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Case No. 51458-3-II

**IN THE COURT OF APPEALS
OF THE STATE OF WASHINGTON
DIVISION II**

FUTUREWISE and PILCHUCK AUDUBON SOCIETY,

Petitioners,

v.

SNOHOMISH COUNTY and
THE GROWTH MANAGEMENT HEARINGS BOARD,

Respondents.

BRIEF OF PETITIONERS FUTUREWISE AND PILCHUCK AUDUBON SOCIETY

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I. INTRODUCTION

The March 22, 2014, Oso landslide "claimed the lives of 43 people, making it the deadliest landslide event in United States history."[1] Unfortunately, Snohomish County did not fully incorporate the lessons of the Oso tragedy into the landslide hazard regulations adopted in 2015.[2] The one purpose of this appeal is to prevent another Oso tragedy by requiring Snohomish County to adopt geological hazard regulations that comply with the Growth Management Act (GMA).

The second purpose of this appeal is to require Snohomish County to comply with the GMA requirements to manage critical aquifer recharge areas to prevent excessive ground water pumping and protect instream flows. Snohomish County did not adopt regulations to manage ground water as part of 2015 critical areas regulation update in violation of the GMA.

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[1] Administrative Record page number (AR) 001162, *The 22 March 2014 Oso Landslide, Snohomish County, Washington* p. 1 (Geotechnical Extreme Events Reconnaissance (GEER-036): July 22, 2014) hereinafter *GEER-036*. If the American territories are included, then the Oso landslide is the second deadliest landslide in American history. AR 001448, R.M. lverson *et. al. Landslide mobility and hazards: implications of the Oso disaster* 412 EARTH AND PLANETARY SCIENCE LETTERS 197, 198 (2015). Cited excerpts of *GEER-036* are in Appendix B of this Petitioners' Brief.

[2] AR 000055 – 71, Ord. No. 15-034 pp. 47 – 63.

II. ASSIGNMENTS OF ERROR, ISSUES, AND BRIEF ANSWERS

Assignment of Error 1: The Growth Management Hearings Board (Board) erred in failing to decide Futurewise's and the Pilchuck Audubon Society's (Futurewise) motion to supplement the record.[3]

Issue 1: Did the Board violate RCW 36.70A.290(1) and RCW 34.05.570(3)(f) when it failed to decide Futurewise's motion to supplement the record? Yes.

Assignment of Error 2: The Board erred in making the finding of fact that "[t]here is no disagreement with the fact the County has designated landslide hazard areas."[4]

Issue 2: Is the Board finding of fact that there was no dispute that the County designated landslide hazard areas inconsistent with the GMA, not supported by substantial evidence, or an erroneous interpretation or application of the GMA? Yes.

Assignment of Error 3: The Board erred in making the finding of fact or conclusion of law that "[l]andslide hazard areas are defined to not only include the potential slide area itself but also 'buffer' areas."[5]

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[3] AR 000350, *Futurewise, Pilchuck Audubon Society, and the Tulalip Tribes v. Snohomish County*, Central Puget Sound Region Growth Management Hearings Board (CPSRGMHB) Case No. 15-3-0012c, Deferring Decision on Motion for Supplementation (Jan. 27, 2016), at 2 of 2 hereinafter Order Deferring Decision.
[4] AR 001818 footnote (fn.) 85, *Futurewise, Pilchuck Audubon Society, and the Tulalip Tribes v. Snohomish County*, CPSRGMHB Case No. 15-3-0012c, Final Decision and Order (Feb. 17, 2017), at 22 of 38 fn. 85. Hereinafter FDO.
[5] AR 001818, FDO, at 22 of 38.

Issue 3: Is the Board's finding of fact or conclusion of law that landslide hazards include buffers not supported by substantial evidence or an erroneous interpretation of the GMA? Yes.

Assignment of Error 4: The Board erred in concluding "the GMA does not include a mandate to protect people and development from critical areas" and that "[p]ublic health and safety concerns lie within the purview of the County's legislative authority" under the GMA.[6]

Issue 4: Are the Board's conclusions that "the GMA does not include a mandate to protect people and development from critical areas" and that "[p]ublic health and safety concerns lie within the purview of the County's legislative authority" an erroneous interpretation or application of the GMA or not support by substantial evidence? Yes.

Assignment of Error 5: The Board erred in failing "to reach the issue of whether or not critical area regulations must be crafted in a manner designed to prevent" tragedies similar to the Oso landslide when the Board concluded that Futurewise "failed to cite any GMA requirement supposedly violated by the County's geologically hazardous area regulations listed in Issue C-1"[7] where Futurewise included the GMA provisions violated in its issue statement and citied to Growth

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[6] AR 001818 – 20, FDO, at 22 – 24 of 38.
[7] AR 001825, FDO, at 29 of 38.

Management Hearings Board (Board) decisions based on the GMA requirements.[8] The Board erred in concluding Futurewise failed to meet its burden of proof.[9]

Issue 5: Did the Board erroneously interpret or apply the GMA, the Board's rules of practice and procedure, and the State of Washington Administrative Procedure Act (APA) when it failed to decide Issue C-1 and concluded that Futurewise did not meet its burden of proof and are the Board's conclusions not supported by substantial evidence? Yes.

Assignment of Error 6: The Board erred in concluding that the Snohomish County Code (SCC) provisions to designate and protect geologically hazardous areas complied with the GMA.[10]

Issue 6: Is the Board's conclusion that the amended SCC provisions complied with the GMA requirements to designate and protect geologically hazardous areas not supported by substantial evidence or an erroneous interpretation or application of the GMA? Yes.

Assignment of Error 7: The Board erred in concluding that "[w]hile local jurisdictions are now required to address both the legal and actual availability of water for development activity, inclusion of such a

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[8] AR 000863 – 67, Futurewise's and Pilchuck Audubon Society's Petitioners' Prehearing Brief pp. 30 – 34.
[9] AR 001826, FDO, at 30 of 38.
[10] AR 001817 – 20, FDO, at 21 – 24 of 38; AR 001825 – 27, FDO, at 27 – 31 of 38.

requirement within the hydrogeologic report section of the Snohomish County Code protecting [critical aquifer recharge areas] CARAs makes little sense."[11]

Issue 7: Is the Board's conclusion that the CARA regulations comply with the GMA an erroneous interpretation or application or not support by substantial evidence? Yes.

III. FACTS

According to the U.S. Geological Survey (USGS), "[l]andslides, particularly debris flows, have long been a significant cause of damage and destruction to people and property in the Puget Sound region."[12] While the Oso landslide, a debris flow, was the deadliest landside to hit the region, it was not the only deadly landslide in recent years.[13] In 1997, a debris flow landside on Bainbridge Island ran out over a home killing a family of four.[14]

Even though "multiple studies identified the potential for a 'catastrophic' failure affecting human safety and property" at Oso and a landslide occurred in 2006, none of houses at Oso built after the adoption

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[11] AR 001824, FDO, at 28 of 38.
[12] AR 001191, cited excerpts of this USGS report are in Appendix C of this Brief of Petitioners.
[13] AR 001162.
[14] AR 001192.

of Snohomish County's critical areas regulations were reviewed for landslide hazards.[15] As *GEER-036* documented:

> All of the structures affected by the March 2014 landslide were more than 90 m (300 feet) away from the toe of the slope and therefore not subject to land-use restrictions due to landslide hazard (Figure 4.5.1). Several of the building permits issued after the 2006 event did address flood hazards and wetland conservation.[16]

After the 2006 landslide at Oso, Snohomish County failed to change its regulations to address the area's landslide hazards. The new landslide hazard regulations at issue in this appeal also will not prevent another Oso tragedy.

The Oso disaster shows that the counties and cities required by the GMA to adopt critical areas regulations do not respond to natural disasters alone. In addition to the County, fire districts, cities, state agencies, tribes, and federal agencies all had to respond to the Oso tragedy.[17]

IV. STANDARD OF REVIEW

The Washington State Supreme Court has stated the standard of review for appeals of Board decisions:

> ¶ 14 Courts apply the standards of the Administrative Procedure Act [APA], chapter 34.05 RCW, and look directly to the record before the board. *Lewis County*, 157 Wn.2d at 497, 139 P.3d 1096; *Quadrant Corp.*, 154 Wn.2d at 233, 110 P.3d 1132. Specifically, courts review errors of

[15] AR 001172 – 74, *GEER-036* p. 54 – 56.
[16] AR 001174, *GEER-036* p. 56.
[17] AR 000924 & AR 000963 – 71.

> law alleged under RCW 34.05.570(3)(b), (c), and (d) de novo. *Thurston County*, 164 Wn.2d at 341, 190 P.3d 38. Courts review challenges under RCW 34.05.570(3)(e) that an order is not supported by substantial evidence by determining whether there is "'a sufficient quantity of evidence to persuade a fair-minded person of the truth or correctness of the order.'" *Id.* (internal quotation marks omitted) (quoting *City of Redmond v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 136 Wn.2d 38, 46, 959 P.2d 1091 (1998)).[18]

The appellate courts review "the Board's decision, not the decision of the superior court …."[19]

"Under the judicial review provision of the APA, the 'burden of demonstrating the invalidity of [the Board's decision] is on the party asserting the invalidity.'"[20] In this case, Futurewise and the Pilchuck Audubon Society (Futurewise). "Substantial weight is accorded to a board's interpretation of the GMA, but the court is not bound by the board's interpretations."[21] In interpreting the GMA, the courts do not give deference to local government interpretations of the law.[22]

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[18] *Kittitas County v. Eastern Washington Growth Management Hearings Board*, 172 Wn.2d 144, 155, 256 P.3d 1193, 1198 (2011).

[19] *King Cty. v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 142 Wn.2d 543, 553, 14 P.3d 133, 138 (2000).

[20] *Thurston County v. Cooper Point Ass'n.*, 148 Wn.2d 1, 7 – 8, 57 P.3d 1156, 1159 – 60 (2002) citing RCW 34.05.570(1)(a).

[21] *Thurston County v. Western Washington Growth Management Hearings Bd.*, 164 Wn.2d 329, 341, 190 P.3d 38, 44 (2008).

[22] *Kittitas County*, 172 Wn.2d at 156, 256 P.3d at 1199.

On mixed questions of law and fact, the court determines the law independently, and then applies it to the facts as found by the Board.[23] The reviewing court does not weigh the evidence or substitute its view of the facts for that of the Board.[24]

In considering this appeal, it is important to note that appeals by citizens and citizen groups are the mechanism that the Governor and Legislature adopted to enforce the GMA.[25] Unlike some laws, such as Washington's Shoreline Management Act, there is no state agency that reviews and approves or disapproves GMA comprehensive plans and development regulations. The responsibility to appeal noncompliant comprehensive plans and development regulations to the Board is that of citizens and groups such as Futurewise.

V. ARGUMENT

A. The GMA requirements for designating and protecting critical areas

"The GMA directs counties and cities to designate critical areas. RCW 36.70A.170."[26] "'The GMA requires the county to designate and protect

[23] *Thurston County v. Cooper Point Ass'n*, 148 Wn.2d 1, 8, 57 P.3d 1156, 1160 (2002).
[24] *Callecod v. Wash. State Patrol,* 84 Wn. App. 663, 676, 929 P.2d 510, 516 fn. 9 (1997) *review denied Callecod v. Wash. State Patrol*, 132 Wn.2d 1004, 939 P.2d 215 (1997).
[25] *King County v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 138 Wn.2d 161, 175 – 77, 979 P.2d 374, 380 – 82 (1999).
[26] *Ferry Cty. v. Concerned Friends of Ferry Cty.,* 155 Wn.2d 824, 832, 123 P.3d 102, 106 (2005).

all critical areas within its boundaries.' *Stevens County v. Futurewise,* 146 Wn. App. 493, 511, 192 P.3d 1 (2008)."[27] For many critical areas, such as geologically hazardous areas, performance standards are adopted that can be used to identify their location.[28] Others are mapped based on definitions or standards.[29]

Counties and cities must also adopt development regulations to protect critical areas.[30]

> "Critical areas" include "geologically hazardous areas," which are defined as "areas that because of their susceptibility to erosion, sliding, earthquake, or other geological events, are not suited to the sitting of commercial, residential, or industrial development consistent with public health or safety concerns." RCW 36.70A.030(5)(e), (9).[31]

The Washington State Supreme Court defined a standard for critical areas protection as the "no-harm standard," which "in short, protects

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[27] *Ferry Cty. v. Growth Mgmt. Hearings Bd.*, 184 Wn. App. 685, 734, 339 P.3d 478, 500 (2014).

[28] *Friends of Skagit County* (*FOSC), et al. v. Skagit County,* Western Washington Growth Management Hearings Board (WWGMHB) Case No. 96-2-0025, Final Decision and Order (Jan. 3, 1997), at *2, 1997 WL 8935, *1; AR 000070 – 71. Formerly the GMA had three separate regional Growth Management Hearings Boards. In 2010, they were consolidated into a single board. The WWGMHB formerly covered the Western Washington counties and cities that fully planned under the GMA except for King, Kitsap, Pierce, and Snohomish Counties.

[29] *Olympic Stewardship Found. v. W. Washington Growth Mgmt. Hearings Bd.*, 166 Wn. App. 172, 178 – 81, 274 P.3d 1040, 1042 – 44 (2012) *review denied Olympic Stewardship Found. v. W. Washington Growth Mgmt. Hearings Bd.*, 174 Wn.2d 1007, 278 P.3d 1112 (2012).

[30] RCW 36.70A.060(2); *Olympic Stewardship Found.*, 166 Wn. App. at 176, 274 P.3d at 1041.

[31] *Olympic Stewardship Found.*, 166 Wn. App. at 176, 274 P.3d at 1041 – 42 (2012).

critical areas by maintaining existing conditions."[32] The Supreme Court concluded that "under GMA regulations, local governments must either be certain that their critical areas regulations will prevent harm or be prepared to recognize and respond effectively to any unforeseen harm that arises."[33]

"In designating and protecting critical areas under [the GMA], counties and cities *shall include the best available science* in developing policies and development regulations to protect the functions and values of critical areas."[34] As the court of appeals has held, this requires the protection of "… all functions and values."[35] The Washington State Supreme Court wrote that "the GMA does not require the county to follow BAS; rather, it is required to 'include' BAS in its record. RCW 36.70A.172(1). Thus, the county may depart from BAS if it provides a reasoned justification for such a departure."[36] However, if a county departs from best available science, the county must still comply with the requirement to protect critical areas.[37]

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[32] *Swinomish Indian Tribal Cmty. v. Western Washington Growth Mgmt. Hearings Bd.*, 161 Wn.2d 415, 430, 166 P.3d 1198, 1206 (2007).
[33] *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 436, 166 P.3d at 1209.
[34] *Olympic Stewardship Found.*, 166 Wn. App. at 188, 274 P.3d at 1047 citing RCW 36.70A.172(1).
[35] *Whidbey Envtl. Action Network v. Island Cty. (WEAN)*, 122 Wn. App. 156, 175, 93 P.3d 885, 894 (2004) *review denied Whidbey Envtl. Action Network v. Island Cty.*, 153 Wn.2d 1025, 110 P.3d 756 (2005).
[36] *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 430–31, 166 P.3d at 1206.
[37] *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 424 & 434–37, 166 P.3d at 1203 & 1208–09.

The Board has held that the GMA's "directive that local governments are to 'protect' critical areas means that they are to preserve the structure, value and functions of … geologically hazardous areas."[38] The Western Washington Growth Management Hearings Board concluded that "the function and value of a CMZ[, channel migration zone (a type of geologically hazardous area),] is the prospective protection against loss of life and property due to the geomorphic and ecological processes of rivers and streams as they migrate throughout their alluvial valleys and this function and value presently exists."[39]

B. Issue 1: Did the Board violate RCW 36.70A.290(1) and RCW 34.05.570(3)(f) by failing to decide Futurewise's motion to supplement the record? (Assignment of Error 1.)

RCW 36.70A.290(1) requires in relevant part that "[t]he board shall render written decisions articulating the basis for its holdings." RCW 34.05.570(3)(f) requires that "[t]he court shall grant relief from an agency order in an adjudicative proceeding only if it determines that: … (f) The agency has not decided all issues requiring resolution by the agency …" As authorized by the GMA in RCW 36.70A.290(4), Futurewise moved to

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[38] *Pilchuck v. Snohomish County (Pilchuck II)*, CPSGMHB Case No. 95-3-0047c, Final Decision and Order (Dec. 6, 1995), at *17, 1995 WL 903206, at *16 bolded in original. The Central Puget Sound Growth Management Hearings Board (CPSGMHB) formerly heard GMA appeals from King, Kitsap, Pierce, and Snohomish Counties.

[39] *Citizens Protecting Critical Areas v. Jefferson County*, WWGMHB Case No. 08-2-0029c, Final Decision and Order (Nov. 19, 2008), at 2 of 51, 2008 WL 5267906, at *1, *affirmed Olympic Stewardship Found. v. W. Washington Growth Mgmt. Hearings Bd.*, 166 Wn. App. 172, 201, 274 P.3d 1040, 1054 (2012).

supplement the record with a recent peer-reviewed study of the history of landslides in the Oso area.[40] The Board first deferred the decision on the motion[41] and then failed to decide the motion.[42] Futurewise reminded the Board of the deferral in its reply brief.[43]

In the *LIHI* decision, the court of appeals held that in a challenge to a comprehensive plan's compliance with the GMA's housing element requirements that the Board violated the GMA and the APA because the Board did make any findings regarding the City's current needs for affordable housing or how the comprehensive plan "will affect the future availability of affordable housing."[44] The court of appeals wrote that where "the Board presents no basis for its decision, we cannot review its analysis. It has failed to decide all issues requiring resolution as required by RCW 36.70A.290(1) and the APA (specifically RCW 34.05.570(3)(f))."[45]

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[40] AR 000286 – 000330, Futurewise Motion to Supplement the Record pp. 1 – 9 and exhibits.
[41] AR 000350, Order Deferring Decision, at 2 of 2.
[42] AR 001797 – 1834, FDO, at 1 – 38 of 38.
[43] AR 001721 fn. 72, Futurewise's and Pilchuck Audubon Society's Petitioners' Reply Brief p. 15 fn. 72.
[44] *Low Income Hous. Inst. v. City of Lakewood (LIHI)*, 119 Wn. App. 110, 118, 77 P.3d 653, 657 (2003).
[45] *Id.* 119 Wn. App. at 119, 77 P.3d at 657; *accord Suquamish Tribe v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 156 Wn. App. 743, 778, 235 P.3d 812, 831 (2010).

In this case, the Board made no decision and no findings on the motion to supplement the record other than deferring the decision.[46] So like the board in *LIHI*, this Board "failed to decide all issues requiring resolution as required by RCW 36.70A.290(1) and … RCW 34.05.570 (3)(f)."[47] This Court should remand this case back to the Board to decide the motion.[48]

C. Issue 2: Is the Board finding of fact that there was no dispute that the County designated landslide hazard areas inconsistent with the GMA, not supported by substantial evidence, or an erroneous interpretation or application of the GMA? (Assignment of Error 2.)

The Board found that "[t]here is no disagreement with the fact the County has designated landslide hazard areas."[49] But the Board contradicted this finding later in the FDO where the Board wrote that "Futurewise-Pilchuck argues that the discretion granted to the Director [in SCC 30.628.390] somehow conflicts with the County's RCW 36.70A.170(1) requirement to 'designate' critical areas."[50] Futurewise did argue that Snohomish County did not properly designated geologically hazardous areas.[51] Substantive evidence does not support the Board's

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[46] AR 000350, Order Deferring Decision, at 2 of 2; AR 001797 – 1834, FDO, at 1 – 38 of 38.
[47] *Low Income Hous. Inst.*, 119 Wn. App. at 119, 77 P.3d at 657.
[48] *Low Income Hous. Inst.*, 119 Wn. App. at 119, 77 P.3d at 657.
[49] AR 001818, FDO, at 22 of 38 fn. 85.
[50] AR 001826, FDO, at 30 of 38.
[51] AR 000863 & AR 000866 – 68, Futurewise Petitioners' Prehearing Brief p. 30 & pp. 33 – 35.

finding of fact that there is no disagreement on the designation of geologically hazardous areas. This Court should reverse this finding.

D. Issue 3: Is the Board's finding of fact or conclusion of law that landslide hazards include buffers not supported by substantial evidence or an erroneous interpretation of the GMA? (Assignment of Error 3.)

"The GMA directs counties and cities to designate critical areas,"[52] including geologically hazardous areas.[53] "[T]he GMA requires the county to designate and protect all critical areas within its boundaries."[54]

The GMA defines "[g]eologically hazardous areas" as "areas that because of their susceptibility to erosion, sliding, earthquake, or other geological events, are not suited to the siting of commercial, residential, or industrial development consistent with public health or safety concerns."[55] As the Oso landslide so tragically shows, areas on the top and side can fail damaging land and anything on it.[56] The landslide runout areas are also not suited to siting development consistent with public health or safety concerns due to the earth sliding over land, homes, and other buildings. At Oso the landslide ran out for over a mile, sliding through and over homes,

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[52] *Ferry Cty. v. Concerned Friends of Ferry Cty.*, 155 Wn.2d 824, 832, 123 P.3d 102, 106 (2005).
[53] RCW 36.70A.030(5)(e).
[54] *Stevens Cty. v. Futurewise*, 146 Wn. App. 493, 511, 192 P.3d 1, 10 (2008) *review denied Stevens County v. Futurewise*, 165 Wn.2d 1038, 205 P.3d 132 (2009).
[55] RCW 36.70A.030(9).
[56] AR 001177, *GEER-036* p 68.

buildings, and a highway.[57] Other landslides are capable of damaging commercial, residential, or industrial development at both the tops, slides, and toes of slopes due to the earth sliding and other geological events.[58] The areas at the top, toe, and sides of the slope are geological hazards.

SCC 30.91L.040 defines "[l]andslide hazard areas" as

> areas potentially subject to mass earth movement based on a combination of geologic, topographic, and hydrologic factors, with a vertical height of 10 feet or more. These include the following:
>
> (1) Areas of historic landslides as evidenced by landslide deposits, avalanche tracks, and areas susceptible to basal undercutting by streams, rivers or waves;
>
> (2) Areas with slopes steeper than 33 percent which intersect geologic contacts with a relatively permeable sediment overlying a relatively impermeable sediment or bedrock, and which contain springs or ground water seeps;
>
> (3) Areas located in a canyon or an active alluvial fan, susceptible to inundation by debris flows or catastrophic flooding.
>
> For sections 1, 2, and 3 above, the landslide hazard area also includes lands within a distance from the top of the slope equal to the height of the slope or within a distance of the toe of the slope equal to two times the height of the slope. The director may expand the boundary of a landslide hazard area pursuant to 30.628.390 SCC.[59]

So, the areas at the top and toe of the slope are not buffers, they are geologically hazardous areas. SCC 30.91L.040 defines them as landslide

[57] AR 001162 – 62, AR 001180, *GEER-036* pp. 1 – 2, p. 144.
[58] AR 001191 – 92; AR 001734 – 35.
[59] AR 000070 – 71. A diagram defining the parts of a landslide can be found at AR 000911. This diagram is from *The Landslide Handbook.* Cited pages from this document are in Appendix A of this Brief of Petitioners.

hazard areas, a type of geologically hazardous area.[60] County staff agrees they are critical areas.[61] The Board erred in concluding that the top of slope and toe of slope areas were buffers, rather than geologically hazardous areas.[62]

E. Issue 4: Are the Board's conclusions that "the GMA does not include a mandate to protect people and development from critical areas" and that "[p]ublic health and safety concerns lie within the purview of the County's legislative authority" an erroneous interpretation or application of the GMA or not support by substantial evidence? (Assignment of Error 4.)

The Board's conclusion that the critical areas regulations for geologically hazardous areas are not required to protect the health or safety is contrary to the plain language of the GMA.[63] When interpreting the GMA, the Board and the courts "should consider the context of the entire act when interpreting the plain meaning of statutory text[.]"[64] RCW 36.70A.030(9) defines "[g]eologically hazardous areas" to mean "areas that because of their susceptibility to erosion, sliding, earthquake, or other geological events, are not suited to the siting of commercial, residential, or industrial development consistent with public health or safety concerns." RCW 36.70A.170 requires counties and cities to designate these areas.

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[60] AR 000055, Ord. No. 15-034 p. 47 in SCC 30.628.010(1).
[61] AR 001373.
[62] AR 001818, FDO, at 22 of 38.
[63] AR 001818 – 20, FDO, at pp. 22 – 24 of 38.
[64] *Kittitas County*, 172 Wn.2d at 168, 256 P.3d at 1204 *citing Dep't of Ecology v. Campbell & Gwinn, L.L.C.*, 146 Wn.2d 1, 10–12, 43 P.3d 4 (2002).

RCW 36.70A.060(2) requires counties and cities to protect these areas. That these areas are "not suited to the siting of … development consistent with public health or safety concerns" shows the public health and safety is to be considered in designating and protecting landslide hazards and is not to be left to the discretion of the local government when that discretion violates the GMA.[65] The Board's interpretation of the GMA in the FDO writes "not suited to the siting of commercial, residential, or industrial development consistent with public health or safety concerns" out of the GMA. This the Board cannot do. As the State Supreme Court held: "We are required to read legislation as a whole, and to determine intent from more than a single sentence. Effect should be given to all of the language used, and the provisions must be considered in relation to each other, and harmonized to ensure proper construction."[66]

The Board has recognized that the GMA critical areas definitions specify the critical areas that must be designated and protected and limit county and city discretion. The GMA definition of wetlands, for example, excludes from the definition of "wetlands created after July 1, 1990, that were unintentionally created as a result of the construction of a road,

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[65] *Kittitas County,* 172 Wn.2d at 156, 256 P.3d at 1199 "deference to counties remains 'bounded ... by the goals and requirements of the GMA,' …."
[66] *King Cty. v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 142 Wn.2d 543, 560, 14 P.3d 133, 142 (2000).

street, or highway."[67] The City of Kent adopted an exemption for "wetlands accidentally created by human actions prior to July 1, 1990 …"[68] The Board wrote in part that:

> This Board has frequently held that GMA definitions do not, in themselves, create enforceable obligations. See, e.g., *Hanson v. King County*, CPSGMHB No. 98-3-0015c, Final Decision and Order (Dec. 16, 1998), at 7-8. In this case, the enforceable obligation is the duty to designate and protect critical areas, which include wetlands. RCW 36.70A.170; .030(5). The definition in the Act has substance since it defines what wetlands are critical areas that must be designated and protected - it is not a suggestion.[69]

The Board's *City of Kent* reasoning applies here. The definition of geologically hazardous areas in RCW 36.70A.030(9) also has substance defining the geologically hazardous areas that must be designated and protected and the purpose of that protection, protecting geologically hazardous areas from being developed for "commercial, residential, or industrial development" "not suited" to being sited on these areas "consistent with public health or safety concerns." The Board cannot allow local jurisdictions to circumvent the GMA requirements to designate, in RCW 36.70A.170, and protect, in RCW 36.70A.060(2), geologically hazardous areas by writing "not suited to the siting of commercial,

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[67] RCW 36.70A.030(21).
[68] *Washington State Dept. of Ecology and Washington State Dept. of Community, Trade and Economic Development v. City of Kent (DOE/CTED)*, CPSGMHB Case No. 05-3-0034, Final Decision and Order, (April 19, 2006), at 25 of 65, 2006 WL 1111353, at *20.
[69] *Id.*, at 26 of 65, 2006 WL 1111353, at *21.

residential, or industrial development consistent with public health or safety concerns" out of the definition of geologically hazardous areas in RCW 36.70A.030(9). This violates the rule of statutory construction that "[e]ffect should be given to all of the language used, and the provisions must be considered in relation to each other, and harmonized to ensure proper construction."[70]

The courts have concluded that the GMA definition of critical areas identifies the critical areas that must be designated and protected.[71] This is consistent with following the geologically hazardous area definition for designating and protecting those critical areas.

