LAWS & LANDSLIDES: EVALUATING UNSTABLE SLOPES RULE COMPLAINCE AS A FACTOR OF MASS WASTING SUSCEPTABILITY IN WESTERN WASHINGTON FORESTS

by

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A Thesis
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2020

This Thesis for the Master of Environmental Studies Degree

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has been approved for

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ABSTRACT

Laws & Landslides: Evaluating Unstable Slopes Rule Compliance as a Factor of Mass Wasting Susceptibility in Western Washington Forests

Christopher Baus

Landslides are a common and natural process in Western Washington due to the unique geology and topography of the landscape combined with high annual rainfall. Human activities such as natural resource extraction or capital improvements can influence the likelihood of mass wasting events occurring. In forestland, the Washington Forest Practices Act and Rules establishes unstable slopes regulations intended to prevent forest management activities like timber harvesting from increasing the number of landslides beyond a natural background rate. During the peak of early industrial logging in the late 1800's and early 1900's regulations were minimal, and firsthand accounts described frequent landslides across large-scale clear cuts. As a part of modern land management and regulation, the Washington Department of Natural Resources has two programs that examine annual compliance rates with unstable slopes and all reported landslides. This study used statistical and geospatial methods to investigate if unstable slopes compliance rates impacted the annual number of landslides. Results indicated that a relationship likely exists, but the nature of it is inconclusive due to the small sample size available with high variability and low number of compliance monitoring sites intersected with reported landslides. Based on accounts from early loggers, the number of landslides has also likely decreased with more regulations. Spatial analysis did show that 88% of landslides occurred in areas previously identified as having some level of mass wasting potential and that 62% of landslides were in primarily ash or glacially derived soils. More years of compliance monitoring and reported landslide data are needed to determine how regulations relate to landslide frequency. Focusing unstable slopes compliance monitoring in areas where landslides commonly occurred could also be useful for continuing this study. Exploring the impacts of climate change and urban landscapes on landslides could also provide useful information for determining effectiveness of current regulations.

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Acknowledgements

I would first like to thank my wife Hanna for all of the support and encouragement throughout this project and my academic career, I would not have gotten to this point without her. Garren Andrews and the rest of the DNR Compliance Monitoring staff were instrumental in helping me shape and develop this thesis project. I would also like to thank the DNR Forest Practices Geologists Mitch Allen and Liv Bowden for their expertise on this topic and assistance with GIS, I won't take the knowledge they've passed on to me for granite. Finally, I would like to thank Dr. Kevin Francis for his careful review and guidance through this dynamic project.

1. Introduction

1.1 Western Washington Landscape

The unique topography of Western Washington is filled with mountain ranges, deep river valleys, and the remnants of powerful glaciers. Millennia of volcanic and tectonic activity combined with the weathering forces of rivers and ice have shaped steep slopes and river valleys over much of the landscape (Hipple, 2011; Gavin & Brubaker, 2014). Northwestern Washington and the Olympic Peninsula in particular owe much of their current landscape features to the glaciers of the last ice age followed by thousands of years of further carving into the landscape by rivers (Michel et al., 2018). This has produced vast mountains and steep slopes made of marine sediments and loose glacial material that among other features, harbors unstable landforms such as deep-seated landslides, bedrock hollows, and groundwater recharge platforms, making landslides a relatively common occurrence [Fig. 1] (Gavin & Brubaker, 2014; Hipple, 2011; Perkins et al., 2016; Smith & Wegmann, 2018).

In Western Washington the layers of sediment, otherwise known as a soil profile, typically consist of deep fine-grained marine sediment or bedrock material overlaid with glacial soils and volcanic ash (Hipple, 2011). This creates conditions that are conducive to land movement on steep slopes, especially in response to heavy precipitation (Barik et al., 2017; Dickensen, 1992; Smith & Wegmann, 2018). Landslides are naturally occurring events that are most commonly initiated by hydraulic forces such as heavy rain saturating soil or the erosional forces of streams and rivers, some of which can initiate even with abundant vegetation mitigating surface water and roots acting as anchors for the soil (Frizzell, 1979; Smith & Wegmann, 2018). The rich glacial and marine soils of this area combined with high annual rainfall also support fast growing conifers and a robust timber industry. However, forestlands with recent human disturbances are also more vulnerable to mass wasting events during the first wet season or severe rainfall event as that is when vegetation cover and surface water mitigation are at minimal levels (Iida, 2004; Ishikawa & Kawakami, 2003).

1.2 Forestland Management

Modern forestry in Western Washington is based around the management of working forests consisting predominantly of Douglas fir along with western red cedar and western hemlock (Buhler, 2018; Gavin & Brubaker, 2014). Activities used in forest management such as harvesting timber, building forest roads, and replanting trees are collectively referred to as forest practices and are governed by the Washington Forest Practices Act and Rules. Trees with their extensive root networks provide stability to soils, especially for unstable landforms (Smith & Wegmann, 2018). Conducting forest practices such as removing trees from these areas or the adjacent areas that contribute to slope stability, known as zones of influence, increase the chances of landslides occurring due to human action (Smith & Wegmann, 2018; Washington Geological Survey, 2020).

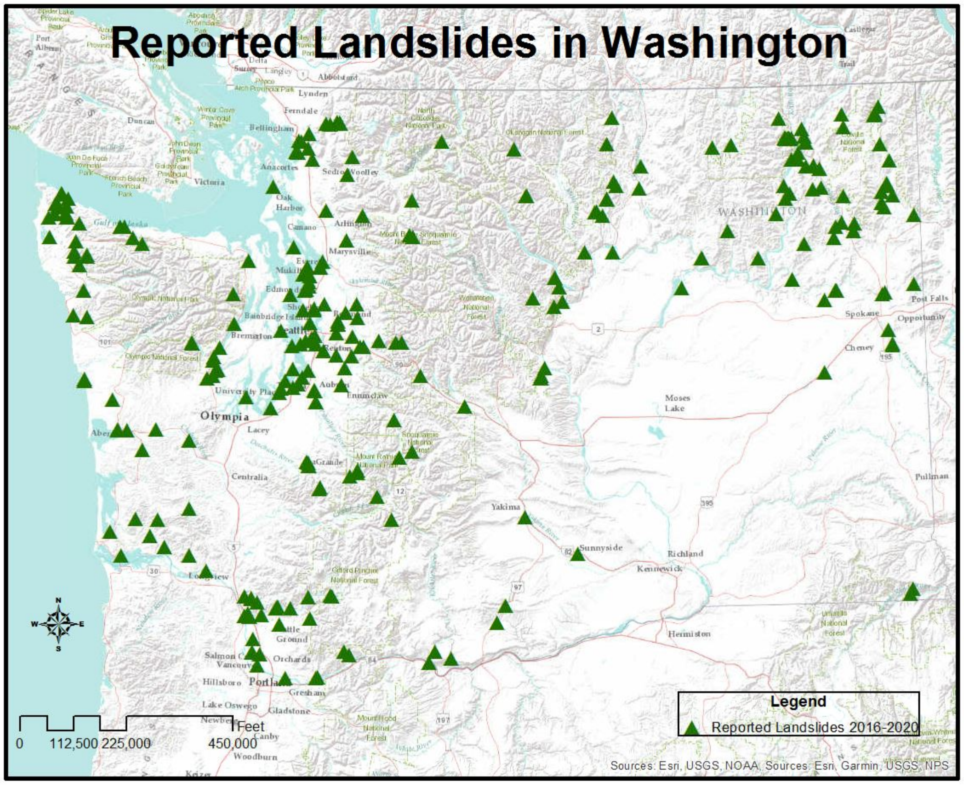


Figure 1. The Number of landslides in Washington reported by the Department of Natural Resources from January of 2016 to February of 2020 (Washington Geological Survey, 2020).

The prevalent unstable features found in Western Washington are made more susceptible to activation when disturbed by human alterations of the landscape. These alterations can include development, excavation, extraction of natural resources, and turning permeable surfaces into impermeable ones. In timberlands, forest practices such as timber harvest, building stream crossings, and creating forest roads disturb the landscape; this increases the chance of activating potentially unstable features within the zone of influence of the activity (Barik et al., 2017; Smith & Wegmann, 2018; WDNR, 2016). Understanding the impacts of forest practices on unstable features is important to protecting both public safety and delicate ecosystems from human induced disturbances (Lahusen et al., 2015). Western Washington timber has been a vital natural resource for the native tribes of the area for thousands of years, as well as for the lumber industry in the region for over one hundred years (Friedman, 1975; Hudson, 1968). Early unsustainable timber harvests in the 19th and early 20th centuries have however left lasting impacts on the landscape such as a small amount of old growth forest remaining, large areas of quality forestland converted to non-forestry use, and artificial dams and impoundments that altered local hydrology (Gavin & Brubaker, 2014; University of Washington, 2015).

Washington forest ownership is generally compromised of federal, state, tribal, and private forestlands. The Washington Department of Natural Resources (DNR) is the agency responsible for managing forests on state owned trust lands as well as regulating forest practices on both state and private land. The U.S. Forest Service, National Park Service, and Bureau of Land Management regulate the federal forestlands within the state according to their statutes, while sovereign tribes set their own specific rules for managing forests on reservation lands. Regardless of ownership, all forest management entities are still bound by some common regulations such as the federal Endangered Species Act and Clean Water Act, the latter of which sediment delivery to waters from landslides can greatly affect (McKean & Tonina, 2013).

1.3 General Background of Landslides

Landslides are a naturally occurring phenomenon anywhere there is perched substrate with potential energy combined with a disturbance event. The volcanic and glacially formed landscape of Western Washington is full of unstable land features that periodically become mobile, most often due to intrusion of water into the ground destabilizing a body of soil (Barik et al., 2017; Stokes et al, 2009). These events can be small and isolated in remote areas or can happen in a sudden and dramatic fashion in residential areas, as was the case with the 2014 landslide near Oso, Washington (Perkins et al, 2017). Unstable land features can become more prone to movement through human-caused disturbances. Activities such as adding or removing fill material, changing the local hydrology, or altering the surface cover can directly or indirectly cause movement of already unstable areas (Barik et al., 2017; Smith & Wegmann, 2018; Stokes et al, 2009).

Depending on size and velocity, debris torrents have the ability to clear away or bury whatever lies in their paths, including people and infrastructure. Even small mass wasting events can be comprised of several tons of material and water that can put lives at risk and damage property (Lahusen et al., 2015; Perkins et al. 2016). Landslides can also have negative environmental impacts by changing hydrology and damaging habitat (Lahusen et al., 2015; Perkins et al. 2016). Landslides can also cause damage to infrastructure and capital improvements as well as injury or death to people, trees, and wildlife that can be caught in debris torrents (Gavin & Brubaker, 2014). Arguably the bigger environmental impact though results from sediment being delivered to water sources, which can also be in violation of the federal Clean Water Act if the landslide was triggered by human activities (Washington Department of Natural Resources, 2016). Mass wasting events can deposit a large amount of debris into streams, rivers, and wetlands often resulting in a blockage of water and an altering of the local hydrology on site and downstream. The fine sediments delivered by a slide can also pose a danger to resident and anadromous fish (Smith & Wegmann, 2018; WDNR, 2016). Fine sediments suspended in water can clog gills and suffocate fish and amphibians, often resulting in mass die-offs immediately following a landslide leading to water (McKean & Tonina, 2013; WDNR, 2016). Gravel deposits from landslides do however deliver gravel substrate into streams that are critical to salmon spawning and viability, which does highlight the importance of periodic mass wasting as a part of the larger ecosystem (McKean & Tonina, 2013).

Not only do landslides represent major disturbances to the landscape, but they can also endanger human life and cause property damage as evidenced by the landslide that occurred in 2014 near Oso, WA (Lahusen et al., 2015). Although landslides are a natural disturbance, human activities such as harvesting timber and construction projects like road building on or near unstable slopes and features can activate even deep-seated landslides with fault lines that lie well below the roots of trees (Barik et al., 2017; Smith & Wegmann, 2018; Stokes et al., 2009; WDNR, 2016). Since it is not practical or possible to completely remove the human element from Washington forests to prevent possible activation of unstable slopes and features, it is therefore important to examine how changes in regulations over time have worked to mitigate these hazards and how effective they are.

1.4 Overview and Application of This Study

The unstable slopes regulations in the Forest Practices Act and Rules are intended to prevent forest practices from increasing the number of landslides in Washington beyond a natural background rate. However, an evaluation of the frequency of landslides in forestland compared to compliance rates with regulations has not been conducted. This is an important metric to examine as rule compliance assessments are performed on recently completed forest practices when vegetation cover is at a minimum and the probability of landslides is greater (Iida, 2004; Ishikawa & Kawakami, 2003). This thesis will attempt to evaluate effectiveness of current unstable slope regulations by assessing changes in the percentage of unstable slopes rule compliance on managed forests with changes in the rates of landslides.

The methods utilized to conduct the evaluation will focus on comparing three years of data (2016, 2017, and 2019) on unstable slopes rule compliance rates of completed forest practices activities with the number of reported landslides. GIS will also be employed to examine the landscape and terrain features at reported landslide locations in relation to human activity in forestland. It will also be used to determine how many landslides occurred in relation to slope angle and soil type as well as how many occurred in urban areas not typically managed for long-term timber production. Additionally, rainfall and stream gauge data from the National Oceanic and Atmospheric Administration will be examined in relation to the timing of landsides that occurred on any Compliance Monitoring sites. Finally, historical forest practices of Western Washington will be taken into account to compare modern forest management and the number of reported landslides with early industrial logging methods and accounts of human induced landslides before best management practices concerning unstable features became more widely utilized.

