Temporal trends and potential contributing factors to shallow landslide rates in timberlands of the Skagit River basin, Washington

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Abstract

To better understand decadal watershed and fishery impacts of shallow landsliding, I assessed landslide rates in six sub-areas of the Skagit River basin of northwestern Washington. All inventory areas contain predominantly forestry lands with ongoing timber management. I compiled existing landslide inventories documenting landslides occurring in the 1950s through the early 2000s and collected new information through 2011. Data were compiled by decade to assess temporal patterns. Landslide rates climbed during the 1980s and 1990s, then dropped sharply from 2002 to 2011. I evaluated numerous possible contributing causes of this pattern, including major precipitation events, logging rates, forestry mitigation practices, legacy effects and changes in landslide detection. Because this landscape-scale approach provides limited insight on individual landslide triggers, I evaluated potential causes based on temporal correlation and conceptual arguments. I conclude that declines in logging rates and improved forestry mitigation practices are likely to be major contributing factors. The effectiveness of strengthened forestry regulations is crucial to land management and watershed recovery, and these results suggest a favorable response. However, stronger conclusions will require additional time to see if landslide rates remain low after 2011, especially in areas where logging rates have accelerated. Extended observations may provide greater certainty on the relative strength among other possible driving mechanisms.

Background

In the Skagit basin, as in other mountainous landscapes, episodic sediment influx to the drainage network strongly affects watershed processes, including river, floodplain and estuary behavior (Benda and Dunne 1997, Beechie et al. 2001, Hood et al. 2016). More than a century of forest clearing, drainage modification and ongoing land use play a substantial role as well. Temporal fluctuations influence floodplain and fan habitat as well as hazards to humans and infrastructure. Such linkages are apparent in the Skagit Basin, where erosion rates respond to abundant precipitation across a landscape shaped by ongoing glaciation, volcanism and uplift (Czuba et al. 2011, Jaeger et al. 2017). Despite this dynamic setting, the Skagit basin supports sizable salmon runs and is a regional priority for salmon recovery (SRSC and WDFW, 2005).

Numerous landslide inventories have quantified densities and rates in Skagit sub-basins and the influences of forestry, precipitation, terrain, and geology (e.g. Heller 1981, Parks 1992, Wolff 1994, Paulson 1997). Past inventories provide data sets that can document sediment inputs over the last half century and evaluate the efficacy of management strategies and forestry regulations.

Across the Skagit basin’s western uplands, timber harvest is the dominant land use. Logging and associated roads have contributed to increased landslide rates (Heller 1981, Paulson 1997), which can adversely impact salmonid habitat, water and soil resources (Sidle et al 1985, Beechie et al. 2001). Salmon and other organisms are impacted by resulting pool filling, lateral destabilization and channel dredging conducted in response to aggradation (Wolff 1994, Beechie et al. 2001). Extensive management-related landsliding is evident throughout parts of the basin, where clearcut logging has been ongoing since the late 1800s (Beechie et al. 2001). Stronger forestry regulations have been in place for two decades, providing opportunities to evaluate their effectiveness (Stewart et al. 2013).

Since 1975, Washington has had Forest Practice Rules (Washington Administrative Code (WAC), Chapter 222-16) of increasing scope that are designed, in part, to limit sediment impacts to humans and aquatic resources. Milestone upgrades to forestry rules followed the 1987 Timber/Fish/ Wildlife Agreement and the 1999 Forest and Fish Report (U.S. Fish and Wildlife Service et al. 1999). Both resulted from expanded documentation of impacts (e.g. Swanson et al. 1987), recognized collectively by state and federal agencies, native tribes, forest industry, and environmental groups. The current regulatory process is linked to an effectiveness monitoring program that included a study focusing on practices intended to reduce landslide frequency and sediment delivery (Stewart et al. 2013). Despite confounding effects of stand age, the authors found evidence that mature forest buffers on unstable terrain had reduced landslide frequency and impacts (Stewart et al. 2013). Although Stewart et al. (2013) and similar studies (Grizzel et al. 2009, Turner et al. 2010) have characterized landslide response under contemporary regulations, all are confined to a limited geographic area under a single storm event. Thus, additional research is required to capture an expanded spatial and temporal scope. The goal of this study was to evaluate temporal trends in landslide rates in Skagit basin timberlands over the past half century and explore possible causative factors.