Contrary to the Board's conclusion, the GMA does <u>not</u> relegate public health and safety concerns to the exclusive authority of the County's legislative authority.[72] Instead, the GMA requires the Board to review the designation and protection of critical areas, including geologically hazardous areas, for compliance with the GMA.[73]

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[70] *King Cty. v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 142 Wn.2d 543, 560, 14 P.3d 133, 142 (2000).

[71] *Ferry Cty. v. Concerned Friends of Ferry Cty.*, 155 Wn.2d 824, 832, 123 P.3d 102, 106 (2005); *Olympic Stewardship Found. v. W. Washington Growth Mgmt. Hearings Bd.*, 166 Wn. App. 172, 176, 274 P.3d 1040, 1041–42 (2012) "The GMA, chapter 36.70A RCW, requires participating counties to designate critical areas 'where appropriate' and to adopt development regulations to protect these areas. RCW 36.70A.170(1)(d); RCW 36.70A.060(2). 'Critical areas' include 'geologically hazardous areas,' …."

[72] AR 001820, FDO, at 24 of 38.

[73] *Ferry Cty. v. Concerned Friends of Ferry Cty.*, 155 Wn.2d 824, 833, 123 P.3d 102, 106 (2005) "The Board adjudicates compliance with the GMA and must find compliance unless a county's or city's action is clearly erroneous. RCW 36.70A.280, .320(3)." This

In the *HEAL* decision the court of appeals recognized the Board's duty to review local government critical areas regulations for compliance with the GMA and critical areas policies for compliance with the GMA's best available science requirement.[74] As the court of appeals wrote:

> Whether scientific evidence is respectable and authoritative, challenged or unchallenged, controlling or of no consequence when balanced against other factors, goals and evidence to be considered, is first in the province of the city or county to decide. Then, if challenged, it is for the Growth Management Hearings Board to review.[75]

The Board missed two important lessons from the *HEAL* opinion applicable to this case.[76] First, the Board failed to realize that the policies and regulations at issue in *HEAL* were geologically hazardous area policies and regulations.[77] Second, the court of appeals concluded that if geologically hazardous policies or regulations are challenged, the Board is to review the policies and regulations for compliance with the GMA

Ferry County decision concerned the designation of critical areas. *Swinomish Indian Tribal Cmty. v. W. Washington Growth Mgmt. Hearings Bd.*, 161 Wn.2d 415, 423, 166 P.3d 1198, 1203 (2007) "The Board is charged with determining compliance with the GMA and, when necessary, invalidating noncomplying comprehensive plans and development regulations. *King County v. Cent. Puget Sound Growth Mgmt. Hr'gs Bd.*, 142 Wn.2d 543, 552, 14 P.3d 133 (2000) (citing RCW 36.70A.280, .302)." The *Swinomish* decision addressed the protection of critical areas.

[74] *Honesty in Envtl. Analysis & Legislation (HEAL) v. Cent. Puget Sound Growth Mgmt. Hearings Bd.*, 96 Wn. App. 522, 527 – 28, 979 P.2d 864, 867 – 68 (1999), *as amended on reconsideration in part* (Aug. 25, 1999).

[75] *HEAL*, 96 Wn. App. at 532, 979 P.2d at 870 underlining added.

[76] AR 001820, FDO, at 24 of 38.

[77] *Honesty in Environmental Analysis and Legislation (HEAL) v. City of Seattle*, CPSGMHB Case No. 96-3-0012, Final Decision and Order (Aug. 21, 1996), at *16 – 17, 1996 WL 681285, at *12 – 13.

including the best available science requirement.[78] The court of appeals also upheld the Board's substantive review of geologically hazardous area regulations for compliance with the GMA in the *Olympic Stewardship Foundation* decision.[79] Because of these legal errors, the Board failed to substantively review Snohomish County's new landslide hazard regulations in violation of the GMA.[80] This violates the GMA and APA requirements that the Board must review all issues presented to it.[81]

One of the reasons the GMA was adopted was to protect the public health and safety.[82] Contrary to the Board's FDO in this case,[83] nothing in the GMA evidences a legislative intent to grant counties and cities unfettered discretion over health and safety concerns either generally or specifically for geological hazards such as landslide hazards.[84] In fact the Board is <u>required</u> to consider whether property owners should be prohibited from applying for and vesting building permits for certain single-family homes "to protect the public health and safety."[85] One of the

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[78] *HEAL*, 96 Wn. App. at 532, 979 P.2d at 870.
[79] *Olympic Stewardship Found.*, 166 Wn. App. at 186 – 87, 274 P.3d at 1047.
[80] AR 001818 – 20, FDO, at 22 – 24 of 38.
[81] *Low Income Hous. Inst. v. City of Lakewood*, 119 Wn. App. at 119, 77 P.3d at 657.
[82] RCW 36.70A.010.
[83] AR 001820, FDO, at 24 of 38.
[84] Chapter 36.70A RCW.
[85] RCW 36.70A.302(3)(b)(i). Vesting refers to the process by which developers freeze the policies and regulations that apply to certain development applications. In Washington, "developers are entitled 'to have a land development proposal processed under the regulations in effect at the time a complete building permit application is filed, regardless of subsequent changes in zoning or other land use regulations.'" *Potala Vill. Kirkland,*

remedies available if the Board finds policies or regulations violate the GMA is invalidity.[86] If a Board makes determination of invalidity, most types of development regulations cannot vest or be approved until the Board determines the county or city comprehensive plan or development regulations no longer substantially interfere with the fulfillment of the goals of the GMA.[87] However, a determination of invalidity does not apply to certain permits including a "permit for construction by any owner, lessee, or contract purchaser of a single-family residence for his or her own use or for the use of his or her family on a lot existing before receipt by the county or city of the board's order, except as otherwise specifically provided in the board's order to protect the public health and safety …."[88] If the Board concludes that it is necessary to protect the public health and safety, it can apply invalidity to permits for single-family residences that would otherwise be exempt from the determination. So rather than divesting the Board of the authority to review comprehensive plans and development regulations to determine if they adequately address the public health and safety, the GMA requires the Board to consider the

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LLC v. City of Kirkland, 183 Wn. App. 191, 197, 334 P.3d 1143, 1145 – 46 (2014) *review denied Potala Vill. Kirkland, LLC v. City of Kirkland*, 182 Wn.2d 1004, 342 P.3d 326 (2015).

[86] RCW 36.70A.302.

[87] RCW 36.70A.302(3)(a).

[88] RCW 36.70A.302(3)(b)(i) underlining added.

public health and safety when deciding the types of permits covered by a determination of invalidity.

None of the decisions cited by the Board identify any GMA provision that prohibits or excuses the Board from determining whether comprehensive plans and development regulations comply with the GMA requirements that protect the public health and safety such as designating and protecting geologically hazardous areas as RCW 36.70A.170(1) and RCW 36.70A.060(2) require and including best available science when developing critical areas regulations as RCW 36.70A.172 requires.[89] The Board cites the *Sno-King* decision. However, the *Sno-King* decision does not identify any GMA provision that prohibits the Board from reviewing regulations that address the public health and safety.[90]

In sum, reading RCW 36.70A.030(9), RCW 36.70A.170, and RCW 36.70A.060(2) together shows that critical areas regulations are required to consider the public health and safety when designating and protecting geologically hazardous areas. The Board improperly interpreted and applied the GMA in concluding there is no GMA mandate to protect people and property from geologically hazardous areas and that health and

[89] AR 001819 – 20, FDO, at 23 – 24 of 38.
[90] *Sno-King Environmental Alliance v. Snohomish County (Sno-King),* CPSGMHB Case No. 06-3-0005, Final Decision and Order (July 24, 2006), at 11 – 17 of 24.

safety concerns are the exclusive purview of the county legislative authority.

F. Issue 5: Did the Board erroneously interpret or apply the GMA, the Board's rules of practice and procedure, and the APA when it failed to decide Issue C-1 and concluded that Futurewise did not meet its burden of proof and are the Board's conclusions not supported by substantial evidence? (Assignment of Error 5.)

Futurewise's issue statement for Issue "C-1" cited to RCW 36.70A.060(2), RCW 36.70A.170, and RCW 36.70A.172(1) which require the designation and protection of critical areas and including best available science in their designation and protection.[91] Futurewise's Petitioners' Prehearing Brief also cited to the *Pilchuck, et al. v. Snohomish County* Order Partially Granting Motions for Reconsideration and Clarification.[92] This order cited to and relied on RCW 36.70A.030(10), RCW 36.70A.060(2), and RCW 36.70A.170.[93] Futurewise also cited to another Board decision to identify a rule of law.[94]

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[91] AR 000863, Futurewise Petitioners' Prehearing Brief p. 30.

[92] AR 000863 – 62, Futurewise Petitioners' Prehearing Brief pp. 30 – 31 citing *Pilchuck, et al. v. Snohomish County (Pilchuck II)*, CPSGMHB Case No. 95-3-0047c, Order Partially Granting Motions for Reconsideration and Clarification (Jan. 25, 1996), at *7 – 8, 1996 WL 650336 pp. *5 – 7.

[93] *Pilchuck, et al. v. Snohomish County (Pilchuck II)*, CPSGMHB Case No. 95-3-0047c, Order Partially Granting Motions for Reconsideration and Clarification (Jan. 25, 1996), at *7 – 10, 1996 WL 650336 pp. *5 – 8.

[94] *Diehl v. Mason County*, WWGMHB Case No. 95-2-0073, Compliance Hearing Order (#14) (Geologically-Hazardous Areas) (July 13, 2001), at *7, 2001 WL 933666, 4 cited in AR 000865, Futurewise Petitioners' Prehearing Brief p. 32.

The GMA, in RCW 36.70A.290(1), provides in relevant part that "[a]ll requests for review to the growth management hearings board shall be initiated by filing a petition that includes a detailed statement of issues presented for resolution by the board." Other than that, there are no special pleading or briefing requirements in the GMA. There is no prohibition on relying on Board decisions to set out legal rules as Futurewise did. The APA also does not have pleading or briefing requirements that prohibit citing to Board decisions for legal rules.[95] The GMHB Rules of Practice and Procedure, in WAC 242-03-590(1), provide that "[a] petitioner … shall submit a brief addressing each legal issue it expects the board to determine. Failure by such a party to brief an issue shall constitute abandonment of the unbriefed issue. Briefs shall enumerate and set forth the legal issue(s) as specified in the prehearing order." Futurewise's Prehearing Brief did all of this for Issue "C-1."[96] The Board did not cite to any law, rule, court decision, or Board decision that precludes Futurewise from citing Board authority to identify rules of law or that excuses the Board from deciding Issue "C-1."[97]

The Board failed to decide Issue "C-1." Like the Board in the *LIHI* decision, this failure to decide all issues requiring resolution violated

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[95] RCW 34.05.410 – RCW 34.05.494.
[96] AR 000863 – 67, Futurewise Petitioners' Prehearing Brief pp. 30 – 34.
[97] AR 001825 – 26, FDO, at 29 – 30 of 38.

RCW 36.70A.290(1) and RCW 34.05.570(3)(f).[98] Like the *LIHI* decision, this Court should remand Issue "C-1" back to the Board for a decision.[99]

G. Issue 6: Is the Board's conclusion that the amended SCC provisions complied with the GMA requirements to designate and protect geologically hazardous areas not supported by substantial evidence or an erroneous interpretation or application of the GMA? (Assignment of Error 6.)

1. SCC 30.62A.130 and SCC 30.62B.130 violate the GMA.[100]

SCC 30.62A.130 and SCC 30.62B.130 were amended by Ordinance No. 15-034.[101] SCC 30.62A.130 and SCC 30.62B.130 limit the application of protections for geological hazards to "[d]evelopment activities, actions requiring project permits, and clearing" and even some of these uses and activities are exempted from the protections.[102] "'Development activity' means any construction, development, earth movement, clearing, or other site disturbance which either requires a permit, approval or authorization from the county or is proposed by a public agency."[103] So even development activities require a county permit, approval, or authorization or must be undertaken by public agencies to be regulated.

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[98] *Low Income Hous. Inst.*, 119 Wn. App. at 119, 77 P.3d at 657.
[99] *Id.*
[100] AR 001817 – 20 & AR 001825 – 26, FDO, at 21 – 24 & 29 – 30 of 38. This is a subset of Issues "B-1" and "C-1" from the FDO.
[101] AR 000028, Ord. No. 15-034 p. 20; AR 000056, Ord. No. 15-034 p. 48.
[102] AR 000028, Ord. No. 15-034 p. 20; AR 000056, Ord. No. 15-034 p. 48.
[103] AR 001248, SCC 30.91D.240.

RCW 36.70A.060(2) requires that "[e]ach county and city shall adopt development regulations that protect critical areas …" Counties must include "best available science" (BAS) in the adoption of development regulations for critical areas.[104] Those regulations must also "protect the functions and values of critical areas."[105] As the court of appeals has held, this requires the protection of "… all functions and values."[106] Discharging storm water onto a landslide hazard will not require a geological report or be regulated.[107] "Slope saturation by water is a primary cause of landslides."[108] Owners or occupants of existing homes or other facilities could divert downspouts or runoff onto slopes, triggering a landslide. These activities are not regulated by SCC 30.62A.130 and SCC 30.62B.130 because they are not included in the definitions of clearing or development activity and do not require a "project permit."[109] Therefore, SCC 30.62A.130 and SCC 30.62B.130 fail to protect geologically hazardous areas because they do not maintain the existing conditions of

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[104] RCW 36.70A.172.
[105] RCW 36.70A.172(1)(b).
[106] *WEAN*, 122 Wn. App. at 174 – 75.
[107] AR 000028, Ord. No. 15-034 p. 20; AR 000056, Ord. No. 15-034 p. 48; AR 001247, SCC 30.91C.112; AR 001248, SCC 30.91D.240; AR 001249, SCC 30.91P.350.
[108] AR 000908.
[109] AR 001247, SCC 30.91C.112; AR 001248, SCC 30.91D.240; AR 001249, SCC 30.91P.350.

these critical areas as RCW 36.70A.060(2) and RCW 36.70A.172(1) require.[110]

SCC 30.62A.130(1) was amended by Ordinance No. 15-034 to require that for any development activity or action requiring a "project permit," the applicant shall submit a site development plan … which includes … (g) [the l]ocation of all other critical areas regulated pursuant to chapters 30.62B, 30.62C and 30.65 SCC on or within ((~~200~~)) <u>300</u> feet of the site …."[111] Ordinance No. 15-034 amended SCC 30.62B.130(7) to require the identification of the location of other critical areas regulated by chapters 30.62A, 30.62C, and 30.65 SCC, including geologically hazardous areas, on and within 300 feet of the site.[112] RCW 36.70A.170(1)(d) and RCW 36.70A.030(5) and (9) require counties and cities to designate geologically hazardous areas. RCW 36.70A.060(2) requires that "[e]ach county and city shall adopt development regulations that protect critical areas …" Counties must include "best available science" (BAS) in the adoption of policies and development regulations that designate and protect critical areas.[113] SCC 30.62A.130(1)(g) and SCC 30.62B.130(7) fail to meet these requirements.

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[110] *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 430, 166 P.3d at 1206.
[111] AR 000028, Ord. No. 15-034 p. 20 the addition is underlined and the deletion is struck through in the original.
[112] AR 000056, Ord. No. 15-034 p. 48.
[113] RCW 36.70A.172.

Landslides are capable of damaging developments much farther than 300 feet from the landslide. All the homes and buildings destroyed by the March 2014, Oso landslide "were more than … 300 feet … away from the toe of the slope and therefore not subject to land-use restrictions due to landslide hazard[s] …."[114] Even after the 2006 Oso landslide, Snohomish County did not even consider landslide hazards when issuing building permits because the building sites were more than 300 feet from the toe of the slope.[115]

The 2014, Oso landslide ran out for over a mile (5,500 feet) killing 43 people, injuring 10 more, and destroying 35 homes.[116] "The closest home to the slope before the 2014 event was approximately … 400 feet … from the toe of the slope …."[117] If the 300 feet is measured from the toe of the slope plus twice the height of the 600 foot tall slope height at the Oso landslide site, only houses within 1,500 feet would identify the Oso landslide as a geologically hazardous area.[118] This is just 27 percent of the Oso landslide's runout distance.[119] Homes were destroyed by the 2014

[114] AR 001174, *GEER-036* p. 56.
[115] AR 001174, *GEER-036* p. 56.
[116] AR 001162, *GEER-036* p. 1; AR 001172, *GEER-036* p. 54; AR 001180, GEER-036 p. 144.
[117] AR 001172, *GEER-036* p. 54.
[118] AR 001180, *GEER-036* p. 144; AR 000070 – 71, SCC 30.91L.040 in Ord. No. 15-034 pp. 62 – 63.
[119] AR 001172, GEER-036 p. 54; AR 001180, *GEER-036* p. 144.

Oso landslide well beyond that distance.[120] One destroyed home was measured as being 2,300 feet from the toe of the slope and other destroyed homes were farther from the slope.[121] The 2014 Oso landslide was not an outlier, its runout distance was consistent with other landslides of its size.[122]

Other landslides in the northwest are capable of damaging homes and other buildings more than 300 feet from the toe of the landslide. In a study of shallow landslides along Puget Sound from Seattle to Everett, the average runout length was 197.5 feet and the maximum runout length was 771 feet.[123] In a study of 38 large, catastrophic landslides that occurred in northern British Columbia in the last three decades, researchers calculated the length for 37 landslides, they all ran out for 1,640 feet or more.[124] Researchers were able to calculate height to length ratios for 17 of the landslides. Based on the height to length ratios, all but one of the landslides had runout distances longer than twice the height of the slope, in many cases the runout was much longer than twice the height of the slope plus 300 feet.[125]

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[120] AR 001177, *GEER-036* p. 68.
[121] AR 001177, *GEER-036* p. 68.
[122] AR 001181, *GEER-036* p. 152.
[123] AR 001197.
[124] AR 001201 & AR 001205 – 06, this article is from a peer-reviewed scientific journal. AR 001226 – 28.
[125] AR 001201 & AR 001205 – 06. The standard for including the runout area as a critical area of twice the height of the slope yields a height to length ratio of 0.5.

Building too close to or on landslide prone areas can cause landslides.

> Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. … landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes.[126]

The "alteration of the local groundwater recharge and hydrogeological regime due to previous landsliding and, possibly, land use practices … (most notably, timber harvesting)" are among the "many other factors that likely contributed to destabilization of the landslide mass" causing the 2014 Oso landslide.[127] SCC 30.62A.130(1) and SCC 30.62B.130(7) fail to protect landslide prone areas from development and development from landslides as the GMA requires.[128] Best available science does not support limiting the consideration of landslide hazards to those within 300 feet as SCC 30.62A.130(1) and SCC 30.62B.130(7) do. In *Diehl v. Mason County*, the Board concluded a 200-foot triggering distance from a landslide hazard for when a geotechnical report or geological assessment

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[126] AR 000910.
[127] AR 001184, *GEER-036* p. 160.
[128] RCW 36.70A.060(2); RCW 36.70A.172(1); *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 430, 166 P.3d at 1206.

would be required was not supported by best available science where an expert recommended 300 or 400 feet.[129]

In addressing the SCC 30.62A.130(1) amendment, the Board concluded Snohomish County adopted landslide hazard area regulations that balanced the GMA goals of "the protection of people and property with restrictions on the use of land" as allowed by the *HEAL* decision.[130] However, in the *WEAN* decision the court of appeals held that in balancing GMA goals against critical areas regulations, there must be evidence in the record showing that GMA goal is furthered by the provision the county adopted.[131] The Board cited no evidence showing that the 300-foot limit on considering geologically hazardous areas in SCC 30.62A.130(1) and SCC 30.62B.130(7) are "necessary" to meet any GMA goals as the *WEAN* decision requires.[132] The Board's decision on SCC 30.62A.130(1) and SCC 30.62B.130(7) are not supported by substantial evidence. It is also an erroneous interpretation or application of the GMA resting as it does on the Board's conclusion that the GMA does not require considering public health or safety concerns in designating and protecting geologically

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[129] *Diehl v. Mason County*, WWGMHB Case No. 95-2-0073, Compliance Hearing Order (#14) (Geologically-Hazardous Areas) (July 13, 2001), at *7, 2001 WL 933666, 4.
[130] AR 001820, FDO, at 24 of 38.
[131] *WEAN*, 122 Wn. App. at 183 – 84, 93 P.3d at 899.
[132] AR 001820, FDO, at 24 of 38; *WEAN*, 122 Wn. App. at 181, 93 P.3d at 898.

hazardous areas.[133] As was argued in Section V.E, beginning on page 16 of this brief, the GMA requires considering the public health or safety in designating and protecting geologically hazardous areas.

Also based on its misconception that SCC 30.91L.040 included buffers and not geological hazards, the Board framed "[t]he question presented is whether the GMA requires jurisdictions to protect people and property on the land in addition to protecting the designated critical areas?"[134] As was demonstrated in Section V.D of this Petitioners' Brief, beginning on page 14, SCC 30.91L.040 designates critical areas not buffers. The question presented was do SCC 30.62A.130 and SCC 30.62B.130 fail to require the designation of all geologically hazardous areas, fail to protect the functions and values of critical areas, and were not based on best available science?[135] The answer is yes. The Board erroneously interpreted the GMA.

2. SCC 30.62B.140, SCC 30.62B.160, SCC 30.62B.340, and SCC 30.91L.040 violate the GMA.[136]

The GMA directs counties and cities to designate and protect critical areas, including geologically hazardous areas.[137] SCC 30.62B.140 and

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[133] AR 001819 – 20, FDO, at 23 – 24 of 38.
[134] AR 001819, FDO, at 23 of 38.
[135] AR 001817 fn. 77, FDO, at 21 of 38 fn. 77.
[136] AR 001825 – 26, FDO, at 29 – 30 of 38. This is "Issue C-1" from the FDO.
[137] RCW 36.70A.170(1)(d); RCW 36.70A.030(5); RCW 36.70A.030(9); RCW 36.70A.060(2).

SCC 30.62B.340 were amended by Ordinance No. 15-034.[138] SCC 30.62B.140 only requires a geotechnical report for development activity, actions requiring "project permits," or clearing.[139] SCC 30.62B.340 only applies to development activities, actions requiring "project permits," or clearing.[140] For all of these sections discharging storm water onto a landslide hazard, for example, will not require a geological report or be regulated because diverting water is not clearing and does not require a "project permit."[141] "Slope saturation by water is a primary cause of landslides."[142] So water discharges can mobilize landsides as can other unregulated activities. Therefore SCC 30.62B.140 and SCC 30.62B.340 fail to protect geologically hazardous areas because they do not maintain the existing conditions of these critical areas as RCW 36.70A.060(2) and .172(1) require.[143]

Ordinance No. 15-034 amended SCC 30.62B.140 to delete the requirement that a geotechnical report must be prepared for any development activity, action requiring a "project permit," or clearing

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[138] AR 000056 – 58 Ord. No. 15-034 pp. 48 – 50; AR 000062 – 63, Ord. No. 15-034 pp. 54 – 55.
[139] AR 000056, Ord. No. 15-034 p. 48.
[140] AR 000063 Ord. No. 15-034 p. 55.
[141] AR 001247, SCC 30.91C.112; AR 001248, SCC 30.91D.240; AR 001249, SCC 30.91P.350.
[142] AR 000908.
[143] *Swinomish Indian Tribal Cmty.*, 161 Wn.2d at 430, 166 P.3d at 1206.

within a landslide hazard setback.[144] Landslides expand laterally, not just up and down.[145] Geotechnical reports are no longer required for development on the side of a landside that may be engulfed by a future landside.

SCC 30.62B.160 suffers from similar defects. It only applies to a "development activity or action requiring a project permit…."[146] It does not apply to clearing or vegetation removal that does not require a project permit or approval.[147] Grading or "removing vegetation are common human-induced factors that may initiate landslides."[148] In a *Diehl* compliance order, the Board concluded that the critical areas regulations must require a permit for clearing activities in landslide hazard areas.[149]

SCC 30.91L.040 limits landslide hazards to areas at the top of the slope equal to a distance equal to the height of the slope and areas at the bottom of the slope equal to two times the height of the slope.[150] The limitations based on the height of the slope are not supported by the best available science or any scientific evidence. The 2014, Oso slide had a

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[144] AR 000056, Ord. No. 15-034 p. 48.
[145] AR 001177, *GEER-036* p. 68.
[146] AR 000058, Ord. No. 15-034 p. 50.
[147] AR 001248, SCC 30.91D.240.
[148] AR 000910.
[149] *Diehl v. Mason County*, WWGMHB Case No. 95-2-0073, Order Regarding Compliance Hearing #10, and Finding Continued Noncompliance (Geologically-Hazardous Areas) (March 22, 2000), at *6, 2000 WL 313407, 3.
[150] AR 000070 – 71, Ord. No. 15-034 pp. 62 – 63.

slope height of 600 feet but ran out for over a mile (5,500 feet), nine times the slope height.[151] In a study of 38 large, catastrophic landslides that occurred in northern British Columbia, researchers were able to calculate height to length ratios for 17 of the landslides. Based on the height to length ratios, all but one of the landslides had runout distances longer than twice the height of the slope.[152]

After analyzing many landslides and the scientific literature, Legros concluded in a peer-reviewed study that "[t]he ratio [height to length] H/L may therefore be physically meaningless. The good correlations between runout distance and volume, and area and volume, suggest that landslide spreading is essentially controlled by their own volume, and not by H."[153] He also wrote that "hazard zonation for landslide events should rely on their area–volume relationship ...."[154] This is consistent with the best available science cited by Snohomish County.[155] Snohomish County wrote that "[t]he run out length is a function of the height of the slope being evaluated on a site, slope angle, mass volume, degree of soils saturation and potentially the proximity to a fault or river system."[156]

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[151] AR 001180, *GEER-036* p. 144.
[152] AR 001201 & AR 001205 – 06.
[153] AR 001001, this article is from a peer-reviewed scientific journal. AR 001226 – 28.
[154] AR 001001 – 02.
[155] AR 000721 – 24.
[156] AR 000721.