Analyzing how compliance with unstable slopes regulations may be a factor in preventing anthropogenically influenced landslides is of importance to land managers and government entities for several reasons. Public safety and resource protection are important objectives of forest management and also required by rule and statute. For both public and private land managers, having data that shows how compliance does or does not impact the rate of landslides could be a valuable tool in helping to guide silvicultural prescriptions and best management practices for maximizing land productivity without increasing landslides beyond a natural rate. For government regulators and rulemaking bodies the benefit would be similar as this data could also be valuable to guide future changes to improve unstable slopes rules or best management practices that would aid in protecting public safety and resources. Additionally, this research has the potential to act as an effectiveness monitoring study for unstable slopes regulations using two existing datasets. Typically, effectiveness monitoring studies are complex and highly involved, but using existing data from two programs that already have long-term funding would ease the burden of trying to secure resources to accomplish that goal.

2. Literature Review

2.1 Introduction

Washington is one of the most geologically active and naturally landslide prone areas of the country (Washington Geological Survey, 2020). This places landslides at the forefront of public safety and natural resource protection concerns for land managers and regulatory government agencies charged with upholding relevant rules and statutes. The environmental and anthropogenic factors that can influence landslides are complex and numerous, which makes developing regulations and best management practices to prevent human activation of landslides a challenging task. This is an ever-developing field of research that continues to adjust based on the best available science at the time.

This literature review integrates important information about the geologic history of Western Washington including the common types of unstable features found on the landscape and how those features can become active to provide context. Next, it will examine the different types of landslides and how they can be triggered. It will also cover the history of forest management in the region to explore how changes from early indigenous forest practices to western industrial logging changed the landscape and impacted unstable features, as well as the impacts science-based regulations in the late 20th and early 21st centuries had on preventing landslides. Finally, this literature review will examine how modern forest management and current forest practices regulations aim to reduce the likelihood of landslides due to human disturbances.

2.2 Geology of Western Washington

To better understand the unstable landforms of Western Washington at present, it is important to consider the history of how the landscape formed. Western Washington is relatively new when looking at it through the lens of geologic time, only starting to form around 200 million years ago between the Triassic and Jurassic Periods (Cowan & Brulen, 1992; Saleeby & Busby-Spera, 1992). Prior to that, Eastern Washington was on the coast of the landmass that would eventually become North America (Barksdale, 1975). The diverse Western Washington landscape seen today was forged by molten rock, carved by rivers and glacial ice, and shaped through plate tectonics.

During the Triassic Period a large volcanic island chain on a microplate known as the Intermontane Islands formed off the coast of ancestral Washington (Cowan & Brulen, 1992; Dickensen, 1992; Saleeby & Busby-Spera, 1992). As the supercontinent Pangea broke apart in the Early Jurassic, the North American plate began drifting westward to eventually collide with the island chain and incorporate it into what is now the Okanogan Highlands in Central Washington (Tennyson & Cole, 1978; Friedman & Armstrong, 1988). During the Cretaceous Period around 100 million year ago, a similar collision happened between the Insular Island chain and the North American plate, adding on the area of what is now the North Cascade Mountain Range and Northwestern Washington (Cowan & Brulen, 1992). As this terrain was colliding, the Farallon Plate was being subducted beneath the North American Plate and created the Coast Range Volcanic Arc extending from around modern-day Snoqualmie Pass to the northern extent of the Cascade Range in British

Columbia (Armstrong, 1988; Umhoefer & Schiarizza, 1996). These collisions and volcanic activity further built the new Western Washington coast with igneous rock and what would become the North Cascade Range (Miller et al., 1992; Townsend & Figge, 2002).

As the volcanic arc became less active, major rivers including the Columbia were depositing large amounts of sediment around 50 million years ago during the Eocene Epoch just offshore in the area that would eventually become Southwest Washington (Frizzell, 1979; Johnson, 1984). During this same time, a large basalt accretion and the plate it sat on offshore of the ancient Washington coast began to subduct beneath the North American Plate. As this accretion tilted and rotated it uplifted the landmass of what is the modern Olympic Peninsula and the greater South Puget Sound Region (Gavin & Brubaker, 2014). Subduction and uplift continued and by the Oligocene around 30 million years ago, the Olympic Mountain range had formed. The subducted plate that uplifted the Olympic Peninsula was also fueling the Cascade Range Volcanic Arc. This was in large part responsible for the development of the Central and Southern portions of the Cascade Mountains (Everts & Swanson, 1994). This volcanic arc was additionally responsible for depositing large layers of basalt, pyroclastic mud, and ash across much of Southwestern Washington (Everts & Swanson, 1994).

Beginning around two million years ago, the Pleistocene Epoch encompassed much of the last great glaciation events that shaped Western Washington into the topography seen today (Heller et al., 1987). A shifting of the continents combined with a cooling global climate allowed large ice sheets to form and advance cross much of Northern North America (Porter et al., 1983). Assisted by the erosional forces of existing rivers, these glaciers carved enormous valleys and carried millions of tons of sediment and rock across Washington. During the glacial maximum of the Pleistocene Epoch, it is estimated that the glaciers were nearly 2km thick near the present-day city of Bellingham (Townsend & Figge, 2002). The glaciers during this ice age went through several cycles of advancing and retreating, further shaping the landscape with each event and depositing more rock and sediment (Clague et al., 1992). Additionally, these glaciation advances and retreats created a vast inland out of the Puget Sound, which accumulated much of the clays seen today on its lakebed (Easterbrook, 1986). The widespread glaciation event ended around 11,000 years ago near the start of the Holocene Epoch, and continued to slowly retreat to the present where remnants of these giants still reside in parts of the Cascade and Olympic Mountain Ranges (Clague et al., 1992; Easterbrook, 1986; Townsend & Figge, 2002).

Western Washington's geologic history lends itself to the complex landscape seen today that is further compounded by the matter of still being rather active, both volcanically and tectonically. The Western Washington landscape is a dynamic mix of ancient continental bedrock material, old volcanic islands, seafloor sediments lifted to become mountain ranges, alluvial and lacustrine sediment deposits, newer igneous rock and mud flows, volcanic ash, and glacial till and outwash from the last ice age (Hipple, 2011; Townsend & Figge, 2002). With such a wide variety of material deposited on or mixed with one another in a relatively small area, it becomes apparent why Western Washington is so geologically active in the short-term with landslides and in the long-term with several dormant volcanoes and the Juan de Fuca Plate actively being subducted beneath the North American Plate (Gavin & Brubaker; Michel et al., 2018).

2.3 Landslide Geology

Types of Landslides

Landslides are characterized as the movement of substrate down a slope usually stemming from some type of a natural disturbance like a heavy rain event, or a non-natural event such as the development and modification of a landscape for human uses (Jakob, 2000). In the case of anthropogenic influences on forestlands, landslides are more likely to occur during the first sustained period of soil saturation following management activities such as timber harvest or road building when the percentage of freshly exposed soil is highest and vegetation cover is at a minimum (Adams & Flint, 1991; Barik et al., 2018; Coffin & Harr, 1992; Jakob, 2000). In landscapes such as western Washington, land movement and mass wasting events are common natural processes and can range in size from small debris torrents of a few cubic meters of soil to large slides that encompass entire hillsides and thousands of tons of materials that can flow for several miles depending on the terrain (Coffin & Harr, 1992; Dieu et al., 2008).

The depth and amount of material in a landslide can be used to classify it into the general categories of shallow rapid or deep-seated landslides. Shallow rapid landslides occur when there is loose or unstable material usually only about three meters or less in depth above competent bedrock or parent material, which is the typical rooting depth of sub mature to mature Western Washington forests (Dieu et al., 2008; Iverson, 2000). A disturbance event can more easily activate the unstable surface material but will usually leave the more stable soil in place (Adams & Flint, 1991).

Deep-seated landslides can further be classified as glacial or bedrock deep-seated landslides and are characterized as being large blocks of material usually greater than three meters in depth that are situated on top of competent bedrock but have a plane of separation from the rest of the hillside such as a perched water table or other hydraulic intrusion beneath them (Iverson, 2000; Jakob, 2000; WDNR, 2017). Disturbance events such as an increase in groundwater penetration can saturate the soil and effectively cleave the hydraulically separated soil mass from its surroundings and initiate movement of the material in mass (Iida, 2004; Ishikawa & Kawakami, 2003). This is especially true when the lowest stabilizing portion of the deep-seated landslide or “toe” experiences a disturbance causing gravity to pull material from above to fill that void in a cascading event (WDNR, 2017). Small, shallow rapid debris torrents are much more common than large deep-seated debris flows due to the stream laden topography of Western Washington, the force of disturbance needed to activate a slide, and the amount of material that would need to become mobile in order for larger mass wasting events to occur (Rice et al., 1972; WDNR, 2017).

The amount of time it takes for a slide to move is also of importance when determining landslide characteristics. Shallow rapid landslides are indeed just that; a usually sudden and quick debris flow of primarily surface and shallow material that rapidly tumbles down a slope (Washington Geological Survey, 2020). There can be signs that a shallow rapid landslide may occur such as small patches of freshly exposed soil or newly tilted trees, but the rapid nature of this type of slide usually occurs quickly and without much warning (WDNR, 2016; Washington Geological Survey, 2020).

Like shallow rapid landslides, deep-seated landslides can also mobilize quickly and dramatically when the right amount of disturbance occurs, such as the Nile Valley landslide that occurred in 2009 near Yakima, WA following unusually heavy rains (Washington Geological Survey, 2020). This is not typical of deep-seated landslides as it takes a tremendous amount of force and the right conditions to cause rapid movement in a large block of a hillside. A disturbance event strong enough to overcome the force of friction on the plane of instability and negate other stabilizing factors like tree roots would need to occur, such as a sustained period of groundwater oversaturation or construction activities on the toes of landslides (WDNR, 2017; Washington Geological Survey, 2020).

More commonly though, deep-seated landslides that are considered to be active are rather slow-moving masses usually changing in position a few meters to a few centimeters per year (Dieu et al., 2008; Ishikawa & Kawakami, 2003). Deep-seated landslides that are considered dormant typically move on a geologic time scale that can be to the order of a few centimeters every century (Dieu et al., 2008; Ishikawa & Kawakami, 2003). Active deep-seated landslides typically show signs of slow movement such as stress cracks in the soil or roads, slumps on the hillside, tilted or pistol-butted trees, and freshly exposed soil (WDNR, 2016; WDNR 2017; Washington Geological Survey, 2020).

The presence of trees and their age can also be of importance when determining susceptibility of a landslide in both forest and non-forestland. Plants in general are valuable contributors to soil stability as they provide cover on the surface and their roots intertwine and provide an anchor beneath the substrate (Adams & Flint, 1991; Coffin & Harr, 1992). Trees are especially important when considering soil stability due to the sheer size and depth of their root systems as well as their longevity compared to most herbs, shrubs, and grasses. Stands of trees also add to soil stability through water absorption and transpiration, providing a buffer against oversaturated soils during heavy rains or runoff. Additionally, when stumps with intact roots are left on a landscape after timber harvest occurs, they can continue to contribute to soil stability for five years or more depending on site specific conditions and rate of decay (Adams & Flint, 1991; Coffin & Harr, 1992; Dieu et al., 2008).

Impacts of Landslides

Landslides are usually a major disturbance and leave long-lasting marks on the landscape. Areas where a landslide occurred will often result in that patch of forest not usually reaching its previous stand density and percentage of canopy closure for several decades or longer depending on factors such as tree species and whether natural regeneration occurs, or planting is employed. Even if the disturbed area is replanted soon after the landslide event, tree size will continue to lag behind compared to the surrounding forest potentially creating issues in management plans (Reid, 1998; Rice et al., 1972; Stokes et al., 2009; WDNR 2016). Landslides that occur in the soft sediment of steep river valleys also result in large amounts of sediment being deposited into rivers, which often times results in mass fish kills and buries the gravel substrate necessary for successful salmon spawning, even for years after the event (Gavin & Brubaker, 2014; Lahusen et al., 2015; McKean & Tonina, 2013; WDNR, 2016). Smaller infrequent landslides do however serve as an important source of gravel input into streams for salmon spawning substrate, although fine sediments mobilized from the deposit do pose an initial danger to fish and amphibians (McKean & Tonina, 2013).

2.4 Historical Forest Management and Landslides

Indigenous Forest Practices

Evidence of human presence in parts of Washington has been dated to around 13,000 years ago, with established settlements in Western Washington appearing consistently in the archeological record between 3,000-6,000 years ago (Friedman, 1976; Kruckeberg, 1991). The indigenous people of Washington were likely decedents of the early humans who crossed a massive ice bridge from Siberia to Alaska during the last glacial maximum that ended around 11,000 years ago (Clague et al., 1992; Kruckeberg, 1991). The tribes that established in Western Washington made use of the abundant natural resources around them, developing unique and highly skilled methods of forest management and forest product harvesting (Friedman, 1975).

Indigenous forest practices of Western Washington were generally centered around a selective harvest of timber and other forest products stemming from a focus of sustainable resource management (Friedman, 1975; Gleeson 1980; Hudson, 1968). Until industrial logging began in the late 1800's, a large portion of Western Washington consisted of mixed old growth forests with small areas of various seral stages where disturbance events had occurred (Friedman, 1975; Hudson, 1968; Kruckeberg, 1991). When timber was harvested, primarily cedar, it was typically small in numbers and very selective for a specific end product such as a building or canoe (Friedman, 1975; Gleeson 1980). Branches, bark, and other tree parts typically considered non-valuable material or "slash" by industrial standards were also used in buildings or crafted into items such as fishing and hunting gear in order to get the most use out of the tree (Friedman, 1976; Gleeson, 1980; Kruckeberg, 1991). Another common forest practice was to strip long, narrow swaths of bark from Western Red Cedars in order to make items out of the fibers (Kruckeberg, 1991). When done correctly, this allowed large amounts of cedar bark to be harvesting without causing fatal damage to the trees (Friedman, 1975; Gleeson, 1980).