Methods

The primary data were landslide inventories collected in six inventory areas (Figure 1), using aerial photography that spans over a half-century. The inventory areas contain predominately private and state-owned forest lands subject to ongoing forest management, typically clearcut logging on rotations of 40 to 70 years. By 2011, air photos suggest that nearly all of the area had been logged, typically two or three times. The study area boundaries exclude most federally-owned timberlands, so results are not representative of forests managed by the US Forest and National Park Services, which dominate the eastern portion of the Skagit basin.

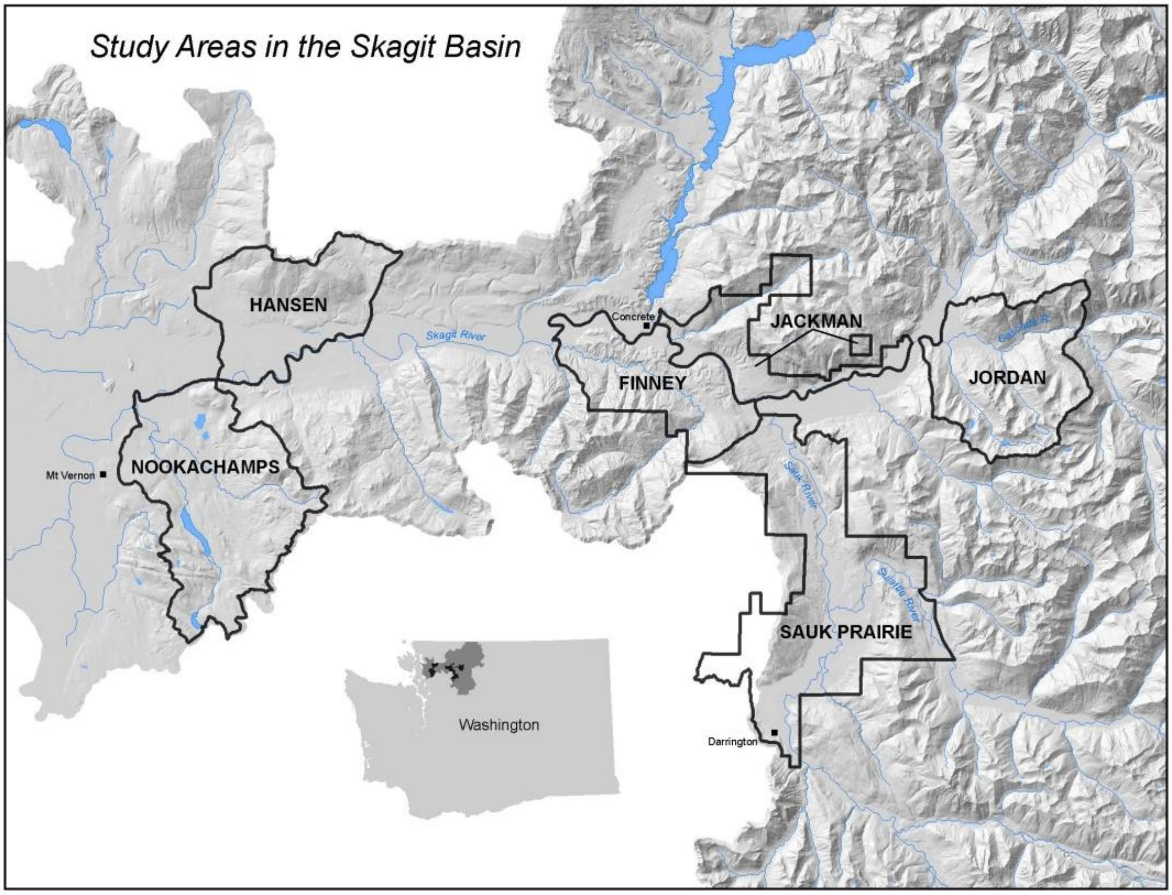

Figure 1. Map of Skagit-Samish Basin showing the six inventory areas where landslides were evaluated. Boundaries of the inventory areas generally follow drainage divides and limits of state and private ownership.

Landslide data came from three sources: 1) mass wasting inventories in Watershed Analyses (Washington Forest Practices Board 1995), 2) Landslide Hazard Zonation inventories conducted by the Department of Natural Resources Geology Division (Boyd and Vaugeois 2003, UPSAG 2006), and 3) new mapping of landslides occurring up through mid-2011 imagery by the author (Table 1). All sources identified landslides from visible scars that contrast to the surrounding vegetation on aerial imagery (Reid and Dunne 1996), supplemented by field visits to a sub-set of scars for verification. Other landslide attributes focused on the effects of forestry and included details on landslide type and size, as well as previous management activities and other characteristics at the landslide initiation site (UPSAG 2006).

