CHEHALIS SLOUGHS WATERSHED

LANDSLIDE HAZARD
ZONATION PROJECT

Grays Harbor County, Washington

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Adaptive Management Program
in coordination with the
Washington State Division of
Geology and Earth Resources

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1.0 Project Summary

The Chehalis Sloughs watershed administrative unit (WAU) covers 22,516 acres located in Grays Harbor County, western Washington. Seven hundred and forty seven landslides encompassing 1,478 acres were mapped for this study using aerial photos, limited field review, and some LiDAR (light detection and radar) imaging. Twelve mass wasting landforms were created and assigned slope stability hazard ratings from low to very high. Three of the landforms (Flats, Ridges and Noses, and Low Gradient Hills) have a low hazard rating; two landforms (River Terrace Margin and Meander Bends & Overbank Deposits) have a high hazard rating; and seven landforms (Inner Gorges, Bedrock Hollows, Active Scarps of Deep-seated Landslides (DSLS), Non-rule Identified DSLS Toes, Non-rule Identified Inner Gorges, Steep Gradient Hillslopes and Moderated Gradient Hillslopes) are identified as very high hazard. Hazard ratings are based on landslide history as delineated in the Washington State Landslide Hazard Zonation Project Protocol (Table 1).

Land-form number	Name of landform	Landform slope stability hazard rating	Slope of land-form	Total area of landform in acres	No. of delivering landslides in landform	Comment
#1	Inner Gorges	Very High	>70%	265	78	Rule identified feature
#2	Bedrock Hollows	Very High	>70%	113	36	Rule identified feature
#4	River Terrace Margin	High	>30%	521	20	Forest Practice Board Manual
#7	Active Scarps of Deep-seated landslides	Very High	>30%	204	29	Unique feature
#8	Non-rule Identified Deep-seated Landslide Toes	Very High	>25%	24	3	Rule identified feature (slope criteria modified)
#9	Meander Bends & Overbank Deposits	High	>11%	920	37	Rule identified feature
#10	Non-rule Identified Inner Gorges	Very High	40-70%	557	117	Unique feature
#11	Steep Gradient Hillslopes	Very High	>60%	363	63	Unique feature
#12	Moderate Gradient Hillslopes	Very High	41-60%	1,823	119	Unique feature
#14	Flats	Low	<10%	11,882	0	Protocol
#15	Ridge Tops and Noses	Low	<10%	389	0	Protocol
#16	Low Gradient Hillslopes	Low	11-40%	5,455	56	Protocol
	Totals			22,516	558	

Table 1. Summary of the twelve landforms mapped in the Chehalis Sloughs watershed.

2.0 Introduction

The Chehalis Sloughs watershed is located in central western Washington and covers 22,516 acres on the eastern edge of Grays Harbor. The WAU extends from the east side of Aberdeen and includes a portion of South Aberdeen, Cosmopolis, and Central Park (Figure 1).

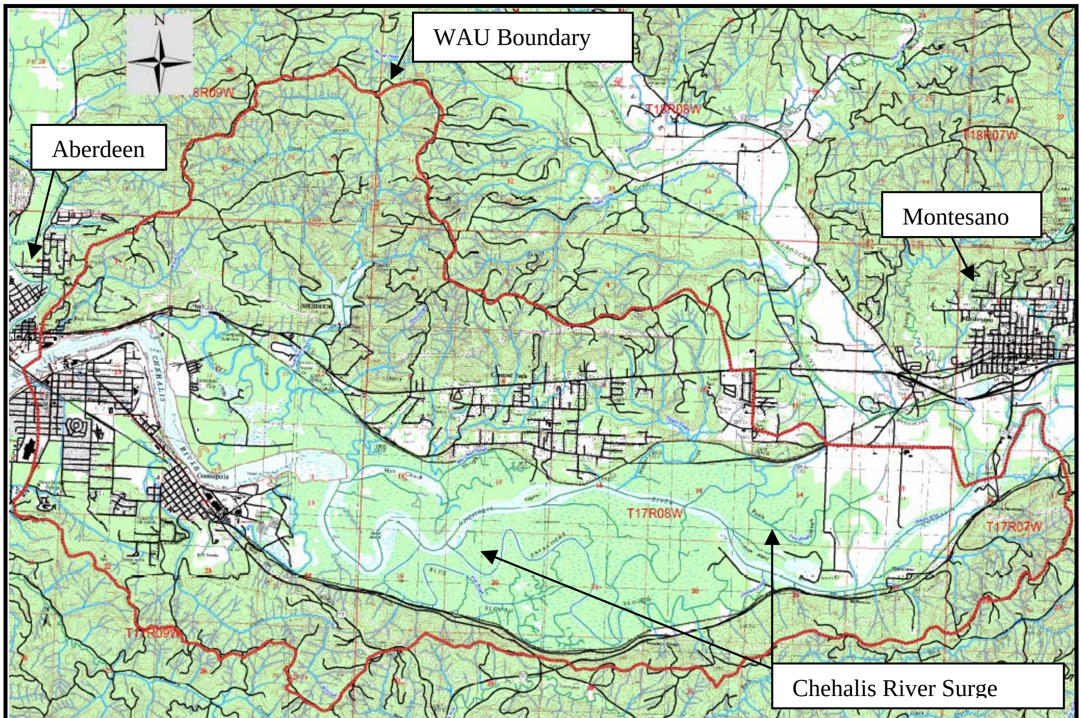

Figure 1. Chehalis Sloughs watershed (WAU) includes the surge plain just east of Aberdeen and Grays Harbor. WAU boundary outlined in red.