Prior to the latter half of the 20th century, very little in the way of records was kept for documenting landslides on forestland. A few accounts of large early landsides such as the one that buried the ancient Makah village near Cape Alava have been passed down through oral histories, although some details have been lost over time (Friedman, 1976; Kruckeberg, 1991). In the modern landscape, there are many sites where evidence of land movement within the last few thousand years is present, as are ancient deep-seated landslides (Johnson, 1984; Lahusen et al., 2015). The prevalence of relic debris flows and material from landslide runouts combined with oral histories of some large mass wasting events highlights that landslides occurred somewhat regularly in Western Washington despite minimal timber harvest compared to the industrial era. The relatively sparse population and forest conditions must be taken into account though when comparing potentially human induced landslides to more modern times. Predominantly mature or old growth forests with few stand breaks also likely added more stability to the soil than the typical early seral forests of today (Adams & Flint, 1991; Dieu et al., 2008).

Early Commercial Logging

The rise of commercial logging in what would eventually become Washington out of The Oregon Territory began in the mid 1800's, coinciding with the California Gold Rush (Robbins, 1985). The gold rush brought thousands of settlers to the west coast which in turn put a demand on lumber for developing the infrastructure of many new and growing towns. Demand for forest products also outweighed supply at this time for the eastern half of the United States that was just coming to the close of the industrial revolution and had nearly depleted that part of the country of timberlands (Cox, 1974; Hudson, 1968). Settlers and timber companies quickly realized the market potential of the vast Pacific Northwest forests and a robust logging and milling industry was established in Washington by 1880 (Cox, 1974; Robbins, 1985).

During the late 1800's and into the early 1900's industrial logging was only regulated by market demand on private forestland (Cox, 1974; Robbins, 1985). Timber resources were plentiful, and it was common practice for a small logging town and mill to establish in a remote area and continue to harvest until all the trees in a reasonable hauling distance were cut or equipment wore out. The operation would then pick and move to a new unharvested location to repeat the process (Cox, 1974; Rajala, 1996; Robbins, 1985). By the late 1800's concerns surfaced among professional foresters about the sustainability of the "cut and move" practice of timber harvesting after the Eastern U.S. and Midwest were depleted of their timber resources (Robbins, 1985). Under the guidance of Gifford Pinchot and his idea of conservation ethic, forestlands under the jurisdiction for the newly created US Forest Service began regulating timber harvest to ensure federal forests would supply a sustainable harvest (Robbins,1985; University of Washington, 2015). Land ethic and sustainable harvest were however not considerations for private forestlands in Washington. Harvesting capacity peaked during the 1920's before falling in the 1930's and remaining low until the latter half of the 20th century due to a combination of The Great Depression, obsolete sawmill town infrastructure, and a depletion of most of Western Washington's large conifer forests (Cox, 1974; Robbins, 1985; University of Washington, 2015). World War II did bring a small increase in the demand for Washington timber, but not to the extent seen before the depression (Robbins, 1985). Wartime production also highlighted the need for a sustainable source of domestic timber, and the conservation movement and regulations started decades earlier on federal forestlands started to become a reality for the rest of the state [Fig. 2] (University of Washington, 2015).

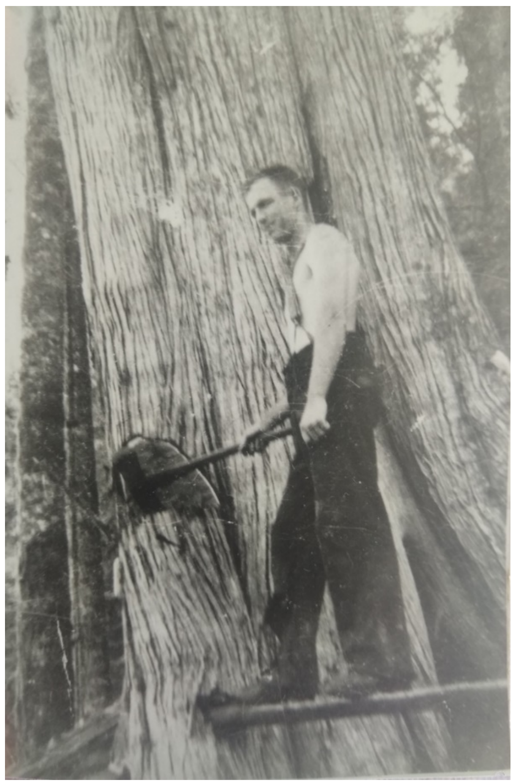


Figure 2: The Author’s great grandfather Robert Whitmarsh felling a mature Western Red Cedar on the Olympic Peninsula circa 1940. Conservation and harvest regulations for state and private timberlands were in their infancy. Image from Whitmarsh family archives.

Unregulated timber harvest across much of Western Washington in the late 1800’s and early 1900’s removed most of the mature and old growth forests across the landscape, resulting in bare lands, altered hydrology and damaged watersheds (Cox, 1974; Dieu et al., 2008; Robbins, 1985; University of Washington, 2015).

The mass deforestation also resulted in conditions that were ripe for landslide activation. Unstable features that are known today such as bedrock hollows and inner gorges were not considerations in the early years of industrial logging, and all merchantable trees were harvested (Hudson, 1968; Kruckeberg, 1991). Removal of nearly all of the forest canopy also resulted in an increase of precipitation runoff and erosion which created muddy and landslide prone areas that also made logging operations dangerous and difficult (Rajala, 1996; Robbins, 1985). Additionally, as the roots of stumps decayed without another generation of trees to fill the space, slope stability decreased and further added to landslide susceptibility (Adams & Flint, 1991). Landslides during this time period were of little concern except when they impacted the ability to harvest and haul timber, so detailed records are essentially nonexistent, except for the few instances when they impacted a more populous town or roadway (Cox, 1974; Dieu et al., 2008; Robbins, 1985; University of Washington, 2015). Accounts from loggers and other workers of the early industry do however describe widespread and frequent landslides in the areas that had been harvested which regularly destroyed haul routes, buried equipment, and caused injury or death (Cox, 1974; Rajala, 1996; Robbins, 1985). Although anecdotal, these accounts paint a vivid picture of the dangerous working condition of the time as well as indicate how common landslides were following large-scale clear cuts without any best management practices or regulations regarding slope stability.

2.5 Modern Forest Management for Landslides

Forest practices in Washington on non-federal and non-tribal land are bound by the regulations in the Forest Practices Act and Rules with the Forest Practices Board Manual outlining best management practices for activities such as mitigating measures for unstable slopes and managing water flow on forest roads. The Forest Practices Act and Rules are administered by the Department of Natural Resources and Forest Practices Board which is also the rule making body for forest regulations as appointed by the Washington legislature. This act and the associated rules require landowners wanting to conduct forest practices on state or private land to submit a forest practices application that clearly identifies the proposed activities and the natural resources that could be impacted. The Department of Natural Resources then reviews these applications to ensure public safety and natural resources are protected according to the applicable regulations. The regulations regarding unstable slopes are found in Washington Administrative Code (WAC) Title 222 which also contains the rest of the forest practices rules. These rules for unstable slopes are based around protecting public safety and natural resources by keeping human activities on forestland from increasing the number of landslides above a natural background rate (WDNR, 2017). The unstable slopes regulations establish the criteria for identifying certain landforms with a high potential for mass wasting which are known collectively as rule identified landforms [Fig. 3]. If forest practices are proposed on or around rule identified landforms or other potentially unstable features, the applicant must do one of two things to be able to conduct the activity. The applicant can either avoid the unstable features and leave a buffer of trees around them, or provide evidence gathered by a qualified licensed engineering geologist that the likelihood for mass wasting caused by the activity conducted with appropriate mitigation measures is low to negligible. The Forest Practices Board Manual identifies avoidance of unstable features followed by mitigation as the preferred methods of preventing anthropogenic activation of landslides that are threats to public safety or resources.

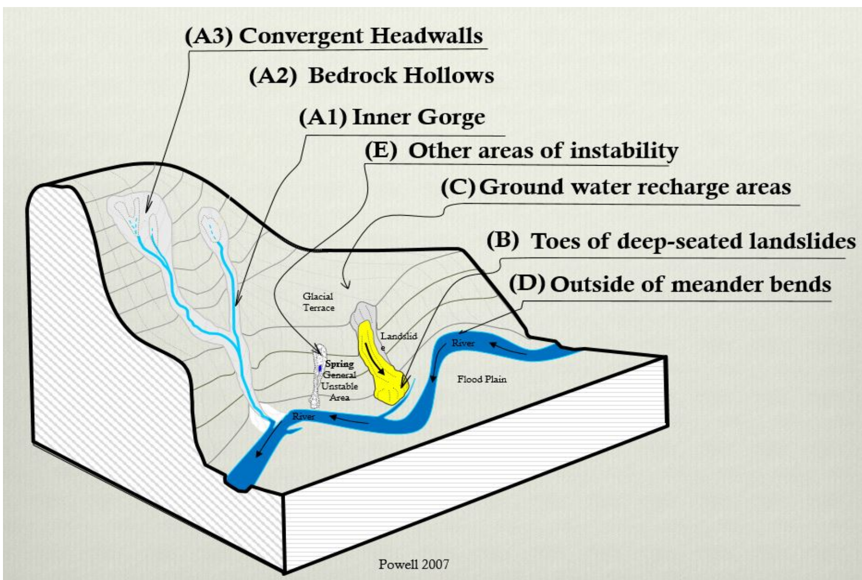


Figure 3: Rule identified landforms listed in WAC 222-16-050 that have a higher potential of mass wasting. Adapted from Powell, 2007.

Programs such as Forest Practices Compliance Monitoring and Adaptive Management provide valuable scientific data to the Forest Practices Board to help guide rule making that will better protect natural resources and support timber production. These programs evaluate aspects of the Forest Practices Act and Rules such as how well the regulations are followed in forest practices, and if the results of following those results meets the environmental and safety outcomes intended by the Forest Practices Board. Landslide reporting and inventorying by the Washington Department of Natural Resources has also provided invaluable data for identifying and mapping unstable features on the landscape to help guide forest management decisions. Related to this, technology such as drones, LiDAR, GIS, and high resolution orthographic photos have made identification and mapping of unstable features and landslides a much more comprehensive process by being able to survey more of the landscape remotely as well as observe the topography in more ways than a traditional site visit could achieve.

2.6 Monitoring Landslide Hazards

Even though landslides are naturally occurring events, they can still pose a threat to public safety and environmental health. As the population of Washington continues to grow, the increased wildland urban interface and urban sprawl also increase the chances of human activities influencing potential slides and putting more people at risk (Barik et al., 2017; Lahusen et al., 2015). Washington has periodic large mass wasting events, but the tragic loss of life resulting from the "Oso landslide" brought the issue of monitoring and preventing landslides to the forefront of public awareness and subsequently as a priority for land management. The Washington legislature passed several measures following that event aimed at identifying, monitoring, and preventing activation of landslides that pose threats to people or the environment. In forestlands, these measures are rules included under the Forest Practices Act and Rules in Washington Administrative Code (WAC) Title 222. These rules identify unstable land features, require evidence that proposed activities to be conducted on or around them have a low likelihood of causing activation, and require a buffer of trees to be left around the features that cannot be mitigated for (Washington Department of Natural Resources, 2016).

Although inventories of landslides and unstable land features in Washington have existed since the mid-1900's, the level of detail, accuracy, and scope is highly variable (Gavin & Brubaker, 2014). This makes sense as technology available to accomplish this was comparatively limited until the end of the 1900's. Even in just the last few years tremendous leaps in the detail and quantity of landslide surveys have been made with the improvements and availability of drones and other remote sensing applications (Buhler, 2018). Prior to the mid-1900's documentation of landslides and landslide hazard areas was nearly non-existent unless it impacted a more populous area or damaged important infrastructure. Regulations protecting water quality from sediment delivery were also non-existent (Robbins, 1985; University of Washington, 2015).

The size and remoteness of much of Washington's forestland still makes a complete inventory of landslides and unstable land features a daunting task even with modern technology. Highly comprehensive data on reported landslides as well as compliance rates for forest practice regulations on unstable slopes were not collected prior to 2016. This is important as unstable slope rule compliance rates compared to the number and scope of reported landslides can be a factor in determining effectiveness of regulations and best management practices for unstable features.

2.7 Conclusion

Landslides are a natural part of the dynamic landscape found in Western Washington. The geology of this region lends itself to being prone to land movement both through its unique soil composition and receiving on average the most annual precipitation in the continental United States (NOAA, 2020 Washington Geological Survey, 2020). Indigenous forest practices likely had a small anthropogenic impact on slope stability, but deforestation during the early industrial logging era resulted in frequent landslides among other environmental issues that persist today such as watershed damage and lack of habitat for several endangered species (Adams & Flint, 1991; Cox, 1974; Dieu et al., 2008 Hudson, 1968). As environmental impacts of early unsustainable logging were realized and public perception on natural resources changed in the 1960's and 1970's, federal regulations such as the Clean Water Act helped shape state forest practices regulations and the Timber Fish and Wildlife Agreement that are intended to protect Washington's natural resources and promote sustainable timber production.

The science of forestry and landslide geology has certainly made progress since large-scale timber harvest began in the late 1800's and continues to add to that knowledge base and improve regulations though programs through compliance monitoring, investigating and reporting landslides, and studying the outcomes of implementing rules through adaptive management. Modern regulations and best management practices based in science have helped forestlands recover from the days of unregulated deforestation. Based on accounts from early loggers of abundant landslides following harvest and current knowledge of appropriate landslide mitigation techniques, the anthropogenic influence on landslides from forest practices has likely been drastically reduced when comparing the first era of industrial logging to the present-day industry. Taking that history and current knowledge of landslide geology and mitigation into account, this thesis will take a closer look at the effect of modern regulations on landslides by evaluating unstable slopes rule compliance as a factor of mass wasting susceptibility in Western Washington forests.