Snohomish County's Sleight Memorandum claims that to "[t]he extent that the County is recommending expansion to the LHA definition [SCC 30.91L.040] to include the prior setbacks and enlarge them would capture the vast majority of landslide events, but likely not every extreme event" citing to lverson *et al.* and Yang *et al.*[157] But neither of these studies support limiting the runout area to twice the height of the slope as SCC 30.91L.040 does.[158]

The lverson *et al.* article does not recommend calculating the runout distance of landslides as twice the height of the slope.[159] The lverson *et al.* article describes the Elm landslide that ran out a distance that is 3.29 times the height.[160] And the Oso landslide ran out a distance that is 9.5 times the height.[161]

The Yang *et al.* article concluded that slope alone is not a good determinate of landslide runout distances. Yang *et al.* concluded that "[t]he peak ground acceleration (PGA), the volume of the sliding mass V, the height H_{L}, and the slope angle θ of a mountain are four important

[157] AR 001373.
[158] AR 001447 – 57, AR 001456 "R.M. lverson *et al.;*" AR 001427 "Yang *et al.*"
[159] AR 001447 – 57, R.M. lverson *et. al. Landslide mobility and hazards: implications of the Oso disaster* 412 EARTH AND PLANETARY SCIENCE LETTERS 197, 197 – 207 (2015).
[160] AR 001447, *Id.* at p. 197.
[161] AR 001447 – 48, *Id.* at p. 197 – 98.

parameters that affect the horizontal run-out distance of a landslide *L*."[162] The reference to twice the height, "$2H_L$," in the article describes the location on the slope where the landslide is likely to start, not the distance the landslide will runout.[163]

The Sleight Memorandum itself does not qualify as BAS because it does not have the characteristics of a valid scientific process listed in WAC 365-195-905(5)(a). The Sleight Memorandum was not peer-reviewed, its methods are not clearly stated and cannot be replicated, no actual data is provided and the conclusions are not supported by data, there is no data and no evidence the data was analyzed using appropriate statistical or quantitative methods, the information is not placed in proper context, and the references do not support the conclusions.[164]

No science in the record, let alone best available science, supports basing the calculation of landside runout areas only on twice the height of the slope as Snohomish County does in SCC 30.91L.040.[165] But SCC 30.91L.040 uses only twice the height of the slope to predict and designate

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[162] AR 001427, Yang, *et al.*, *A prediction model for horizontal runout distance of landslides triggered by Wenchuan earthquake* 12 EARTHQUAKE ENG. & ENG. VIB. 201, p. 206 (2013) attached as Appendix D.

[163] AR 001427 – 28, *Id.* at pp. 206 – 07.

[164] AR 001372 – 73; WAC 365-195-905(5)(a).

[165] AR 001427 – 28, *Id.* at p. 206 – 207; AR 001180, *GEER-036* p. 144; AR 001201 & AR 001205 – 06; AR 001001 – 02; AR 000721 – 24, Draft *Summary Snohomish County 2015 Best Available Science Review for Critical Area Regulation Update* pp. 9 – 12; AR 001433 – 39. SCC 30.91L.040 is at AR 000070 – 71, Ord. No. 15-034 pp. 62 – 63.

the extent of landslide hazards and does not incorporate the other parameters identified by the best available science. This violates the GMA.[166]

3. SCC 30.62B.390 violates the GMA.[167]

RCW 36.70A.170(1) provides that "each county … shall designate where appropriate: … (d) Critical areas." RCW 36.70A.060(2) provides that "[e]ach county and city shall adopt development regulations that protect critical areas that are required to be designated under RCW 36.70A.170." RCW 36.70A.170(1) does not provide that counties "may" designate critical areas. RCW 36.70A.060(2) does not allow the adoption of development regulations that "may" protect critical areas. But that is exactly what SCC 30.628.390 does. Ordinance No. 15-034 adopted SCC 30.628.390 which provides that the director "may expand the boundary of a geologically hazardous area, impose additional or more stringent standards and requirements than those specified in this chapter or impose mitigation requirements …" subject to making certain findings.[168]

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[166] *HEAL*, 96 Wn. App. at 533, 979 P.2d at 870 – 71; RCW 36.70A.172(1); RCW 36.70A.170; RCW 36.70A.060.
[167] AR 001826 – 27, FDO, at 30 – 31 of 38. This is "Issue C-2" from the FDO.
[168] AR 000064, Ord. No. 15-034 p. 56 underling added.

"May" means to "have permission to …" undertake an action.[169] The use of may means the director is not required to expand geological hazardous areas if necessary protect critical areas. The director is not required to impose additional or more stringent standards and requirements if necessary protect critical areas. SCC 30.62B.390 fails to comply with the GMA.

H. Issue 7: Is the Board's conclusion that the CARA regulations comply with the GMA an erroneous interpretation or application or not support by substantial evidence? (Assignment of Error 7.)[170]

RCW 36.70A.060(2) and RCW 36.70A.030(5)(b) require the protection of "areas with a critical recharging effect on aquifers used for potable water." These are commonly referred to as "CARAs," critical aquifer recharge areas. "The GMA includes requirements that counties consider and address water resource issues in land use planning. See, e.g., RCW 36.70A.020(10) (GMA goal to protect the environment, including "water quality [ ] and the availability of water"), …"[171] The goals in RCW 36.70A.020 "guide the development and adoption of comprehensive plans and development regulations of those counties and cities that are required

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[169] WEBSTER'S THIRD NEW INTERNATIONAL DICTIONARY 1396 (2002). When the legislature has not defined a term "used in the GMA," the courts "apply its common meaning, which may be determined by referring to a dictionary." *Quadrant Corp. v. State Growth Mgmt. Hearings Bd.*, 154 Wn. 2d 224, 239, 110 P.3d 1132, 1140 (2005). The supreme court cited to Webster's Third New International Dictionary. *Id.*

[170] AR 001824 – 25, FDO, at 28 – 29 of 38. This is a subset of Issue B-3 from the FDO.

[171] *Kittitas County*, 172 Wn.2d at 175, 256 P.3d at 1208.

or choose to plan under RCW 36.70A.040." These provisions are augmented by other parts of the GMA including RCW 19.27.097.

RCW 19.27.097 requires applicants for building permits for buildings that need potable water to provide evidence of a physically available and legally available water supply.[172] RCW 58.17.110 also requires Snohomish County to assure adequate potable water supplies are available when approving subdivision applications including that the water is physically and legally available.[173] Further, the County must assure that development applications proposing to use permit-exempt wells are within the withdrawal limits applicable to those wells.[174] These requirements protect groundwater resources.[175]

Ordinance No. 15-034 amended SCC 30.62C.140(3)(f)(iv) to require that "[i]f water use is proposed for the development activity, a description of the groundwater source of water to the site or a letter from an approved water purveyor stating the ability to provide water to the site …" in a hydrogeologic report.[176] But SCC 30.62C.140(3)(f)(iv) does not require that water supplies must be legally and physically available for new

[172] AR 001234 – 36, AGO 1992 No. 17 pp. 5 – 7 of 8.
[173] *Whatcom Cty. v. Hirst*, 186 Wn.2d 648, 687 – 88, 381 P.3d 1, 18 (2016).
[174] *Kittitas County*, 172 Wn.2d at 178 – 81, 256, P.3d at 1209 – 10.
[175] *Kittitas County*, 172 Wn.2d at 181, 256 P.3d at 1210.
[176] AR 000067, Ord. No. 15-034 p. 59.

developments that require a water supply as the GMA requires.[177] SCC 30.62C.140(3)(f)(iv) does not require that ground water sources must comply with the withdrawal limits applicable to those wells.[178] Snohomish County has instream flow rules and closed basins in portions of the Skagit basin,[179] instream flow rules, closed basins, and limited reservations for domestic uses in portions of the Stillaguamish River Basin,[180] and instream flow rules and limitations on surface water use in the Snohomish basin.[181] The County has failed to incorporate requirements to protect instream flows and ground water quantity into SCC 30.62C.140(3)(f)(iv). This violates the GMA.

SCC 30.62C.130 limits the requirement to submit a hydrogeologic report to "development activity" or uses or activities requiring a "project permit."[182] As was documented in Sections V.G.1 and 2 of this brief, SCC 30.62C.130 violates the GMA for the same reasons as SCC 30.62A.130, SCC 30.62B.130, SCC 30.62B.140, and SCC 30.62B.340.

In the Final Decision and Order in this case, the Board wrote that

> "[w]hile local jurisdictions are now required to address both the legal and actual availability of water for development activity, inclusion of such a requirement

[177] *Whatcom Cty. v. Hirst*, 186 Wn.2d 648, 687 – 88, 381 P.3d 1, 18 (2016).
[178] *Kittitas County*, 172 Wn.2d at 178 – 81, 256, P.3d at 1209 – 10.
[179] WAC 173-503-040.
[180] WAC 173-505-050; WAC 173-505-060; WAC 173-505-070; WAC 173-505-090.
[181] WAC 173-507-020; WAC 173-507-030.
[182] AR 000066 – 67, Ord. No. 15-034 pp. 58 – 59.

> within the hydrogeologic report section of the Snohomish County Code protecting CARAs makes little sense. The goal of the requirements of chapter 30.62C is to designate and protect CARAs, their water quality and quantity, not to address the availability of water for development activity.[183]

But as the supreme court concluded in the *Whatcom County* decision, one of the purposes of the GMA requirements is to protect quality and quantity of groundwater.[184] This is also one of the purposes of the CARA regulations as the Board concluded in the above quote. So, including these requirements in the CARA regulations is required by the GMA.

Since the Board decided this case, the Legislature has adopted the Laws of 2018, ch. 1. This law because effective on January 19, 2018.[185]

> RCW 34.05.554(1)(d) permits a party to raise a new issue on appeal if "The interests of justice would be served by resolution of an issue arising from ... (i) A change in controlling law occurring after the agency action." The remedy is to remand to the agency for determination. RCW 34.05.554(2).[186]

In this case the interests of justice will be served by a remand to the Board to consider Issue 7 in the light of Laws of 2018, ch. 1. RCW 19.27.097 was first enacted in 1990.[187] RCW 58.17.110 was amended in 1990 to

[183] AR 001824, FDO, at 28 of 38.
[184] *Whatcom Cty. v. Hirst*, 186 Wn.2d 648, 673, 381 P.3d 1, 11 (2016).
[185] Laws of 2018, ch. 1, § 307.
[186] *Olympic Stewardship Found.*, 166 Wn. App. at 200, 274 P.3d at 1053 footnote omitted.
[187] Laws of 1990 1st ex.s., ch. 17, § 63. This law was the original adoption of the GMA.

require consideration of water availability.[188] In 1992, the Attorney General issued AGO 1992 No. 17 which made clear that the adoption of RCW 19.27.097 and the amendment of RCW 58.17.110 mandated that counties must require building permits and subdivision applications to document that water was legally and physically available.[189] The Washington State Supreme Court decided the *Kittitas County* decision in 2011.[190] Despite decades of authority requiring Snohomish County to incorporate requirements for legal and physical water availability into their development regulations, the County refused to incorporate these provisions into Ordinance No. 15-034 in 2015.[191]

The next deadline for Snohomish County to update its comprehensive plan and development regulations is June 30, 2023.[192] For critical areas updates, the next update deadline for Snohomish County is June 30, 2024.[193] Futurewise and the Pilchuck Audubon Society cannot appeal the County's failure to adopt the development regulations required by Laws of 2018, ch. 1, § 102 until these deadlines have passed.[194] Snohomish County's history on water issues recounted above indicates that it is

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[188] Laws of 1990 1st ex.s., ch. 17, § 52 adding "potable" to "water supplies."
[189] AR 001230 – 37, AGO 1992 No. 17 pp. 1 – 8 of 8.
[190] *Kittitas County*, 172 Wn.2d 144, 256 P.3d 1193 (2011).
[191] AR 000067 – 63, Ord. No. 15-034 pp. 59 – 71.
[192] RCW 36.70A.130(5)(a).
[193] RCW 36.70A.130(7)(b).
[194] *Thurston Cty.*, 164 Wn.2d at 344, 190 P.3d at 45..

unlikely the County will adopt the development regulations required by Laws of 2018, ch. 1, § 102 anytime soon. A significant amount of development could vest in watersheds closed to the appropriation of water. This can damage instream flows and senior water rights holders such as farmers. Unlike the *Olympic Stewardship Foundation* decision,[195] there is no published opinion addressing Laws of 2018, ch. 1. As the arguments set out below show, the application of Laws of 2018, ch. 1 is largely a legal question. So extensive factual development is unnecessary. Therefore, justice requires consideration of the arguments related to Laws of 2018, ch. 1. These arguments are set out below. The Court should remand Issue 7 back to the Board to consider these arguments.

There are four Water Resource Inventory Areas (WRIAs) in Snohomish County, WRIAs 3, 5, 7, and 8.[196] The Laws of 2018, ch. 1 apply different requirements to the various WRIA.

The Laws of 2018, ch. 1, § 101(1)(b), (f), and (g)[197] exclude WRIA 3, the Lower Skagit-Samish basin, and WRIA 5, the Stillaguamish basin, from Laws of 2018, ch. 1, § 101(1)(e) which allows a well log for a permit-exempt well to be used as evidence that water is legally and

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[195] *Olympic Stewardship Found.*, 166 Wn. App. at 200–01, 274 P.3d at 1054.
[196] WAC 173-500-990.
[197] Also referred to ESSB 6091 and accessed on April 26, 2018 at: http://lawfilesext.leg.wa.gov/biennium/2017-18/Pdf/Bills/Session%20Laws/Senate/6091-S.SL.pdf.

physically available for a building permit. This is because subsection (1)(g) applies to “other areas of the state,” that is areas other than those listed in Laws of 2018, ch. 1, §§ 101(1)(b) through (f). The WRIA 3, the Lower Skagit-Samish basin, is listed in Laws of 2018, ch. 1, § 101(1)(f). WRIA 5, the Stillaguamish basin, is listed in Laws of 2018, ch. 1, § 101(1)(b). So, for the parts of Snohomish County in WRIAs 3 and 5, the County must require building permit applicants to show that they have a legally and physically available water supply that meets drinking water standards before the County can issue a building permit.[198]

Additional requirements also apply within the parts of WRIA 3 in Snohomish County.[199] Laws of 2018, ch. 1, § 101(1)(f) require that evidence of an adequate water supply for a building permit must comply with the Washington State Supreme Court’s holding in *Swinomish Indian Tribal Community v. Department of Ecology*. In that decision, the State Supreme Court held that Ecology’s amended instream flow rule that included “27 reservations of water for out-of-stream, year-round noninterruptible beneficial uses in the Skagit River basin and that would impair minimum flows set by administrative rule exceeded Ecology's authority because it is inconsistent with the plain language of the statute

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[198] Laws of 2018, ch. 1 § 101(1)(a); *Whatcom Cty. v. Hirst*, 186 Wn.2d 648, 673, 381 P.3d 1, 11 (2016)..
[199] Laws of 2018, ch. 1, § 101(1)(f); WAC 173-503-010.

and is inconsistent with the entire statutory scheme."[200] So permit-exempt wells for domestic uses, such as building permits, must comply with the instream flow rules adopted for WRIA 3.[201]

Additional requirements also apply within WRIA 5. Laws of 2018, ch. 1, § 101(1)(b) provides that evidence of an adequate water supply for a building permit must be consistent with the specific applicable "instream flow rules adopted by the department of ecology under chapters 90.22 and 90.54 RCW that explicitly regulate permit-exempt groundwater withdrawals …"

For WRIAs 7 and 8, evidence of an adequate water supply for a building permit "must be consistent with … " Laws of 2018, ch. 1, § 203 "unless the applicant provides other evidence of an adequate water supply that complies with chapters 90.03 and 90.44 …."[202] Laws of 2018, ch. 1, § 203(3) requires the State of Washington Department of Ecology to prepare and adopt a watershed restoration and enhancement plan in collaboration with a watershed restoration and enhancement committee by June 30, 2021. Laws of 2018, ch. 1, § 203(4)(a) provides that until a watershed restoration and enhancement plan is approved and Ecology adopts rules

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[200] *Swinomish Indian Tribal Cmty. v. Washington State Dep't of Ecology*, 178 Wn.2d 571, 602 – 03, 311 P.3d 6, 21 (2013).
[201] *Id.*; *Swinomish Indian Tribal Cmty.*, 178 Wn.2d at 587 & 598, 311 P.3d at 13 & 19; WAC 173-503-040(5).
[202] Laws of 2018, ch. 1, § 101(1)(d).

under Laws of 2018, ch. 1, § 203(3), Snohomish County must collect fees and limit the quantity of water that may be used when issuing building permits and subdivision approvals in WRIAs 7 and 8.

For all four WRIAs, the GMA was amended to require that Snohomish County's "[d]evelopment regulations must ensure that proposed water uses are consistent with RCW 90.44.050 and with applicable rules adopted pursuant to chapters 90.22 and 90.54 RCW when making decisions under RCW 19.27.097 and 58.17.110."[203] RCW 19.27.097 includes water availability requirements applicable to building permits. RCW 58.17.110 includes water available requirements applicable to subdivisions. Development regulations include critical areas regulations and amendments to critical areas, including those amended by Ordinance No. 15-034.[204] So Snohomish County is required to include water availability requirements in its critical areas regulations or other development regulations.

Whether this Court confines its legal analysis to the law as it existed when the Board decide this case or remands Issue 7 back to the Board to

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[203] Laws of 2018, ch. 1, § 102.

[204] AR 000067, Ord. No. 15-034 p. 59; RCW 36.70A.030(7) "'Development regulations' or 'regulation' means the controls placed on development or land use activities by a county or city, including, but not limited to, zoning ordinances, critical areas ordinances, shoreline master programs, official controls, planned unit development ordinances, subdivision ordinances, and binding site plan ordinances together with any amendments thereto."

decide the application of the Laws of 2018, ch. 1, Snohomish County's failure to amend its critical areas regulations to require that water be legally and physically available consistent with the applicable instream flow rules violates the GMA. This Court should reverse this issue or remand the issue back to the Board.

VI. CONCLUSION

For the reasons set out above, Futurewise respectfully requests that this Court require the Board to decide all of the issues in this appeal and to reverse the Board on its decisions on geologically hazards and CARAs. The Court should then remand this case back to the Board.

Respectfully submitted this 30th day of April 2018.

Tim Trohimovich, WSBA No. 22367
Attorney for Futurewise & the Pilchuck Audubon Society

CERTIFICATE OF SERVICE

I, Tim Trohimovich, declare under penalty of perjury and the laws of the State of Washington that, on April 30, 2018, I caused a PDF file of the original and true and correct copies of the following document to be served on the persons listed below in the manner shown: **Brief of Petitioners Futurewise & the Pilchuck Audubon Society** together with Appendices in Case No. 51458-3-II.

State of Washington Court of Appeals Division Two 950 Broadway, Suite 300 Tacoma, Washington 98402 *Electronic Original*		Ms. Alethea M. Hart Ms. Laura C. Kisielius Snohomish County Prosecutor's Office Civil Division Robert Drewel Bldg., 8th Floor, M/S 504 3000 Rockefeller Ave Everett, Washington 98201-4060 Tel: (425) 388-6330 Attorneys for Snohomish County	
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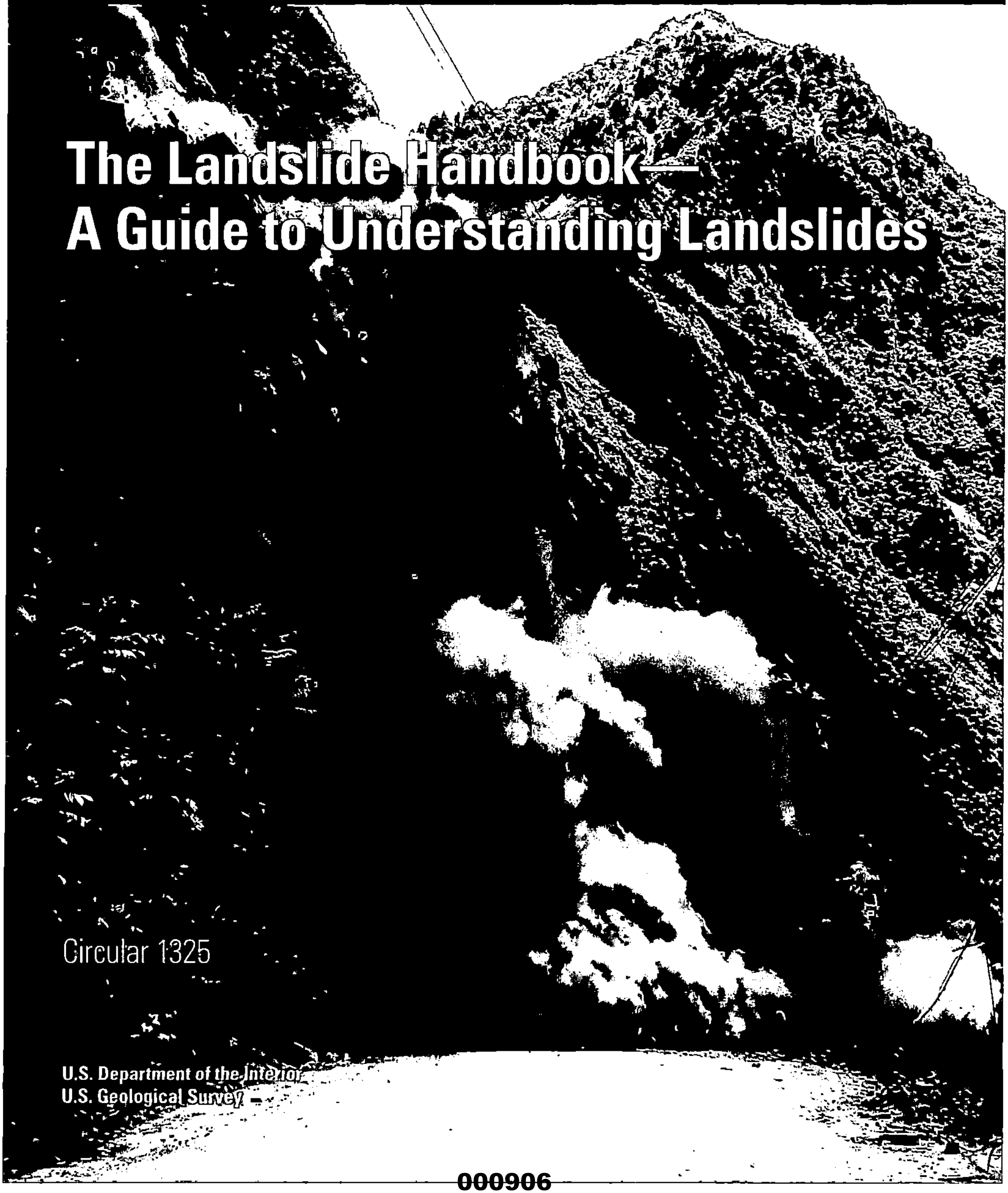
Dated this 30th day of April 2018.

Tim Trohimovich, WSBA No. 22367

USGS
science for a changing world

The Landslide Handbook—A Guide to Understanding Landslides



Circular 1325

U.S. Department of the Interior
U.S. Geological Survey

000906

The Landslide Handbook— A Guide to Understanding Landslides

By Lynn M. Highland, United States Geological Survey, and
Peter Bobrowsky, Geological Survey of Canada

Circular 1325

U.S. Department of the Interior
U.S. Geological Survey

Part D. What Causes Landslides?

There are two primary categories of causes of landslides: natural and human-caused. Sometimes, landslides are caused, or made worse, by a combination of the two factors.

Natural Occurrences

This category has three major triggering mechanisms that can occur either singly or in combination —(1) water, (2) seismic activity, and (3) volcanic activity. Effects of all of these causes vary widely and depend on factors such as steepness of slope, morphology or shape of terrain, soil type, underlying geology, and whether there are people or structures on the affected areas. Effects of landslides will be discussed in more detail in Part E.

Landslides and Water

Slope saturation by water is a primary cause of landslides. Saturation can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and surface-water level changes along coastlines, earth dams, and in the banks of lakes, reservoirs, canals, and rivers. Landslides and flooding are closely associated because both are related to precipitation, runoff, and the saturation of ground by water. Flooding may cause landslides by undercutting banks of streams and rivers and by saturation of slopes by surface water (overland flow). In addition, debris flows and mudflows usually occur in small, steep stream channels and commonly are mistaken for floods; in fact, these two events often occur simultaneously in the same area. Conversely, landslides also can cause flooding when sliding rock and debris block stream channels and other waterways, allowing large volumes of water to back up behind such dams. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Moreover, solid landslide debris can "bulk" or add volume and density to otherwise normal streamflow or cause channel blockages and diversions, creating flood conditions or localized erosion. Landslides also can cause tsunamis (seiches), overtopping of reservoirs, and (or) reduced capacity of reservoirs to store water. Steep wildfire-burned slopes often are landslide-prone due to a combination of the burning and resultant denudation of vegetation on slopes, a change in soil chemistry due to burning, and a subsequent saturation of slopes by water from various sources, such as rainfall. Debris flows are the most common type of landslide on burned slopes (for a description and images of a debris flow, see "*Part B.* Basic Landslide Types" in Section I). Wildfires, of course, may be the result of natural or human causes. Figure 26 shows a devastating landslide caused by rainfall, and possibly made worse by a leaking water pipe, which added even more water to the soil.

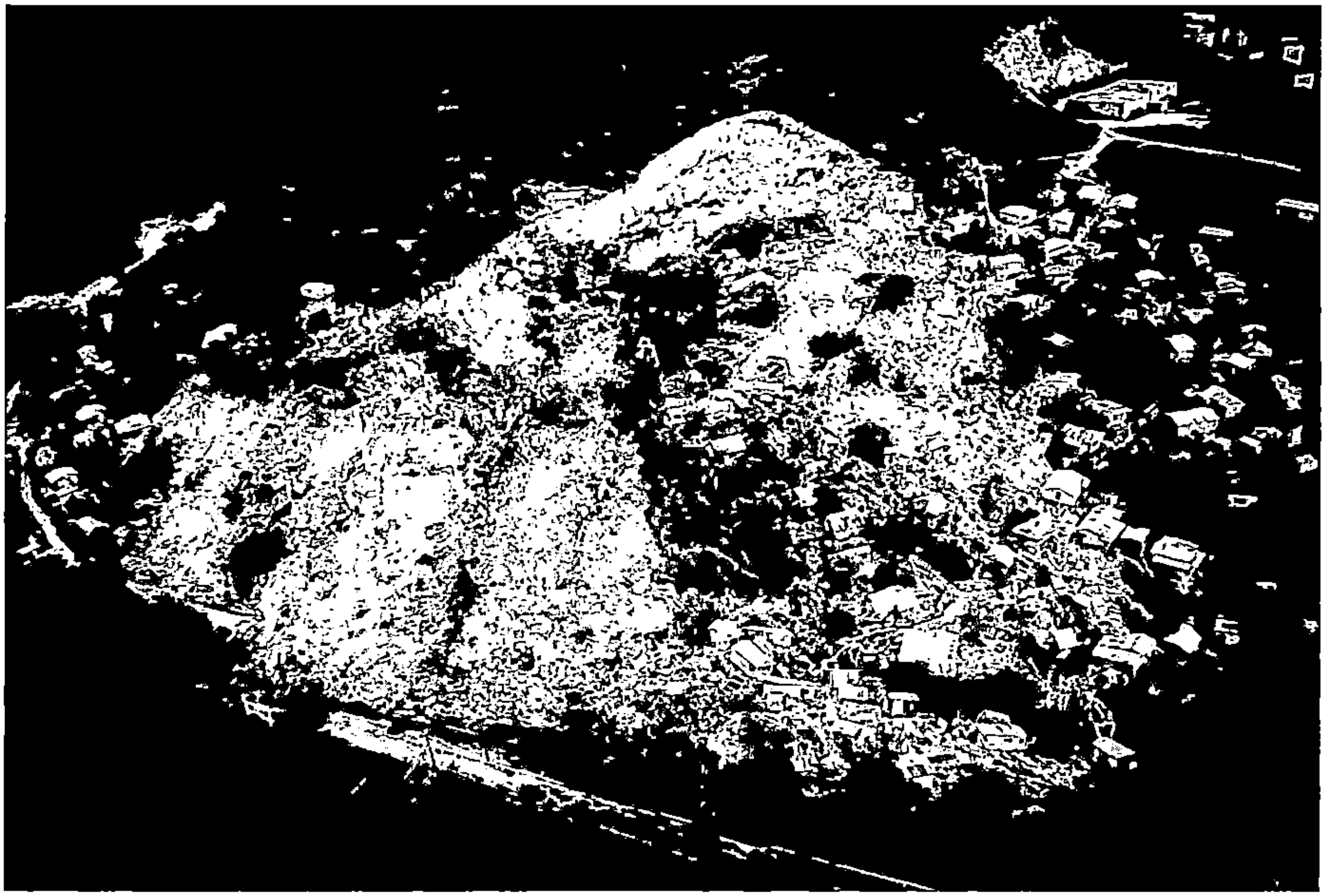


Figure 26. The Mameyes, Puerto Rico, landslide, 1985. This landslide destroyed 120 houses and killed at least 129 people. The catastrophic slide was triggered by a tropical storm that produced extremely heavy rainfall. Contributing factors could also have included sewage saturating the ground in the densely populated area, and a leaking water pipe at the top of the landslide. (Photograph by Randall Jibson, U.S. Geological Survey.)