Aberdeen was settled in 1884 with logging as the primary industry. The Chehalis River served as a transportation route, connecting Aberdeen to cities to the east such as Montesano (there were no roads from Aberdeen to Montesano during the late 1800's). Logging railroads were used to transport logs to the river then to mills. The Lake Aberdeen B-line to the north and the Melbourne (Weyerhaeuser A-line) to the south were the primary rail lines. The Melbourne A-line is an example of the remnants of the Clemons Logging Company rail line. Just south of the WAU is the original logging site that became the first tree farm in Washington in 1941.

The majority of the Chehalis Sloughs watershed is in private ownership, much of it owned and managed as timberland by the following commercial private timber owners: Weyerhaeuser Company, Rayonier Timber Company, City of Aberdeen, and numerous small forest landowners. The Washington State Departments of Fish and Wildlife operates a steelhead hatchery in Lake Aberdeen and Department of Natural Resources (DNR) manages lands within the watershed including the Chehalis River Surge Plain Natural Area Preserve (NAP). All areas in the watershed were included in this study regardless of ownership.

Forests within the Chehalis Sloughs WAU originally consisted of old growth spruce, cedar, and fir (Gannett, 1902). Today remnants of old growth remain along the surge plain due to selective cutting. These remaining old growth areas are unlikely to be harvested under current riparian management guidelines.

Past harvest patterns were driven by topography, with lower elevations along the Chehalis River harvested first. Rivers and sloughs were used as transportation routes for logs. The Classification of Lands map of Washington (1902) has the WAU mapped as almost entirely cut, with exception of the higher elevation areas on the northern portion of the watershed around Lake Aberdeen and the southeast portion which was described as covered in timber ranging between 10,000 to 25,000 board feet per acre (Plummer, 1902).

Development in and around the Chehalis Sloughs WAU also includes railroad lines, most of which were built for transporting logs to the Chehalis River. Some of these lines, for example the one on the north side of the river, are still in use, but many others have been abandoned. In some places, such as along the south side of the Chehalis River, pilings are all that remain of the former tracks. Map A-2 (landforms) shows the locations and names of all known rail lines. It was common practice to use former railroad grades as road locations and in some cases this was done without first removing all wood debris (e.g., railroad ties). This has resulted in an increased likelihood of slope failures. Previous watershed analysis studies have attempted to address the risk of landslides along former railroad grades, but the LHZ Project has utilized new methods that may provide a better indication of the risk of such failures.

3.0 Topography and Climate

Elevations in the Chehalis Sloughs WAU range from sea level along the western edge where the Chehalis River drains into Grays Harbor to approximately 730 ft along the ridge located in the southeastern portion of the WAU.

The Chehalis Sloughs WAU lies to the east of Aberdeen. It is drained by the Chehalis River, which runs westward through the center of the WAU and drains into Grays Harbor. The WAU also includes Blue Slough and Preachers Slough along the south and Elliot Slough, Higgins Slough, and Peels Slough on the north side of the floodplain.

Van Winkle Creek flows southerly into Lake Aberdeen, which was formed by damming the creek and from there continues to Elliot Slough. The lake was created as a recreation area and is also the site of a Washington State Fish and Wildlife steelhead hatchery. Additionally, the Aberdeen industrial water supply is transported to the lake through an aqueduct that brings water from the Wynoochee River and continues on to its customers including the pulp mills in Cosmopolis and South Aberdeen.

Average annual precipitation at the Aberdeen gauging station #45008 is approximately 84 inches and temperature data are as follows; 58ºF average maximum and 43ºF average minimum (Western Regional Climate Center). The WAU occasionally experiences snow, but rain-on-snow events are rare. No surface water gauging station locations exist on the lower Chehalis River, but precipitation data from the Aberdeen gauging station #45008 indicate that stream flow peaks usually occur in late fall to late winter. Total precipitation for the calendar year (Figure 2) has exceeded 100 inches eight times since record keeping began in 1931 (1931, 1932, 1933, 1937, 1983, 1990, 1997, 1999).

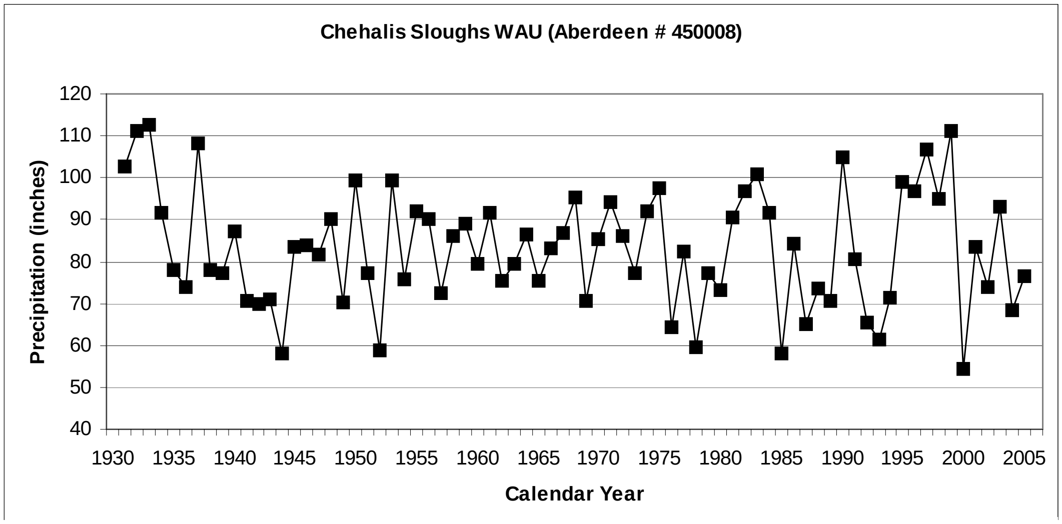

Figure 2. Annual precipitation data 1931-2005 (based on calendar year January to December) at the Aberdeen gauging station (Western Regional Climate Center). No data points are plotted for months in which there are more than 26 days of missing data.