Although there are now three years of data on unstable slopes rule compliance and a detailed landslide inventory mapped from 2016 forward, having this data to guide future rule changes and new best management practices is critical to continuing to protect natural resources and public safety. Despite the objective of reducing the potential of activating landslides through the administration of the Forest Practices Act and Rules, an evaluation of compliance rates with these regulations compared to the number and scope of reported landslides each year has not been conducted.

3. Methods

3.1 Overview of Study Design

To address the question of whether or not compliance with unstable slopes rules decreases landslide risk in Western Washington forests, two primary datasets were analyzed; compliance monitoring for unstable slopes and reported landslides. These datasets were chosen to evaluate this research question as the reported landsides database encompasses all known mass wasting events that occur every year, and annual compliance rate data comes from locations where forest practices have recently been completed so vegetation cover is minimal and the probability of landslides is greater (Iida, 2004; Ishikawa & Kawakami, 2003). Both of these datasets are maintained and updated by the Washington Department of Natural Resources and made publicly available. This study approached the research question by first performing a statistical evaluation of the annual number of reported landslides compared to annual compliance rates for unstable slopes regulations to determine if a relationship exists and what the nature of it is. Next, specific sites were analyzed using photogrammetry and GIS where compliance monitoring had taken place on recent forest practices as well as where landslides occurred in an area without recent activity. Finally, a geospatial analysis was performed on the reported landslides database to determine if any trends existed with respect to potential mass wasting hazards, soil composition, percent slope, and urban areas.

3.2 Data Collection

Data Collection for Compliance Monitoring

To obtain a representative sample of compliance rates for completed forest practices activities with the Forest Practices Act and Rules, the DNR Compliance Monitoring Program biennial report data were utilized for this study. The author assisted with four of the field data collection sites during the 2019 field season. Compliance Monitoring Program staff were responsible for all study design, site selection, and data collection with additional assistance and compliance determinations from Department of Natural Resources and Department of Ecology licensed engineering geologists. Compliance monitoring data is collected on an annual basis from 2006-present, with the unstable slopes compliance data being collected in a pilot study in 2016, then in 2017 with a larger sample size and refined queries, and finally as a permanent addition to the annual data collection in 2019. Data collection for 2020 was suspended indefinitely by DNR due to the COVID-19 pandemic.

The unstable slopes compliance data used in this thesis followed the study design and sampling protocol outlined in Andrews et al., 2018 which draws from the protocols established for forest practices compliance monitoring by the Timber Fish and Wildlife Field Implementation Committee, 1991. This involved on-site post forest practices activity compliance checks of a randomly selected sample of completed and closed forest practices applications that were identified by regulatory DNR permit reviewers as containing potential unstable features in accordance with WAC 222-16-050(d)(i) in their activity areas. Forest practices in these evaluated areas typically included even aged or uneven aged timber harvests ranging in size from 1-50 acres followed by replanting. The data collected through this program involved binary yes or no answers for compliance with the associated forest practices application including activities that were approved for that specific permit. Due to the complexity of landsides and the difficulty of measuring compliance of associated rules in the field, four questions were generated (with one dropped in 2019 for redundancy in data) by grouping related rules and regulations into functional groups or prescriptions for verifying unstable slope compliance with the forest practices application [Table 1].

The first question in Table 1 asks whether or not the landowner identified all potentially rule identified landforms in or around the harvest area as described in WAC 222-16-050. Landowners are required to identify all potential rule identified landforms in or around their harvest area as this determines the classification of the forest practice. The objective of the unstable slopes rules is to protect public safety and resources by not increasing the rate of landslides beyond a natural background rate, and rule identified landforms are inherently more prone to mass wasting. Therefore, it is required for landowners to identify all of these features so the forest practices application can receive a proper classification. Those applications that propose to perform forest practices in or around rule identified landforms then go through proper application reviews to ensure public safety and resources are protected. During Compliance Monitoring site visits, licensed engineering geologists with DNR Forest Practices and the Department of

Ecology evaluate the post-harvest areas to determine if all rule identified landforms were indeed identified by the landowner in their forest practices application.

The second and fourth questions in Table 1 both essentially ask the same question: if mitigation measures for potential rule identified landforms were provided to the landowner by a consulting licensed engineering geologist, were those measures included in the application in fact applied on the landscape? Although these two questions have different wording, it was revealed though the first two years of unstable slopes compliance monitoring that they were collecting duplicate data, which is why the fourth question was removed from the 2019 compliance evaluation. If landowners are proposing forest practices in or around potential rule identified landforms, they may be required to provide additional information to DNR regarding the potential for those landforms to move if management activities occur. That additional information must come in the form of a geotechnical report or memorandum from a consulting licensed engineering geologist evaluating the potential for landslides to occur if the proposed activity took place. The report must also include what mitigation measures should be employed to keep activation by human activity reduced to a low or negligible level in order to protect public safety and resources. During the compliance site visit, all mitigations included in the application are evaluated to determine if they were applied correctly and to all potential rule identified landforms in and around the activity areas.

The third question in Table 1 asks whether or not harvest occurred within no harvest mitigation areas associated with potential rule identified landforms. The current best management practice to mitigate for unstable features in a harvest area is to avoid the areas of instability by leaving a buffer of trees or no harvest area around them. The width of the buffer or no harvest area can depend on the type of unstable feature and how large its zone of influence is. The minimum amount of buffer required for a low likelihood of human influenced mass wasting is typically determined by a licensed engineering geologist. If no harvest areas were mitigation measures included in the forest practices application, then those buffers become a binding obligation to the landowner. The Compliance Monitoring Program evaluates this question by visiting all potential rule identified landforms in the activity area for which no harvest mitigation buffers were applied to ensure it meets the minimum requirements established in the associated application.

Table 1: Unstable slope prescriptions evaluated by the DNR Compliance Monitoring Program. Adapted from Andrews et al., 2018.

Years included in study	Unstable slopes prescription being evaluated
2016,2017,2019	Did the landowner identify all potentially rule identified unstable landforms in/around the harvest area?
2016,2017,2019	Did the landowner apply mitigation for all potentially unstable rule identified landforms as identified on their forest practices application?
2016,2017,2019	Did harvest occur within the no harvest mitigation area associated with potentially rule identified unstable landforms?
2016,2017	If a geotechnical memo, letter, or report prepared by a qualified expert [as defined in WAC 222-10-030(5)] was submitted as part of the forest practices application, was the mitigation identified in their report implemented by the landowner?

The answer of "yes" or "no" to each compliance question in Table 1 was determined after thorough field evaluation of the activity that took place in relation to potentially unstable rule-identified landforms. This evaluation was performed by a DNR licensed engineering geologist in consultation with a licensed engineering geologist from the Department of Ecology. Additional support was typically provided by a DNR forest practices forester and compliance monitoring program staff. Data were collected on a yearly basis since unstable slopes were included in compliance monitoring, except for 2018. The data were then analyzed as a whole for each biennium. Although site specific compliance data were collected, the landowners and their compliance results were reported anonymously. The purpose of this data collection was to evaluate compliance with unstable slopes rules by measuring compliance with approved forest practices applications in order to guide future rule making, not to seek out violations and conduct enforcement. The data were summarized in the 2016-2017 Biennium Compliance Monitoring Report and the 2018-2019 Biennium Compliance Monitoring Report. Statistical analyses and results for these two reports were produced by a third-party consultant as outlined in Andrews et al., 2018.

Data Collection for Reported Landslides

The Washington Geological Survey (WGS) is the entity responsible for reporting known landslides in the state. Since 2016 WGS has been conducting comprehensive tracking of reported landslides, putting that information in a geodatabase, and making it publicly available which is what was used in this study. Landslides can be reported to WGS by anyone, but most commonly it is a state or local government entity. A geologist from either WGS or another available government entity will respond to the reported landslide with the primary objective of assessing any threats to public safety and damage to infrastructure or natural resources. This information along with the location and known or estimated time of the mass wasting event are all included in the published dataset. Depending on safety and accessibility of the reported landslides some responding geologists are also able to include additional information such as the type of slide, soil composition, estimates of debris moved, and weather conditions. Although this additional information is variable in the dataset used in this study.

3.3 Statistics and Calculations

First, the compliance monitoring data collected for unstable slopes were organized by year in excel which consisted of the total number of "yes" and "no" responses to all questions. Site specific compliance data as well as the rate of compliance for each question were not metrics reported in the two biennial reports, and therefore were not analyzed in this study. The objective of the Compliance Monitoring Program is to report biennial trends in rule compliance to the Forest Practices board and not to report rule infractions of individual landowners, so the reported data used in this study consisted of the number of site visits conducted each year and total yes and no responses for all compliance questions for each year. Although these are compliance summaries of each year, it is still a sensible metric to compare to the yearly number of mass wasting events to determine if a pattern exists. This is because the compliance monitoring for unstable slopes is performed during the dry season on sites where forest practices have recently taken place, and human influenced landslides are most likely to occur during the wet season following a disturbance on the landscape such as timber harvest (Iida, 2004; Ishikawa & Kawakami, 2003). The percentage of compliance monitoring questions answering in the affirmative for unstable slopes compliance was calculated for each year of data (2016, 2017, and 2019) as well as the mean for all three years. Excel was used to create descriptive graphs comparing the percentage of compliant samples with the number of reported landslides per year. R studio was also used to conduct the Shapiro-Wilk Test to determine if the data were normally distributed where α=0.05.

Second, landside data were examined and organized. The Washington Geological Survey maintains a database of reported landslides which typically includes the approximate date of mass wasting, type of mass wasting, location data, and any damage that resulted. The total number of reported landsides on forestland per year for 2016, 2017, and 2019 were organized in excel. R studio was also used to conduct the Shapiro-Wilk Test to determine if the data were normally distributed followed by the Pearson's Chi-squared Test to determine if compliance rates were associated with the number of reported landslides where α=0.05. The null hypothesis tested was that compliance rates and the number of reported landslides are independent variables. Similar to the Compliance Monitoring data, the total number of landslides per year were calculated along with the mean for all three years and descriptive graphs highlighting these data were created in Excel.

Finally, since the Pearson's Chi-squared test indicated a rejection of the null hypothesis that compliance rates and the number of reported landslides are independent variables, a correlation analysis was performed to determine the strength and direction of the relationship between compliance and the number of reported landslides. Additionally, a linear regression was performed with percentage of compliance by year as the independent variable and the number of landslides per year as the dependent variable in an attempt to determine if compliance rates can predict a change in the number of landslides. The null hypothesis tested for both was that a relationship does not exist between compliance rates and the number of reported landslides with a significance threshold of $\alpha=0.05$.

3.4 Photogrammetric and Geospatial Analysis

To examine how forest practices intersect with reported landslides, spatial analysis using ArcGIS was employed. The intent of this analysis was to first examine the distribution of reported landslides and compliance monitoring sites across the landscape, followed by a closer look at the topography and any unstable features at locations where the two examined data sets had a geographic nexus. Next, a location in Western Washington was selected for investigation of the topography and forest characteristics where timber harvest had not occurred within the last 10 years. This was intended to serve as a comparison of topography and forest composition to compliance monitoring areas examined after recent activity had occurred. After that, the statewide reported landslides were studied in greater detail to determine how many occurred in relation to percent slope, primary soil composition, and mass wasting hazard levels to see if any trends existed. Finally, an intersection analysis was performed on reported landslides and urban areas statewide to determine how many occurred within city limits and urban growth areas where forestland managed for long-term timber production is uncommon.

Shapefiles created and made publicly available by the Washington Department of Natural Resources (DNR) and the Washington Geological Survey (WGS) were utilized in ArcMap and the DNR Forest Practices Application Mapping Tool. For the maps produced in Figures 6-8 where landslide locations were examined in relation to compliance monitoring sites, six geodatabases and shapefiles used. These were Reported Landslides 2016-2020, Compliance Monitoring Sites 2016-2019, Approved Forest Practices Applications Activity Area Boundaries, Bare Earth Hill Shade LiDAR, Slope Stability Index, and the Landslide Inventory. For the maps produced in Figures 9 and 11 the shapefiles and geodatabases used also included Reported Landslides 2016-2020, Bare Earth Hill Shade LiDAR, and the Slope Stability Index as well as Potential Mass Wasting Hazards, US Department of Agriculture Soils Atlas, and Urban Areas. These shapefiles were joined, new feature classes were created, and they were sorted by attributes to examine the areas where reported landslides intersected with managed forests. In particular, areas under DNR Forest Practices jurisdiction and Compliance Monitoring locations were the primary focus of this study as well as other common factors in statewide landslides like slope and soil composition. Reported landslide locations were examined following the relevant portions of protocols from Slaughter et al., 2017 for analyzing landslide areas using LiDAR. From these data three maps were created showing where intersections of landslides and forests with recent human activity in them occurred, and the site-specific conditions were more closely examined for unstable features and geologic characteristics to include percent slope and primary soil composition. Two additional maps were also created which showed where landslides occurred across the state in relation to surveyed potential mass wasting hazards and where landslides happened in relation to city and urban growth area boundaries.

4. Results

4.1 Statistical Analysis

This study evaluated data from two biennial compliance reports encompassing a total of 85 compliance monitoring for unstable slopes site visits and 286 reported landslides on forestland over the course of 2016, 2017, and 2019. Both compliance rates and the number of reported landslides were lowest during the unstable slopes pilot study conducted in 2016 [Table 2]. The rate of compliance for unstable slopes increased in the subsequent two years to a peak of 98% compliance for unstable slopes, unlike the number of reported landslides which nearly tripled in number to 167 reported slides in 2017 from the 2016 count, and then fell back down to 63 reported slides in 2019 which was much more similar to 2016 [Table 2]. The higher number of landslides in 2017 also coincided with higher than average winter rainfall events (NOAA, 2019). These produced an average of 89% for the overall rate of compliance and an average of 95 landslides on forestland per year over the three-year examined in this study [Table 3]. The standard deviation for both of these means was also moderately low given the sample consisting of only three years of data [Table 3].