Landslides were compiled by decade, starting in the 1960s when complete aerial photographic coverage first became available for all inventory areas. Even so, there were gaps in photo coverage for the Sauk Prairie (pre-1978) and Jackman (1979-97) areas (Table 1). All three datasets were verified with partial field checking, indicating sufficient quality for comparative analysis.

Table 1. Landslide inventories and aerial photography used in this project. Additional landscape information on inventory areas is provided in Appendix 1.

Inventory Area	Reference	Original inventory type	Photo years used	
			Original inventory	Update
Nookachamps	Wegmann, 2004	Landslide Hazard Zonation	1962, 1978, 1991, 2001	2006, 2011
Hansen	Wolff, 1994	Watershed Analysis	1970, 1983, 1991	1998, 2006, 2011
Finney	Lingley and Brunengo, 2007	Landslide Hazard Zonation	1965, 1978, 1987, 1991, 1998, 2001	2006, 2011
Jackman	Lingley and Brunengo, 2004	Landslide Hazard Zonation	1965, 1978, 1998, 2001	2006, 2011
Sauk Prairie	Pringle and Brunengo, 2006	Landslide Hazard Zonation	1978, 1983, 1987, 1996, 2001	2006, 2011
Jordan	Coho, 1997	Watershed Analysis	1964, 1972, 1983, 1987, 1992	1998, 2006, 2011

Although use of aerial imagery is a well-established method to inventory landslides (Reid and Dunne 1996). Field inventories elsewhere have found that many landslides weren't detected on aerial photos, especially under large timber (Brardinoni et al. 2003, Turner et al. 2010). Potential biases in landslide detection are explored further in the following section. The Landslide Hazard Zonation inventories did not record every landslide found in areas with high density (UPSAG, 2006). Despite these limitations, the aerial imagery data were deemed sufficient to assess landslide trends over decades and across broad areas, given that comparable imagery and methods were used in all inventories.

Methodologies for landslide characterization (WFPB 1995 and UPSAG 2006) are similar between the different studies, although there were minor differences in landslide size categories. Although the landslide inventories attempted to distinguish landslides that impacted fish habitat or other streams from those that did not, this study did not use such distinctions. All landslides were analyzed collectively because: 1) the distinction among delivery categories is difficult to make from aerial photography due to the high density of small unmapped streams and, 2) study authors indicated that the great majority of landslides had impacted streams (Wolff 1994, Coho 1997). Additional details on aerial landslide inventories are provided in Appendix 2.

Methods used to explore contributing factors were relatively straight-forward, so are explained in the Results and Analysis section for the sake of continuity.

Results and Analysis

Temporal Landslide Rates

The aggregated landslide densities have a distinct temporal pattern, peaking between 1982 and 2001 (Figure 2) before dropping sharply in the last decade. The period of elevated landsliding coincides with major regional storms documented in 1983, 1989, 1990, and 1995 (Mt Baker Snoqualmie National Forest 1992, Lingley and Brunengo 2007). When decadal values were compared among inventory areas (Table 2), the 1982-91 period stood out as having a high landslide rate in most inventory areas. In the following decade (1992-01), rates continued to be high in the Finney, Jordan and Jackman areas, but lower elsewhere (Table 2). The Nookachamps inventory area had low rates in all periods.