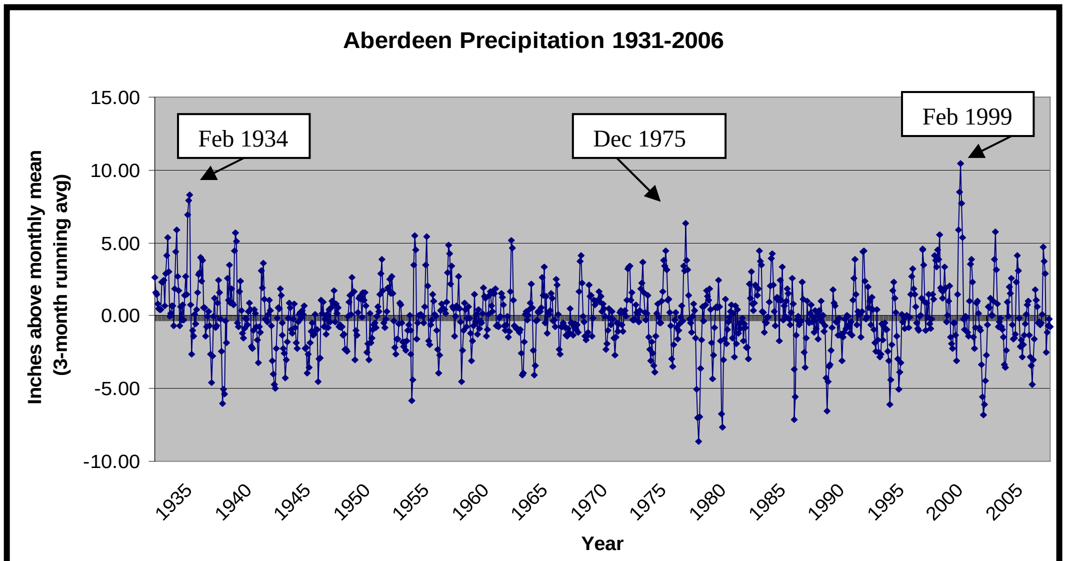

Figure 3. Three month running average of precipitation recorded above the monthly mean from the Aberdeen gauging station from 1931 to 2006.

It is well established that rates of slope failure tend to be higher during and after prolonged periods of above average precipitation (Gerstel and others, 1997; Badger, 1997; Shipman, 2001). Annual precipitation records (Figure 2) provide limited insight into the role of precipitation in slope failure as they do not convey how rainfall was distributed over the year. A more meaningful analysis of rainfall intensity is provided by looking at monthly rainfall totals, expressed in inches above the monthly average. To aid in recognition of time intervals when there were multiple consecutive months with above average precipitation, the data is presented in three month running averages (Figure 3). Examination of Figure 3 shows that the late 1990's had multiple years in a row with annual precipitation totals well above the annual average.

4.0 Geology

The majority of the Chehalis Sloughs WAU is underlain by Tertiary marine sediments and volcanics. The sandstone and siltstone bedrock is primarily Lincoln Creek Formation at lower elevations, and Astoria and Montesano Formations at higher elevations except where formations are folded (Bigelow, 1987; Logan, 1987; Walsh and others, 1987). Unconformities are found between each of these formations as well as folding and faulting (Rau, 1966; Bigelow, 1987; Logan, 1987, 2003). The Lincoln Creek and Astoria Formations are tuffaceous marine siltstones and sandstone; both are prone to rapid weathering, a situation that is exacerbated by the high annual precipitation (Gerstel and Badger, 2002; 2003). Although the WAU remained for the most part unglaciated during the last Ice Age, there is a small unit of Quaternary till (alpine) exposed in the southwest area and older till is found just north of the Chehalis River surge plain (Logan, 1987; 2003). Due to the lack of glaciation, much of this WAU is more susceptible to landsliding (Thorsen, 1989).

Folding and faulting of rock units within the WAU is a result of plate convergence along the continental margin. Among the more prominent folds are double syncline-anticlines pairs located to the north of Aberdeen and to the south of the Chehalis River near Melbourne (Figure 4) (Logan, 1987, 2003; Walsh and others, 1987; Snavely and Wells, 1991; Schuster, 2005). This folding, combined with the presence of easily weathered "bad actor" bedrock units, results in a greater possibility of slope failure as the map below shows a syncline with a large landslide area (Qls) along the south of the Chehalis River (Figure 4).