Table 2: Annual totals for unstable slopes compliance rates and number of reported landslides on forestland from 2016-2019. Unstable slopes compliance monitoring data was not collected during 2018. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

Source	2016	2017	2019
Compliance Rate	76%	92%	98%
Landslides per Year	56	167	63

Shapiro-Wilk Tests for normality were conducted on the unstable slopes compliance monitoring and reported landslides on forestland datasets, which indicated that both were normally distributed [Table 3]. The distribution for compliance rates by year was mostly linear while the plot for landslides per year was more or less bell shaped due to the high number of reported slides in 2017 but was still above the α=0.05 threshold of significance [Fig. 4]. Additionally, the Pearson's Chi-squared Test evaluating the independence of compliance rates and reported landslides produced a χ^2 statistic of 78.8 and a p-value well below the 0.05 threshold of significance, indicating a rejection of the null hypothesis of no association between the two tested variables [Table 4].

Table 3: The average compliance rate and number of landslides per year over the three years covered in this study (2016-2019) and results from the Shapiro-Wilk test for normal distribution. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

Source	Mean	Standard deviation	Shapiro-Wilk p-value
Compliance Rate	89%	7%	0.51
Landslides per Year	95	36	0.11

Table 4: Results of the Pearson's Chi-squared Test investigating the independence of compliance rates and number of reported landslides from 2016-2019. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

Chi-squared	Degrees of freedom	P-value
78.8	4	3.12×10^{-16}

Subjecting the compliance rates and reported landslides datasets to a correlation and linear regression produced results in partial conflict with the outcome of the Pearson's Chi-squared Test. The correlation test indicated that there was a weak, positive relationship between compliance and the number of landslides [Table 5], with the correlation plot showing a rather scattered distribution [Fig. 4]. In the simple linear regression analysis, a low value of the f-statistic and the high p-value above the $\alpha=0.05$ threshold of significance indicated a failure to reject the null hypothesis that the compliance rate for unstable slopes does not affect the number of reported landslides [Table 5]. The coefficient of determination also predicted that only 9% of the variation in the number of reported landslides on forestland per year could be explained by the linear relationship between compliance rates and reported landslides [Table 5]. Furthermore, plots of the residuals from the regression analysis indicate a potentially nonlinear relationship between the two variables as well as points with a higher degree of leverage [Fig. 5].

Table 5: Results of a correlation test and simple linear regression analysis with unstable slope compliance rates as the independent x variable and reported landslides as the dependent y variable. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

R	R^2	F-statistic	Degrees of freedom	P-value
0.31	0.09	0.10	1,1	0.80

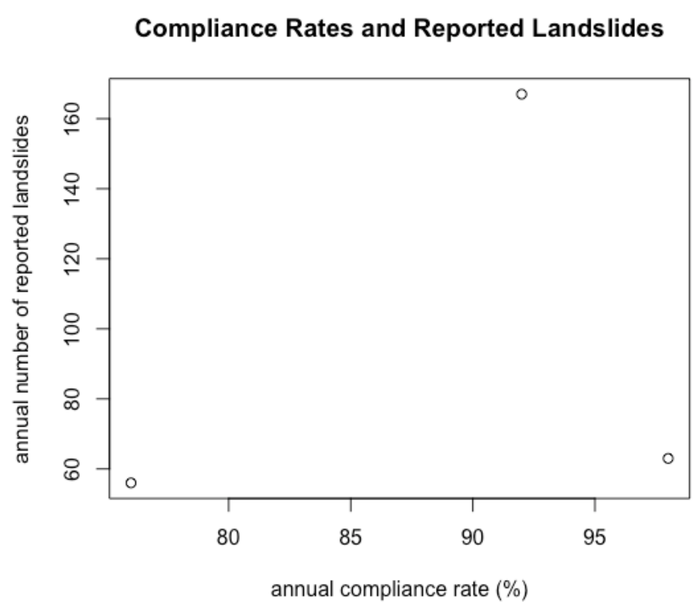
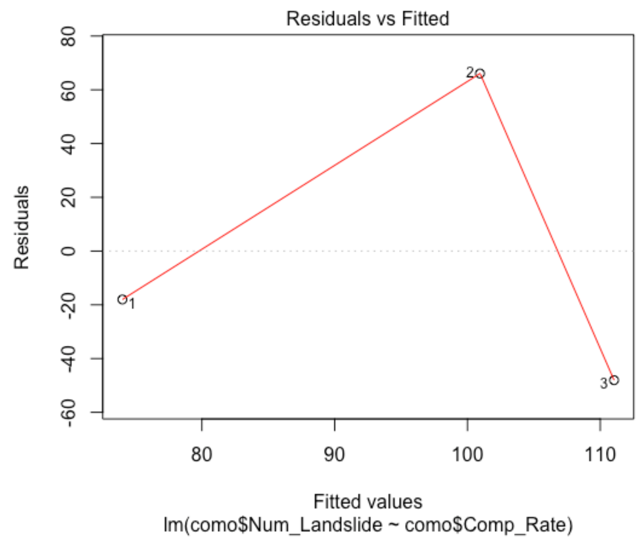


Figure 4: Plot showing the correlation between unstable slopes compliance rates (x-axis) and reported landslides on forestland (y-axis). Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.



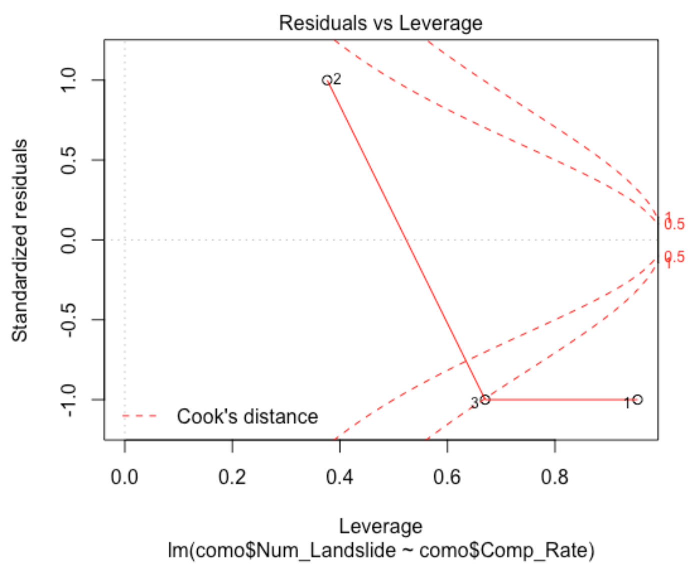


Figure 5: Plots of the residuals from the linear regression analysis showing residuals vs fitted values (top) and residuals vs leverage (bottom) with compliance rates as the independent variable and reported landslides as the dependent variable. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

4.2 Site Specific Analysis

An examination of compliance monitoring site locations using Arc GIS showed a rather even distribution of geographic points across Western Washington where state and private forestlands exists [Fig. 6]. This suggests that spatially, the sample of completed forest practices applications inspected for compliance did achieve the random selection intended by the Compliance Monitoring Program. There were slightly more monitoring locations in the southwestern portion of the state as well as a small cluster of compliance sites in the northwestern corner of the Olympic Peninsula. These regions tend to produce the highest volume of timber in Washington, so a greater number of forest practices applications existed to sample from. An examination of the reported landslide distribution from 2016-2020 revealed some scattered distribution across the state but also clustered areas of slides [Fig. 6]. Landslides were generally located within the footprint of the steep Olympic and Cascade Mountain Ranges as well as the Willapa Hills area near the southwestern coastline. The eastside of the state had a similar distribution of slides with respect to steep terrain, as landslides occurred almost exclusively in the Cascade Range as well as in the mountains of the Okanogan Highlands in the northeastern section of Washington. A conspicuous cluster of reported landslides also exists along the Puget Sound in the metropolitan area near Seattle and Tacoma.

Intersection analysis also revealed that there was a total of two instances over the course of the three years examined in this study where landslides were reported within the activity area of a completed and closed forest practices application area that was randomly selected for compliance monitoring [Fig 7]. The two landslides occurred in October of 2019 and the compliance monitoring site visit occurred earlier that same year. A closer look at the mass wasting potential of this area revealed a low likelihood designation by the Washington Geological Survey and a primary soil composition of glacial till and outwash [Fig. 9]. Analysis of orthographic photos and estimated tree heights from LiDAR of these two reported sites suggest the surrounding forest is approximately 30-year-old Douglas Fir with slopes averaging less than 50%. No rule identified landforms from the landslide inventory were found within the area of these two slides, and LiDAR reveals rather gentle topography with the eastern slide originating from a road and the western one occurring just above a small draw that did not meet criteria to be classified as an inner gorge [Fig. 7].

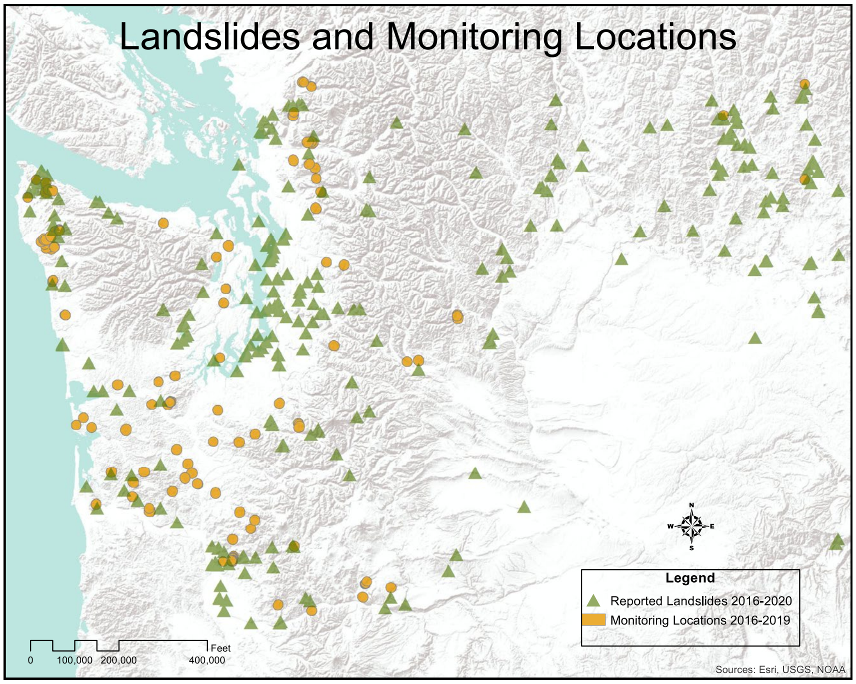


Figure 6: Distribution of compliance monitoring sites and reported landslide locations across Washington. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

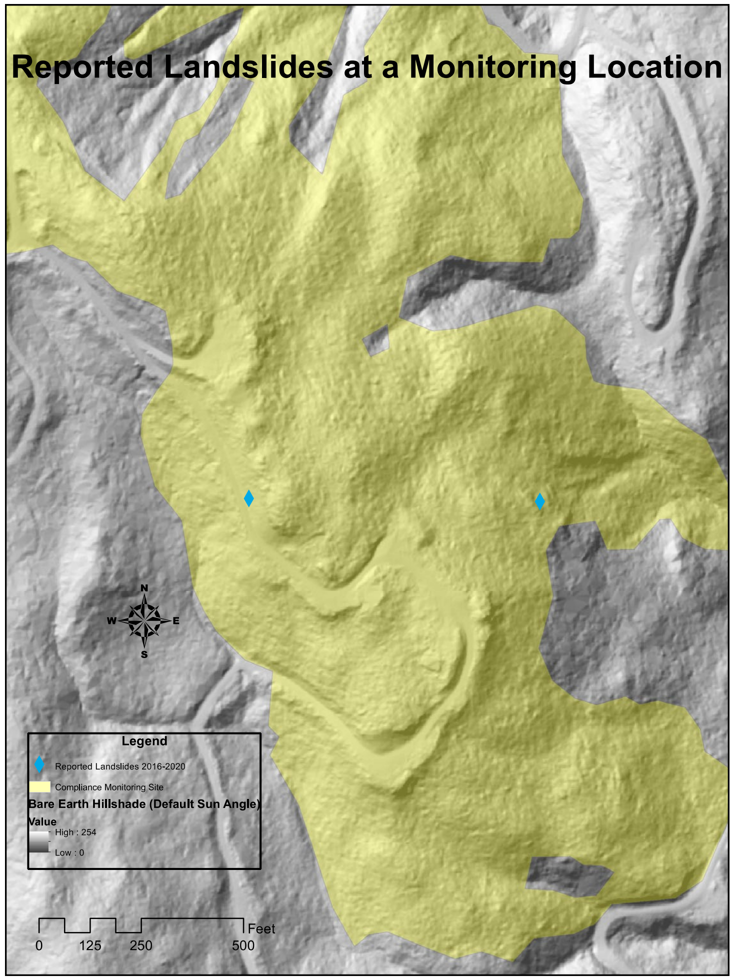


Figure 7: The two reported landslides that occurred at a compliance monitoring location on the Olympic Peninsula. Data from Andrews et al., 2018, Andrews et al. 2020, and Washington Geological Survey, 2020.