Landslides and Volcanic Activity

Landslides due to volcanic activity represent some of the most devastating types of failures. Volcanic lava may melt snow rapidly, which can form a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars, an Indonesian term) can reach great distances after they leave the flanks of the volcano and can damage structures in flat areas surrounding the volcanoes. Volcanic edifices are young, unconsolidated, and geologically weak structures that in many cases can collapse and cause rockslides, landslides, and debris avalanches. Many islands of volcanic origin experience periodic failure of their perimeter areas (due to the weak volcanic surface deposits), and masses of soil and rock slide into the ocean or other water bodies, such as inlets. Such collapses may create massive sub-marine landslides that may also rapidly displace water, subsequently creating deadly tsunamis that can travel and do damage at great distances, as well as locally. Figure 28 shows a collapse of the side of a volcano and the resulting devastation.

Figure 28. The side of Casita Volcano in Nicaragua, Central America, collapsed on October 30, 1998, the day of peak rainfall as Hurricane Mitch moved across Central America. This lahar killed more than 2,000 people as it swept over the towns of El Porvenir and Rolando Rodriguez. (Photograph by K.M. Smith, U.S. Geological Survey.)

Human Activities

Populations expanding onto new land and creating neighborhoods, towns, and cities is the primary means by which humans contribute to the occurrence of landslides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. Other examples include oversteepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes. New construction on landslide-prone land can be improved through proper engineering (for example, grading, excavating) by first identifying the site's susceptibility to slope failures and by creating appropriate landslide zoning.

See Appendix A for an expanded, detailed list of causes/triggering mechanisms of landslides.

For further reading:
References 16, 19, 32, 38, 39, 43, and 45

Part 2. Parts of a Landslide—Description of Features/Glossary

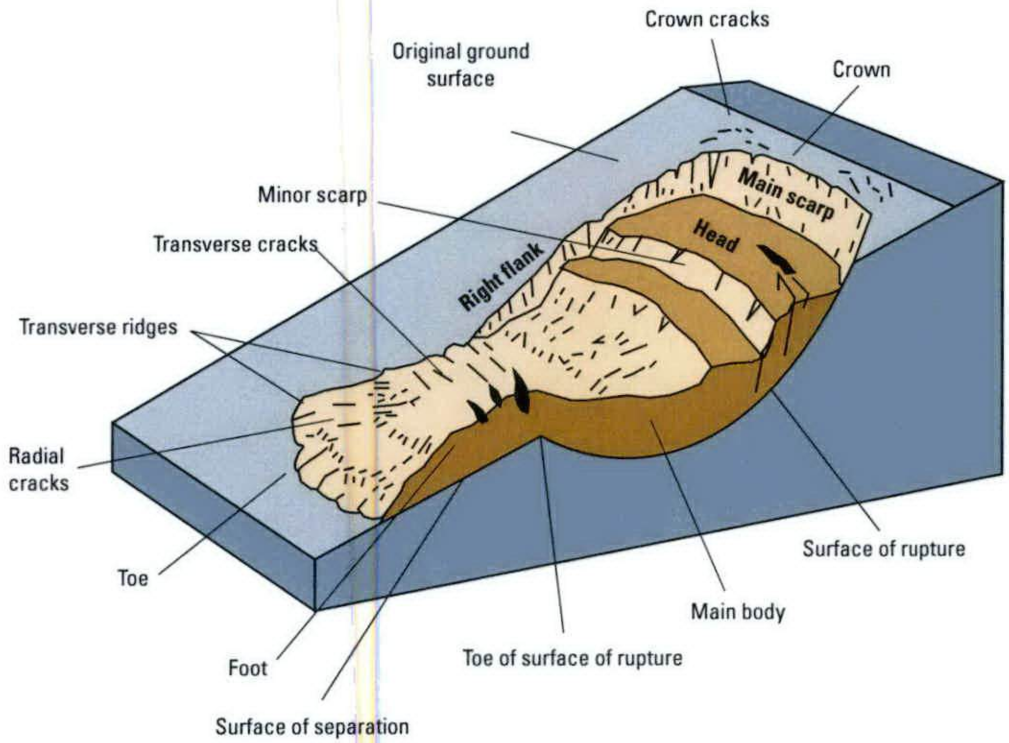


Figure A1. Parts of a landslide. (Modified from Varnes, 1978, reference 43).

accumulation The volume of the displaced material, which lies above the original ground surface.

crown The practically undisplaced material still in place and adjacent to the highest parts of the main scarp.

depletion The volume bounded by the main scarp, the depleted mass and the original ground surface.

depleted mass The volume of the displaced material, which overlies the rupture surface but underlies the original ground surface.

displaced material Material displaced from its original position on the slope by movement in the landslide. It forms both the depleted mass and the accumulation.

flank The undisplaced material adjacent to the sides of the rupture surface. Compass directions are preferable in describing the flanks, but if left and right are used, they refer to the flanks as viewed from the crown.

foot The portion of the landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface.

head The upper parts of the landslide along the contact between the displaced material and the main scarp.

main body The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture.

main scarp A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part of the surface of rupture.

minor scarp A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.

original ground surface The surface of the slope that existed before the landslide took place.

surface of separation The part of the original ground surface overlain by the foot of the landslide.

surface of rupture The surface that forms (or which has formed) the lower boundary of the displaced material below the original ground surface.

tip The point of the toe farthest from the top of the landslide.

toe The lower, usually curved margin of the displaced material of a landslide, it is the most distant from the main scarp.

top The highest point of contact between the displaced material and the main scarp.

toe of surface of rupture The intersection (usually buried) between the lower part of the surface of rupture of a landslide and the original ground surface.

zone of accumulation The area of the landslide within which the displaced material lies above the original ground surface.

zone of depletion The area of the landslide within which the displaced material lies below the original ground surface.

Sources of information on nomenclature:

1. Cruden, D.M., 1993, The multilingual landslide glossary: Richmond, British Columbia, Bitech Publishers, for the IUGS Working Party on World Landslide Inventory in 1993.
2. Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R. J., eds., Landslides—Analysis and control: Transportation Research Board Special Report 176, National Research Council, Washington, D.C., p. 11–23.

Part 3. Landslide Causes and Triggering Mechanisms

Physical Causes—Triggers

- Intense rainfall
- Rapid snowmelt
- Prolonged intense precipitation
- Rapid drawdown (of floods and tides) or filling
- Earthquake
- Volcanic eruption
- Thawing
- Freeze-and-thaw weathering
- Shrink-and-swell weathering
- Flooding

For further reading: References 9, 3, and 45

Natural Causes

Geological causes

- Weak materials, such as some volcanic slopes or unconsolidated marine sediments, for example
- Susceptible materials
- Weathered materials
- Sheared materials
- Jointed or fissured materials
- Adversely oriented mass discontinuity (bedding, schistosity, and so forth)
- Adversely oriented structural discontinuity (fault, unconformity, contact, and so forth)
- Contrast in permeability
- Contrast in stiffness (stiff, dense material over plastic materials)

Morphological causes

- Tectonic or volcanic uplift
- Glacial rebound
- Glacial meltwater outburst
- Fluvial erosion of slope toe
- Wave erosion of slope toe
- Glacial erosion of slope toe
- Erosion of lateral margins
- Subterranean erosion (solution, piping)
- Deposition loading slope or its crest
- Vegetation removal (by forest fire, drought)

Human Causes

- Excavation of slope or its toe
- Use of unstable earth fills, for construction
- Loading of slope or its crest, such as placing earth fill at the top of a slope
- Drawdown and filling (of reservoirs)
- Deforestation—cutting down trees/logging and (or) clearing land for crops; unstable logging roads
- Irrigation and (or) lawn watering
- Mining/mine waste containment
- Artificial vibration such as pile driving, explosions, or other strong ground vibrations
- Water leakage from utilities, such as water or sewer lines
- Diversion (planned or unplanned) of a river current or longshore current by construction of piers, dikes, weirs, and so forth

Spreads

An extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads may result from liquefaction or flow (and extrusion) of the softer underlying material. Types of spreads include block spreads, liquefaction spreads, and lateral spreads.

Lateral Spreads

Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. In rock spreads, solid ground extends and fractures, pulling away slowly from stable ground and moving over the weaker layer without necessarily forming a recognizable surface of rupture. The softer, weaker unit may, under certain conditions, squeeze upward into fractures that divide the extending layer into blocks. In earth spreads, the upper stable layer extends along a weaker underlying unit that has flowed following liquefaction or plastic deformation. If the weaker unit is relatively thick, the overriding fractured blocks may subside into it, translate, rotate, disintegrate, liquefy, or even flow.

Occurrence

Worldwide and known to occur where there are liquefiable soils. Common, but not restricted, to areas of seismic activity.

Relative size/range

The area affected may start small in size and have a few cracks that may spread quickly, affecting areas of hundreds of meters in width.

Velocity of travel

May be slow to moderate and sometimes rapid after certain triggering mechanisms, such as an earthquake. Ground may then slowly spread over time from a few millimeters per day to tens of square meters per day.

Triggering mechanism

Triggers that destabilize the weak layer include:

- Liquefaction of lower weak layer by earthquake shaking
- Natural or anthropogenic overloading of the ground above an unstable slope
- Saturation of underlying weaker layer due to precipitation, snowmelt, and (or) ground-water changes
- Liquefaction of underlying sensitive marine clay following an erosional disturbance at base of a riverbank/slope
- Plastic deformation of unstable material at depth (for example, salt)

Effects (direct/indirect)

Can cause extensive property damage to buildings, roads, railroads, and lifelines. Can spread slowly or quickly, depending on the extent of water saturation of the various soil layers. Lateral spreads may be a precursor to earthflows.

Mitigation measures

Liquefaction-potential maps exist for some places but are not widely available. Areas with potentially liquefiable soils can be avoided as construction sites, particularly in regions that are known to experience frequent earthquakes. If high ground-water levels are involved, sites can be drained or other water-diversion efforts can be added.

Predictability

High probability of recurring in areas that have experienced previous problems. Most prevalent in areas that have an extreme earthquake hazard as well as liquefiable soils. Lateral spreads are also associated with susceptible marine clays and are a common problem throughout the St. Lawrence Lowlands of eastern Canada. Figures 11 and 12 show a schematic and an image of a lateral spread.

For further reading:
References 9, 39, 43, and 45

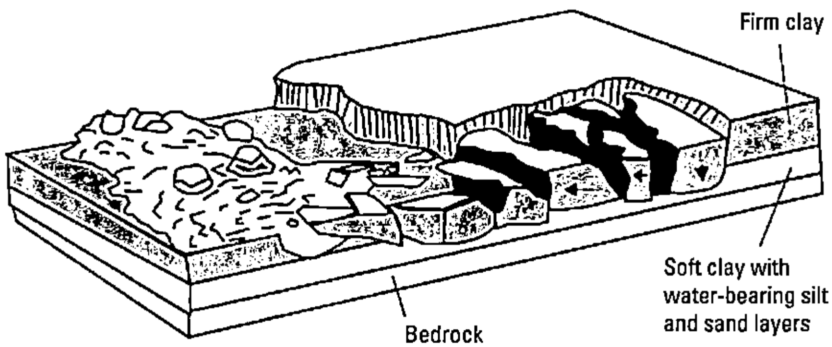


Figure 11. Schematic of a lateral spread. A liquefiable layer underlies the surface layer. (Schematic modified from Reference 9.)

Figure 12. Photograph of lateral spread damage to a roadway as a result of the 1989 Loma Prieta, California, USA, earthquake. (Photograph by Steve Ellen, U.S. Geological Survey.)

Flows

A flow is a spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved. The component velocities in the displacing mass of a flow resemble those in a viscous liquid. Often, there is a gradation of change from slides to flows, depending on the water content, mobility, and evolution of the movement.

Debris Flows

A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows downslope. They have been informally and inappropriately called "mudslides" due to the large quantity of fine material that may be present in the flow. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow. Dry flows can sometimes occur in cohesionless sand (sand flows). Debris flows can be deadly as they can be extremely rapid and may occur without any warning.

Occurrence

Debris flows occur around the world and are prevalent in steep gullies and canyons; they can be intensified when occurring on slopes or in gullies that have been denuded of vegetation due to wildfires or forest logging. They are common in volcanic areas with weak soil.

Relative size/range

These types of flows can be thin and watery or thick with sediment and debris and are usually confined to the dimensions of the steep gullies that facilitate their downward movement. Generally the movement is relatively shallow and the runout is both long and narrow, sometimes extending for kilometers in steep terrain. The debris and mud usually terminate at the base of the slopes and create fanlike, triangular deposits called debris fans, which may also be unstable.

Velocity of travel

Can be rapid to extremely rapid (35 miles per hour or 56 km per hour) depending on consistency and slope angle.

Triggering mechanisms

Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material.

Effects (direct/indirect)

Debris flows can be lethal because of their rapid onset, high speed of movement, and the fact that they can incorporate large boulders and other pieces of debris. They can move objects as large as houses in their downslope flow or can fill structures with a rapid accumulation of sediment and organic matter. They can affect the quality of water by depositing large amounts of silt and debris.

Mitigation measures

Flows usually cannot be prevented; thus, homes should not be built in steep-walled gullies that have a history of debris flows or are otherwise susceptible due to wildfires, soil type, or other related factors. New flows can be directed away from structures by means of deflection, debris-flow basins can be built to contain flow, and warning systems can be put in place in areas where it is known at what rainfall thresholds debris flows are triggered. Evacuation, avoidance, and (or) relocation are the best methods to prevent injury and life loss.

For further reading:
References 9, 39, 43, and 45

Predictability

Maps of potential debris-flow hazards exist for some areas. Debris flows can be frequent in any area of steep slopes and heavy rainfall, either seasonally or intermittently, and especially in areas that have been recently burned or the vegetation removed by other means. Figures 13 and 14 show a schematic and an image of a debris flow.

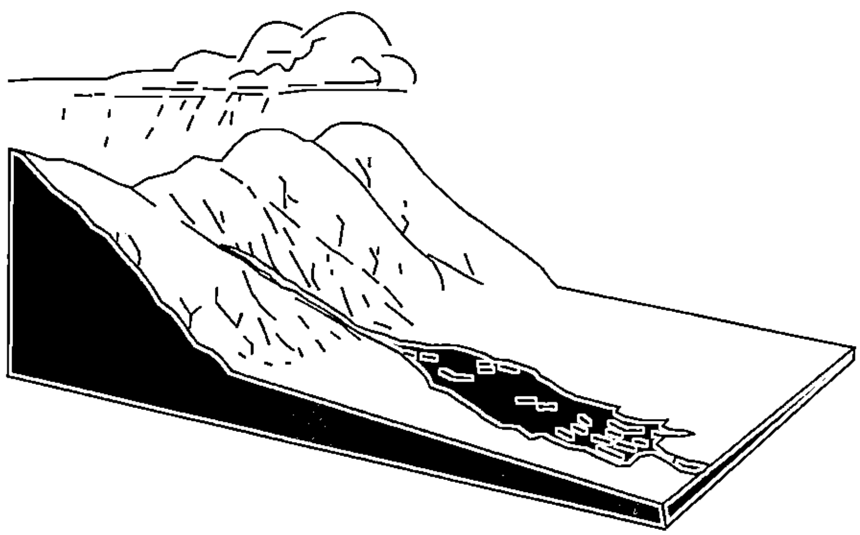


Figure 13. Schematic of a debris flow. (Schematic modified from Reference 9.)

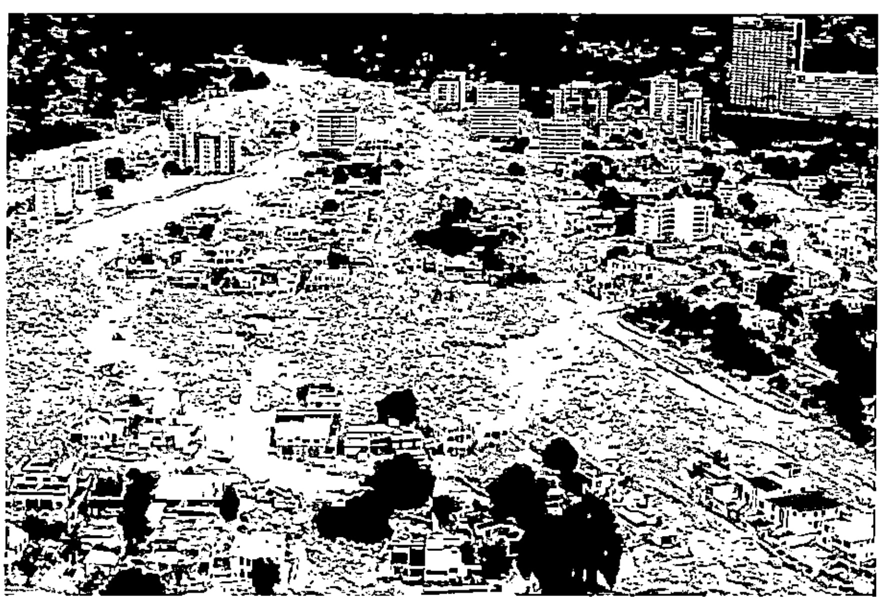


Figure 14. Debris-flow damage to the city of Caraballeda, located at the base of the Cordillera de la Costan, on the north coast of Venezuela. In December 1999, this area was hit by Venezuela's worst natural disaster of the 20th century; several days of torrential rain triggered flows of mud, boulders, water, and trees that killed as many as 30,000 people. (Photograph by L.M. Smith, Waterways Experiment Station, U.S. Army Corps of Engineers.)

Lahars (Volcanic Debris Flows)

The word "lahar" is an Indonesian term. Lahars are also known as volcanic mudflows. These are flows that originate on the slopes of volcanoes and are a type of debris flow. A lahar mobilizes the loose accumulations of tephra (the airborne solids erupted from the volcano) and related debris.

Occurrence

Found in nearly all volcanic areas of the world.

Relative size/range

Lahars can be hundreds of square kilometers or miles in area and can become larger as they gain speed and accumulate debris as they travel downslope; or, they can be small in volume and affect limited areas of the volcano and then dissipate downslope.

Velocity of travel

Lahars can be very rapid (more than 35 miles per hour or 50 kilometers per hour) especially if they mix with a source of water such as melting snowfields or glaciers. If they are viscous and thick with debris and less water, the movement will be slow to moderately slow.

Triggering mechanism

Water is the primary triggering mechanism, and it can originate from crater lakes, condensation of erupted steam on volcano particles, or the melting of snow and ice at the top of high volcanoes. Some of the largest and most deadly lahars have originated from eruptions or volcanic venting which suddenly melts surrounding snow and ice and causes rapid liquefaction and flow down steep volcanic slopes at catastrophic speeds.

Effects (direct/indirect)

Effects can be extremely large and devastating, especially when triggered by a volcanic eruption and consequent rapid melting of any snow and ice—the flow can bury human settlements located on the volcano slopes. Some large flows can also dam rivers, causing flooding upstream. Subsequent breaching of these weakly cemented dams can cause catastrophic flooding downstream. This type of landslide often results in large numbers of human casualties.

Mitigation measures

No corrective measures are known that can be taken to prevent damage from lahars except for avoidance by not building or locating in their paths or on the slopes of volcanoes. Warning systems and subsequent evacuation work in some instances may save lives. However, warning systems require active monitoring, and a reliable evacuation method is essential.

Predictability

Susceptibility maps based on past occurrences of lahars can be constructed, as well as runout estimations of potential flows. Such maps are not readily available for most hazardous areas. Figures 15 and 16 show a schematic and an image of a lahar.

For further reading: References 9, 39, 43, and 45

Figure 15. Schematic of a lahar. (Graphic by U.S. Geological Survey.)

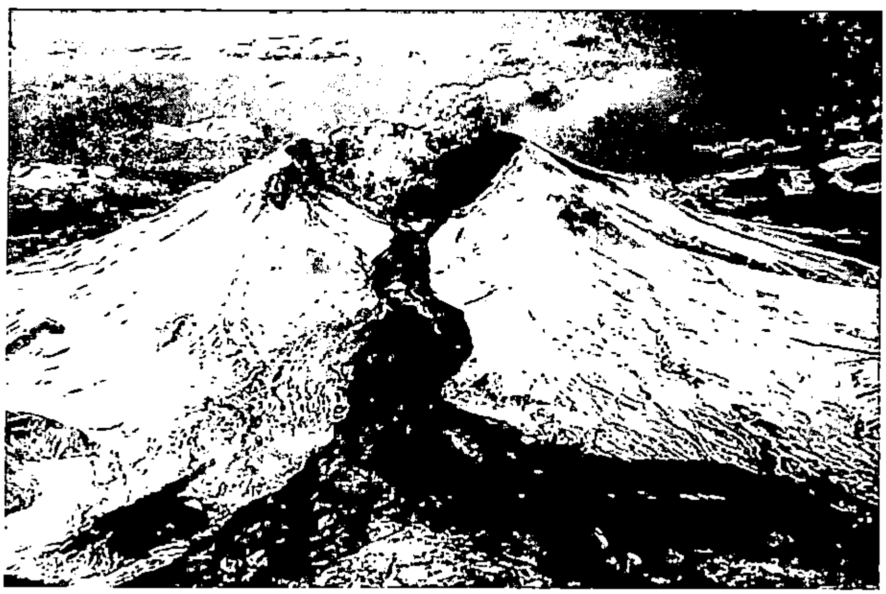


Figure 16. Photograph of a lahar caused by the 1982 eruption of Mount St. Helens in Washington, USA. (Photograph by Tom Casadevall, U.S. Geological Survey.)

Debris Avalanche

Debris avalanches are essentially large, extremely rapid, often open-slope flows formed when an unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope. In some cases, snow and ice will contribute to the movement if sufficient water is present, and the flow may become a debris flow and (or) a lahar.

Occurrence

Occur worldwide in steep terrain environments. Also common on very steep volcanoes where they may follow drainage courses.

Relative size/range

Some large avalanches have been known to transport material blocks as large as 3 kilometers in size, several kilometers from their source.

Velocity of travel

Rapid to extremely rapid; such debris avalanches can travel close to 100 meters/sec.

Triggering mechanism

In general, the two types of debris avalanches are those that are "cold" and those that are "hot." A cold debris avalanche usually results from a slope becoming unstable, such as during collapse of weathered slopes in steep terrain or through the disintegration of bedrock during a slide-type landslide as it moves downslope at high velocity. At that point, the mass can then transform into a debris avalanche. A hot debris avalanche is one that results from volcanic activity including volcanic earthquakes or the injection of magma, which causes slope instability.

Effects (direct/indirect)

Debris avalanches may travel several kilometers before stopping, or they may transform into more water-rich lahars or debris flows that travel many tens of kilometers farther downstream. Such failures may inundate towns and villages and impair stream quality. They move very fast and thus may prove deadly because there is little chance for warning and response.

Corrective measures/mitigation

Avoidance of construction in valleys on volcanoes or steep mountain slopes and real-time warning systems may lessen damages. However, warning systems may prove difficult due to the speed at which debris avalanches occur—there may not be enough time after the initiation of the event for people to evacuate. Debris avalanches cannot be stopped or prevented by engineering means because the associated triggering mechanisms are not preventable.

Predictability

If evidence of prior debris avalanches exists in an area, and if such evidence can be dated, a probabilistic recurrence period might be established. During volcanic eruptions, chances are greater for a debris avalanche to occur, so appropriate cautionary actions could be adopted. Figures 17 and 18 show a schematic and an image of a debris avalanche.

For further reading: References 9, 39, 43, and 45

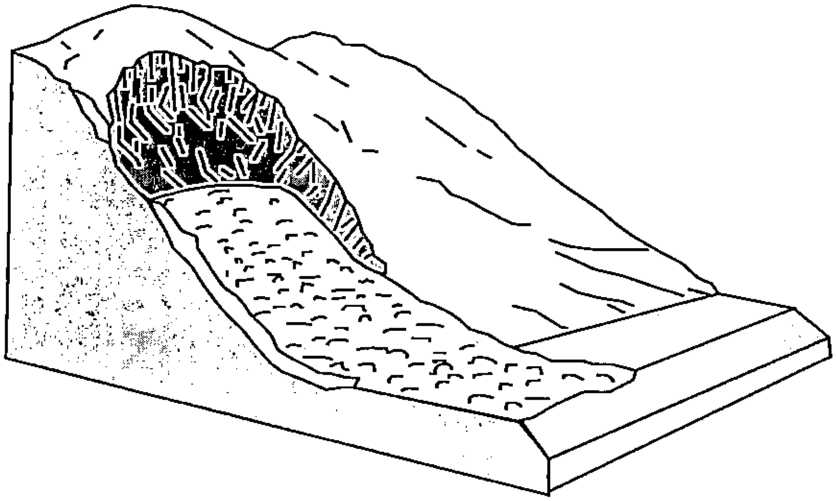


Figure 17. Schematic of a debris avalanche. (Schematic modified from Reference 9.)

Figure 18. A debris avalanche that buried the village of Guinsaugon, Southern Leyte, Philippines, in February 2006. (Photograph by University of Tokyo Geotechnical Team.) Please see figure 30 for an image of another debris avalanche.

Earthflow

Earthflows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earthflow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy, potentially destroying large areas and flowing for several kilometers. Size commonly increases through headscarp retrogression. Slides or lateral spreads may also evolve downslope into earthflows. Earthflows can range from very slow (creep) to rapid and catastrophic. Very slow flows and specialized forms of earthflow restricted to northern permafrost environments are discussed elsewhere.

Occurrence

Earthflows occur worldwide in regions underlain by fine-grained soil or very weathered bedrock. Catastrophic rapid earthflows are common in the susceptible marine clays of the St. Lawrence Lowlands of North America, coastal Alaska and British Columbia, and in Scandinavia.

Relative (size/range)

Flows can range from small events of 100 square meters in size to large events encompassing several square kilometers in area. Earthflows in susceptible marine clays may runout for several kilometers. Depth of the failure ranges from shallow to many tens of meters.

Velocity of travel

Slow to very rapid.