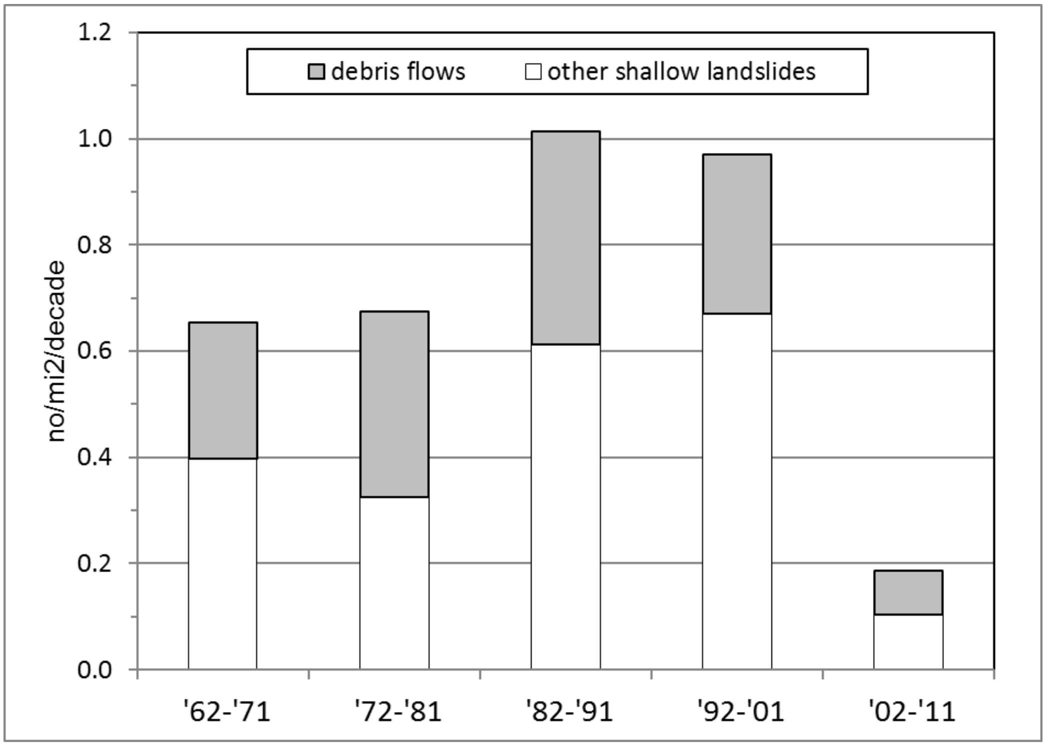

Figure 2. Shallow landslide frequencies averaged from six Skagit basin inventory areas, illustrating the sharp upswing from 1982-2001 and lower rate thereafter.

The high landslide densities in the Jackman and Finney areas (Table 2) may reflect particularly unstable bedrock. Both areas have friable low-grade metamorphic bedrock and an abundance of very large older slides from which numerous shallow landslides originate (William Lingley, personal communication).

Table 2. Decadal landslide frequencies (number/mi^2/decade) for the inventory areas shown in Figure 1. Shaded cells highlight landslide density.

Inventory area	1962-71	1972-81	1982-91	1992-01	2002-11	**1962-11**
Nookachamps	0.11	0.17	0.16	0.16	0.06	0.13
Hansen	0.86	0.09	1.46	0.26	0.19	0.57
Finney	0.17	0.84	0.90	2.06	0.49	0.89
Jackman	1.70	1.00	ND	1.39	0.05	1.04
Sauk Prairie	ND	0.14	1.90	0.65	0.08	0.69
Jordan	0.43	1.81	0.65	1.56	0.25	0.94
Average	0.65	0.67	1.01	1.01	0.19	0.71
* ND indicates 'no data' due to lack of aerial photography within period						

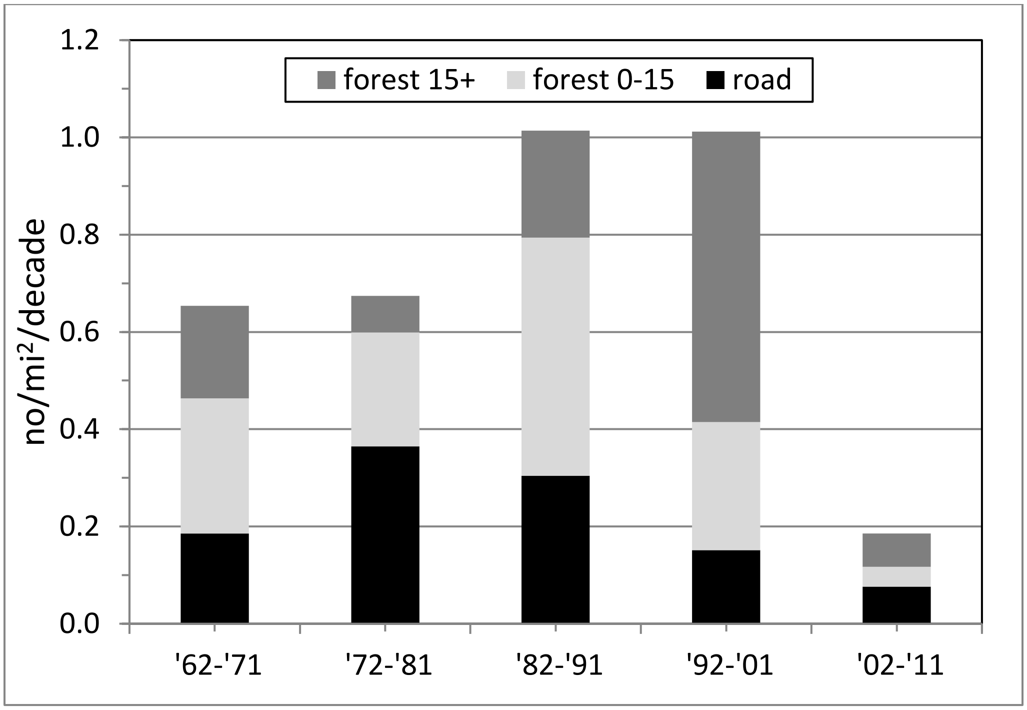

Figure 3. Shallow landslide rates segregated by land use at initiation. Within the overall trend, note that declines began in the 1980s for road-adjacent landslides and in the 1990's for landslides originating in young forests (age 0-15 years).