Four additional sites were examined where landslides were reported in Western Washington managed forests, but no timber harvest or road building activities took place within at least the last 10 years, and therefore were also outside of the window for potential random selection in the compliance monitoring review. This examination revealed from orthographic photos and estimated tree heights from LiDAR that the average composition of forests at these sites were primarily early seral Douglas Firs likely around 30-40 years in age. It also showed that all four landslides occurred in areas that were already likely to be unstable and susceptible to slope failure. Additionally, the northern most slide occurred within the vicinity of several scarps and deep-seated landslides [Fig. 8].

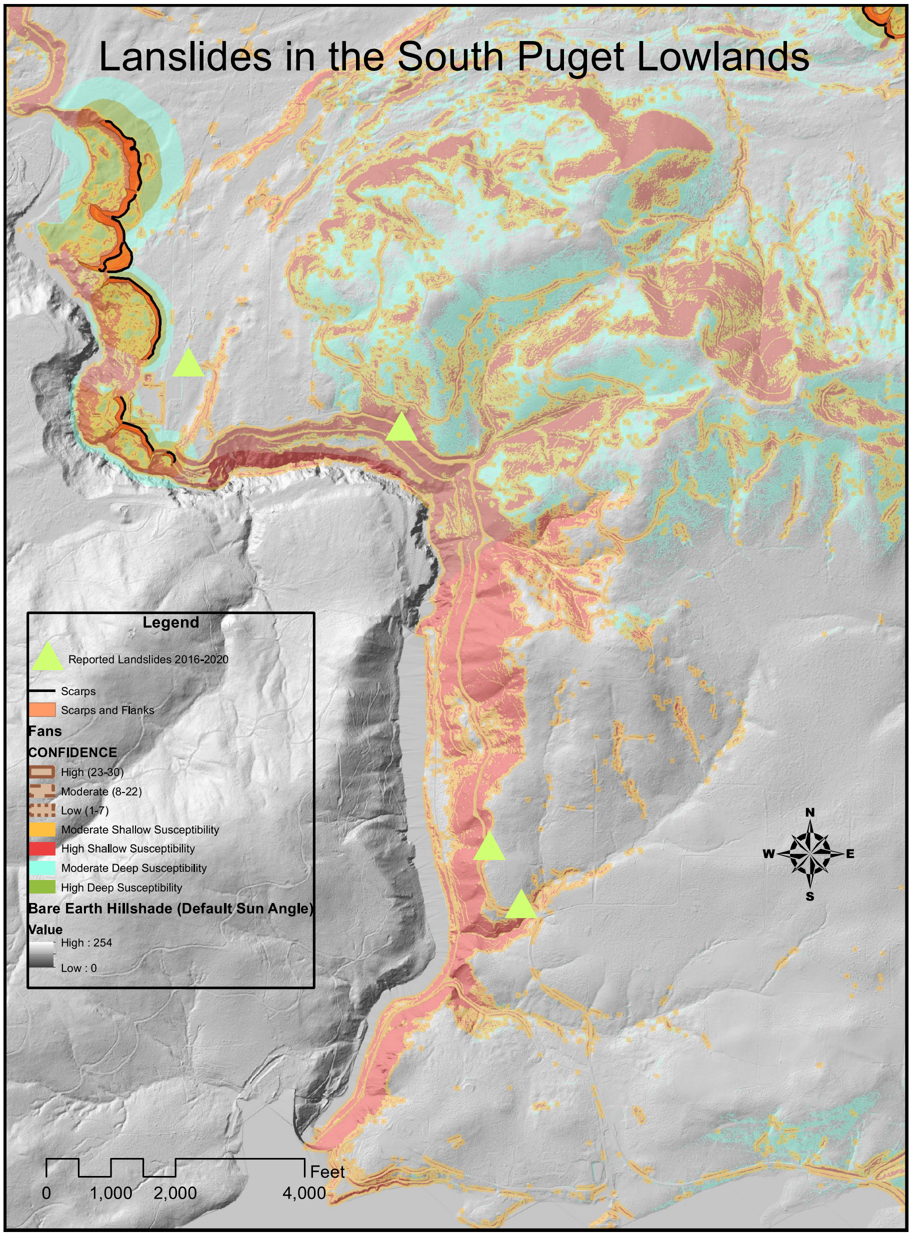


Figure 8: Reported landslides in Western Washington managed forests along State Route 7 where no timber harvest or new road construction took place within the last 10 years. Data from DNR, 2020 and Washington Geological Survey, 2020.

4.3 Geospatial Analysis

Spatial analysis of the statewide landslide locations also provided insight into some of the relevant geologic characteristics to include mass wasting potential, primary substrate composition, and slope steepness. Of the 316 reported landslides from January 2016 to February 2020, 278 occurred in areas where the levels of mass wasting potential had been surveyed and identified by the Washington Geological Survey, which included most state and privately owned forestland in Washington [Fig. 9] [Table 5]. Most of the 278 reported landslides that occurred in surveyed areas also happened where soils were identified as having moderate to insignificant potential for mass wasting (83%), with 53 landslides occurring in areas identified as having high mass wasting potential [Table 6]. Additionally, 54 reported landslides occurred where slopes averaged greater than 50% and 28 occurred where slopes were at or greater than 65% which is the threshold at which mass wasting becomes more likely [Table 6]. An intersection analysis of primary soil composition with reported landslides revealed that volcanic ash was the most common soil type where mass wasting occurred followed by glacial sediments (till and outwash) then bedrock [Fig. 10]. 13% of landslides occurred in soils that either were not identified or were of mixed composition beyond distinction, and less than 10% occurred in all other soil types to include lake sediments, alluvial deposits, and areas that contained multiple distinct soil profiles [Fig. 10].

Soils with Mass Wasting Potential

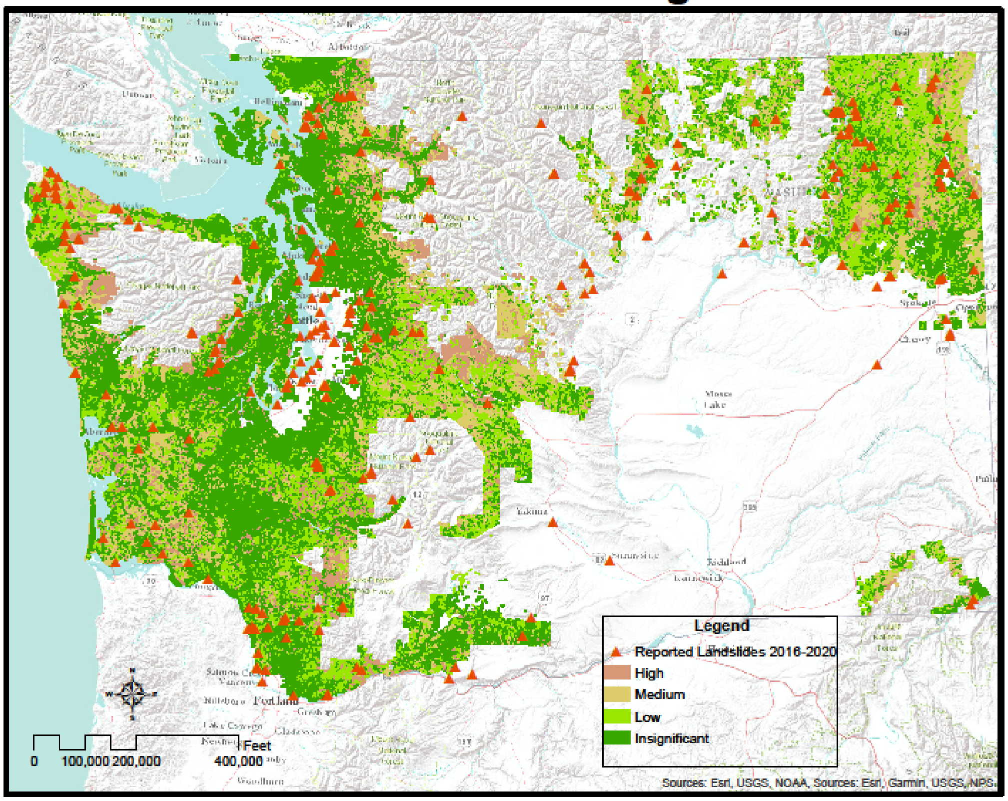


Figure 9: Reported landslides from 2016-2020 in relation to areas of known soil stability. Data from DNR, 2020 and Washington Geological Survey, 2020.

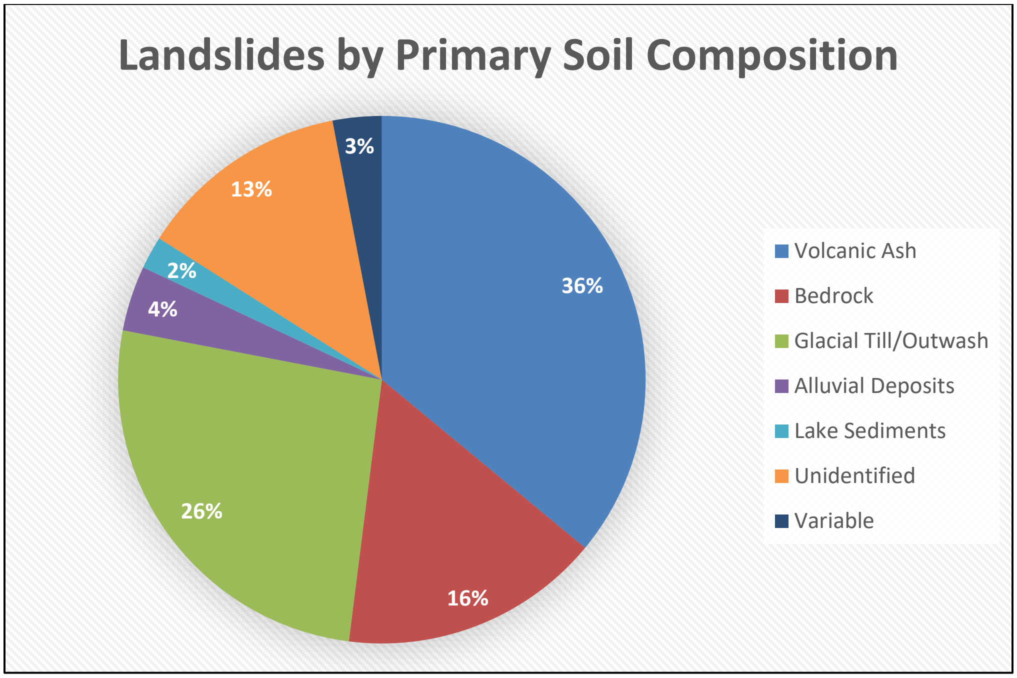


Figure 10: Percentages of landslides by primary soil composition in areas of surveyed soil instability. Data from DNR, 2020 and Washington Geological Survey, 2020.

Table 6: Results from spatial analyses of landslides from 2016-2020 showing how many occurred in areas with mass wasting potential, what the minimum slope was, and how many occurred in urban areas. Data from DNR, 2020 and Washington Geological Survey, 2020.

	Potential mass wasting area	High mass wasting potential	Slope >50%	Slope ≥65%	Urban area
# landslides	278	53	54	28	48
% landslides	88%	17%	17%	9%	15%

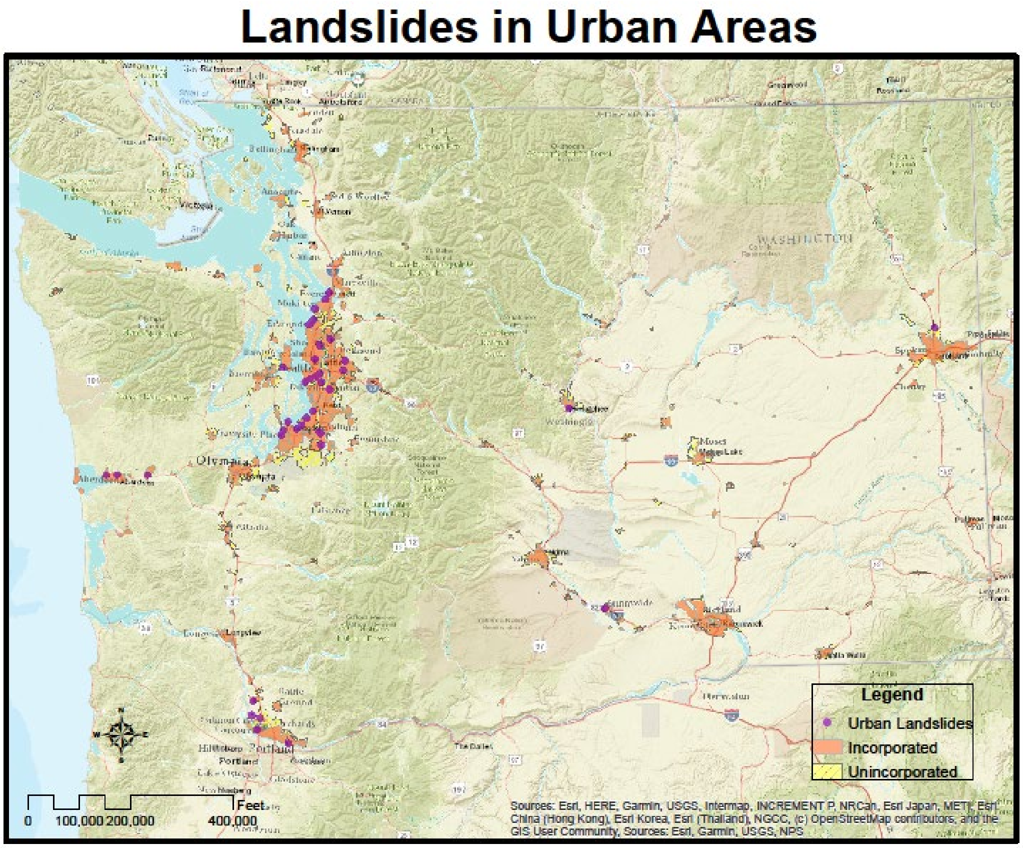


Figure 11: Reported landslides that occurred within city limits and unincorporated urban growth areas from 2016-2019. Data from DNR, 2020 and Washington Geological Survey, 2020.