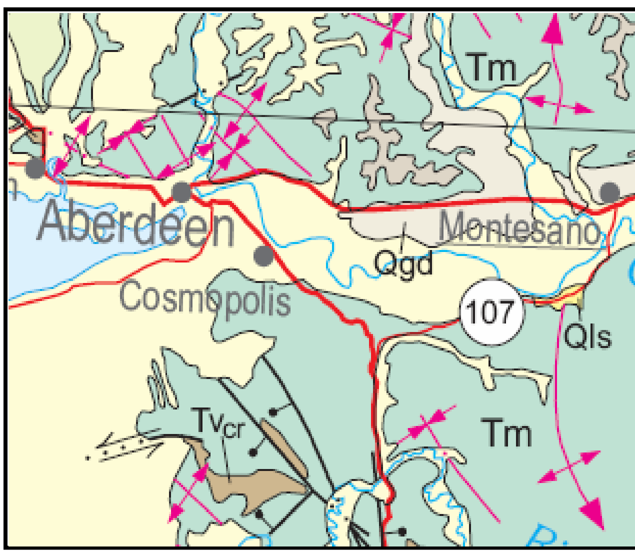

Figure 4. The Chehalis Sloughs WAU has experienced tectonic activity that resulted in much folding of marine sediments (Schuster, 2005). Pink Lines with arrows pointing toward the lines are synclines; lines with arrows pointing away from the lines are anticlines. The area northeast of Aberdeen along Highway 12 is known locally as the "Aberdeen Bluffs" and has failed multiple times due to the

5.0 Previous Investigations

Although no comprehensive landslide studies have been conducted within the Chehalis Sloughs WAU the Washington State Department of Transportation (DOT) has begun compiling a state-wide unstable slopes inventory. Included in this database are landslides, debris flows, erosional features and areas of settling ground that may pose a risk to state managed roads. Within the Chehalis Sloughs WAU the DOT inventory currently identifies seven areas of risk along Highway 12, fourteen along Highway 101, and ten along Highway 107. Some landslides that result in road closures are classified as emergencies and are mitigated promptly prior to being added to the database. In addition to the DOT database, descriptions and analysis are available for two individual landslides, one on the western side of the watershed on the north side of Highway 12 and the other a 2006 landslide that occurred on commercial forest land along Highway 107.

<u>Highway 12</u>
On 29 December 1996 a slope failure occurred on the north side of Highway 12, in an area on the east side of Aberdeen known as the Aberdeen bluffs (Badger 2002). The failure measured 400 ft long by 130 high by 70 ft thick. This slope had previously failed in 1994 after the completion of the road excavation project. Proximity to large-scale folds (which are accompanied by faulting), the weak, incompetent nature of the bedrock (sandstone and siltstone), and high precipitation during the preceding month (> 31 inches) contributed to the 1996 failure. Mitigation measures included installing steeply inclined drains which have lowered ground water levels approximately 19 ft. Water levels now appear to be static implying that pore water is not responding to rainfall (Badger, 1997; 2002). This slope continues to have small, minor landslides that terminate in the highway ditch.

<u>Highway 107</u>
A Landslide Technology (a division of Cornforth Consultants) report dated April 2006 for DOT was specific to the Highway 107 landslide between milepost 4 and 5 near Montesano, Grays Harbor County. This landslide occurred in January 2006 moving the highway approximately 15 feet north toward the Chehalis River. This landslide is located above an outside meander bend of the river and is located within the middle of a much older landslide. Orthophotos flown for the Olympic Region (OLC-QT 2005) were taken in June 2005 and show the recently (spring time?) harvested area. Tension cracks or suspicious depressions can be seen adjacent to the logging road (Figure 5). Map A-1 show dormant indistinct and active recent landslides along Highway 107. These landslides are drawn within the River Terrace Margin Landform as shown on Map A-2. Dormant indistinct deep-seated landslide #912 is shown on Figure 5 as a long dashed line and the active recent deep-seated landslide #26 (January 2006 landslide mentioned above) is shown within #912 with a dotted line.

6.0 Summary of Landslide Inventory

The Chehalis Sloughs WAU evaluation consists of a representative sample of 747 mass-wasting features inventoried from aerial photography, minimal coverage of LiDAR imagery, and field investigations (Form A-1). Landslides identified during this mass wasting assessment include 78% mapped as shallow undifferentiated failures, 2% were debris flows, 7% were debris slides/avalanches and topples, and 13% were deep-seated landslides (Table 2). The resulting mass wasting coverage is displayed as Map A-1. Pertinent attributes of individual features were recorded on data sheets and are included in this report as Appendix A, Form A-1.