Overall, 34% of landslides in this study were classified as debris flows (Figure 2), which are commonly the most damaging shallow landslide type because of their relatively long run-out distances and scour volumes. Debris flows were especially prevalent in the Hansen (64%) and Jordan (52%) inventory areas.

Physical Influences Upon Landslide Initiation

This project explored numerous potential contributing factors, one or more of which may have contributed to reduced landsliding:

1. Change in frequency of major storm events?
2. Change in rates of forest harvesting and road construction?
3. Improved forest practices, which provided greater mitigation?
4. Soil evacuation legacy from previous harvest

Frequency of Major Storm Events: Because slope failures are triggered by large rainfall and/or snowmelt events (Reid and Dunne 1996), the apparent drop in landsliding could result from fewer high-precipitation events. Due to the lack of long-term precipitation stations in upland portions of the Skagit basin, I utilized streamflow records to indicate periods of unusually high soil moisture which would be expected to trigger increased landsliding (Hayman, et al. 1991, Jakob and Weatherly 2003). I compiled peak flow histories for the Samish and Sauk River (Figure 4) to analyze major storm events affecting the inventory areas. The Samish and the Sauk rivers are located on opposite ends of the study area geographically and represent lowland rain-dominated and mountainous snowmelt hydrographs,

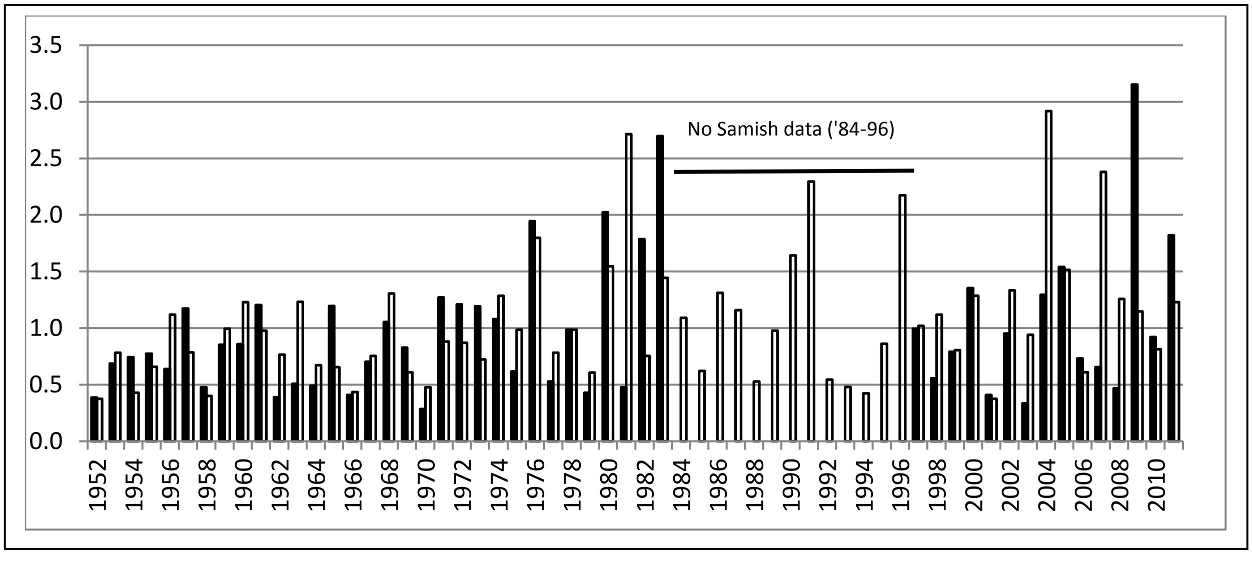

Figure 4. Annual peak flows at the Samish and Sauk River gages (solid and hollow bars, respectively) during the landslide inventory (based on Water Years beginning October 1 of prior calendar year). Bar heights indicate the ratio of each year's maximum flow relative to the station average over the entire gage record. Thus, bars exceeding 1.0 indicate larger-than-average peak flows and those exceeding 2.0 are significant high flow events. USGS gage numbers are #12189500 and #12201500 (USGS 2014).

respectively. In addition, the Samish and Sauk are unregulated (i.e. unaffected by dams) unlike the Skagit and Baker Rivers.

