landslide Wet” values.

3.5 Annualized Loss Results

On the basis of historical data, about 30 landslides occur per year within the study area of Tillamook County. The number of landslides multiplied by the average loss estimates provides a preliminary estimate of losses per year. In a previous study, Burns and others (2017, Table 4), found an average cost of $89,300 per landslide based on building permits for landslide repair, $144,000 exposed on private property per landslide, and $102,500 public property exposed per landslide for the City of Portland. The average of these three approximated loss values per landslide is ~$99,000, Although landslides in the Tillamook County area may differ in type, style, and amount of damage as compared to landslides that have caused damage in the City of Portland, the Portland loss data are the best available and can be useful for landslide loss estimates in Tillamook County area.

A total of 605 landslide points are included in this study's historic landslide point database, recorded from an unknown, pre-1995 year to 2016. From the years 1996 to 2016, there were 563 landslides recorded; there are 42 landslides with unknown or undetermined years of occurrence prior to 1995. In the past 20 years on average there are approximately 30 landslides per year. Therefore, based on the best available data the range of losses from landslides in a typical year is ~$2.5M to $4M (using the range in estimates from $89,300 to $144,000 per landslide). Stormy, wet, or otherwise extreme landslide years, such as the 1996 winter, can cause hundreds of landslides and millions of dollars' worth of damage (Wang and others, 2002).

4.0 CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

This study was initiated to alert communities in portions of Tillamook County of the need to be prepared for landslides. The main purpose of this project was to help communities in the study area become resilient to landslide hazards by providing detailed, new digital databases locating the landslide hazards as well as community assets and the risk that exists where the two overlap. Although we cannot predict when landslide events will occur, or how big they will be, our analyses have identified historical landslides and their locations, the estimated scale of a potential disaster, and the areas more or less susceptible to future landslides and we have estimated what the damage and losses might be. We note that the portion of Oregon included in this study has high average annual precipitation as well as high 24-hour-duration precipitation related to storm events. Both factors are extremely important in triggering landslides, especially when combined with the local geology and geomorphology. The area also has a relatively moderate to high seismic hazard potential. Both high precipitation and large earthquakes are primary triggers for new landslides and the reactivation of existing landslides. Human activities may also trigger landslides.

To summarize our findings:

- Lidar-based landslide inventory mapping (**Figure 3-1**) identified 4,096 landslides throughout the study area. These data cover ~13% of the study area, or 43.7 square miles of a total 327 square miles of study area;
- Of the 4,091 identified landslides, ~650 are considered to be shallow, while ~2,470 are deep-seated landslides. The other 971 landslides are mostly debris flow fans (957) and rock fall talus;
- Our new historic landslide point dataset consists of 605 records with dates ranging from earlier than 1995 to 2016 within the study area;

- Annual loss estimates from landslides in the study area are expected to be between ~$2.5M to $4M; and
- Almost 5,000 people live in the shallow landslide high susceptibility zone and approximately 1,650 live in the deep landslide high susceptibility zone.

Although we did not create a channelized debris flow susceptibility map, the combination of the shallow susceptibility map and the landslide inventory map showing debris flow fans could be used to identify where these types of landslides might initiate and where they might deposit. In addition, work by Hofmeister and others (2002) could be used with these newer datasets to evaluate potential channelized debris flow hazards. In many cases, debris flow fan areas have the potential for life safety risk, and therefore we recommend extra caution is taken in these areas.

The main reason for the landslide hazard in the current study area appears to be the combination of high relief, steep topography, and landslide susceptible geologic units and contacts. Numerous geologic contacts exhibited high susceptibility to deep landsliding. Many deep landslides are related to contacts between the mafic volcanic units, such as the basalt and mafic dikes and sills with the coarse- or fine-grained marine sedimentary units.

Compared to areas covered by previous landslide studies that used similar approaches, the Tillamook County area as a whole has a moderate to high landslide hazard. This study area has a landslide density, or percent landslide inventory deposit coverage of the total area, of ~13.3%, which is less than that of areas covered by previous studies elsewhere in the state using the same methodologies (**Table 4-1**). Some of these previous studies are centered in mountainous, entirely steep terrain, making a direct comparison to a mean landslide density slightly misleading, as the hazard locally can have a considerable range.

Table 4-1. Landslide density reported from past studies in Oregon.

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

Cascadia subduction zone (CSZ) earthquake and tsunami impacts were not a major focus of this study. However, we did analyze the portion of CSZ earthquake-induced damage and loss solely from landslides, which resulted in up to ~20% of the total losses with a dollar value of ~$147M. Several recent DOGAMI reports focus on CSZ impacts along the Oregon coast: Bauer and others (2020) provided detailed socioeconomic impacts for five communities along the Oregon coast, including Rockaway Beach, and is a resource to inform community-based decision making. Work by Priest and others (2013) provided more detailed information on specific tsunami inundation scenarios affecting Tillamook County (more information may be found at www.OregonTsunami.org). Additional CSZ-related risk reduction and information for Tillamook County can be found in evacuation modeling studies for the unincorporated communities of Tillamook County (Gabel and others 2019), Pacific City (Gabel and others, 2018), and Rockaway Beach (Gabel and Allan, 2017).