The intersection analysis of reported landslides from 2016 to 2020 with urban areas showed that 48 occurred in either city limits or unincorporated urban growth areas [Table 6]. Of those 48 urban landslides, 35 occurred in the greater Seattle-Tacoma metropolitan area, and only three occurred in urban areas east of the Cascade Mountain Range [Fig. 11]. The remaining urban landslides were clustered near the city of Vancouver in the southwestern part of Washington, as well as in Aberdeen and Hoquiam towards the west-central coast [Fig. 11].

5. Discussion

It is well established in the literature that landslides are a very natural phenomenon most commonly activated by a sudden increase in groundwater infiltration, but that anthropogenic influences and alterations on the landscape can cause an increase in the number of landslides (Adams & Flint, 1991; Barik et al., 2017; Coffin & Harr, 1992; Dieu et al., 2008; Washington Geological Survey, 2020). Some of these alterations include forest practices such as timber harvest and roadbuilding that are common activities in Western Washington forests. These can alter the local hydrology or other means of potentially activating an already unstable land feature. Landslides are also more likely to occur during the first wet season following a forest practice when the landscape is at its most altered state with the highest amount of exposed soil (Adams & Flint, 1991; Barik et al., 2017; Washington Geological Survey, 2020). The current unstable slopes regulations in the Forest Practices Act and Rules were developed by the Forest Practices Board using the best available science on how to protect public safety and reduce the anthropogenic impact on the environment by decreasing the chances of human influenced mass wasting events (WDNR, 2017). As the knowledge base of landslide geology and forest management improved since the late 1800's, so did the regulations in place to protect public safety, and eventually, natural resources.

The dynamic geologic history of Western Washington resulted in the mosaic landscape seen today composed of marine and alluvial sediments, glacial deposits, and the new material produced from volcanic events (Armstrong, 1988; Clague et al., 1992; Everts & Swanson, 1994). The modern-day result of these geologic processes is a landscape that is still continuously changing due to plate tectonics, periodic volcanism, and mass wasting events driven by high annual rainfall (Gavin & Brubaker, 2014; Miller, 2016). Indigenous forest practices were centered around sustainable use of the landscape and minimal negative impact to natural resources; this likely had a negligible effect on the number of landsides beyond a natural rate (Friedman, 1976; Gavin & Brubaker, 2014; Ishikawa & Kawakami, 2003; Kruckeberg, 1991). Early industrial logging did however cause damage to watersheds and habitat composition still observed today due to widespread harvest of mature forests with little regard to environmental factors or maintaining land in long-term forestry use (Hudson, 1968; Kruckeberg, 1991; University of Washington, 2015).

As the need for a sustainable timber supply grew so did the need for new management and regulations. Along with a paradigm shift in how society viewed natural resources, this eventually resulted in the current regulations found in the Forest Practices Act and Rules aimed at preventing the activation of landslides from forest management activities (University of Washington, 2015; Washington Department of Natural Resources, 2017; Ziemer, 1981). Modern technology such as LiDAR and drones have made valuable contributions to delineating unstable land features and getting a more complete catalog of landslides on forestland. Programs such as Forest Practices Compliance Monitoring and Adaptive Management continuously evaluate how well regulations are being applied on the landscape and what the outcomes of rule implementation are. This is important as evaluating how the rules are being applied on the ground and if intended resource protection objectives are met is critical to continually improving regulations while also supporting timber production. The objective of this thesis was to contribute to that knowledge base of the post hoc evaluation of unstable slopes rule implementation and the measured effects on the landscape through the number of reported mass wasting events.

Accounts from timber workers and surveyors during the rise of industrial logging in Western Washington describe rampant landslides following the massive clear cuts common to that era that frequently dammed or diverted waterways and buried logging roads and equipment (Hudson, 1968; Kruckeberg, 1991; University of Washington, 2015). Even though those accounts are not quantified, their descriptions imply that the average annual total for landslides was likely much higher than the average of 95 landslides per year from 2016, 2017, and 2019 included in this study [Table 3]. Although analyzed on a much smaller timescale, compliance rates also improved over time from the start of unstable slopes data collection in 2016 increasing over 20% during the last unstable slopes compliance monitoring completed in 2019 [Table 2]. Landslides and unstable features are complex and variable pieces of the landscape. This in turn means that developing unstable slopes regulations and following them can be just as complex. In the spring of 2016 guidance updates for the Forest Practices Board manual chapter on evaluating potentially unstable slopes and landforms was modified and updated, which could explain why that was also the lowest of the three years for compliance rates as landowners figured out how to implement this guidance. The Compliance Monitoring Program also takes the time with each site visit to implement a learning opportunity by discussing any issues found with non-compliant prescriptions. This combined with unstable slopes trainings hosted by DNR Forest Practices geologists in 2017, 2018, and 2019 likely aided in reaching the 98% compliance rate in 2019.

The Shapiro-Wilk tests performed on the annual compliance monitoring and reported landslides data indicated normal distribution of both, even though 2017 had nearly triple the number of landslides compared to 2016 and 2019 [Table 2] [Table 3]. Most landslides in Western Washington occur during the winter months when groundwater saturation and runoff is highest, as was the case with the unusually large swarm of landslides that occurred in 2017 mostly during the months of December, January, and February. It was observed that this anomaly also coincided with sustained rates of higher than average winter precipitation during that year as well as several severe storms that together were very likely to have been driving force behind the mass wasting events despite a high compliance rate that year of 92%. Pearson's Chi-squared Test gave a strong indication that there was indeed a relationship between unstable slopes compliance rates and the number of annual reported landslides, which was weakly supported by a correlation test [Table 5]. The correlation test did however raise suspicion of the validity of the test results. The output showing the weak correlation and the positive relationship it suggested of the higher the compliance rates were, the more landslides there would be, was in contradiction to historic accounts of frequent and widespread landslides when little to no regulations were in place. The linear regression analysis that followed contradicted the chi-squared and correlation tests by indicating that a relationship between the two variables does not exist and also showed a high degree of leverage and variability in the data [Fig. 5]. These contradictions between tests and high variability in the plotted results do not offer a clear answer as to whether or not compliance rates are a factor in mass wasting susceptibility.

There were several limitations in the statistical analysis portion study that likely contributed to the inconclusive results. The first and obvious limitation is the small sample size of unstable slopes compliance monitoring data. Since compliance rates are calculated on an annual rate only three years of data were available. Data collection began in 2016 with a pilot study followed by an emphasis study in 2017. 2018 was skipped while the results from these trial collections were analyzed and then discussed by the Forest Practices Board. Data collection resumed in 2019 but was cancelled indefinitely in 2020 due to the COVID-19 pandemic. Landslide reporting data from the Washington Geological Survey going back to 2016 is continually updated and publicly available through shapefiles but cannot be used in statistical analyses without the accompanying year of compliance data. The level of variability in the number of landslides reported per year in the data set used for this study also suggests that a larger sample of annual totals would produce more conclusive results when analyzed in conjunction with a larger compliance monitoring dataset.

Another limitation to this study was the lack of detailed historic data on the number of landslides on forestland as well as compliance rates with forestland regulations as they developed over time. Prior to the latter half of the 1900's only large landslides impacting human settlements and roadways were investigated and recorded in detail. It was not until the mid-1900's that environmental impacts of anthropogenically influenced landslides were realized, not just their impacts to public safety. Anecdotal accounts exist from early industrial timber workers describing frequent landslides following widespread harvest of mature timber, but these provide little or no detail of the actual number of mass wasting events, location, topography, or other factors that could be used to compare them to modern reported landslide events. The same is true for data regarding how compliant landowners were with actually implementing regulations as they came into existence and evolved, for which collection did not reliably and regularly begin until 2006 when the Compliance Monitoring Program began their work. Having these data would likely be invaluable to aid in determining what a theoretical baseline was before industrial timber harvesting began. The data could have also been used to quantitatively evaluate whether rule compliance over time was a factor in the number of landslides that occurred. This in turn could have been used as a metric to evaluate rule effectiveness over time in preventing landslides as well. Quantitative historic data would also have been useful in showing long-term trends in the numbers of landslides related to regional weather patterns as well as lessen the leverage of extremely high or low years of landslides when performing analyses, which is what occurred in 2017 of the landslide datasets for this study.

Spatial analysis using GIS revealed that over the three years examined in this study, two landsides were reported at a compliance monitoring location [Fig. 13]. The landslides occurred towards the end of 2019 which was the same year as the compliance evaluation for that particular site. Compliance rates are calculated and published as annual totals, so the results of site-specific monitoring surveys remain anonymous, but given the 98% compliance rate for 2019 there is a high probability that this site was compliant during the survey. Fall of 2019 had more precipitation than average and a storm event with heavy rainfall coincided with the day both landslides occurred (NOAA, 2020; Parks, 2019). Close to eight inches of precipitation fell in the northwest corner of the Olympic Peninsula events over a 24-hour period on October 22nd, 2019 which was followed by a number of landslides across the region [Fig. 12] (NOAA, 2020; Parks, 2019). The two reported landslides at the compliance monitoring location were likely already experiencing some degree of soil saturation due to the persistent rain prior to the mass wasting event. The likely pre-saturated conditions along with nearly eight inches of rain falling in a short time frame probably resulted in oversaturation as well as surface runoff and scour that resulted in mass wasting. This is further evidenced by the high number of landslides reported following that storm event, which also demonstrates that even forestland properly managed in accordance with unstable slopes regulations are still prone to mass wasting through natural events. The reports associated with these two mass wasting events indicated that they were fairly small shallow rapid landslides with one originating from a forest road and the other from within a recently harvested area, and did not note any potential rule violations that may have exasperated the situations (Washington Geological Survey, 2020).

Images of the landslides [Fig. 13] and an aerial view using LiDAR [Fig. 7] do show some gentle to moderate slopes in the areas of the two landslides, but do not indicate that the slides occurred on any rule identified landforms or other potentially unstable features, which in this case can be characteristic of landslides caused by unusually high rain events that are normally quite stable (Iida, 2004; Ishikawa & Kawakami, 2003; Ziemer, 1981). Additionally, images from the sites show that several best management practices were followed to mitigate post-harvest conditions which included dispersing branches and other leftover woody material across the harvest area to prevent surface erosion, leaving stumps intact to provide slope stability, and replanting so the next stand of trees will begin growing in. Whether or not these two mass wasting events would have happened if harvest had not occurred is difficult to determine, but even though regulations were followed and best management practices were implemented, extreme natural events can still cause slope movement.

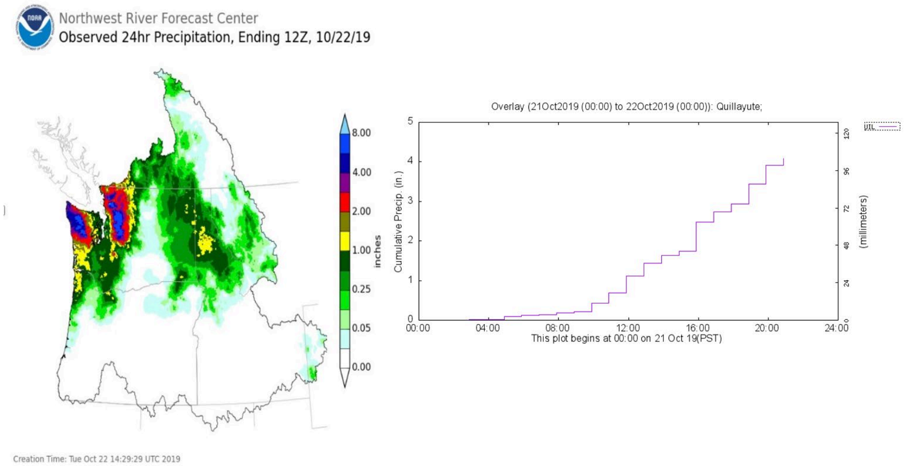


Figure 12: Precipitation measurements from the October 2019 storm event that coincided with the two reported landslides at a compliance monitoring location in the Northwest region of the Olympic Peninsula. Chart generated by Dave Parks-DNR, 2019 with Data from NOAA, 2019.

Related to this, the four landsides shown in Figure 8 from 2017, 2018, and 2019 occurred in approximately 30-40-year-old forests with no recent forest practice activities having taken place and were examined in order to compare the landscape to mass wasting events that had occurred on recent timber harvests. No forest practices violations were noted in the reports for these landslides, but an analysis of the landscape using LiDAR, the landslide inventory, and the unstable slopes index revealed an environment rich in potentially unstable slopes. All four reported landslides occurred in areas of at least moderate susceptibility to shallow landslides, with three of the four also in areas of high shallow susceptibility. Two of the four also occurred in close proximity to deep seated landslides with moderate susceptibility of wasting. The reports indicated that these landslides occurred during the winter wet season for Western Washington and were primarily shallow rapid landslides which is consistent with the slope stability index. Even though the data analysis portion of this study produced inconclusive results on rule compliance as a factor of mass wasting susceptibility, historic accounts suggest that forest practices regulations do prevent human induced landslides to a degree not able to be quantified in this thesis, but also that even properly managed or unharvested forests can still be susceptible to natural processes.

Figure 13: Images of the two landslides that occurred at a compliance monitoring location in October of 2019. The slide in the top image originated from the forest road inside of a replanted area (note trucks for scale) and the slide in the lower image originated inside of a harvest area that had also been replanted. Images by Dave Parks (DNR), 2019.