Figure 4 shows large variation in annual peaks, both interannually and between the two basins, owing to local topographic effects. The weak correlation between the two gages illustrates the limits of extrapolating major events to ungaged tributaries, including those included in this study. Figure 4 shows an increase in major discharge events after 1975, which helps explain the high landslide rates in the 1980s and 90s (Figure 2). Major peaks are evident in the early 1980s and 1991, storms known to have triggered many landslides and resulting stream disturbance (Mt Baker-Snoqualmie National Forest 1992). Figure 4 also shows major flows in 2004, 2007 and 2009, all during the 2002-11 decade when landslide rates dropped. This undermines a lack of storm events as an explanation of declining landsliding.

Rates of Forest Harvest and Road Construction: All inventory areas have histories of extensive forestry activities, including clearcut logging, road construction, and silviculture (replanting, herbicide treatment, etc.) that have influenced landslide initiation (Wolff 1994, Lingley and Brunengo 2004). Because logging rates fluctuate over time, I investigated whether the downturn in landsliding after 2001 correlated with changes in logging rates. Logging and roading rates were inferred using forest age data from three major forest landowners, which collectively own about 80% of the industrially-managed forest land in the Skagit basin.

Rates of logging (Figure 5) and landsliding (Figure 2) both peaked in the 1980s, supporting the notion that logging rates may have contributed to elevated landsliding. To further evaluate this correlation, I normalized decadal landslide rates by the amount of logging in the previous decade, indicated by the sloping line in Figure 5. Harvest data from the previous decade was used to reflect the expected lag between logging and landslide initiation (Sidle et al. 1985). The flat mid-section in the line suggests a consistent relationship between landslides and harvest through the 1970s, 80s and 90s. The decline after 2001 indicates that fewer landslides occurred than would have been predicted based on rates of previous logging. This drop could reflect that harvesting was employing better mitigation techniques or perhaps occurring on less unstable terrain.

Improved Forest Practices: Another factor likely to contribute to the observed reduction in landslides in the last two decades is improvements in forest practice mitigations. In the late 1980s and 1990s, the expanded appreciation of linkages between forestry, mass erosion, channels and aquatic resources was greatly advanced in the regional literature (e.g. Sidle et al. 1985, Swanson et al. 1987) spurring the implementation of Watershed Analysis in Washington. Stronger regulations were adopted in 1987 and expanded again in 2001, including additional restrictions on logging and road operations on potentially

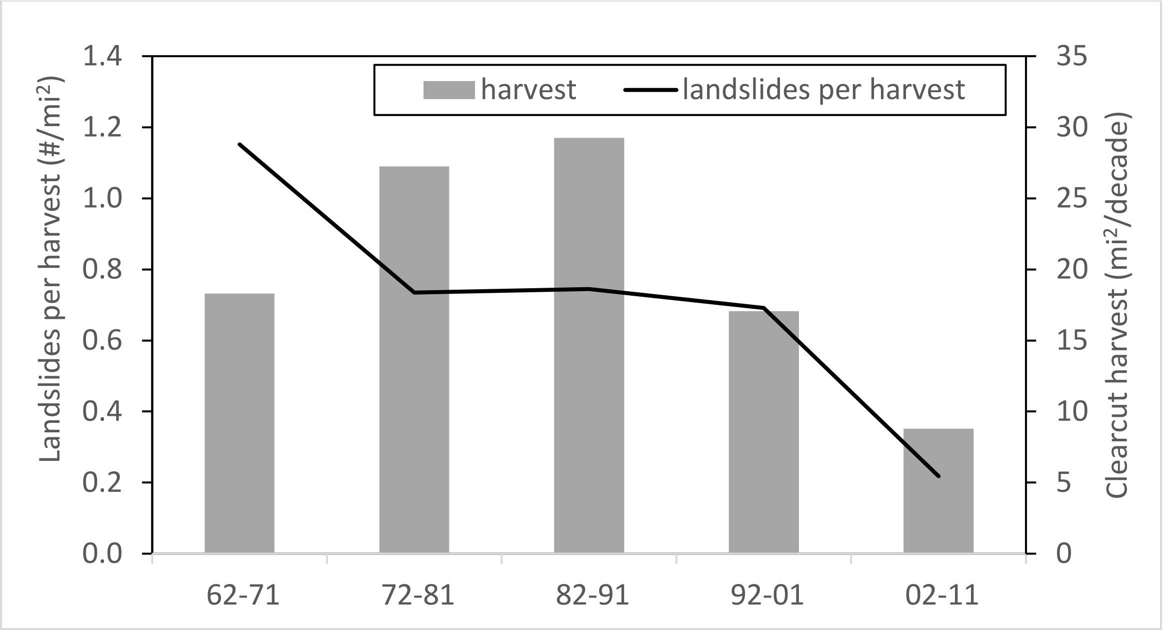

Figure 5. Trends in clearcut harvest (bars), and landslides normalized by harvest in the prior decade (line). Note that the rate of harvest-normalized landsliding dropped sharply from 1972-81 and again after 2001.