Triggering mechanisms

Triggers include saturation of soil due to prolonged or intense rainfall or snowmelt, sudden lowering of adjacent water surfaces causing rapid drawdown of the ground-water table, stream erosion at the bottom of a slope, excavation and construction activities, excessive loading on a slope, earthquakes, or human-induced vibration.

Effects (direct/indirect)

Rapid, retrogressive earthflows in susceptible marine clay may devastate large areas of flat land lying above the slope and also may runout for considerable distances, potentially resulting in human fatalities, destruction of buildings and linear infrastructure, and damming of rivers with resultant flooding upstream and water siltation problems downstream. Slower earthflows may damage properties and sever linear infrastructure.

Corrective measures/mitigation

Improved drainage is an important corrective measure, as is grading of slopes and protecting the base of the slope from erosion or excavation. Shear strength of clay can be measured, and potential pressure can be monitored in suspect slopes. However, the best mitigation is to avoid development activities near such slopes.

Predictability

Evidence of past earthflows is the best indication of vulnerability. Distribution of clay likely to liquefy can in some cases be mapped and has been mapped in many parts of eastern North America. Cracks opening near the top of the slope may indicate potential failure. Figures 19 and 20 show a schematic and an image of an earthflow.

For further reading: References 9, 39, 43, and 45

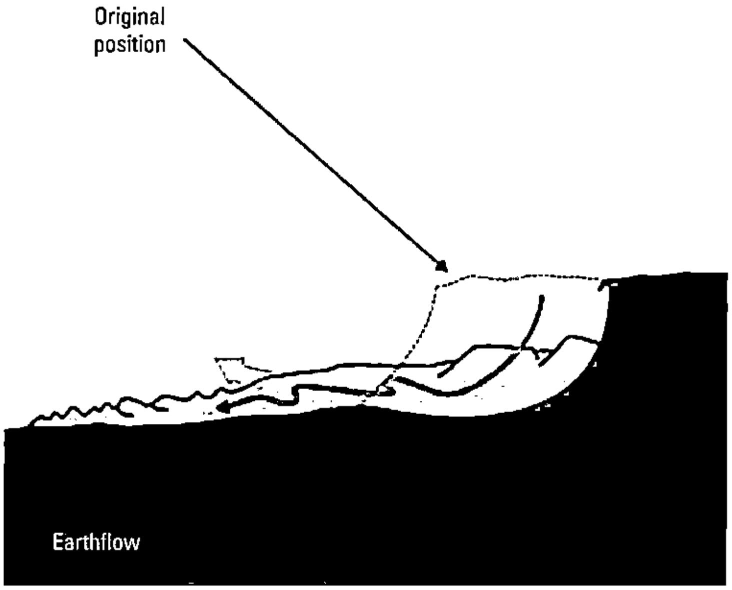


Figure 19. Schematic of an earthflow. (Schematic from Geological Survey of Canada.)

Figure 20. The 1993 Lemieux landslide—a rapid earthflow in sensitive marine clay near Ottawa, Canada. The headscarp retrogressed 680 meters into level ground above the riverbank. About 2.8 million tons of clay and silt liquefied and flowed into the South Nation River valley, damming the river. (Photograph by G.R. Brooks, Geological Survey of Canada.)

Slow Earthflow (Creep)

Creep is the informal name for a slow earthflow and consists of the imperceptibly slow, steady downward movement of slope-forming soil or rock. Movement is caused by internal shear stress sufficient to cause deformation but insufficient to cause failure. Generally, the three types of creep are: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure for other types of mass movements.

Occurrence

Creep is widespread around the world and is probably the most common type of landslide, often preceding more rapid and damaging types of landslides. Solifluction, a specialized form of creep common to permafrost environments, occurs in the upper layer of ice-rich, fine-grained soils during the annual thaw of this layer.

Relative size/range

Creep can be very regional in nature (tens of square kilometers) or simply confined to small areas. It is difficult to discern the boundaries of creep since the event itself is so slow and surface features representing perceptible deformation may be lacking.

Velocity of travel

Very slow to extremely slow. Usually less than 1 meter (0.3 foot) per decade.

Triggering mechanism

For seasonal creep, rainfall and snowmelt are typical triggers, whereas for other types of creep there could be numerous causes, such as chemical or physical weathering, leaking pipes, poor drainage, destabilizing types of construction, and so on.

Effects

Because it is hard to detect in some places because of the slowness of movement, creep is sometimes not recognized when assessing the suitability of a building site. Creep can slowly pull apart pipelines, buildings, highways, fences, and so forth, and can lead to more drastic ground failures that are more destructive and faster moving.

Corrective measures/mitigation

The most common mitigation for creep is to ensure proper drainage of water, especially for the seasonal type of creep. Slope modification such as flattening or removing all or part of the landslide mass, can be attempted, as well as the construction of retaining walls.

Part E. What are the Effects and Consequences of Landslides?

Landslide effects occur in two basic environments: the built environment and the natural environment. Sometimes there is intersection between the two; for example agricultural lands and forest lands that are logged.

Effects of Landslides on the Built Environment

Note: In many areas of the world that provide private disaster insurance, damage from landslides is not covered in these insurance policies, and the costs of damages must be borne by the individual homeowner.

Landslides affect manmade structures whether they are directly on or near a landslide. Residential dwellings built on unstable slopes may experience partial damage to complete destruction as landslides destabilize or destroy foundations, walls, surrounding property, and above-ground and underground utilities. Landslides can affect residential areas either on a large regional basis (in which many dwellings are affected) or on an individual site basis (where only one structure or part of a structure is affected). Also, landslide damage to one individual property's lifelines (such as trunk sewer, water, or electrical lines and common-use roads) can affect the lifelines and access routes of other surrounding properties. Commercial structures are affected by landslides in much the same way residential structures are affected. In such a case, consequences may be great if the commercial structure is a common-use structure, such as a food market, which may experience an interruption in business due to landslide damage to the actual structure and (or) damage to its access roadways.

Fast-moving landslides such as debris flows are the most destructive type of landslide to structures, as they often occur without precursors or warnings, move too quickly for any mitigation measures to be enacted, and due to velocity and material are often very powerful and destructive. Fast-moving landslides can completely destroy a structure, whereas a slower moving landslide may only slightly damage it, and its slow pace may allow mitigation measures to be enacted. However, left unchecked, even slow landslides can completely destroy structures over time. Debris avalanches and lahars in steep areas can quickly destroy or damage the structures and lifelines of cities, towns, and (or) neighborhoods due to the fact that they are an extremely fast-moving, powerful force. The nature of landslide movement and the fact that they may continue moving after days, weeks, or months preclude rebuilding on the affected area, unless mitigative measures are taken; even then, such efforts are not always a guarantee of stability.

One of the greatest potential consequences from landslides is to the transportation industry, and this commonly affects large numbers of people around the world. Cut and fill failures along roadways and railways, as well as collapse of roads from underlying weak and slide-prone soils and fill, are common problems. Rockfalls may injure or kill motorists and pedestrians and damage structures. All types of landslides can lead to temporary or long-term closing of crucial routes for commerce, tourism, and emergency activities due to road or rail blockage by dirt, debris, and (or) rocks (fig. 29). Even slow creep can affect linear infrastructure, creating maintenance problems. Figure 29 shows a landslide blocking a major highway. Blockages of highways by landslides occur very commonly around the world, and many can simply be bulldozed or shoveled away. Others, such as the one shown in figure 29, will require major excavation and at least temporary diversion of traffic or even closure of the road.

As world populations continue to expand, they are increasingly vulnerable to landslide hazards. People tend to move on to new lands that might have been deemed too hazardous in the past but are now the only areas that remain for a growing population. Poor or nonexistent land-use policies allow building and other construction to take place on land that might better be left to agriculture, open-space parks, or uses other than for dwellings or other buildings and structures. Communities often are not prepared to regulate unsafe building practices and may not have the legitimate political means or the expertise to do so.

Effects of Landslides on the Natural Environment

Landslides have effects on the natural environment:

- The morphology of the Earth's surface—mountain and valley systems, both on the continents and beneath the oceans; mountain and valley morphologies are most significantly affected by downslope movement of large landslide masses;
- The forests and grasslands that cover much of the continents; and
- The native wildlife that exists on the Earth's surface and in its rivers, lakes, and seas.

Figures 30, 31, and 32 show the very large areal extent of some landslides and how they may change the face of the terrain, affecting rivers, farmland, and forests.

Forest, grasslands, and wildlife often are negatively affected by landslides, with forest and fish habitats being most easily damaged, temporarily or even rarely, destroyed. However, because landslides are relatively local events, flora and fauna can recover with time. In addition, recent ecological studies have shown that, under certain conditions, in the medium-to-long term, landslides can actually benefit fish and wildlife habitats, either directly or by improving the habitat for organisms that the fish and wildlife rely on for food.

The following list identifies some examples of landslides that commonly occur in the natural environment:

- ***Submarine landslide*** is a general term used to describe the downslope mass movement of geologic materials from shallower to deeper regions of the ocean. Such events may produce major effects to the depth of shorelines, ultimately affecting boat dockings and navigation. These types of landslides can occur in rivers, lakes, and oceans. Large submarine landslides triggered by earthquakes have caused deadly tsunamis, such as the 1929 Grand Banks (off the coast of Newfoundland, Canada) tsunamis.
- ***Coastal cliff retreat***, or ***cliff erosion***, is another common effect of landslides on the natural environment. Rock-and-soil falls, slides, and avalanches are the common types of landslides affecting coastal areas; however, topples and flows also are known to occur. Falling rocks from eroding cliffs can be especially dangerous to anyone occupying areas at the base of cliffs, or on the beaches near the cliffs. Large amounts of landslide material can also be destructive to aquatic life, such as fish and kelp, and the rapid deposition of sediments in water bodies often changes the water quality around vulnerable shorelines.
- ***Landslide dams*** can naturally occur when a large landslide blocks the flow of a river, causing a lake to form behind the blockage. Most of these dams are short-lived as the water will eventually erode the dam. If the landslide dam is not destroyed by natural erosional processes or modified by humans, it creates a new landform—a lake. Lakes created by landslide dams can last a long time, or they may suddenly be released and cause massive flooding downstream. There are many ways that people can lessen the potential dangers of landslide dams, and some of these methods are discussed in the safety and mitigation sections of this volume. Figure 32 shows the Slumgullion landslide one of the largest landslides in the world—the landslide dam it has formed is so large and wide, that it has lasted 700 years. Figures C53, C54, and C55 (in Appendix C) also show aspects of another large landslide dam.

For further reading:
References 4, 11, 14, 16, 19, 31, 35, 36, 39, and 43

See Appendix C for more information on mitigating the effects of landslide dams.

Geotechnical Extreme Events Reconnaissance

Turning Disaster into Knowledge

Sponsored by the National Science Foundation

July 22, 2014

The 22 March 2014 Oso Landslide, Snohomish County, Washington

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1.0 INTRODUCTION

The Oso Landslide struck the community of Oso, Snohomish County, Washington (Figure 1.1) on Saturday, 22 March 2014, at approximately 10:37 a.m. local time on a clear, sunny day. Winter precipitation in the region was generally high but not atypical for the Pacific Northwest. Still, the landslide occurred immediately after a three-week period that was marked by unusually high levels of rainfall locally. The Oso Landslide initiated within an approximately 200-m-high (650 ft) hillslope comprised of unconsolidated glacial and colluvial (i.e., previous landslide) deposits (Figure 1.2). It transitioned to a catastrophic debris flow (often referred to as a "mudslide") and rapidly inundated "Steelhead Haven," a neighborhood of approximately 35 single-family residences that was established in the 1960's. The debris flow separated into east and west segments as it traveled more than a kilometer (0.6 mi) across the valley floor. The overall size of the Oso Landslide was approximately 7.6 million cubic meters (~ 270 million cubic feet) [USGS 2014], placing it among the upper tier of mass movements that have occurred in Washington over recent decades. The slope at the location of the landslide has slid several times since the 1930's and also is the site of an ancient landslide. The most recent prior activity took place in 2006, when a landslide known as the "Hazel Landslide" occurred and blocked the North Fork Stillaguamish River. This 2006 landslide traveled over 100 m (300 feet), but came to rest before reaching the Steelhead Haven neighborhood.

The Oso Landslide's human toll was heart wrenching. The event claimed the lives of 43 people, making it the deadliest landslide event in United States history. Of the approximately 10 individuals who were struck by the landslide and survived, several sustained serious injuries. Many residents of the local community as well as members of search-and-rescue teams dispatched to the area in the days following the landslide have reported ongoing psychological distress as a result of the disaster. The landslide additionally caused significant economic losses, which Washington State officials have estimated to be more than $50 million. The landslide completely destroyed the Steelhead Haven neighborhood, as well as several homes located off of the nearby State Highway 530. Approximately 600 m (~ 2,000 ft) of highway was buried under up to 6 m (20 ft) of debris, which closed this major east-west transportation route for over 2 months.

In addition to its tragic human toll, the Oso Landslide has a number of important aspects that make it a highly significant geologic disaster.

1) After its initiation, portions of the landslide transitioned into a rapidly moving debris flow that traveled long distances across the downslope floodplain. This aspect of the landslide appears to be largely responsible for the significant loss-of-life.

2) Topographic conditions in the area of the landslide are well documented in a series of high-resolution airborne lidar surveys taken before the 2006 landslide, after the 2006 landslide but before the 2014 landslide, and after the 2014 landslide. Analysis of these

data sets allows for high resolution mapping of the landslide source area and depositional zones, and for characterization of the hazard.

3) The landslide was recorded at several seismographic stations deployed as part of the Pacific Northwest Seismic Network. The recordings provide unique insight to the landslide's failure sequence and duration.

4) The landslide produced unique morphologic features that are rarely observed in the field. These include regions of "sand boils" within the distal portion of the landslide debris and high mud splashes on surviving trees and nearby ground.

5) Despite having no precipitation monitoring instruments onsite, rain and stream gauges in the vicinity and NEXRAD Doppler weather radar data make it possible to bracket the possible range of antecedent rainfall over a wide range of time intervals (days, months and years).

6) Eyewitness accounts of the landslide have been reported by multiple individuals who observed and survived the event, including several who were struck by and subsequently became entrained in the debris flow.

This report presents the findings of the National Science Foundation (NSF)-supported Geotechnical Extreme Events Reconnaissance (GEER) Association scientific research team that performed a field reconnaissance of the Oso Landslide beginning approximately 8 weeks after its occurrence. The GEER team consisted of interdisciplinary group of professionals with expertise in geology, geomorphology, engineering geology, hydrology, hydrogeology, risk assessment and geotechnical engineering. The primary goals of the GEER field reconnaissance were to document conditions at the landslide and to collect potentially perishable field data. The report primarily focuses on observations made and data collected at the landslide site, but also reviews regional and local geologic conditions, climatic setting, eyewitness accounts, local land-use and landslide risk assessment. Based on this information, preliminary hypotheses are proposed that addresses landslide initiation, mobilization, and subsequent runout behavior. This report is based largely on data collected during a four-day team reconnaissance across the entire landslide area in late May 2014, two months after the Oso Landslide occurred. Additional information was obtained from review of airborne lidar, aerial photographs, and satellite imagery; pre- and post-event photographs and videos (including ultra-high resolution gigapixal panoramic images), precipitation- and stream-gauge data, Doppler weather radar data, professional reports and articles, seismologic data, interviews with community officials and residents, media accounts, and limited laboratory testing. The field reconnaissance and data products are described in more detail in Appendix A.

The publication of this report two months after the field reconnaissance reflects GEER's commitment to timely and open dissemination of data and findings. Field access to the landslide was granted to the GEER team shortly after search-and-rescue (SAR) and recovery activities had nearly concluded at the site. The SAR and recovery activities extended over a multi-week period due to the treacherous conditions at the site and the difficulty emergency response officials had in locating victims. The GEER investigation is not intended to be a final, conclusive study of the landslide; instead, it should be regarded as a preliminary assessment based on reconnaissance observations and other available data. It is recommended that additional research be conducted to test and challenge the interpretations and hypotheses presented in this report.

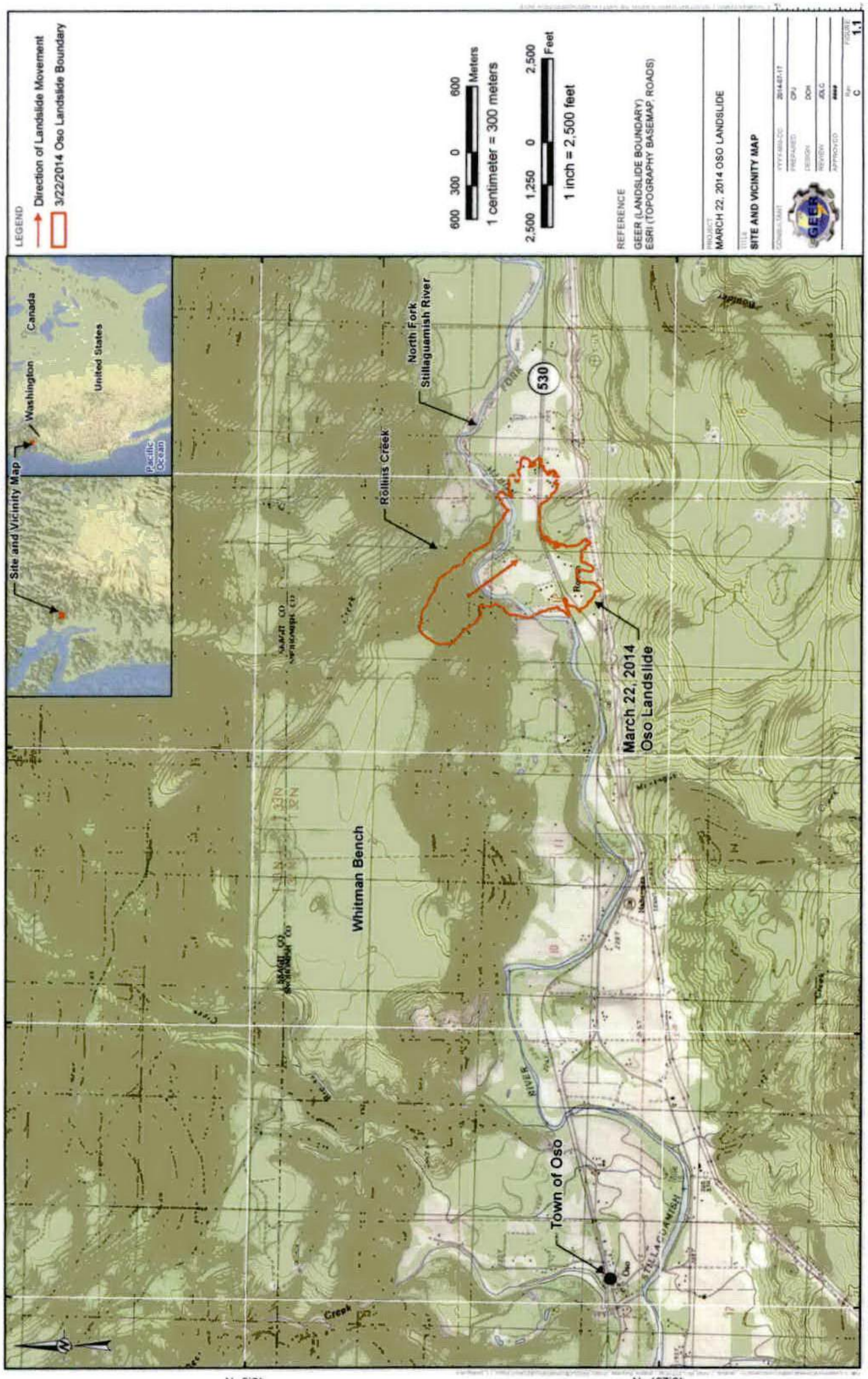

Figure 1.1 Site and vicinity map

Figure 1.2 The 22 March 2014 Oso, Washington Landslide (photograph courtesy of the Washington Dept. of Transportation)

2. GEOGRAPHIC AND GEOLOGIC SETTING

2.1 Physiography

The Oso Landslide is situated in a west-trending valley within the northern Cascade Range physiographic province (Figure 2.1.1). The Cascade Range is a volcanic arc that hosts active volcanoes that exceed elevations of 3,000 m (~10,000 ft) above sea level (asl), with the most recent historical activity being the 1980 eruption of Mount St. Helens (west of Mt. Adams in Figure 2.1.1). The Puget Lowland province is immediately west of the Cascade Range.

Topographic conditions in the area around the Oso Landslide are dominated by major valleys surrounding mountains with ridges and some sharp peaks (Figure 2.1.2). Mountains in the southeast part of Figure 2.1.2 have peaks that rise to elevations of nearly 2,100 m (~ 6,900 ft) asl. The North Fork Stillaguamish River valley is east-west trending and the river flows to the west. The north-trending valley on the east side of Figure 2.1.2 is the Sauk River valley.

Slope inclinations in the area immediately around the Oso Landslide (Figure 2.1.3) are dominated by relatively gently sloping valley bottoms and prominent upland benches with strip-like zones of steep slopes running along the valley walls. Channels of the North Fork Stillaguamish River and Rollins Creek have cut down into geologic materials deposited by glaciers, pro-glacial streams, or in glacier-dammed lakes. The scalloped morphology of the valley side slopes is clearly visible in the map of slope inclination (Figure 2.1.3).

Whitman Bench is one of the upland benches defining a low-relief landscape element at an elevation of about 275 m (900 ft) at its eastern end, adjacent to the Oso Landslide, and between bedrock slopes to the north and the river valley to the south. An unnamed bench at the same elevation as Whitman Bench is located on the southern side of the valley in the southeast part of Figure 2.1.3 implying that in early post-glacial time the bench-forming deposits likely extended across the valley bottom. The scalloped shape of the valley sides, the low-relief upland benches, and the strip-like pattern of steeper slopes implies repeated rotational slope movements (referred to as "slumps") that involved the full height of the valley sides. The river elevation prior to the 2014 Oso Landslide was approximately 76 m (250 ft) asl, amounting to approximately 200 m (650 ft) of local relief at the site of the Oso Landslide.

The 250-m topographic contour in Figure 2.1.2 suggests that the Oso Landslide is in the narrowest location within the North Fork Stillaguamish River valley. A more detailed, yet simple, analysis of the valley width was performed using the 200-m contour lines. The width between the 200-m contours shows that the Oso Landslide occurred within a relatively narrow (i.e., 2 to 2.4 km wide; 1.2 to 1.5 mi), roughly 10-km (~ 6 mi) long valley reach (Figure 2.1.4). In such a relatively narrow valley reach the geomorphic effects of both lateral channel migration on valley-wall landsliding, and therefore landslide-induced shifts in river-channel position, would be expected to be more pronounced than in the wider valley reaches both upstream and downstream.

2.2 Geologic Setting

The Oso Landslide occurred at a location where earlier landslides had been documented along the North Fork Stillaguamish River near a location called Hazel on an old railroad line (east part of Figure 2.2.1). The river drains part of the west slope of the Cascade Range and is underlain by rocks of variable lithology including Jurassic metasedimentary, metavolcanic, and ultramafic rocks in the western portion and Tertiary sedimentary and volcanic rocks in its eastern portion (Dragovich et al., 2002). The seismically-active, left-lateral Darrington-Devils Mountain Fault is mapped as running through the 2014 landslide runout zone beneath the valley bottom (Dragovich et al., 2003). Surficial Quaternary deposits of glacial-fluvial outwash, till, and glacial-lacustrine silts and clays blanket bedrock and form extensive topographic surfaces into which the river incised and carved its modern valley during the Holocene. Preservation of relatively large terraces underlain by unconsolidated glacial-fluvial outwash above thick deposits of glacially-associated lacustrine silts and clays is typical of west-draining valleys in the northern Cascade Range (Tabor et al., 1988; Booth, 1989).

Whitman Bench is one such terrace (Figures 2.1.3 and 2.2.1) that probably was a continuous topographic surface across the North Fork Stillaguamish River valley and contiguous with a similar but unnamed bench at the time the glaciers receded. The scalloped valley walls below Whitman Bench and below the companion unnamed bench are the heads of landforms mapped as landslides by Dragovich et al. (2003).

Dragovich et al. (2003) mapped the site of the 2014 Oso Landslide as part of a massive landslide complex, with local in-place exposures of Olympia non-glacial sediments (fluvial sands where exposed at the base of the section), overlain in turn by Vashon stade advance lacustrine deposits and till, with Everson interstade recessional lacustrine and outwash deposits forming the top of the section and the topographic surface of the Whitman Bench. Dragovich et al. (2003) report two radiocarbon dates (ages) of 35,040 ± 450 b.p. and 38,560 ± 640 b.p. for detrital wood fragments collected from forest beds in well-sorted oxidized sands from an exposure of Olympia age fluvial sediments exposed at river-level along the right bank in the area that was to become the eastern margin of the 2014 Oso Landslide.

Dragovich et al. (2003) mapped extensive areas of landsliding along the valley of the North Fork Stillaguamish River upstream and downstream of the Oso Landslide. In a cross-section constrained by well logs, Dragovich et al. (2003) show that the modern valley bottom alluvium overlies deposits from older (Holocene) landslide complexes beneath the valley floor in the runout zone of the 2014 Oso Landslide (Figure 2.2.1 shows the cross-section location in the runout zone, but the cross-section example is for the prehistoric landslide complex covering the valley bottom immediately west of the Oso Landslide). A well boring at station W55 on the cross section in Figure 2.2.1 shows landslide deposits burying valley bottom alluvial deposits. Together the cross-sections on the Dragovich et al. (2003) geologic map indicate a history of

Holocene landslides on valley slopes with deposits locally accumulating on the valley bottom in the immediate vicinity of the 2014 Oso Landslide location.

The stratigraphy of the landslide site is disrupted below the elevation of the "ancient headscarp" apparent on the 2003 hillshade image (Figure 2.2.2). But the undisturbed section now exposed in the 2014 landslide headscarp (Figure 2.2.3), together with exposures on the landslide lateral margins, indicates that the site geology consists of deposits that are typical of the sequence found throughout the Puget Lowland. [Note that "headscarp" in this report would be called "main scarp" by Cruden and Varnes (1996).]

Following glacial retreat approximately 16,000 years before present (b.p.) in northern Puget Sound (Porter and Swanson, 1998), the Stillaguamish River incised into the glacial sediments, with an early post-glacial landscape characterized by a wide valley bottom with low-relief terraces and low-gradient tributaries (Beechie et al., 2001). Immediately after glacial retreat the land surface was about 200 m (~ 650 ft) lower than today (due to isostatic depression), sea level was about 90 m (300 ft) lower, and the river valley at Arlington was close to sea level (Beechie et al., 2001). Around 12,500 b.p., lahar deposits from an eruption of Glacier Peak diverted the Sauk River from its course as a headwater tributary to the Stillaguamish and redirected it to flow into the upper Skagit River, significantly decreasing the stream power of the North Fork Stillaguamish River (Dragovich et al., 2000).

Post-glacial evolution of the valley involved river incision and lateral channel migration undermining the valley walls. Incision of the glacially-associated valley filling deposits created conditions conducive to mass wasting, as recorded in the scalloped morphology of the valley walls. Lateral river erosion where the outside of meander bends impinged upon the base of valley walls contributed to instability that could produce large landslides capable of shifting the river to the far side of the valley, which could, in turn, destabilize the opposite valley wall. The resulting back and forth would have contributed to gradual valley widening to form the modern valley bottom. As shown in Figure 2.1.4, the area near the landslide is now the narrowest part of the valley.