The analysis of the statewide reported landslide layer from January 2016-February 2020 did give some valuable insight as to where landslides occurred in relation to several geologic attributes as well as urban areas. Of the 316 reported landslides during this timeframe 278 occurred in areas surveyed by the Washington Department of Natural Resources for mass wasting potential [Fig. 9]. Only 53 of the 278 landslides in areas surveyed for mass wasting potential occurred where a designation of high potential was given [Table 6]. Although only 17% of the landslides occurred in areas of high mass wasting potential it is also important to consider that not many areas received this designation; the majority of the surveyed portions of the state are considered to have low to insignificant potential of mass wasting [Fig. 9]. Similarly, 83% of landslides that occurred in theses surveyed areas had mild to moderate slopes less than 50%, with only 28 landslides reported in areas where the slope was known to be at a minimum of 65% or greater. Slopes with grades at least 65% become more prone to mass wasting events, and in particular, toes of deep-seated landslides (DNR, 2017). Although identifying areas of higher potential slope instability is an important part of protecting public safety and resources, landslides also frequently occurred in areas with mild slopes and low mass wasting susceptibility. While predictive surveys for mass wasting potential catalog places where extra caution and scrutiny should be taken when conducting forest practices, the data from this analysis indicate there are also other factors in initiating landslides that can go beyond soil stability and slope angle.

Trends of primary soil composition in relation to landslides were also revealed in this study. Over half of reported landslides occurred in soils consisting primarily of volcanic ash or glacial sediments and debris, which also compose a large portion of Washington's overall soil composition [Fig. 10] (Hipple, 2011).

Volcanic ash soils in Washington are typically very fine grained and loosely compacted which lends them to be more easily mobilized by surface scour and have a high water capacity internally (Gavin & Brubaker, 2014). Both of these characteristics make volcanic ash soils prone to shallow rapid landslides as their soil profiles are typically three meters or less in depth deposited over bedrock or other more compacted and stable material (Hipple, 2011; Iida, 2004).

Similarly, glacial sediments and debris typically consist of fine clays and silts mixed with cobble resulting from the grinding process of ice on rock (Easterbrook, 1986; Hipple, 2011). The clays and silts both have high water capacity and slow percolation rates making ground saturation and mass wasting more likely events during prolonged wet periods (Iverson, 2000). In Western Washington the profile of glacially derived soils is commonly greater than 10 feet in depth or the average rooting depth of trees; this combined with the slow percolation rate can make these soils prone being unstable features like glacial deep-seated landslides or groundwater recharge areas (Hipple, 2011; Iida, 2004; WDNR, 2016). Additionally, 16% of landslides examined in this study occurred in bedrock material which means just over three quarters of examined landslides occurred in either volcanic ash, glacial derived soils, or bedrock. Although bedrock tends to be more stable than glacial soils or volcanic ash, it can still be a component in bedrock hollows, deep-seated landslides and other unstable features [Fig. 10].

Spatial analysis of reported landslides with urban areas also revealed a total of 48 that occurred within city limits or urban growth areas [Table 6]. This included a cluster of 35 mass wasting events in the Seattle-Tacoma metropolitan area. Although patches of forestland exist in this metropolitan area, forests managed for long-term timber production are uncommon within highly developed city limits and urban growth areas [Fig. 11]. Compared to the rest of the state where landslides typically occurred in mostly continuous forestland, this sizeable cluster of mass wasting events in the most populated and developed part of Washington is anomalous. A closer look at reports of the 35 landslides revealed that all had some form of impact to public or private infrastructure, with the most common being landslides blocking roads or rail lines. Additional information provided in the reports was focused on public safety and impacts to transportation, unlike the reports for the two landslides that occurred at a compliance monitoring site, which were focused on evaluating potential environmental damage. This metropolitan area was also not included in the forestland survey for mass wasting potential so geologic attributes like slope and soil composition were unable to be analyzed in this study. Two of the landslide reports from the greater Seattle-Tacoma area did however identify broken underground water mains as the likely causes for those slides.

Vegetation cover and forestlands play import roles in precipitation absorption and mitigation, but capital improvements such as building roads and structures creates impermeable surfaces and forces water to be diverted elsewhere instead of going directly into the water table or established stream systems (Coffin & Harr, 1992; Washington Geological Survey, 2020). In highly developed locations like the Seattle-Tacoma metropolitan area there can be limited locations where permeable ground exists, and storm water diversion and management become a serious concern (WDNR, 2017; Seattle Office of Emergency Management, 2018). This large urban area is also built on steep terrain and experiences high annual rainfall, which when combined with the highly altered landscape, helps to explain the cluster of reported landslides here (Seattle Office of Emergency Management, 2018). The smaller groups of landslides in the cities of Aberdeen, Hoquiam, and Vancouver as well as the three scattered across the east side of the state can also likely be explained by the same impacts as experienced in the Seattle-Tacoma area, just on smaller scales. The single urban landslide near Spokane was a bit anomalous in that it occurred in a partially forested golf course with not many impermeable surfaces. The associated report however identified topography that indicated the likely presence of an unstable feature on the golf course, which could have been influenced by frequent watering of the greens. Overall though, compounding factors such as soil composition, percent slope, human alterations of the landscape, and heavy rain events all contribute to the likelihood of a landslide occurring.

6. Conclusion & Recommendations for Continued Research

Comparing three years of unstable slopes compliance monitoring and reported landslides data is not enough to sufficiently show whether compliance is a factor of landside susceptibility in Western Washington forests, and therefore cannot be used as a metric to evaluate effectiveness of current unstable slope regulations. Although the data used in this study were robust for each individual year analyzed, only having three years of summary statistics to use for evaluation of the research question produced a small sample size with high variability and inconclusive results. This also highlights the complexity of landslides and just how difficult it is to develop regulations concerning the activation of landslides, as shown by the nearly threefold increase in reported landslides during 2017 compared to the other two years of the study despite an increase in the unstable slopes compliance rate from the 2016 pilot study. Unusually heavy winter rainstorms and rain on snow events during 2017 were likely responsible for the activation of many landslides that year despite the 92% compliance rate. Advances in remote sensing technology along with drone use and aerial surveys becoming more accessible in the last five years also likely aided in achieving more accurate totals of annual landslides given the remoteness of much of Washington's forests. Given these advances in reporting technology combined with fluctuations in weather patterns at a regional level, it makes sense as to why three years of data is simply not enough to show any true trends of compliance rates and the number of landslides given the variability that can occur between years. Additionally, having rather high rates of unstable slopes compliance in all three years analyzed means that landslide frequency in a year of low compliance is unknown. While this adds to the inconclusive nature of these particular results, it is certainly a positive in terms of resource protection, public safety, and landowners following the Washington Administrative Code.

The literature shows that certain land features such as bedrock hollows and active deep-seated landslides are naturally more prone to slope failure, and that certain forest management practices like avoiding harvest on or building drainage structure to these potentially unstable features reduces an increased likelihood of mass wasting (WDNR, 2017; Washington Geological Survey, 2020). Based on this and the historical accounts of large, frequent landslides during the early days of industrial logging, it is rather unlikely that compliance with unstable slopes regulation would result in more landslides as indicated by the weak positive relationship plot produced in this study [Fig. 4]. The opposite is likely true to at least some degree when management techniques are employed that identify and exclude unstable features from activity areas and divert water runoff on forest roads away from them, resulting in less anthropogenic influences on already unstable landforms (Adams & Flint, 1991; Coffin & Harr, 1992; Dieu et al., 2008; Iverson, 2000; Miller, 2016; Rice, 1972).

Forest management regulations have become more comprehensive in terms of public safety and natural resource protection since the late 1800's, particularly in terms of unstable slopes management. It has been an incremental process as both scientific understanding and public perception on landslides changes. Dedicated programs such as Forest Practices Compliance Monitoring and Forest Practices Adaptive Management continue to evaluate the effectiveness of rule implementation and outcomes for state level management objectives such as endangered species preservation. Compliance monitoring for unstable slopes is a relatively new addition to the program and the data had not yet been evaluated in a way that could potentially show if changes in the number of landslides changed as compliance rates did, which could give some indication of whether the associated rules were achieving the desired outcome of protecting public safety and natural resources while also supporting a viable timber industry. Unfortunately, that gap in research is still not able to be answered at this time, but this thesis did demonstrate the necessity for continuing evaluation of compliance rates in relation to landslides and has provided the framework to do so.

This thesis also showed that landslides in urban areas and in particular the greater Seattle-Tacoma metropolitan area represent unique challenges in preventing landslides beyond a natural rate. Regulations for unstable slopes and landslide prevention in urban non-forestlands fall under the jurisdiction of the local government entity, but patches of urban forestland are usually still under the jurisdiction of the Forest Practices Act and Rules. While the forest practices rules for unstable slopes are still relevant and applicable to urban patches of forests, they were developed primarily for more rural forests managed for long term timber production, not for areas surrounded by highly developed landscapes. Even if unstable slopes regulations are adhered to within urban forests there could be other factors such as excess stormwater entering from an adjacent neighborhood or road cuts and fills just outside of the forest that could impact slope stability within. This is a complex interaction of the forestland urban interface that would likely require long-term cooperative study from the Department of Natural Resources and local government entities to determine the ways in which human influences on non-forestlands impact slope stability in urban forests. Specific policies would also likely have to be developed depending on the general conditions of the region, as factors such as snow management and melt in Eastern Washington urban areas would not be as relevant in the Puget Sound region.

Although results from this particular study were inconclusive, it showed there is great potential for continued research and future studies on the subject of evaluating unstable slope rule compliance as a factor of mass wasting susceptibility in Western Washington forests. The Forest Practices Compliance Monitoring Program has a rigorous process in place for evaluating many aspects of how well the Forest Practices Act and Rules are implemented on the landscape including compliance with roads, wetland protection, and certain harvest prescriptions. This thesis focused solely on evaluating unstable slopes compliance rates in relation to landslides, but the factors that can influence slope stability are multifaceted. For instance, a forest road with a noncompliant design could potentially be delivering excess water to a rule identified landform or the recharge area of an unstable feature that could increase the risk of initiating a landslide, even though the unstable slopes prescriptions may be compliant. Similarly, noncompliance with certain timber harvest prescriptions could indirectly impact slope stability if it resulted in an altered local hydrology. Given the time and resources, evaluating these other aspects of compliance in addition to unstable slopes may provide more insight into landslide susceptibility. Moreover, using a multivariate regression analysis with these variables could potentially produce more definitive results than evaluating only one explanatory variable.

An adjustment of compliance monitoring for unstable slopes to focus on areas predisposed to a higher likelihood of mass wasting could also be useful in determining current rule effectiveness. The unstable slopes compliance sampling technique used in the last three study years followed the same general protocol used for the rest of compliance monitoring which consists of a randomized subsample of all completed forest practices applications that included relevant prescriptions. In the case of unstable slopes compliance monitoring this included all completed applications that were identified as having potentially unstable slopes in or around the activity area of the forest practice, regardless of the level of potential instability. This protocol does achieve a random and unbiased sample of the population, but over the course of the three years examined in this study only two reported landslides occurred at a compliance monitoring location. This limits the extent to which landslides can be examined with respect to known variables such as the unstable slopes compliance rate and exactly what human activities occurred that could have influenced the slide.

Adjusting the sampling method for unstable slopes to focus on areas identified as having higher mass wasting potential, slopes at or greater than 65%, and primary soil composition of either volcanic ash or glacial deposits could be beneficial for two main reasons. The first is that focusing unstable slopes compliance monitoring of forest practices conducted in these identified areas would likely increase the number of intersections with reported landslides. This could aid in determining how effective current unstable slopes rules are at not increasing the rate of landslides beyond a natural rate by providing a greater number of sites to examine where landslides occurred where annual compliance rates are known. If site specific compliance data were also available this could aid in determining if any violations of unstable slopes rules may have influenced the landslide. Similarly, if site specific compliance was reported and all prescriptions were compliant at a high percentage of monitoring locations where landslides occurred, then that could indicate that current regulations may not be as effective as intended or mitigate for all impacts. The two reported landslides identified in this study that occurred at a compliance monitoring location did not equate to a big enough sample size to answer these points.

The second primary benefit of having a more selective unstable slopes compliance monitoring sample would be a greater chance at identifying high risk landslide hazards before they potentially impact public safety or natural resources. The prescriptions compliance monitoring evaluates includes key safety and resource protection points to include whether or not all potentially unstable features in and around the activity area were identified, if harvest occurred in no-cut buffers for potentially unstable features, and if all identified mitigation measures were followed [Table 1]. Compliance monitoring in areas where landslides are more common would identify any deficiencies in the evaluated prescriptions; this in turn could allow for appropriate mitigation to be applied if the Forest Practices Geologist and Forest Practices Forester, who is also an enforcement officer, deem it necessary to protect public safety and resources. This has the potential to decrease the number of human influenced landslides in forestland by focusing compliance where reported slides have most frequently occurred over the last four years of reported landslides evaluated in this study.

Another avenue for further research on this topic could be investigating the effects of climate change in Western Washington on landslide susceptibility in conjunction with compliance rates for unstable slopes. Climate data from the National Oceanic and Atmospheric Administration suggests a trend in the Pacific Northwest towards winters with heavier rainfall and drier summers. This has the potential to increase unstable feature activation both through more groundwater infiltration in the winter and drought stress in the summer on trees aiding in stabilization of shallow unstable features (Gariano & Guzzetti, 2016; Iida, 2004). Researching long-term trends in Western Washington weather patterns compared to reported landslides and unstable slopes compliance rates could provide valuable insight into the efficacy of current regulations in diminishing human influences on mass wasting events in a changing climate. In addition to the study conducted in this thesis, these areas for potential research and policy improvements would likely require the continued collection of valuable unstable slopes compliance monitoring data and landslide reporting to achieve conclusive results that could aid in management decisions protecting public safety and the unique natural resources found in Washington.

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