unstable slopes. Although the improvements are numerous and scientifically based, their effectiveness remains unquantified. New regulations can't be tested immediately because it takes many years for sizable areas to be harvested under new protections and additional time for major storms to test such treatments. The post-2001 rules are likely reducing our ability to identify landslides from aerial photography because mature trees retained in buffers may be obscuring landslides, as discussed further below.

The legacy effects of older practices, especially roads, can extend for decades, confounding response to improved practices (Grizzel et al. 2009) across a landscape with mixed forest ages. Of the 42 landslides identified from 2002-11, 78% originated either from areas last logged prior to 1987 or roads, mostly older as well. Only four landslides (10%) were from sites logged since 2001, supporting the notion that recent practices are triggering fewer landslides. The longer-term response to new regulations is important and remains unproven.

Although forest roads are a significant landslide trigger in the Skagit River basin (Heller 1981, Paulson 1997), Figure 3 suggests that road failures began to decline in the 1980s. This follows initiation of Washington's initial Forest Practices Rules in 1975 which addressed road construction and drainage.

Many currently active roads were built prior to 1975, though many had undergone significant improvements (e.g. larger culverts, side-cast removal) by 2011.

It is also possible that improved reforestation practices (e.g. replanting and brush control) compared to previous decades may be contributing to faster recovery of rooting reinforcement after logging. Although temporal changes in practices or resulting recovery rates have not been quantified, Turner et al. (2010) also found greatly reduced landslide rates 11+ years after logging compared to stands under 10.

Soil Evacuation Legacy: Shallow rapid landslides (debris flows, debris avalanches, etc.), generally involve evacuation of the regolith, the accumulation of soil and colluvial material resting on bedrock or more cohesive sediments. Once a landslide occurs, it may require a century or more before sufficient regolith has accumulated such that another landslide may occur in the same location (Dietrich et al. 1988, Benda and Dunne 1997). Because of this, if the initial logging entry triggered failures from a high proportion of marginally stable locations, fewer landslides would follow later harvest until regolith re-accumulates. I considered whether this type of legacy effect could contribute to the decline observed in 2002-11.

First, prevalent geologic materials, notably Darrington phyllite and glacial sediment deposits, are observed to weather rapidly enough that individual failure sites can refill within the temporal scope of this study (William Lingley, personal communication). And second, given that much of the inventory areas had been logged twice prior to the high landslide rates of the 1980s and 90s (Figure 2), it would seem unlikely that a strong dampening effect would become evident so suddenly after 2001. So, this appears to be a minor influence, aside perhaps from road sidecast failures.

Factors Affecting Landslide Detection

It is important to evaluate the uncertainties inherent to landslide detection using aerial photography (Brardinoni et al. 2003, Turner et al. 2010), including the following potential effects:

5. Reduced landslide detection due to different imagery quality?
6. Reduced landslide detection due to mature forest buffers obscuring unstable slopes?

Change in Imagery Quality: Landslide inventories prior to 2002 were based on images viewable as stereographic pairs. In contrast, post-2001 updates used individual 1:12,000 digital orthophotography (pixel size = 1m), which does not depict topography without cross-referencing topographic information (e.g. USGS topos, LiDAR hillshades). Although resolution and image quality of recent orthophotography is generally high (e.g. focus, lack of shadows), topography helps distinguish landslide scars from other canopy gaps resulting from quarries, windthrow, roads, etc. However, all inventories incorporated partial field truthing by the photo interpreter (e.g. Appendix 2) which supported high confidence in all data.

Forest Buffers Obscuring Unstable Slopes: As explained above, retention of forest buffers on unstable slopes became common the 1990s and mandatory after 2001. Buffers could have made landslides more difficult to detect during the latest period, when landslide rates appeared to drop (Figure 2). Reduced visibility would obscure the most landslide-prone parts of the landscape. However, harvest rates have been modest since buffers received wider use (Figure 5), so their footprint is only recently becoming extensive.