2.3 Groundwater Setting

The groundwater setting of the Oso Landslide is poorly known in detail, but groundwater flow to the Oso Landslide is controlled generally by local topography and stratigraphy. The recessional outwash sand and gravel capping the local slope above the Oso Landslide and the advance outwash separating the glacial till and the glacial-lacustrine deposits are highly permeable, whereas the glacial till and glacial-lacustrine silt and clay formations are of much lower permeability. These differences in permeability create the potential for an unconfined aquifer perched on the glacial till and a confined aquifer between the till and glacial-lacustrine deposits. Evidence for local seeps along the recessional outwash/till contact was apparent on the headscarp face after the 2014 landslide during the field reconnaissance. In addition, active seepage and

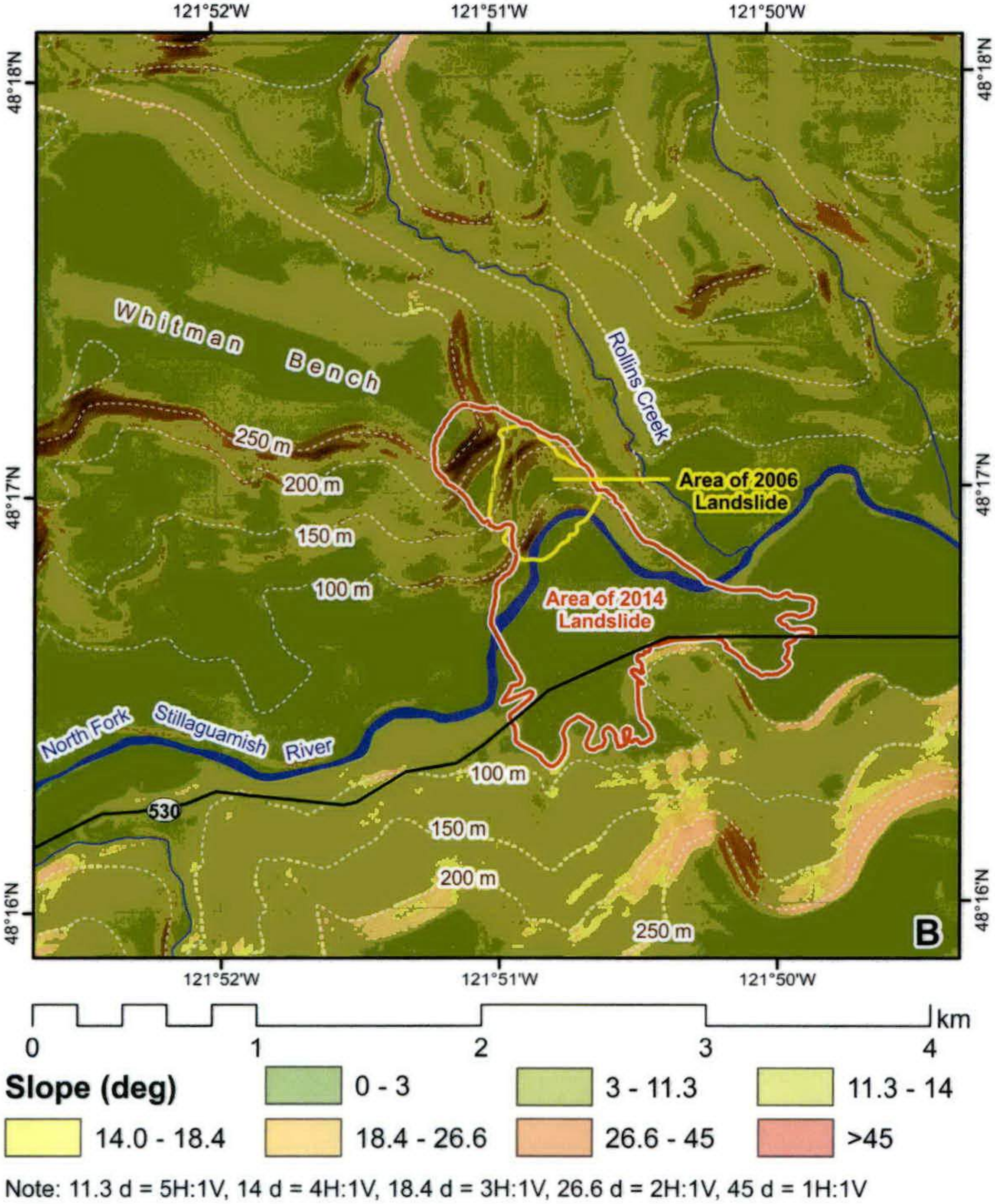

Figure 2.1.3 Slope inclination in the area around the Oso Landslide (red outline).

4.4 Subsurface Characterization

The slide mass has been characterized by only one subsurface investigation that we are aware of, and that is the report by Shannon (1952). They advanced three borings just behind the 1949 slide scarp and within the ancient slide mass and one near the drainage divide with Headache Creek that is likely not part of the ancient slide mass that mobilized into the Oso Landslide, but probably was part of a ancient slide mass in the Headache Creek drainage basin. Logs of the borings from the Shannon (1952) report are presented in Figure 4.4.1. The boring near the divide (B-1) shows gray fine sand, silt and clay from 6 to 221 feet (1.8 to 67 m) depth, where the hole was terminated. This is consistent with the in-place section of glaciolacustrine deposit. The other three borings (B-2, B-3 and B-4) show variable stratigraphy despite being located quite close to each other. They identify strata of various grain sizes and characteristics, but a generally oxidized sandy material to a depth that varies from approximately 18 to 49 feet (5.5 to 15 m). This material is underlain by gray strata of silt and medium to hard clay with some sand and gravel. It also appears that a loose layer of oxidized brown sand was encountered beneath 74 feet (22.5 m) of medium to hard blue (gray) clay in boring B-4; the need for casing to control caving of this layer was the reason the hole was terminated at 221 ft (67 m) depth. The logs also indicate that drill water was lost at several depths ranging from 18 to 71 feet (5.5 to 22 m) in both sandy and clayey strata. Water loss is indicated in the boring logs with an asterisk symbol at the appropriate depth; note that no drill water was reported lost in the log of boring B-1 to a depth of 221 feet (67 m) [Figure 4.4.1].

Four samples of lacustrine clays taken from these borings had natural water contents ranging from 27% to 31%, plastic limits of 23% to 27%, liquid limits of 44% to 56%, and shear strength of about 1 to 2 tons per square foot (100 to 200 kPa) (Thorsen, 1969). Other than the surface expressions now visible, the report with boring logs and test results from 1952 are the best descriptions available of what mobilized as the flow slide on March 22, 2014.

At a Seattle location, Palladino and Peck (1972) reported large differences in peak and residual strength values for glacially over-consolidated clays similar to those at the Oso Landslide site, with peak strength characterized by a cohesion of 62 kPa (9 psi) and a friction angle of 35°, and residual strength characterized by a cohesion of zero and a friction angle of 14° to 18° for disturbed clays.

4.5 Land-Use and Risk

Risk is the possibility of suffering loss, and it is represented by the consequence and probability of a loss[1]. This section summarizes available information about the consequences and

[1] Risk is mathematically defined as the expected value of a loss, which is the sum of the product of each possible consequence multiplied by the probability of the consequence. In terms of natural landslides, the probability of a particular landslide (i.e., landslide involving a given volume of material and runout) occurring is typically referred to as the hazard.

probabilities of landslides in this valley of the North Fork Stillaguamish River. It concludes with a discussion of means that were in place to manage landslide risk at the time of the March 2014 event.

People, Property, Resources and Infrastructure at Risk

The portion of the valley directly below the slope and affected by the 2014 event contained 108 lots zoned for Single Family Residences. Some form of structure was located on 49 of the lots; 25 were occupied year round and 10 were occupied part time as vacation homes. The Steelhead Haven Plat was recorded in 1960. About one-half of the homes were built after 1996. After the 2006 landslide, five new homes were built in Steelhead Haven and two were built outside of it but within the area affected by the 2014 landslide.

The closest home to the slope before the 2014 event was approximately 120 m (400 feet) from the toe of the slope; this home was nearly twice as far from the toe of the slope before the 2006 event moved the toe and shifted the river. This information is summarized on a map produced by the Snohomish County Planning and Development Division following the 2014 event (Figure 4.5.1). Additional occupied properties are located both upstream and downstream from the Oso Landslide area that could be impacted by flooding induced by a landslide dam.

The North Fork Stillaguamish River serves as habitat and spawning grounds for Chinook salmon, a species listed under the Endangered Species Act. The river below and downstream from the Oso Landslide slope is within the "Usual and Accustomed" fishing area for the Stillaguamish Tribe of Indians. The Tribe owns the right to take up to 50 percent of the harvestable fish resources, and they manage, protect and conserve this resource.

The valley wall up to the Whitman Bench (i.e., the slope) is mostly private property and was not developed. This land had previously been used for forestry up until the late 1980's.
The valley contains a two-lane highway, State Route (SR) 530, which serves as the primary route for transportation between Arlington and Darrington. High-tension power lines operated by Seattle City Light run approximately parallel to SR 530 on the south side of the valley.

Probabilities of Landslides

We are not aware of any formal assessments for the probability of a landslide in this valley. However, multiple studies identified the potential for a "catastrophic" failure affecting human safety and property. A 2001 report by GeoEngineers, which made use of earlier geotechnical and geological studies by Shannon and Associates (1952) and Miller (1999), expressed the status quo conditions as follows (page 9):

- "Large, persistent, deep-seated landslides don't just go away
- Current slide activity has a detrimental effect on fisheries habitat and productivity

• Stillaguamish Summer/Fall Chinook have been listed under Endangered Species Act
• Catastrophic failure potential places human lives and properties at risk."

The Miller (1999) study estimated the expected run-out distance to be less than 275 m (900 feet), based on the assumption of a landslide volume comparable to prior landslides at the site. The run-out distances from the three major landslides preceding the 2014 event were all 100 to 200 meters (325 to 650 feet). We are not aware of any predictions that the debris from a landslide in this valley could run-out thousands of feet across the valley floor like it did in the 2014 event.

Risk Management Means

Risk management involves balancing benefits of reducing risk against the costs required to reduce it. Risk can be reduced by reducing either the probability of an event occurring (say by buttressing or draining surface water and groundwater from the slope) or by reducing the severity of consequences given that an event occurs (say by removing people or property from harm's way).

Over the past 60 years, a variety of means were considered to manage the risk associated with this slope. A 2001 study by GeoEngineers for the Stillaguamish Tribe of Indians identified alternatives for remediating the landslide that ranged from stabilizing the river bank to minimize erosion to moving the river channel and removing development by buying out properties.

At the time of the 2014 event, the two means that had been employed to manage risk from a landslide were land-use restrictions implemented by Snohomish County and the Washington Department of Natural Resources and river bank stabilization implemented by the Stillaguamish Tribe of Indians.

Land-Use Restrictions

Snohomish County is responsible for managing development in this valley. If a property is within a "Landslide Hazard Area" as per the definition established in the Snohomish County Unified Development Code[2], then the following restrictions on land use apply:

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[2] "Landslide Hazard Areas" are defined as areas potentially subject to mass earth movement based on a combination of geologic, topographic, and hydrologic factors, with a vertical height of 10 feet or more. These include the following: (1) areas of historic landslides as evidenced by landslide deposits, avalanche tracks, and areas susceptible to basal undercutting by steams, river or waves; (2) areas with slopes steeper than 33% which intersect geologic contacts with a relatively permeable sediment overlying a relatively impermeable sediment or bedrock, and which contain springs or ground water seeps; (3) areas located in a canyon or an active alluvial fan, susceptible to inundation by debris flows or catastrophic flooding" (Chapter 30.91L.040). This setback distance is greater than that required by the International Building Code.

• Development activities are not permitted in landslide hazard areas or their required setbacks (unless there is no alternate location on the subject property).

• Structures shall be setback from landslide hazard areas, such that:

o The minimum setback at the top of the slope is the maximum of (i) the slope height divided by three and (ii) 50 feet[3] (15 m).

o The minimum setback at the toe of the slope is the maximum of (i) the slope height divided by two and (ii) 50 feet[3] (15 m).

o Exceptions can be made if there is no alternative placement for the structure on the property, or if a geotechnical study proves that the alternative setback provides protection equal to that provided by the standard setbacks.

• Vegetation must not be removed (unless recommended otherwise in a site-specific geotechnical study)

• The factor of safety for landslides must exceed 1.5 for static conditions or 1.1 for dynamic conditions.

• Tiered piles or piers should be used for structural foundations.

• Retaining walls that allow for the maintenance of natural slopes shall be used instead of artificial slopes.

• If there is no alternative, utilities can be placed in landslide hazard areas (provided the conditions listed in the county code are met).

• Point source discharge of storm water can be placed in landslide hazard areas (provided the conditions listed in the county code are met).

• It is the responsibility of the developers to verify the accuracy of mapped landslide hazard areas.

Landslide Hazard Areas mapped in the vicinity of the slope are shown in Figure 4.5.2. If the full 183-m (600-foot) height of the slope that failed in 2014 were used to calculate the required setback distance from the toe (as opposed to the 60-m (200-foot) high slope that had failed in 1951, 1967 and 2006), then the required setback is 90 m (300 feet). All of the structures affected by the March 2014 landslide were more than 90 m (300 feet) away from the toe of the slope and therefore not subject to land-use restrictions due to landslide hazard (Figure 4.5.1). Several of the building permits issued after the 2006 event did address flood hazards and wetland conservation.

[3] This setback distance is greater than that required by the International Building Code.

The Washington Department of Natural Resources is responsible for regulating logging in this valley on non-federal lands. The area of the earlier (pre-2014) landslides was classified as a Mass Wasting Mapping Unit where logging was not permitted. In addition, to reduce the probability of a slope failure caused by groundwater recharge, the Washington Department of Natural Resources had instituted logging restrictions on this valley wall above the pre-2014 landslides and including a portion of the Whitman Bench identified as in the groundwater recharge zone of the landslide based on an assessment by Benda el al. (1988).

River Bank Stabilization

The Hazel landslide slope was a source area for sediment to the river to an extent believed to be adversely impacting the fish downstream since at least the 1930's. The sources of sediment were 1) erosion of the river bank as the river cut through the toe of landslide debris, and 2) sediment-rich run-off originating from the disturbed surface of the landslide. The fine sediment was accumulating in downstream areas of the river and degrading the fish habitat.

In order to reduce the impact of sediment on the fish resource, the Stillaguamish Tribe of Indians obtained a grant for $1,000,000 in 2005 to move the river channel 150 m (500 feet) to the south and construct a log revetment. Before construction started, the river channel was relocated more than 150 m (500 feet) to the south due to the January 2006 landslide event. A modified revetment was constructed in August to September of 2006 to the north of the new river channel. The revetment wall was 430 m (1,400 feet) long and constructed with 5 layers of 18-m (60-foot) long, 0.6-m (2-foot) to 0.9-m (3-foot) diameter logs lashed together with steel cables and anchored with concrete blocks every 18 m (60 feet). The cables were kept slack to provide flexibility for the revetment to conform to settlement and lateral movement. The revetment wall reduced sediment loads enough after 2006 to promote a measurable increase in spawning of Chinook salmon downstream from the landslide. Two similar walls had been built in the recent past: one was a berm made of river bank material in 1960 that lasted less than one year, and the other was made of rock in 1962 that was overrun by the 1967 landslide.

Between 2006 and 2014, sections of the log revetment had settled about one-half meter (1.5 feet) and required one major repair following settlement that allowed the river to erode 3 m (10 feet) back toward the slope. This erosion likely resulted from undercutting due to the river excavating a pool in the channel along the outer edge of the river meander bend. A tribal representative observed the log revetment two days before the 2014 Oso Landslide event and reported that further erosion or new activity in its vicinity was not noticed.

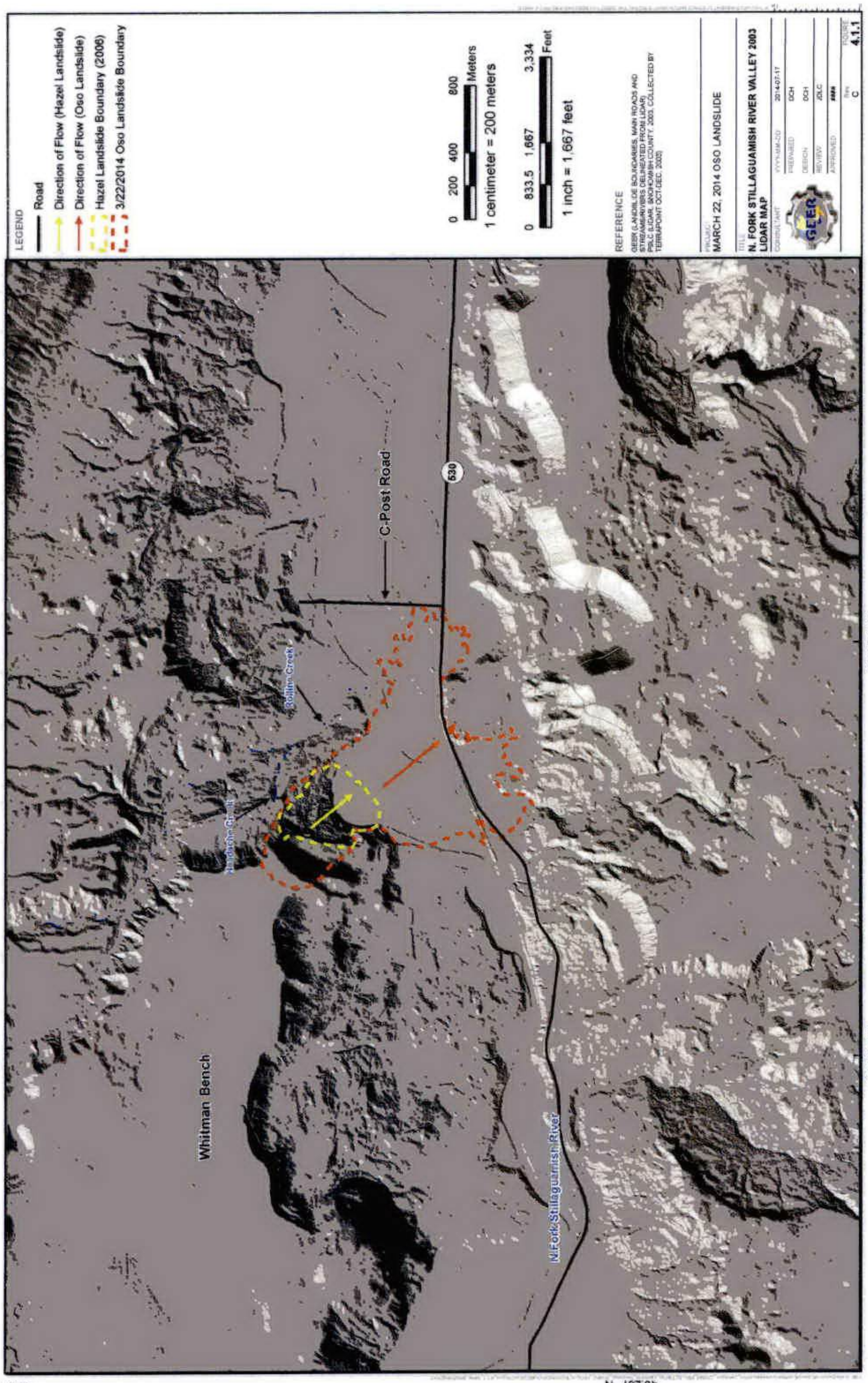

Figure 4.1.1 North Fork Stillaguamish River Valley (2003 lidar map).

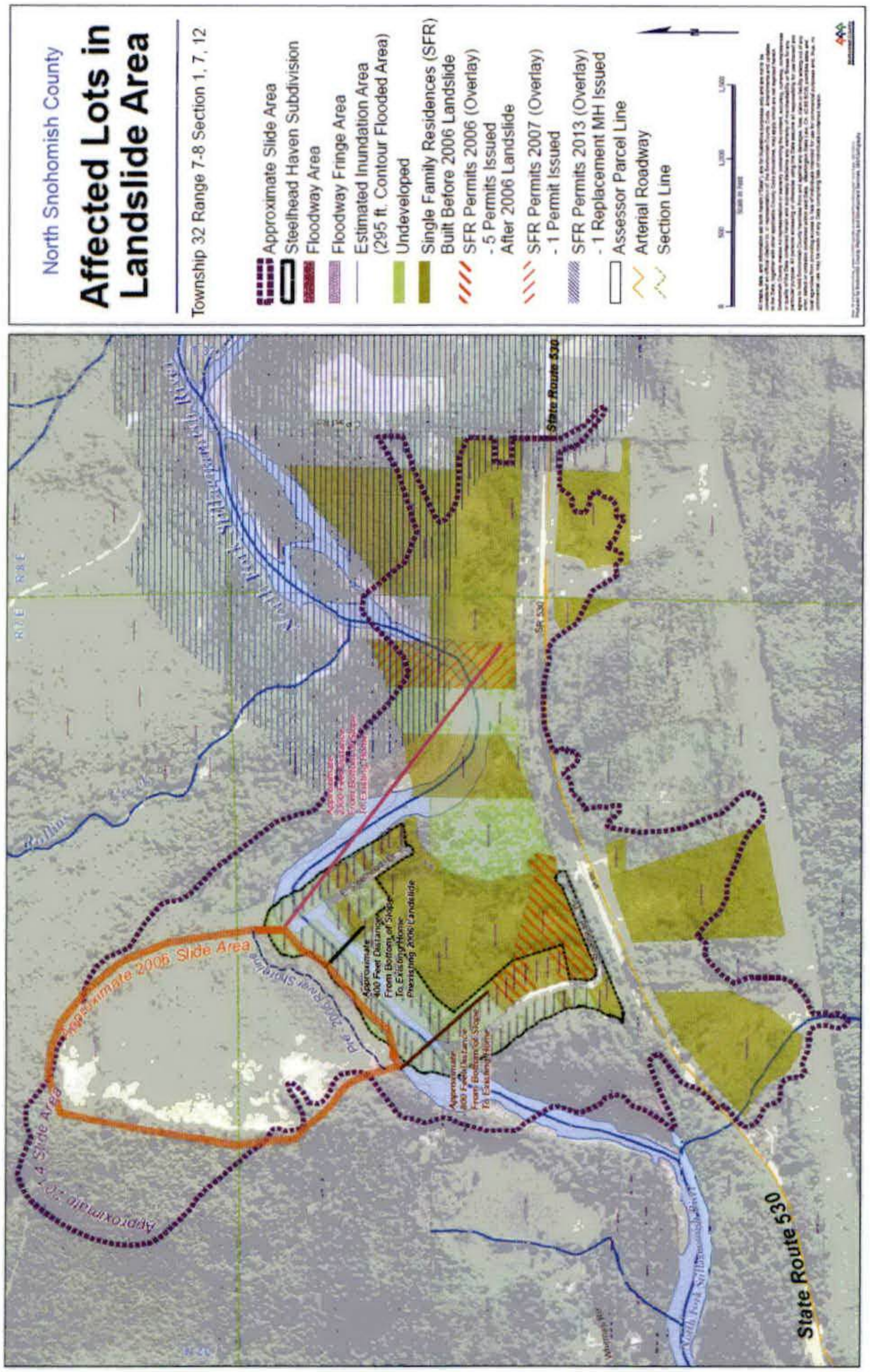

Figure 4.5.1: Land-use at Time of Slide (produced by Snohomish County after 2014 event)

7. DISCUSSION

This discussion section provides context for some of our observations. The mission of the GEER reconnaissance is to observed conditions in the field rather than determine the causality of the event. However, the extent of our reconnaissance effort has allowed us to point to some of the factors that we believe pertinent to the landslide at Oso.

7.1 Historical Context

Slope failures can occur on natural slopes or as a result of excavations, cuts, fills, embankment loadings, groundwater flow and seepage forces, earthquakes, and other processes that induce stresses. Understanding and predicting the timing and extent of these events have challenged the geotechnical engineering community for decades. Some slope failures result in significant losses and casualties, especially when they occur in developed areas and debris flows accompany them. Several well-documented cases have shown that the runout from these events can reach significant distances even on relatively shallow slopes and occur at great velocities. Fast-moving debris flows are arguably the most destructive class of mass movements. For example, an M7 earthquake in El Salvador in 2001 caused the collapse of a section of the crest of the Balsamo Ridge overlooking the suburb of Santa Tecla (Evans and Bent, 2004; Konagai et al., 2001). About 150,000 m^3 (~196,000 yd^3) of pyroclastic material slid down slopes varying from 30° to 15° for about 275 m (900 ft) and then ran out an additional 460 m (1,500 ft) on a slope of about 3°. The velocity was estimated to range from about 16 m/sec (35 mph) to 5 m/sec (11 mph ~top speed of running person) on the flatter slope. Once it reached the residential area it continued for another 200 m (650 ft) burying houses. The furthest reach was 740 m (2,400 ft) with flow thickness of about 2 m (6.5 ft) at the distal end. The slide caused more than 700 fatalities with a total duration estimated to be less than one minute.

Rainfall-induced landslides are also common occurrences. For example, the 1985 Jizukiyama landslide in Japan was thought to be triggered by 449 mm (17.7 inches) of rainfall in the rainy season which is twice the amount of rainfall in a typical year in the Nagano area. The volume of the slide was estimated at 5 x 106 m^3 (~6.5 million yd^3) with a total length of 700 m (2,300 ft), and an initial slip surface located at 30 to 50 m (100 to 165 ft) depth. The runout travelled approximately 200 to 300 m (650 to 1000 ft) resulting in the destruction of 50 houses and 26 deaths (Sassa, 1985). The Jizukiyama landslide runout moved at fairly low velocity (~ 10 cm/sec, 0.22 mph) and entrained several meters of surficial soils as it travelled. The landslide mass consisted of ancient landslide debris, probably ten thousand years old, and was composed of volcanic tuff (ash and pumice). The 2006 Guinsaugon slide on the island of Leyte in the Philippines was also triggered by rainfall, where an 11 million m^3 (~14.4 million yd^3) rockslide entrained an additional 4 million m^3 (~5.2 million yd^3) of finer debris, evolving into an extremely rapid slide which traveled about 1.3 km (0.8 mi) on a practically flat surface, burying the town of Guinsaugon and resulting in more than 1000 fatalities (Evans et al., 2007).

Before the Oso Landslide occurred, most landslide disasters in the US resulted in significant material losses with fewer casualties. Nevertheless, according to USGS, the average death toll in the United States from landslides and debris flows is about 25 per year (NRC, 2004). The largest documented rock slide-debris flow, estimated at 2.8 km^3 (0.7 mi^3) (Schuster and Highland, 2001), was produced by the eruption of Mount St. Helens, Washington in May 1980. The flow traveled roughly 22 km (14 mi), damaging or destroying roads, railway lines, bridges, and creating landslide-dammed lakes. Other well documented events include La Conchita in Southern California which had two events a decade apart (1995 and 2005). The bluff above La Conchita, composed chiefly of weakly cemented materials, had a long history of landslides, some prehistoric, with the 2005 rainfall-induced slide causing extensive destruction as well as 10 fatalities (Gibson, 2006).