We have discussed the broad results in this report (detailed data in appendices). From our analyses, we note the following four key conclusions:

- Over 1,700 people live on debris flow fans. Debris flows can be a life-threatening hazard, due to the rapid and destructive nature of their movement.
- 5,000 buildings are located in the shallow landslide high susceptibility zone, with approximately $877M value.
- On average, 30 landslides occur per year. Annual historic landslide losses range from $2.5M to $4M.
- Damage and losses from landslides alone (wet scenario), induced by a Cascadia subduction zone earthquake, may result in an estimated $147M damage, which is ~20% of the total damage and losses and would result in an additional 1,800 moderately damaged homes and 600 completely damaged homes.

These data indicate moderate to high landslide hazard and risk in the study area. This amount of landslide risk indicates an opportunity for proactive landslide risk management, which may be addressed in a variety of ways. One approach is to conceptualize the risk management components as illustrated in **Figure 4-1**.

Figure 4-1. Landslide risk management diagram (Y. Wang, written communication, 2010).

Our analyses have addressed two landslide risk management steps, namely, hazard identification and risk assessment. Further work is needed with respect to the other steps highlighted in **Figure 4-1**. We provide the following recommendations to communities in the study area for continued work on landslide risk management. These recommendations are not comprehensive, but they should provide an adequate foundation for many of the risk management phases shown in **Figure 4-1**. The primary actions are related: awareness, regulation, and planning.

4.1 Awareness

Awareness of local hazards is crucial to understanding associated dangers and how to prepare for them. One of the main purposes of this report and data is to help residents and landowners in the study area 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 flyers can be linked from DOGAMI websites and/or distributed to help educate landowners of activities that individuals can take in order to reduce landslide risk. These flyers 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 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.

4.2 Warnings

Preparing for emergency situations such as storm events and earthquakes can be done in several ways. One can assess the level of readiness and preparedness to deal with a disaster, prior to the disaster occurring; this may be accomplished by estimating damage and losses for specific hazard events. This was done at a regional scale during this project. Another approach is developing a landslide warning system to help increase understanding about when these events might happen. Oregon has a general statewide landslide warning system operated by the National Weather Service (NWS); when the NWS initiates warnings, several Oregon state agencies (Oregon Emergency Management [OEM], Oregon Department of Transportation [ODOT], and DOGAMI) disseminate the warnings. The current warning system could be used by the communities in the study area. In the future, a monitoring system that tracks rainfall thresholds at which landslides can be expected to initiate could be developed by monitoring precipitation and resulting slide activity. Knowing when there will be periods of increased landslide potential will help communities prepare, respond, and recover, should landsliding occur. If known very high hazard areas, such as debris flow fans, with the potential for life safety issues are identified, evacuation could be considered, recommended, or required under conditions that likely would trigger such a failure.

4.3 Development and Infrastructure Planning

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 planning that engage leaders, residents, and landowners include 1) focus on future development and 2) focus on existing infrastructure.

A recent joint publication from the Oregon Department of Land Conservation and Development (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 study are clearly essential to developing long-term planning, including in assessments when discussing expansion of urban growth boundaries. Another long-term planning tool is adopting the results from this study in 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 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 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 culvert outlets in order to evaluate any discharge onto highly susceptible zones. Planning could focus on private landowner education and awareness in order to gain landowner partnership in the control of stormwater.

4.4 Regulation

Connecting landslide inventory and susceptibility maps and data to regulations such as development codes and ordinances can be very effective. Such regulations use landslide hazard maps to identify proposed development and grading or other activities that may increase landslide risk in high hazard areas. Examples of 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 or slopes in high susceptibility zones 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.

4.5 Large Deep Landslide Risk Reduction

Large, deep-seated 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 (generally, city or county and landowners) because the slides can span or even cross entire neighborhoods. 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 landslide areas could participate in a neighborhood risk reduction program where all affected entities help reduce the overall risk.

There are many actions to reduce risk on large deep landslides. Risk reduction measures should include these as a minimum:

- Water
  - minimize or eliminate irrigation on landslide;
  - intercept and collect surface water above landslide area to reduce natural water infiltration into the landslide;
  - collect surface water runoff from within the landslide area from impervious surfaces, for example: roof downspouts, streets, and driveways; and
  - reduce any onsite storm water retention and inflation within the landslide area.

- Grading
    - Avoid grading within the landslide area unless a detailed geotechnical evaluation has been performed including recommendations on how and when to perform grading safely.
- Site-specific Evaluation
    - Consult a geotechnical engineer and engineering geologist to conduct a site-specific evaluation to develop further site-specific risk reduction activities.

Some mitigation actions are more affordable and easier to accomplish than others. Large-scale mitigation activities for deep landslides commonly include engineered retaining structures and underground dewatering drainage systems. These activities would be prioritized by the community on the basis of funding and acceptable level of risk for the community. A Geologic Hazard Abatement Districts (GHAD) designation may be a useful mechanism to fund and implement some landslide risk reduction actions (Curtin and Zovod, 2005). The report by Curtin and Zovod (2005) is a useful resource to understand GHADs specifically as they relate to landslide risk reduction.

4.6 Emergency Response

Finally, we recommend that neighborhoods and communities create landslide emergency response plans before the next 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 immediate actions required following the 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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7.0 APPENDICES

Appendices are available as separate documents in the digital file set.

Appendix A. Exposure Analysis Results (Microsoft® Excel® spreadsheet and Adobe® PDF formats)

- Exposure Landslide Analysis

Appendix B. Hazus-MH Analysis Results (Microsoft® Excel® spreadsheet and Adobe® PDF formats)

Subduction Zone M9.0 earthquake scenario: Cascadia Fault

- Hazus CSZ Results
- Hazus Property Damage