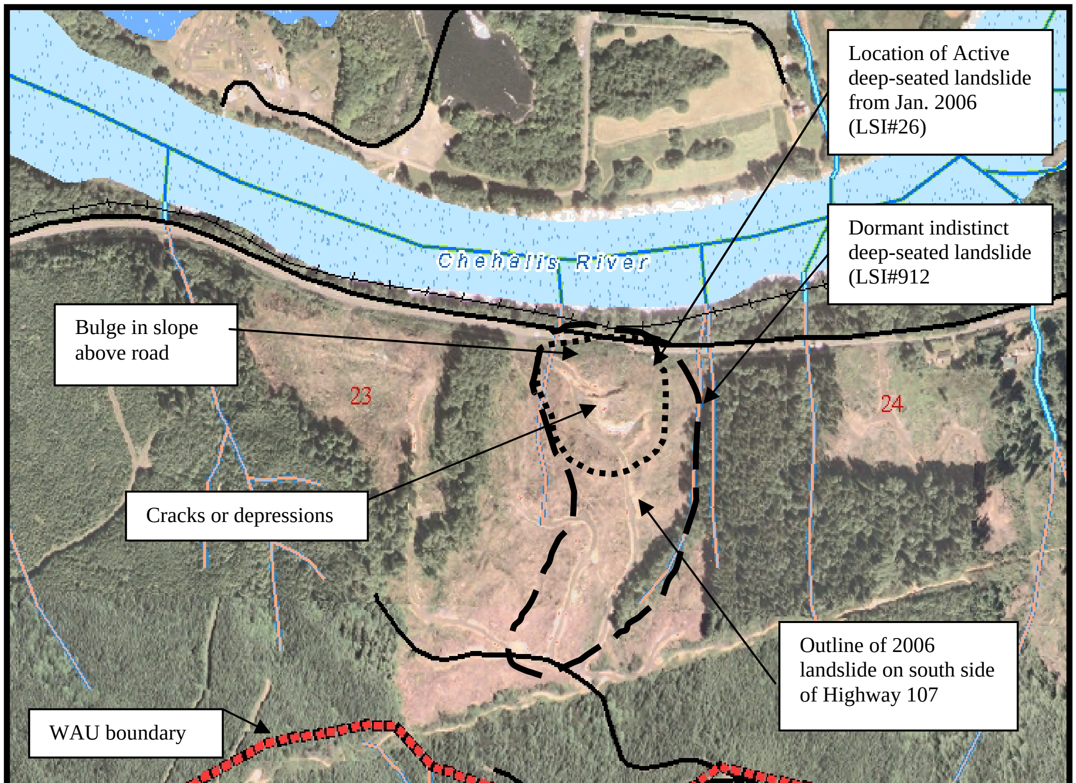

Figure 5. Highway 107 landslide orthophoto taken in June 2005 prior to recent landslide activity. Note bulge just south of road surface within the dashed polygons.

Based on landslide mapping and land use associated with the landslides, it was found that approximately 47% of the inventoried mass wasting features was located in sub-mature timber (15-50 years old). Land use was determined for each feature (Appendix B, Form A-3).

Mass Wasting Type	Number of Mass Wasting Features Mapped	Area (acres) of Mass Wasting Features	Percentage of Total Landslides
Shallow undifferentiated landslides	585	137	78%
Debris flows	11	6	2%
Debris slide/avalanche	52	25	7%
Deep-seated landslides	99	1310	13%
Total	747	1478	100%

Table 2. Summary of the type and number of LHZ Protocol-specified mass-wasting features mapped in the Chehalis Sloughs WAU.

7.0 Landforms

Distribution of the twelve landform units identified in the Chehalis Sloughs WAU study area is shown on Map A-2 and described in Appendix C, Form A-2. These units represent areas having similar mass wasting potential, potential to deliver to public resources, and/or potential to impact public safety. Mass wasting potential is based primarily on landslide process, failure density, lithology, geomorphology, hydrogeology, and topography. The following subsections briefly describe the characteristics of each landform with additional information provided in Appendix C. Landform numbers here match those listed in the Landslide Inventory, Appendix A, and Form A-1. Not all rule-identified landforms occur in a given watershed and therefore the identifying numbers of landforms in any given watershed may not be listed consecutively. Landslide hazard ratings have been summarized on Form A-4, Appendix D.

7.1 LANDFORM #1: Inner Gorges – Rule-identified high mass wasting potential and high delivery potential features. Inner gorges are present as both asymmetrical and symmetrical forms and may be intermittent in lateral extent. Slopes are generally greater than 70%, although failing gorge walls have been observed on slopes of 65%. Shallow and deep-seated landslides are commonly located along the gorge walls. Debris-filled channel bottoms yield useful evidence (alder trees can be cut to determine post-landslide minimum age of deposit in channel) for approximate age determination of slide activity. Inner gorges are sensitive to both roads and harvest. Eighty-nine percent of the landslides in this landform were shallow undifferentiated landslides.

7.2 LANDFORM #2: Bedrock Hollows – Rule-identified high mass wasting and high delivery potential features. Hollows can be long, pointed and elliptical, round, or inverted spoon-shaped features. These features occur primarily on convergent slopes but can also be found on planar slopes. They are often found upgradient from inner gorges and non-rule identified inner gorges. Field-observed bedrock hollow failures were observed in this watershed to occur on ~60% slopes. Ninety percent of the landslides in this landform were shallow undifferentiated landslides. Bedrock hollows were observed filled with debris and those that had evacuated showed thin soils draping weakly cemented bedrock.

7.3 LANDFORM #4: River Terrace Margin – High mass wasting and delivery potential. This landform responds similarly to terrace faces. The current river, carved by glacial meltwaters, is undersized for its floodplain. After the meltwaters receded, it is possible the terrace faces were typical planar-type faces, which have since experienced extensive landsliding and erosion. The weak nature of the marine sedimentary bedrock, heavy precipitation, and stream action had all contributed to instability and erosion of the terrace margins. The Chehalis River often undercuts the toes of slopes which serve to reactivate landsliding within the toes of dormant and dormant-indistinct deep-seated landslides along the southern side of the floodplain. Regardless of slope gradient, landslides have occurred above and below road cuts along Highways 101 and 107. Road construction may have increased the frequency of slope failures within this landform.

7.4 LANDFORM #7: Active Scarps of Deep-seated Landslides – Very high mass wasting and delivery potential. This landform is composed of previously failed deep-seated landslide head and interior scarps in which slopes are mostly steep (>65%), but can be as gentle as 30% (DEM derived, and underestimated). Seventy-five percent of the secondary landslides consist of shallow landslides, primarily shallow undifferentiated.