7.2 Empirical Predictions of Runout

It is generally agreed that rapid flows involve liquefaction of the granular matrix of the sliding material, resulting in segregation of grain sizes into a coarser snout and lateral levees which basically exhibit drained behavior and a liquefied interior made up of finer particles that is capable of violently impelling the coarser snout over long runout distances (Iverson, 1997; Major and Iverson, 1999; Wang and Sassa, 2001). In the Guinsaugon case, for example, boulders up to 5 m in diameter were observed at the distal limit of the slide (Evans et al., 2007).

A clear understanding of the mechanics of flow slides and debris flows is essential to model the consequences of this type of failure and to help decision makers regarding hazard zoning and possible mitigation measures. However, a full understanding is lacking of how flow slides maintain the ability to move long distances at high velocities over low-angle slopes. Their mobility is greatly dependent on the nature and volume of the slide mass, the presence of water in the sliding mass, the size and nature of debris that is entrained in the flow, the slope angle at failure zone, the slope angle and ground surface roughness and constrictions/obstacles in the run out zone, and the presence of any water bodies, such as entrainable river or stream flow, along the runout path.

Two issues are involved: 1) triggering of the slide and 2) subsequent high-velocity, unsteady, non-uniform motion. With regard to triggering, a high degree of saturation in the pre-slide failure zone seems to be required; one basic scenario would be that, as pore pressures increase due to a rising groundwater table, the effective stresses decrease, and thus the shearing resistance on the potential failure plane decreases allowing the slope to fail and the sliding material to mobilize (e.g., Anderson and Sitar, 1995). Whereas many landslides can be modeled as solid blocks sliding over defined failure surfaces, debris flows ultimately mobilize the whole mass of sliding material as a viscous flow with distributed shearing.

Evaluating runout distances is based on several factors including volume of the sliding mass, slope height, slope angle, site topography and morphology, obstructions, geologic material type,

Table 7.2.1 Regression coefficients for Equation 7-2 (adapted from Hungr et al. 2005).

Landslide Type	Paths	A	B	R^2
Debris Flows	All	-0.012	-0.105	0.76
	Obstructed	-0.049	-0.108	0.85
	Unobstructed	-0.031	-0.102	0.87

Rickenmann (1999) estimated the maximum runout distance based on data from 154 debris flow events as shown in Equation 7-3:

$$L_{max} = 1.9\ V^{0.16}\ H^{0.83} \qquad \text{Equation 7-3.}$$

Legros (2002) proposed a relationship between landslide runout length and volume rather than the apparent friction angle, travel angle or angle of reach (H/L). He contended that the ratio H/L is physically meaningless in predicting runout length and therefore proposed a relationship based on volume (V in km^3) rather than height of fall. Equation 7.4 shows the general form of his powerlaw equations with the coefficients c and n shown in Table 7.2.2 for non-volcanic and volcanic landslides and debris flows:

$$L_{max} = c\ V^{n} \qquad \text{Equation 7-4.}$$

Table 7.2.2 Parameters for empirical relationships of Legros (2002) in Equation 7-4.

Event Type	c	n
Non-volcanic	8	0.25
Volcanic	15.6	0.39
Debris Flow	235	0.39

Landslides tend to develop into debris flow given sufficient fluid input and consequently increase in mobility (Iverson, 1997). Figure 7.2.3 displays the data gathered from numerous case histories (Legros, 2002)

These various formulations have been used with the observations made at the Oso landslide considering the possibility of a two phase failure as well as a single phase incorporating the entire slide mass.

For Phase 1 of the Oso Landslide, L_{max} can be measured from cross-sections shown in Figure 7.2.4 and is estimated at 1,433 m (4,700 ft) with a height H equal to 90 m (300 ft). Incorporating both phases yield an L value of 1,677 m (5,500 ft) and H of 182.9 m (600 ft). The total volume of the Oso slide can be estimated at approximately at 7.6 million m^3 (9.9 million yd^3) with Stage 1 being estimated anywhere between 50 and 85 % of the total volume. Using values shown in Table 7.2.2, the predicted runout using Equation 7-3 from Rickenmann (1999) underestimates the

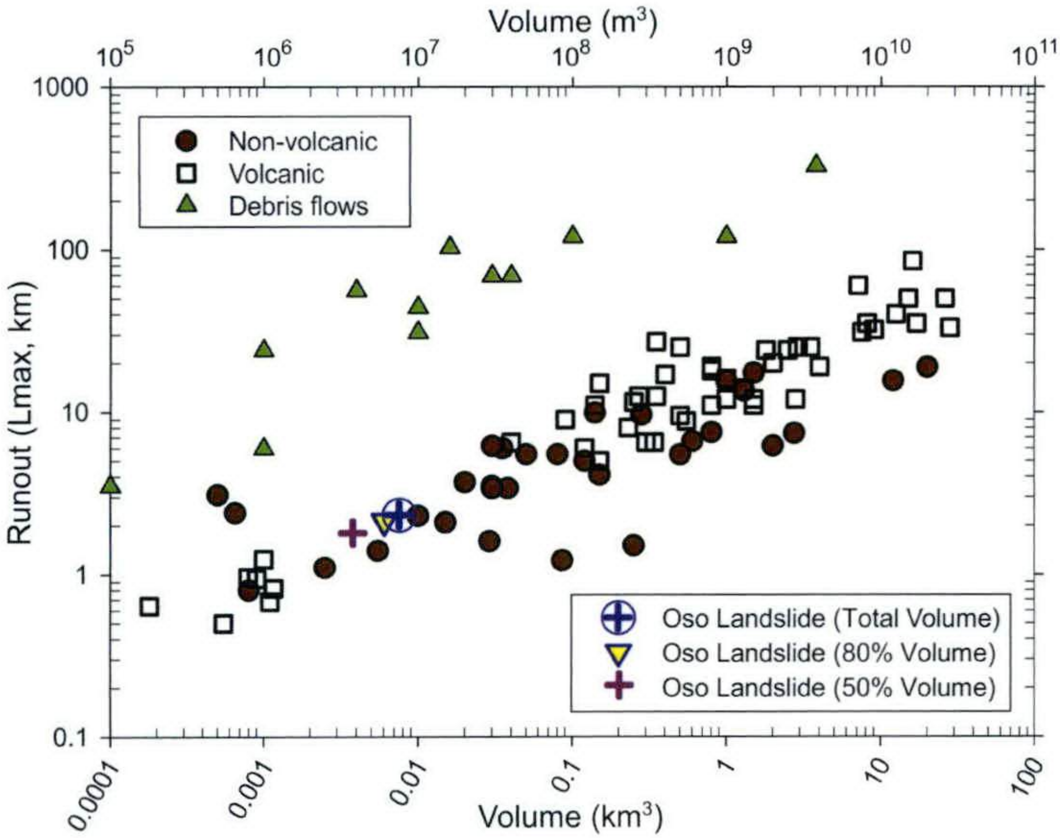

Figure 7.2.3 Relationship between volume and runout distance (after Legros, 2002).

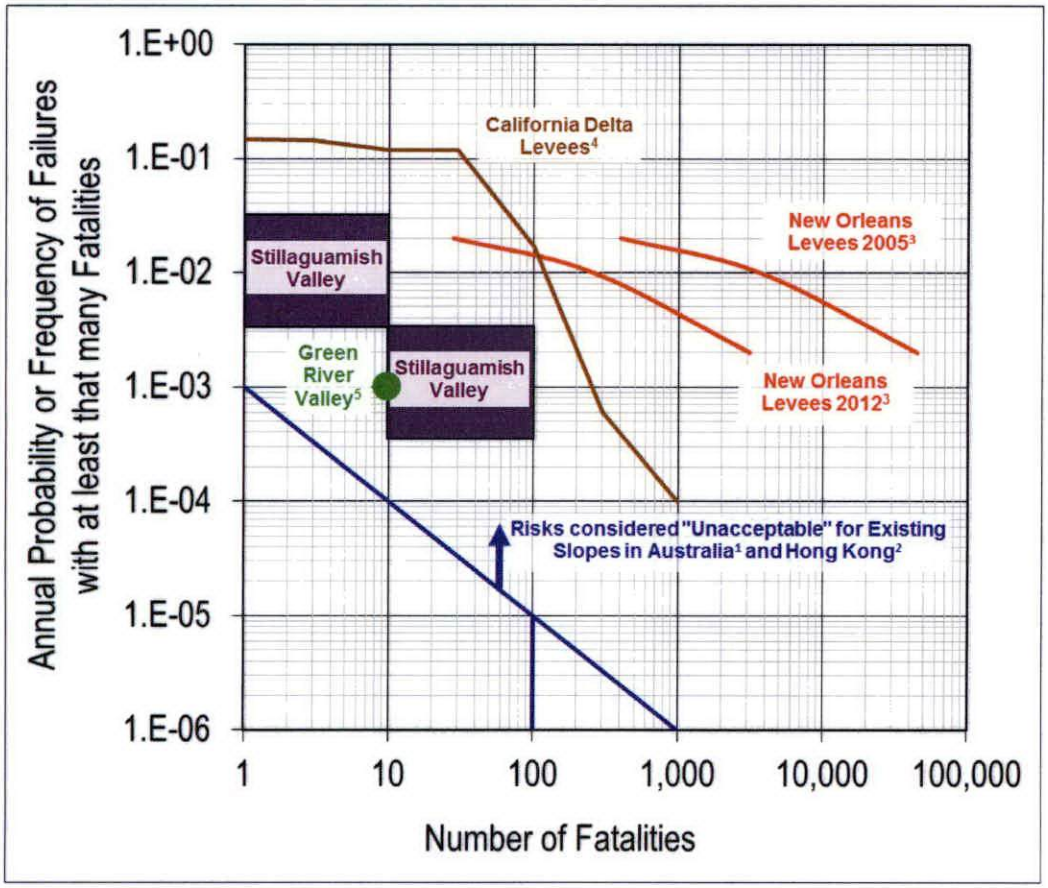

Figure 7.5.1 Rough approximation of risk from landslides in 5-km stretch of North Fork Stillaguamish River Valley in vicinity of Oso compared with related benchmarks for human safety risk ([1]AGS 2000; [2]GEO 1998; [3]IPET 2009; [4]DWR 2008; [5]Gilbert 2013).

8. CONCLUSIONS AND RECOMMENDATONS

The 22 March 2014 Oso Landslide provides an opportunity for the profession to build on our knowledge of the stability and behavior of natural slopes and to reflect on the influence of people, climate, and time on natural valleys and slopes. This event also highlights the importance of assessing and managing risk from natural slopes. Below we present conclusions specific to the 2014 landslide and additionally offer several recommendations. As discussed earlier in this report, our investigation is not intended to be a final, conclusive study of the landslide and we did not seek to unequivocally establish causative factors; instead, this report is a preliminary assessment based on reconnaissance observations and other available data. We recommend that our conclusions, findings, and hypotheses should be tested and challenged through additional research and investigation.

8.1 The 22 March Oso, Washington Landslide

• **Impacts and Significance:** The Oso Landslide claimed 43 lives, making it the deadliest landslide disaster in United States history. In addition, it caused significant injuries to at least 10 people who were struck by the landslide, but fortunately survived. Washington State officials have estimated capital losses associated with the landslide to be at least $50 million. The landslide completely destroyed Steelhead Haven, a community of almost 50 homes, as well as several residences located off a nearby roadway. The landslide also buried portions of State Highway 530, resulting in complete closure of this important arterial thoroughfare for over 2 months, and several more months of reconstruction.

• **Landslide Setting:** The last glacial advance into the Puget Lowland deposited a thick sequence of sediments into the North Fork Stillaguamish River valley, including the portion of the valley at the Oso Landslide. The glacially-derived sediments include interbedded layers of clay, silt, sand, gravel, cobbles, and boulders. Some of these glacially-derived sediments are landslide susceptible, especially when they form steep slopes or have abundant groundwater. The geomorphic evidence in the valley reveals that the portion of the North Fork Stillaguamish River Valley in the vicinity of Oso Landslide has experienced multiple large landslides over at least the past six thousand years. Many of these ancient landslides have similar morphology to the 2014 Oso Landslide, and indeed the Oso Landslide was a reactivation of one of these ancient landslides. The 2014 Oso Landslide was large, but the other ancient landslides in the valley are of similar size. There is geomorphic evidence that a landslide that is even larger than the Oso landslide is located immediately to the west of the Oso Landslide. This larger unnamed landslide similarly ran out across almost the entire North Fork Stillaguamish River Valley and appears to have pushed the river channel to the south margin of the valley. Many portions of the valley bottom are covered with old landslide deposits. We believe areas of the valley bottom not currently covered with landslide deposits have been covered in the past but the deposits in these areas been reworked by active channel migration and floodplain-forming alluvium deposition.

We estimate a maximum recurrence frequency of about 400 to 1,500 years for large landslides in this portion of the valley. The range in this estimate is constrained by carbon dating, which suggests four generations of large landslides, and a total of 15 mapped large landslides over about 6,000 years, as described herein. It is not known how many prior landslides occurred during valley incision and widening and which are no longer preserved in the topography; the presence of additional landslides in this immediate portion (~12 km^2 or ~5 mi^2) of the valley could reduce the recurrence interval to the order of hundreds of years.

• **History of Landslides at the Oso Site:** Multiple episodes of historic movement of the Oso landslide have been described in several studies dating back to the 1950s. The historic landslide activity is occurring within the ancient Oso Landslide. The observed historic activity appears to be periodic with the modern headscarp (i.e., upper portion) episodically advancing headward between 1952 and 2006, but with the main slide mass constrained to approximately the same portion of the slope where the earlier 2006 landslide failed. Review of the available historic data indicates several dates of renewed activity on portions of the slope since the 1930s. A complete chronology of actual dates and the sizes and type of failures has not been compiled; however these are known to include rotational slumps, transverse sliding of blocks where the forest has remained intact, and debris flows. The size of the landslide area grew relatively slowly until a large increase occurred in 2006, followed by the catastrophic enlargement in 2014.

• **Initiation of the 2014 Oso Landslide:** The Oso Landslide initiated on Saturday, 22 March 2014, at approximately 10:37 a.m. local time on a clear, sunny day. Records indicate no significant seismic activity in the days preceding the landslide and therefore it is unlikely that it had a siesmogenic origin. Instead, it is highly probable that the intense 3-week rainfall that immediately preceded the event played a major role in triggering the landslide. The intense rainfall in the first three weeks of March at the nearest rain gauge was determined to be less than the 100-year event for this period of time, and the previous months in the fall and winter of 2013 and 2014 were relatively dry. Precipitation in the Oso region is highly variable and analysis of weather radar for the area for the week preceding the landslide indicates that precipitation at the Oso Landslide was at least 229 mm (9 inches), suggesting that the precipitation at the Oso Landslide for March 2014 might have been more than 760 mm (30 inches).

Beyond the rainfall trigger itself, there are many other factors that likely contributed to destabilization of the landslide mass. These include: (i) alteration of the local groundwater recharge and hydrogeological regime due to previous landsliding and, possibly, land use practices, (ii) weakening and alteration of the landslide mass due to previous landsliding and other natural geologic processes, and (iii) changes in stress distribution resulting from removal and deposition of material from earlier landsliding. Detailed consideration of land use practices (most notably, timber harvesting) was beyond the scope of our investigation; however, it is known most of the large landslides in the Stillaguamish River Valley pre-date logging. Given the size and depth of the landslide, if timber harvest practices did influence on the landslide, it was through modification of the groundwater recharge regime rather than by any shallow-depth loss of root mass reinforcement.

• **Oso Landslide Morphology and Dynamics:** During our field reconnaissance we identified six distinctive zones and several subzones of the landslide mass that are characterized by different geomorphic expression resulting from different styles of deformation, geologic materials, and vegetation. These reflect the highly complex nature of the landslide. It is apparent from the seismic recording of the landslide that the event was marked by two major episodes of mass movement separated by a few minutes. This corroborates with our data found during the reconnaissance, which provides evidence of multiple stages of failure. Clearly the most significant episode of landsliding involves the massive and fast-moving debris flow ("mudflow"), which devastated Steelhead Haven and caused most if not all of the fatalities. We found that the runout of this debris flow was indeed long (greater than 1 km); however, it was not exceptional for a landslide of its size. Runout may have also been aided by the inclusion of the Stillaguamish River water increasing the mobility of the debris flow, particularly on the east side, where the debris flow travelled up the river channel.

• **Hypothesized Landslide Sequence:** Based on the reconnaissance observations, seismic recordings, and other available data, we hypothesize that the landslide occurred in two distinct and markedly different stages. The first major stage of movement (Stage 1) is interpreted to be a remobilization of the 2006 slide mass and a headward extension that included part of the forested slope of the ancient landslide. As such, Stage 1 was comprised largely or entirely of previous landslide deposits and it mobilized as a debris flow and traveled across the valley. The second stage (Stage 2) occurred several minutes later in response to the unloading (i.e., loss of "buttressing") and the redirection of stresses within the landslide mass. Stage 2 was a retrogression into the Whitman Bench of up to nearly 90 m (300 feet) horizontally from the ancient slide scarp. The Stage 2 slip surface probably joined the slip surface of Stage 1 (and that of the 2006 and ancient slides) at depth, but also included shearing along a length up to 300 m (1000 feet) or more through previously in-place outwash, till and glacial lacustrine deposits that had not been part of earlier landslides. The Stage 2 landslide moved rapidly on the existing Stage 1 slip surface until it essentially collided with the more intact blocks at the trailing edge of the Stage 1 slide mass, and came to rest. The current morphology suggests there was back rotation and extension of the Stage 2 landslide mass as it failed and came to a reestablished equilibrium on the slope.

• **Landslide Risk Assessment, Management, and Communication**: Studies conducted in the decades preceding the Oso Landslide clearly indicated a high landslide hazard at the site. However, these studies were primarily focused on the impacts of landslides to the river versus the impacts to people or property. In addition, it does not appear that there was any publicly communicated understanding that the debris from a landslide could run-out as much as 1 km, as it did in the 2014 event. Since the 1950s, a variety of means were considered to manage the risk associated with this slope, ranging from stabilizing the riverbank to minimize erosion to moving the river channel and removing development by buying out properties. At the time of the 2014 event, two means had been employed to manage risk from a landslide: (i) conventional land-use restrictions implemented by Snohomish County and the Washington Department of Natural Resources and (ii) riverbank stabilization implemented by the Stillaguamish Tribe of Indians. Our assessment of the risk for fatalities due to landslides in this portion of the valley indicates that it is comparable to risks from flooding in other areas in the United States but relatively high compared to guidelines for landslides in other developed countries and for large dams in the United States. Currently there are no national or state guidelines in the United States concerning levels of risk due to natural landslides that warrant action.

8.2 Recommendations

Several broader lessons have been learned in this investigation that may benefit others involved in the study of landslides and the zoning of communities adjacent to sloping ground and potentially unsafe slopes.

- The history and behavior of past landslides and associated colluvial soil masses should be carefully investigated when mapping areas for zoning purposes. At the Oso Landslide site, multiple past failures retrogressively moved upslope each time creating new conditions with increased susceptibility to groundwater infiltration, and preferential underground seepage pathways, and further weakening the previously failed mass over time and increased overall volume of potentially unstable landmass.

- The risk of landslides to people and property should be assessed and communicated clearly and consistently to the public. These assessments should be continuously updated as new information about slope behavior becomes available and as potential consequences change due to changes in development or mitigation.

- The ability to implement monitoring and warning systems to reduce the impacts of landslides to people and property should be considered and advanced.

- The influence of precipitation on destabilizing a slope should consider both cumulative amounts and short-duration intensities in assessing the likelihood of initial or renewed slope movement.

- Methods to identify and delineate potential landslide runout zones should be revisited and reevaluated.

- Advancements in imagery to understand slope behavior should be exploited to the greatest extent possible. Lidar imagery has proven to be a very useful an valuable tool in identifying landslide deposits, reconstructing landslide history, and evaluating mass movements of the current landslide event. This technology has been made feasible over the last decade or so and still does not cover most of the country. Its availability here, and its availability at multiple times

(2003, 2013, and after the failure in 2014) allows an understanding of slope and landslide morphology, and thereby hazard and risk, that was not present prior to 2003 in this valley and is currently not present in most locations. Additionally, high-resolution aerial photography also is a valuable tool to help delineate zones within the failed mass and document damages prior to recovery and clean up efforts

• Seismological recordings of landslides should be utilized to assist in understanding failure sequence in terms of the timing of significant movements, especially in large and complex events. Use of conventional slope stability analysis methods alone may be insufficient for accurate evaluation of failure mechanisms.

• Doppler weather radar should be utilized in providing data regarding precipitation intensity, amount, and variability estimates at locations of interest that are distant from established gauges.

Shallow-Landslide Hazard Map of Seattle, Washington

By Edwin L. Harp[1], John A. Michael[1], and William T. Laprade[2]

[1] U.S. Geological Survey, Golden, Colorado 80401

[2] Shannon and Wilson, Inc., Seattle, Washington 98103

U.S. Geological Survey Open-File Report 2006–1139

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Harp, Edwin L., Michael, John A., and Laprade, William T., 2006, Shallow-Landslide Hazard Map of Seattle, Washington: U.S. Geological Survey Open-File Report 2006–1139, 18 p., 2 plates, map scale 1:25,000.

Cover photograph: Slopes along Puget Sound north of Carkeek Park where numerous debris flows have traveled downslope and across the tracks of the Burlington-Northern-Santa Fe Railroad.

Shallow-Landslide Hazard Map of Seattle, Washington

By Edwin L. Harp[1], John A. Michael[1], and William T. Laprade[2]

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ABSTRACT

Landslides, particularly debris flows, have long been a significant cause of damage and destruction to people and property in the Puget Sound region. Following the years of 1996 and 1997, the Federal Emergency Management Agency (FEMA) designated Seattle as a "Project Impact" city with the goal of encouraging the city to become more disaster resistant to the effects of landslides and other natural hazards. A major recommendation of the Project Impact council was that the city and the U.S. Geological Survey (USGS) collaborate to produce a landslide hazard map of the city. An exceptional data set archived by the city, containing more than 100 years of landslide data from severe storm events, allowed comparison of actual landslide locations with those predicted by slope-stability modeling. We used an infinite-slope analysis, which models slope segments as rigid friction blocks, to estimate the susceptibility of slopes to shallow landslides which often mobilize into debris flows, water-laden slurries that can form from shallow failures of soil and weathered bedrock, and can travel at high velocities down steep slopes. Data used for analysis consisted of a digital slope map derived from recent Light Detection and Ranging (LIDAR) imagery of Seattle, recent digital geologic mapping, and shear-strength test data for the geologic units in the surrounding area. The combination of these data layers within a Geographic Information System (GIS) platform allowed the preparation of a shallow landslide hazard map for the entire city of Seattle.

INTRODUCTION

The glacial bluffs bordering Puget Sound within the city of Seattle have long been recognized as susceptible to shallow landslides that often transform into debris flows triggered by periods of intense rainfall or rapid snowmelt. Debris flows have caused significant damage to people and property in Seattle and

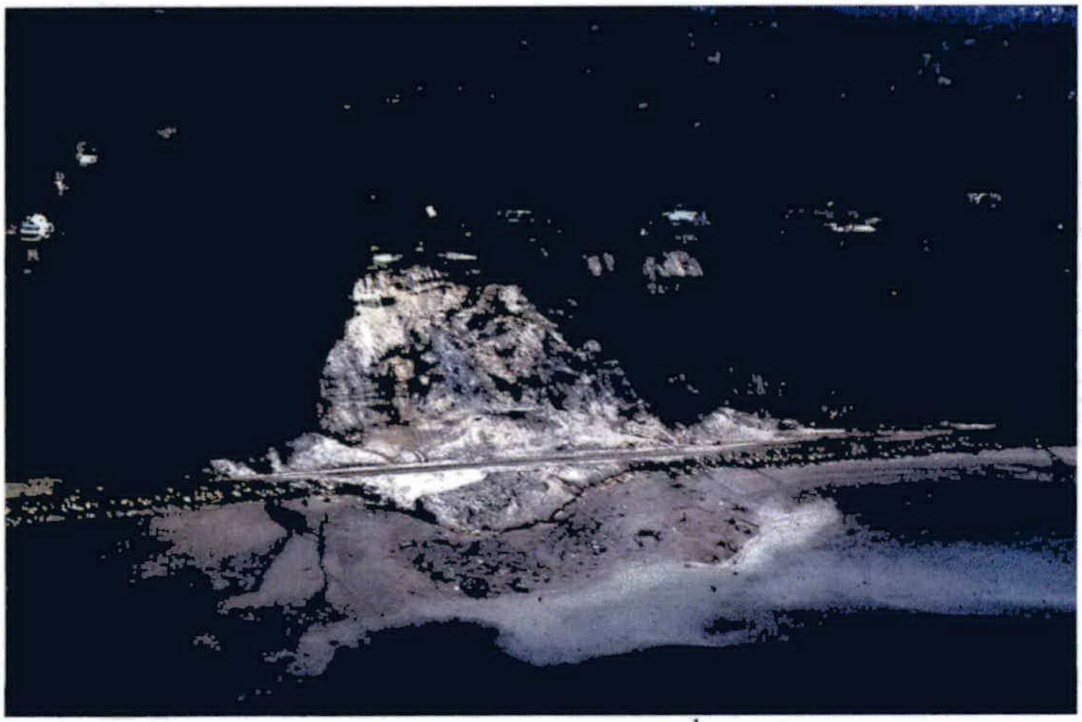


Figure 1. Slump/debris flow near Woodway, Washington, that overran several freight cars of the Burlington-Northern-Santa Fe railroad on January 17, 1997. The train was almost through the slide area when the last few cars were hit by the debris flow.

will continue to do so in the future. Severe episodes of intense precipitation are frequent enough in Seattle that a quantitative method to estimate the spatial hazard from shallow landslides is necessary to ensure future prudent and efficient land-use and emergency-response decisions.

The role of landslides, once again causing destruction and damage to people and property in the Pacific Northwest became readily apparent in the early months of 1996 and 1997. During the week of February 4, 1996, sustained heavy rainfall on a late-season snowpack in the Cascade Range of Washington and Oregon, and three to four days of heavy rainfall (with cumulative rainfall totals in excess of 685 mm; Taylor, 1996) at lower elevations caused more than $300 million damage from the combined effects of flooding and landsliding (FEMA Interagency Hazard Mitigation Team, 1996). After 450–600 mm of snow had fallen in the Puget Lowland of northwest Washington near Seattle in late December 1996, the snow changed to rain and, beginning on December 29, 25 mm/day of rain fell for the next three days at Seatac Airport (Lott and others, 1997). The rain rapidly melted the snow causing infiltration of the snowmelt and widespread flooding and landsliding in January and mid-March 1997, as additional rain triggered more landslides. Notable landslides triggered by these storms included the Woodway slump/debris flow (fig. 1), which derailed five cars of a Burlington-Northern-Santa Fe freight train, and a highly publicized debris flow on Bainbridge Island at Rolling Bay Walk that killed a family of four (Baum and others, 1998, fig. 2).

Shortly after these two years of flooding and landslide damage, the Federal Emergency Management Agency (FEMA) designated Seattle as a "Project Impact" city and followed up with a $1 million grant to stimulate additional funding and to form a Project Impact Council consisting of public and private partners committed to building a more disaster-resistant city. A major recommendation of this council was that the U.S. Geological Survey (USGS) and the city of Seattle work together to produce a landslide hazard map of the area (fig. 3). A major factor in promoting this effort was the existence of a database spanning more than 100 years, maintained by the city of Seattle, consisting of locations and other information about landslides that had been triggered by major storms. These data were compiled into a database using a Geographic Information System (GIS) format by Shannon and Wilson, Inc. for the City of Seattle (Nashem and Laprade, 1998; Laprade and others, 2000) and are used in this report to compare with our analysis of the shallow landslide processes that commonly mobilize as debris flows.