7.5 LANDFORM #8: Non-rule Identified Deep-seated Landslide Toes – Very high mass wasting and delivery potential. This landform includes toes of deep-seated landslides that are stream adjacent and have high potential for delivery. Shallow and small deep-seated landslides were observed in the field along extended reaches of shoreline. Lake Aberdeen was created by the damming of Van Winkle Creek. Hydrostatic liquefaction caused by pore water pressure within the weak marine sedimentary bedrock loosens material along the slopes creating unstable conditions leading to massive slumping of the slopes. The lower stretches of the slopes into the lake are now continually saturated, increasing their instability. Not all deep-seated landslide toes have been mapped within the WAU. All toes should be field reviewed, especially on slopes adjacent to Lake Aberdeen due to project limitations of field verifying along the shore of the lake.

7.6 LANDFORM #9: Meander Bends/Overbank Deposits of Chehalis Surge Plain (Figure 6) – Rule-identified and high mass wasting and high delivery potential features. Alluvium found along the Chehalis River surge plain is highly susceptible to landsliding. Ninety-seven percent of the landslides are shallow landslides and are failing along the outer edges of the meander bends due to the daily rise and fall of the tides, which affects pore water pressure of the slopes adjacent to the river. Landslide debris delivers directly to the Chehalis River.

Figure 6. Photo taken of the east end of the WAU showing a meander bend of the Chehalis River. Montesano is in the background.

7.7 LANDFORM #10: Non-rule Identified Inner Gorges – Very high mass wasting and delivery potential features. These features contain DEM slopes between 41% and 60% with convergent asymmetrical and symmetrical inner gorge characteristics. Slopes were mapped with computer generated DEM slopes (41%-60%) which are typically underrepresented. These features are present as both asymmetrical and symmetrical inner gorges that are often intermittent in lateral extent. Many of these features were field identified as having steeper slopes and re-mapped as rule-identified inner gorges. The remaining landform #10 features may also be rule-identified and should be field reviewed. Ninety-seven percent of the landslides within this landform occured as shallow landslides located along the gorge walls.

7.8 LANDFORM #11: Steep Gradient Hillslopes (>60%) – Very high mass wasting and delivery potential features. These steep slopes are found throughout the watershed and often adjoin inner gorges and bedrock hollows. This landform is found throughout the watershed, as convergent to planar slopes. Ninety-six percent of the landslides within this landform are shallow landslides.

7.6 LANDFORM #12: Moderate Gradient Hillslopes (41-60%) – Very high mass wasting and delivery potential. Computer generated DEM slopes were used to draw this landform and slope angles are typically underrepresented. The weak nature of the marine sedimentary bedrock, folding and faulting within the WAU, and high precipitation values have resulted in landslides occurring on gentle slopes in this landform. Deep-seated landslides often move as earthflows in their slow down slope motion and subdued irregular topography, especially surrounding Lake Aberdeen. A slope adjacent to Lake Aberdeen was measured as 55% and showed slow earthflow movement such as cut stumps moving down slope (Figures 7 a) and b)). Eighty-two percent of the landslides within this landform are shallow landslides.

7.7 LANDFORM #14: Flats – Low mass wasting and delivery potential. Low gradient (0-10%) valley and stream bottoms are generally composed of alluvium, colluvium, soil, glacial, and landslide deposits. Wetlands are included in this landform. This landform contains those areas in and around rivers and streams and is more likely to be the recipient of debris and alluvial deposits rather than erosional processes. Mass wasting on these naturally stable slopes is unlikely but possible due to improper routing of surface waters and the inherently unstable nature of unconsolidated deposits. The till plain north of the Chehalis River surge plain is included in this landform due to its low gradient and lack of landslides.

7.8 LANDFORM #15: Ridge Tops and Noses (0-10%) – Low mass wasting and delivery potential. Low gradient (0-10%) areas along the tops of the ridges and along the noses of ridges are included. Landslides have occurred below and outside of some of these low gradient ridge tops but these failures are excluded from this landform.

7.9 LANDFORM #16: Low Gradient Hillslopes (11-40%) – Low mass wasting and delivery potential. Eighty-three percent of the landslides within this landform are shallow landslides, but due to the size of the landform, mass wasting and delivery potential are low. Failures within this landform probably occur on slopes steeper than 40% but inaccuracies in the DEM data preclude identification of steeper slopes. Areas near the mapped slope failures should be field verified by foresters when applications are submitted.

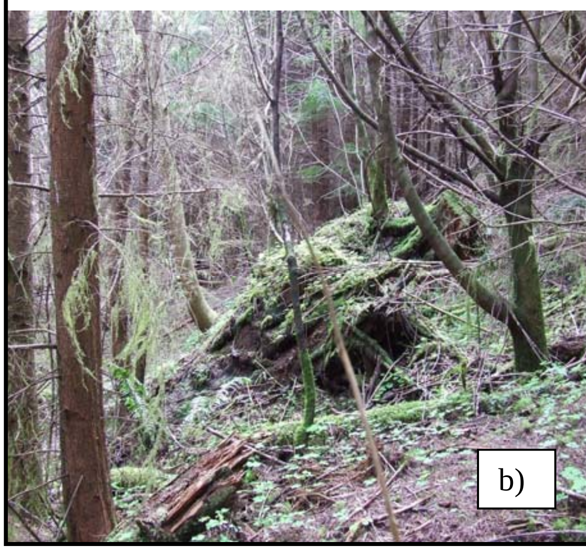

Figure 7 a) and b). Due to slow earth movements, Moderate Gradient Hillslopes (Landform #12) has a very high hazard rating. Photo (a) shows a stump that has been flipped 180° on top of the cut stump. Photo (b) is a stump that has been back rotated ≈45°. These two stumps are located within 50 feet of each other and the slope was measured as 55%. Road above has a crushed culvert that may concentrate water that promotes slope failure.

8.0 Summary of Methods

Landslide inventory - The procedures described below follow, with minor modification, the Landslide Hazard Zonation Protocol version 2.1 dated September 2006 found at: http://www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2.1_final.pdf
Color photo copies of four sets of 1:12,000 aerial photographs from 1962 to 1997 and one set of 1:40,000 photos from 1974 were analyzed with a mirror stereoscope at 3x magnification (Table 3). Original photos were not available for this project. Original photos were photocopied using a color photocopier on cardstock paper. Image quality varied from good to poor. Color ortho-photographs from 2005 were used as a layer during GIS analysis and mapping.

Cadastral and archival topographic maps produced between 1898 and 1902 were used to determine pre-aerial photography logging activities, transportation routes, and areas affected by forest fires. Early General Land Office plat maps are the earliest map source for a portion of the Chehalis Sloughs WAU and were used as a basis for inferring the pre-settlement historical landscape. However, most information about logging activity, transportation routes, and areas affected by forest fires came from the 1902 USGS Forest Service Map of Washington showing

Classification of Lands. These historical maps were scanned and entered into ArcGIS and geo-referenced using a methodology adapted from Collins and others (2003).

Year	Scale	Image	Flight Line Number	Reference Ownership	Comment
1962	1:12,000	Black & White	GH-62 26A-33 to 38B-11	DNR	Complete coverage
1981	1:40,000	Black & White	OSI 81 7-16-109 to 3-20-27	DNR	Complete coverage
1981	1:12,000	Black & White	OL81 1-45-141 to 2-57-53	DNR	Partial coverage
1990	1:12,000	Black & White	OL-90 15-46-115 to 9-57-80	DNR	Complete coverage
1997	1:12,000	Black & White	OL-97 7-45-75 to 9-56-110	DNR	Complete coverage
2005	3 ft pixel*	Color Digital Orthophotos	OLC-QT05 150-010 to 013 160-010 to 015 170-010 to 015 180-010 to 013 190-010 to 012	DNR	Complete coverage in corporate geo-database

Table 3. Photocopies of aerial photographs used in this study.
* Source photography was flown at a scale of 1:32,000.

Slope failures observed on the stereo photocopies were classified and catalogued according to the mass wasting feature type. For the purposes of this analysis, slopes that failed below rooting depth are categorized as deep-seated landslides (Washington Forest Practices Board, 2004); all remaining landslides are classified as shallow. The mass wasting feature types include shallow-undifferentiated landslides, debris flows, debris slides, topples, and avalanches, and deep-seated landslides.

Mapped landslides were ranked according to their relative level of certainty as definite, probable, or questionable. Definite landslides are characterized by some combination of distinct head scarps, lateral margins, scoured run-outs, over-steepened toes, obvious deposits with hummocky topography, or vegetation patterns that suggest landslide disturbance. Probable landslides are those whose features were more subdued or concealed by vegetation than those mentioned above could not be identified with the same level of certainty. Questionable landslides are features that resemble degraded landslides but could have been formed by non-mass wasting processes (following Wieczorek, 1984). Most landslides were mapped from air photos; however some that were identified in the field were not evident on the photos, mostly in areas of heavy canopy. Many of these field identified landslides postdated the most recent photo set.

Following stereo air photo analysis, all observed landslides were mapped directly into GIS by “heads-up” digitization of landslides into a GIS map. The final map (Map A-1) also displays these data layers: streams, roads, townships, geology, and a LiDAR digital elevation model with derived contours (where available). The landslides mapped on A-1 are also itemized in Appendix A - Landslide Inventory.

Typically, DEM-derived slope gradients are underestimated by at least 10% relative to field-measured gradients (Dragovich and others, 1993), and more so on smaller features that are smoothed over by the DEM's coarse resolution. Based on limited comparisons between the DEM and field measurements, gradients in the field may be steeper than those shown on Landform Map A-2. It should be emphasized that all slope gradient estimates presented in this report are likely minimum values.

LiDAR from 2002 was available for a small portion of the watershed that includes the Chehalis River flood plain and small areas of upland slopes. Maximum resolution of the LiDAR derived map base is approximately 3 meters (~9 feet).

Slope gradients for shallow landslides were determined by calculating the maximum 10 meter DEM-derived slope angle within each landslide initiation polygon. For deep-seated landslides, the average slope angle over the entire landslide polygon was calculated. Bilderback (2006) found that using the average slope gradient for deep-seated landslides provides the quickest and most reasonable representation of the pre-failure slope surface compared to other GIS slope measurement methods.

<u>Mass wasting map units</u> – As part of an LHZ project, landforms derived from the landslide inventory and the physical attributes of the landscape where the landslides occurred are mapped. The landforms are intended to help in screening potential forest practices within the WAU that pose hazards for mass wasting.

The aerial photograph survey was also used to determine land use and landforms. Low hazard landforms (Flats, Ridge Tops and Noses, and Low Gradient Hills) were delineated first according to the LHZ Protocol by using a slope map with standardized slope angles. Following this rule-identified landforms were delineated. The remainder of the WAU was divided into analyst-described landforms. These landforms were developed from on the physical attributes of the landscape where the landslides occurred. A combination of slope gradient and elevation data (derived from LiDAR), slope convergence data (derived from the DNR SLPSTAB model based on a slope morphology model (Shaw and Johnson, 1995)), geologic data (from USGS 1:100,000 geologic maps), and precipitation data aided in the delineation of these landforms.