This study uses this database, together with geotechnical and slope data, to derive a susceptibility map and subsequently a relative hazard map for shallow landslides in Seattle. These maps, published at a scale of 1:25,000 (Map Sheets 1, and 2), show similar patterns to those prepared by Montgomery and others (2001) showing theoretical critical rainfall levels in Seattle,

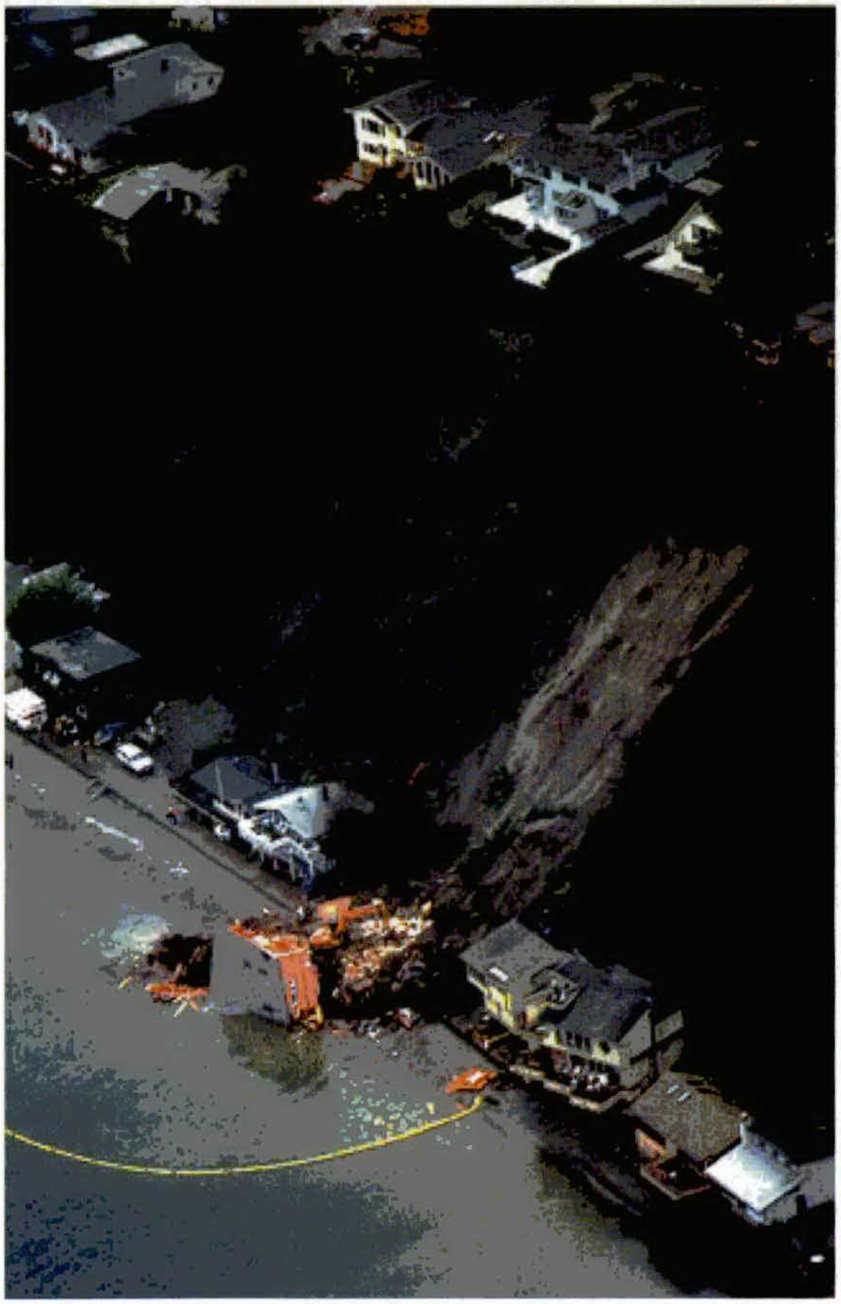


Figure 2. Shallow debris flow that initiated above Rolling Bay Walk on Bainbridge Island. It destroyed the house at the foot of the slope and resulted in four fatalities. Photo reprinted with permission of Seattle Times.

of FS. Because the data set only consists of point locations, areal percentages are not possible, and the various debris-flow concentrations can only be evaluated with respect to each other. These concentration levels can be compared to those within bins that have FS values of 6.0 or greater and have few or no debris flows within their areas. Areas of high FS value are relatively stable, generally flat-lying, and provide an end member of the stability spectrum of possible slopes.

Comparison of Factor of Safety with Variable Strength Properties versus Slope alone as a Predictor of Hazard

To compare the predictive ability of Factor of Safety to that of slope alone, we conducted a similar Factor-of-Safety analysis as described in the previous sections with slope as the only variable. The shear strength components, c' and ϕ' were held constant at $c' = 14.4$ kPa and $\phi' = 30°$. The distribution of shallow landslide density versus FS for this condition is shown in fig. 10*A*. A visual comparison with fig. 9*A* reveals a striking similarity. An exponential regression curve similar to that in figure 9 B is fit to these data and shown in fig. 10*B*. The fit of these data with the curve yields an $R^2 = 0.86$. From the histograms and regression curves plotted in figs. 9 and 10, it is obvious that the model using variable shear strengths for the different geologic units is a slightly superior predictor of shallow landslide density or relative hazard. The model using slope as the only variable is almost as effective as that using differing shear strengths when considering only the statistics themselves. Why then use a more complicated model with differing material properties if only modest improvement in statistical prediction is achieved?

The answer to this question lies in the details of spatial information provided by the susceptibility map shown in fig. 7 and Map Sheet 1, the slope map shown in fig. 6, and the geologic map shown in fig. 5. Within the area of steep slopes in these figures (shown in brackets) just to the south of Magnolia Avenue, the bluffs consist of Vashon Till, one of the stronger units in the Seattle area. This is an area where FS values are mostly greater than 3.0 and where only one debris flow (black dot) is located from the data set, clearly an area of relative stability. Yet the slope map (fig. 6) shows this area as having slopes in excess of 40°, one that would be labeled as high susceptibility or hazard based on slope alone. The model using slope alone as a variable cannot discriminate FS based on material strength. It portrays these source areas as having low FS values, high susceptibility, and is completely in error. Also, the model with slope alone as a variable will not discriminate areas of relatively low slope where extremely weak geologic units exist, where FS values can range from 1.0 to 2.0 due to low cohesion or friction angle. Errors such as these, although involving relatively small areas, do affect densely populated urban portions of the city. From this example, we see that the locations where FS values are estimated are just as important as the overall statistical effectiveness of the model. For this reason, a model using variable shear strengths as well as slope is preferable because it avoids the mistakes made by the model using slope alone where it ignores the effects of stronger or weaker geologic units.

Statistical Distribution of Data in Time

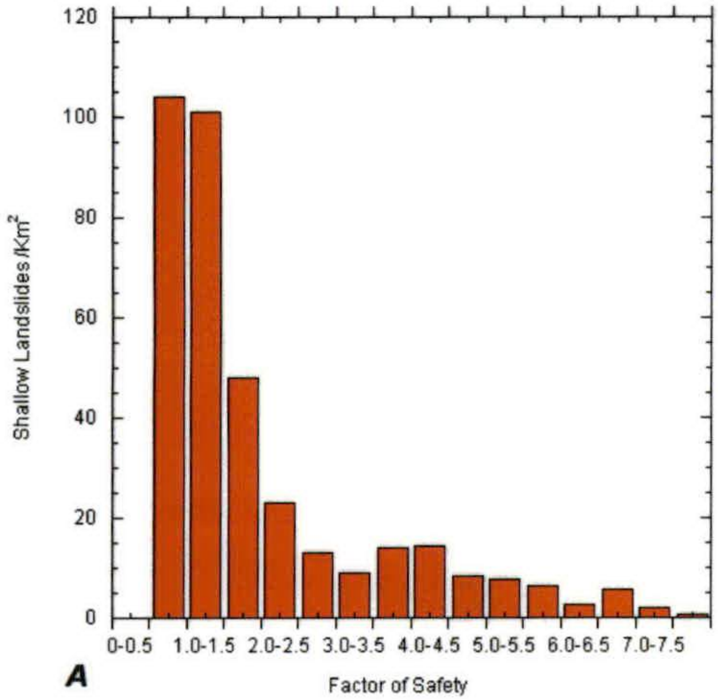
The landslide data set for Seattle spans a time period of 114 years. The two FS bins, 0.5-1.0 and 1.0-1.5 each have a concentration of approximately 100 shallow landslides/km^2 (fig. 9*A*). Dividing these concentrations by the total timespan (114 years) of the data set shows that each square kilometer having FS values within these two FS bins has 0.91 and 0.88 failures per year per square kilometer, or approximately one failure per year per square kilometer, as an average frequency of failure. This frequency is similar to that found by Coe and others (2004) for the areas of steepest slopes. Dividing by the total timespan of the data set assumes a uniform distribution of failures in time rather than a distribution associated with specific storm events. However, if we look at the distribution of the failures through time, we see the data clustered about specific years (fig. 11) when severe storm events occurred. The three years having the greatest number of failures were 1933, 1986, and 1997. The relatively high numbers of failures reported in 1986 and 1997 probably reflect more accurate and complete reporting in later years in addition to high numbers of failures.

Problems Introduced by Urban Features

The urban landscape introduces its own topography as it overlies or excavates into the natural slopes. Urban development also introduces artificially weakened or reinforced slopes often in close juxtaposition. Because of this often intricate spatial intermixing of materials having widely differing strengths, we have not been able to accurately characterize some slopes. A particular example of this is evident in the upland residential areas of Seattle where most of the houses have yards that are bounded by vertical rock retaining walls of about 1 m height. Because these slopes are vertical or nearly so, they show up as red and magenta (FS = 1.0 or less) on the susceptibility map (Map Sheet 1). In reality, however, the FS values are much higher than 1.0 because of the retaining walls made out of interlocking basalt blocks or concrete, which are not mapped.

RUNOUT LENGTHS OF SHALLOW LANDSLIDES

All of the data discussed and analyzed above refer to initiation points or source areas of slope failures. However, just as relevant to the hazard situation presented by shallow landslides is the runout distance for those that transform into debris flows. Although we have no runout data for the failures in this data set, we do have a map of debris flows, their travel paths, and other types of landslides that were produced during the winter of 1996/97, most of which occurred during two precipitation events, on January 1 and March 18. Most of the failures in this data set are debris flows and were mapped from stereo aerial photography acquired in April 1997 and plotted on 1: 24,000-



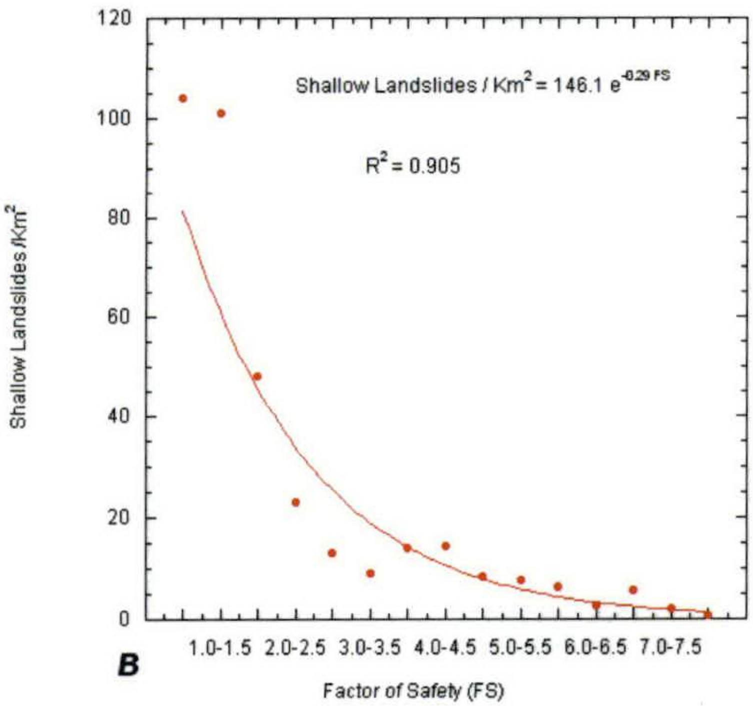
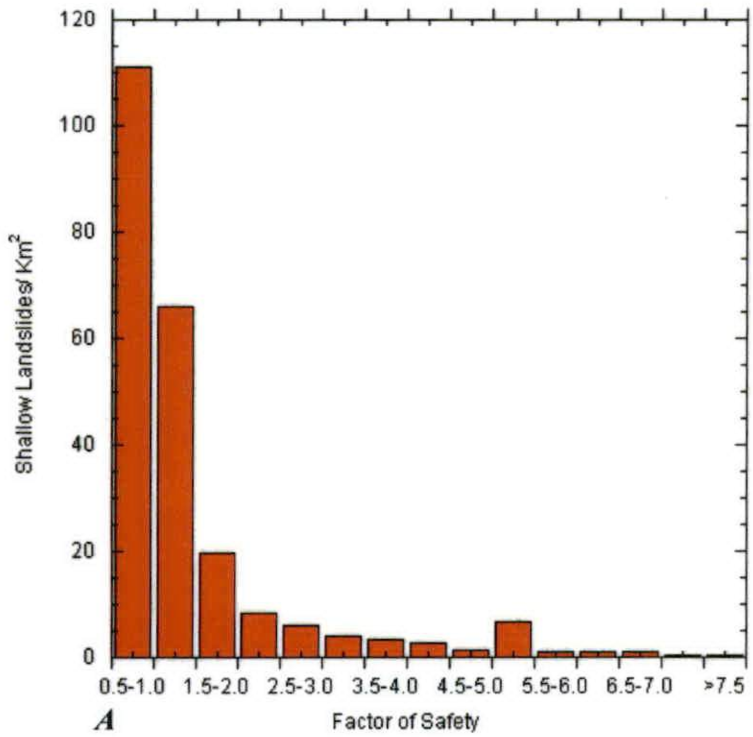


Figure 9. *A*, Bar chart showing number of shallow landslides per square kilometer from Seattle landslide data set versus FS value. *B*, Scatter plot of the data in *A* with an exponential curve fit to the data.



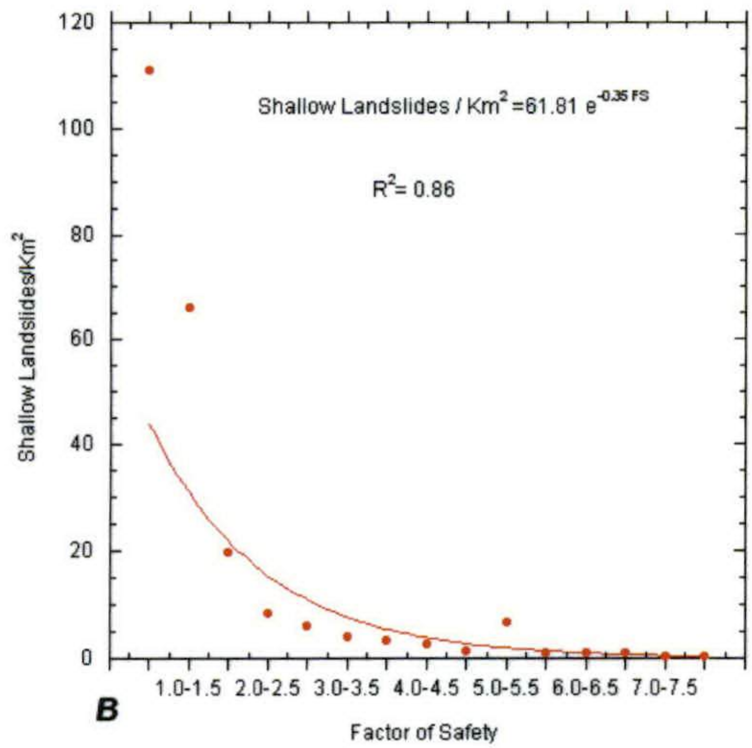


Figure 10. *A*, Bar chart showing number of shallow landslides per square kilometer from Seattle landslide data set versus FS value with shear strength held constant. *B*, Scatter plot of the data in *A* with an exponential curve fit to the data.

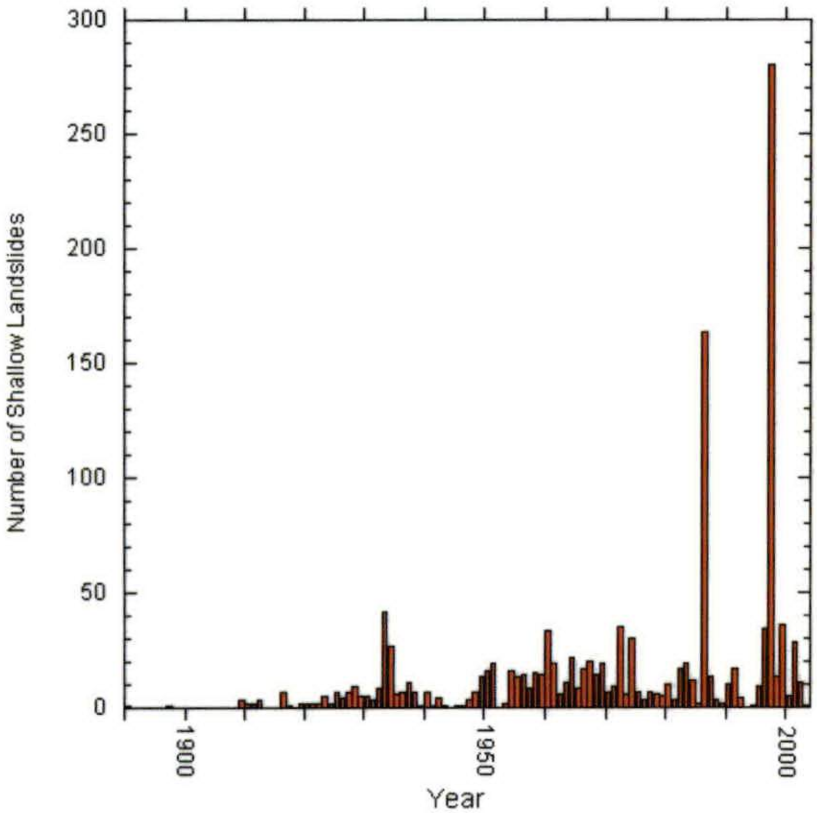


Figure 11. Bar chart showing the number of shallow landslides from the Seattle landslide data set versus the year of occurrence.

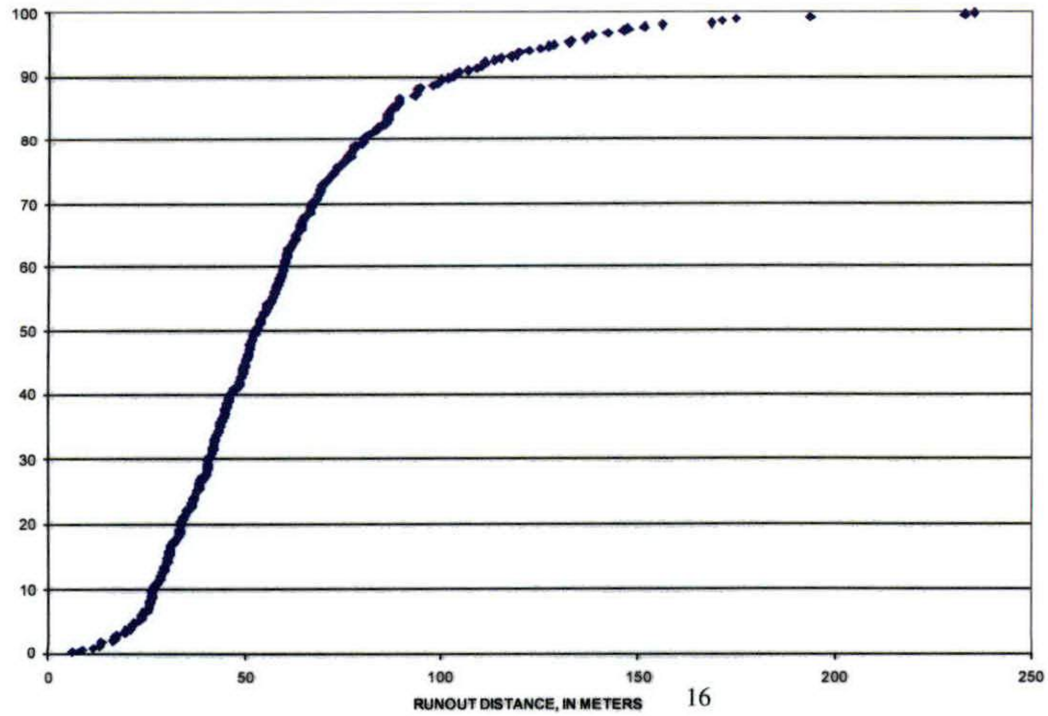


Figure 12. Cumulative frequency plot of runout distances for the 326 debris-flow runout lengths mapped from north Seattle to Everett.

scale USGS topographic maps (Baum and others, 2000). Except for large failures, such as the Woodway slump/debris flow, few debris flows crossed the Burlington Northern-Santa Fe railroad tracks and embankment which presented a significant barrier to debris-flow runout at the base of the slopes. Also, nearly all of the flat terrain at the base of the slopes is at, or seaward, from the shoreline of Puget Sound.

The mapped area consists essentially of the coastal bluffs along Puget Sound from north Seattle to Everett, Washington. Within this corridor along the bluffs, 326 debris flows and other landslides were mapped and their dimensions measured. The minimum length of these failures from headscarp to toe is about 6 m. The maximum length is about 235 m. The mean length is 60.2 m while the median is 52.6 m. The standard deviation from the mean is ± 34.1 m. The distribution of runout lengths within this data set is shown in fig. 12 (Baum, unpub. data). The slopes along this section of Puget Sound are representative of Puget Sound coastal bluffs throughout Seattle. Typical slope lengths range from less than 100 m to sections where lengths are greater than 1,000 m. Therefore, in some areas, debris flows with mean runout lengths will extend across most of the length of the slope. In other areas, the maximum runout length from this data set is less than the length of slope.

Models of granular or particle flow have been used to attempt to match the distances and paths of debris flows (Hungr and Morgenstern, 1984; Denlinger and Iverson, 2004; Iverson and others, 2004). However, no current models accurately model runout distances except in uniform materials that contain few irregular particles. Trees and other types of vegetation that commonly become incorporated in debris flows in the Seattle area are irregularities that cannot be modeled successfully by these methods but can impart considerable influence on runout distances and flow paths. Therefore, the most accurate information available on runout lengths is that from actual debris flows, and although the data set from January/March 1997 only represents two storm events, the runout lengths that it yields are the best information that we have to evaluate the hazard presented by the travel paths of debris flows in Seattle.

Although most of the source areas for debris flows are located near the tops of slopes in the Seattle area, debris-flow sources are scattered among lower parts of the slopes as well. There are enough of these that a runout zone established below susceptible cells based on the mean or maximum runout length from this data set would cover most of the existing slopes. For this reason, we conclude that the runout data indicate that all areas of steep slopes forming bluffs of Puget Sound and along other bluffs in the Seattle area should be considered hazardous. Furthermore, where flat-lying areas exist in Seattle below steep slopes that are above water and can be occupied, a runout zone based on the mean (60.2 m) or maximum (235 m) runout length would provide a degree of protection for the runout areas of most of the existing slopes of concern.

SHALLOW-LANDSLIDE HAZARD MAP

The distribution of shallow landslide concentration values as a function of factor of safety (fig. 9*A*) was used to establish relative hazard categories for shallow landslide source areas. Fig. 9*A* shows that the data can be divided into three obvious categories of hazard: FS = 0.5-1.5 (>75 shallow landslides/km^2) is the highest category, FS = 1.5-2.5 (20-75 shallow landslides/km^2) is a medium category, and the remainder of the data, FS > 2.5, (<20 shallow landslides/km^2), is in a category of low relative hazard. Other placements of FS boundaries could be constructed to define four or five categories of hazard instead of just three. It is worth mentioning here that the category of medium relative hazard, with an upper FS limit of 2.5 corresponds, in most cases, to a 20° slope threshold, which has been, and continues to be used, as a regulatory threshold in the city of Seattle.

A map based on a three-category hazard model outlined above is shown in fig. 13 and on Map Sheet 2. This map can now be used by the city of Seattle for planning purposes related to public utilities, city infrastructure, land use, and emergency response during severe shallow landslide-triggering storms (for example, >2 mm/hr rainfall for 24 hours; Godt and others, 2006). As city agency personnel become familiar with both the susceptibility and hazard maps, they also can use the maps in a regulatory capacity to support land-use policy. With such a high correlation between the map categories of shallow landslide susceptibility and the historical data set, the city has an extremely robust model upon which to base planning and policy decisions.

SUMMARY AND CONCLUSIONS

A simple infinite-slope analysis has been used together with a historical landslide data set collected for the city of Seattle, Washington, to establish a reliable correlation between a slope-stability measure (factor of safety, FS) and the locations of shallow slope failures that form debris flows.

The resulting FS map (Map Sheet 1) of the city shows the lowest FS values in areas where slopes are steep and where geologic units have low shear strengths. The majority of these areas are along the steep bluffs of Puget Sound, such as the Magnolia area (figs. 5-7, fig. 13) and the slopes above Alki Avenue W. in west Seattle (Map Sheet 1). However, many inland areas are also highly susceptible to shallow landslide failure. Areas of numerous low FS values include the Madrona area along the western shore of Lake Washington and many of the slopes adjacent to Lake Washington both to the north and south of this area. In general, many of the slopes that occupy the steep slopes of glacially formed ridges and hills within the Seattle area are sites of highly susceptible terrain.

The FS values of the susceptibility map (fig. 7, Map Sheet 1) were compared with the locations of failures from the landslide data set (fig. 8), and the resulting model of shallow landslide concentration versus FS (fig. 9*B*) shows excellent correlation with an R^2 of greater than 90 percent. FS values calculated using slope as the only variable also show excellent correlation with shallow landslide concentration (figs. 10*A* and *B*) and, in fact appear to be nearly as good, from a statistical standpoint, as those calculated using differing shear strengths. Montgomery and others (2001) also noted the effectiveness of slope alone as a predictor of slope instability in Seattle as it produced results comparable with SHALSTAB. However, as noted using figs. 5, 6, and 7, a slope-stability model using slope as the only variable will inevitably lead to spatial errors in calculation of FS where relatively resistant units occupy steep slopes and relatively weak units occupy low slopes. For these reasons, we favor using a model that uses the additional discriminator based on material properties.

Based on the levels of shallow landslide concentration versus FS shown in fig. 9*A*, we established three categories of shallow-landslide hazard: high, medium, and low. This map (Map Sheet 2) will allow Seattle city officials and planners to make decisions regarding areas of shallow-landslide hazard within the city. As development proceeds, portions of these maps will become outdated and will need to be updated with different shear-strength and slope attributions as construction and grading change the susceptibility of these areas. With its own mapping and GIS facilities, the city of Seattle can use its expertise and knowledge of ongoing construction activities to keep pace with the changing face of the city and keep the maps of susceptibility and relative hazard current.

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