9.0 Hazard Ratings

Each landform identified on Map A-2 and described in Appendix C was assigned an overall Hazard Rating based on landslide frequency rate (LFR) and a landslide area rate for delivery (LAR). The hazard rating (low, moderate, or high) is then assigned as called for by the LHZ Protocol [www.dnr.wa.gov/forestpractices/lhzproject/lhz_protocol_v2.1_final.pdf]. Hazard ratings for mass-wasting landforms were determined by the following: 1) rule-identified status (WAC 222-16-050), 2) the LFR and the LAR, 3) in rare occasions, the professional judgment of the analyst may be used in lieu of the LFR and LAR matrices, or, for deep-seated landslides, 4) an interpretation of deep-seated landslide hazard. The Landslide Area Rate for Delivery is the area of delivering landslides normalized to the period of study and the area of each landform. The resulting values are multiplied by one million for easier interpretation. Limited application suggests that Landslide Area Rates for Delivery less than 76 are low hazard, rates of 76 to 150 are moderate hazard, rates of 151 to 799 are high hazard, and rates greater than 799 are very high hazard (Lingley, 2004). Note that higher Landslide Area Rates for Delivery can be achieved by reducing the area of the Landform. While this may appear to be 'data gerrymandering', it helps limit the area of high-hazard landforms to those areas that are actually demonstrated to have high hazard. The Landslide Frequency Rate is calculated similarly; however the *number* of delivering landslide is used instead of the *area* of delivering landslides. Deep-seated landslides are not included in the calculations for Form A-4. As of the writing of this report, the qualitative rating system below is used (Table 3). Landform hazard ratings in the Chehalis Sloughs WAU are summarized in Appendix D, Form A-4.

Qualitative Ratings	Landslide Frequency Rate (LFR)	Landslide Area Rate for Delivery (LAR)
Low	< 100	<76
Moderate	100 to 199	76 to 150
High	200 to 999	151 to 799
Very High	>999	>799

Table 4: Qualitative rating system for the LFR and LAR.

10.0 Confidence in Work Products

The confidence in this mass wasting assessment is moderate based on a range of photocopy quality and coverage, and field observation. This rating is based on the Landslide Hazard Zonation Project design to provide a watershed administrative unit overview of slope stability in a timely manner with minimal field verification. As a consequence of the project design, fieldwork and the number of aerial photograph sets examined are held to reasonable minimums. Omissions will be present due to the limited field verification of individual features; particularly in heavy canopy forested areas.

It is critical for the reader to understand that while these decisions are sufficient to characterize aspects of the slope failure as functions of forest management, <u>this assessment would be entirely insufficient and misleading if it is used as a stand alone document for protecting private and public resources or for land use planning.</u> As this is only a reconnaissance study, some landslides may have been accidentally omitted and some benign features may be improperly mapped as landslides.

In addition, there are some typical sources of systematic error that reduce the confidence in the work products of this analysis, those being omission, misinterpretation, accuracy, and precision. Misinterpretation may occur when a mass-wasting feature is identified but incorrectly classified or data are transposed, and where unrecognized software/file instability occurs. Accuracy involves the degree to which the physical parameters of a mass-wasting feature are correctly measured, and precision describes how variability within an assessment can be controlled when making multiple measurements over varying time and spatial scales. This mass wasting assessment was primarily conducted with color copies of aerial photographs, and as a result, there is a likelihood that errors of omission occurred primarily in areas covered by mature forest canopies, steep north facing slopes always in shadow (Brardinoni and others, 2003). DEM data available for a majority of this watershed was observed to be of a lower resolution and thus, lower utility. However, the author has a moderate level of confidence in the assessment based on good photo coverage, limited LiDAR coverage, and limited field observations.

Because many deep-seated landslide features are quite large, remain heavily vegetated during movement, and may not have obvious scars visible through the vegetation canopy, misinterpretation is more likely. A detailed study in Cowlitz County, Washington, suggests that up to 25 percent of inferred deep-seated landslides identified from aerial photograph analysis are misinterpreted (Wegmann, 2003). In spite of this, confidence in work products related to classification of deep-seated landslide processes in this WAU is high-moderate due to visibility, field verification, and completeness of photo coverage.

11.0 Use of Report

Information was collected and compiled in a manner that was designed to respond to the Critical Questions that are outlined in Section II of the LHZ Protocol, and to direct attention to areas where more detailed analysis is necessary. The objective of the data collection was to generate information sufficient to establish:

- A generalized characterization of mass wasting processes that are active in the WAU;
- Areas of landscape that share similar physical characteristics related to mass-wasting behavior;
- The relative potential for mass wasting to occur among the various landform units.

The purpose of this mass wasting assessment is to identify all areas on private and state land within the Chehalis Sloughs WAU that have a risk of landsliding due to both natural phenomena and to the effects of forest practice activities (logging, roading, thinning, yarding, etc.). All areas and ownerships in the watershed have been included in this study for and is therefore a comprehensive landslide assessment. All lands within the WAU have been divided into mass wasting hazard landforms. Maps of landforms are designed for use by landowners in determining the areas likely to create landslide hazard and by Department of Natural Resources (DNR) staff to identify sites where future forest practice applications (Chapter 222-20 WAC) may require detailed investigation prior to forest practice classification (Chapter 222-16-050 WAC).

This is a reconnaissance survey, and its relatively broad resolution must be considered when using this document and its accompanying maps. Moreover, the survey was conducted within a constrained timeline that was budgeted to produce a statewide unstable slopes screening tool as quickly as possible. Thus, the landslide inventory presented in this report (Map A1 and Form A1) is intended to be a representative but not an exhaustive inventory.

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