As mentioned above, landslides too small to be visible through mature forest canopy were excluded in order to reduce canopy-driven bias between decades. Even so, concentrated harvesting has shifted among the inventory areas during the 50 years of this study, so the aggregate temporal effect should be diluted. A more definitive analysis would require a temporal inventory quantifying buffer implementation among the inventory areas, which exceeded the scope of this study.

Sediment Volume and Aquatic Implications

The temporal pattern shown in Figure 2 is useful for interpreting temporal changes in watershed and estuary response during this time period (e.g. Hood et al. 2016). As a metric for landslides impacts to aquatic habitat, sediment volume is arguably more applicable than landslide frequency, the metric explored here. Landslide frequency was judged an adequate proxy that avoids inherent measurement uncertainties of aerial detection such as landslide depth and proportion of sediment volume delivered. For similar reasons, this study excluded all deep-seated landslides and small shallow landslides, which comprise around 36% and 17%, respectively, of landslide sediment volume delivered to Skagit tributaries (Appendix 5-1 in Paulson 1997).

Although managed forest lands contribute substantial sediment (Paulson 1997), a basin-scale perspective also requires consideration of other major sediment sources, including non-forest land uses (Beechie et al. 2001). The extensive alpine terrain and unmanaged forests in the Skagit basin, though pristine, are also geomorphically dynamic (Jaeger et al. 2017) due to steep slopes, intense weather, and glacial activity. Sediment routing is also a key factor influencing delivery to mainstem rivers and estuaries (Benda and Dunne 1994), as evidenced by the ubiquitous fans and floodplain deposits in the Skagit basin. Hydro-power dams strongly affect sediment export from the Baker and upper Skagit Rivers. Further exploration of these components is needed to gain a more complete understanding of response in fish habitat and other downstream environments.

Conclusions

Aerial inventories suggest that decadal rates of shallow landslides in timberlands of the Skagit basin climbed in the 1980s and 90s, then dropped sharply from 2002-11 (Figure 2). It is less certain what the primary contributing mechanisms were, though I explored the six plausible factors (Table 3).

Potential factors that seemed unlikely to have played a significant role included: lack of major rainstorms, the cumulative legacy of soil evacuation, and reduced landslide detection due to inferior imagery. It is likely that unstable slope buffers and other maturing forests are obscuring some landslides on unstable terrain that in past imagery was recently logged, and thus highly visible. Still, detection issues are not likely to be a major factor driving observed trends due to this study's exclusion of small landslides which are readily obscured.

There is strong temporal evidence that changes in logging - both the slow pace and associated improved mitigation practices - are contributing to lower landslide rates. Given that reduced logging rates and improved practices both coincided with reduced landsliding since 2001, it is difficult to separate their relative importance. However, this question is critically important to forest managers and regulators anticipating future increases in harvest. Most likely, the sharp decline in landslide densities reflects a combination of these two factors and perhaps others not considered.

Hopefully causative factors will become clearer as the stability of buffered slopes and improved roads continues to be tested. As new imagery becomes available, landslide inventories can be updated, which will verify or refute the durability of the downward trend. In the meantime, it is prudent to continue to diligently implement existing forestry rules and mitigation practices to maximize the watershed benefits that have already resulted from the reduced landslide rates documented above.

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Table 3. Summary of potential factors contributing to reduced landslide observation from 2002 through 2011. Directional signs (+, -) indicate whether bullet supports or detracts from factor being analyzed.

Major storm events – Small Effect • Unregulated basins had major flows during last decade of study (Figure 4) (-) • River gages might not reflect localized precipitation events in all inventory areas (- or +)
Rates of forest harvest: Large Effect • Slower logging reduces area affected by reduced root reinforcement and new road construction (+) • Temporal correlation between reduced landslides and reduced harvest (Figure 4) (+)
Improved forest practices: Large Effect • Drop in landslides followed improvements directed by Watershed Analysis and Forest Practices Rule upgrades (+) • Regulatory changes (e.g. slope buffers and road improvements) address documented triggers (+) • Most landslides in the last decade initiated outside locations affected by recent forestry activities (Figure 4) (+) • Improved reforestation should shorten period of reduced root reinforcement (+)
Soil evacuation legacy effect: Small Effect • No decline evident in 1980s and 90s, when many second growth stands were being relogged (-) • Local bedrock types weather rapidly, reducing delay before landslides can reoccur (-) • Only a small percentage of potential initiation sites (<10%) fail in any storm, leaving many areas vulnerable throughout the study (-)
Reduced detection due to imagery: **Small Effect** • High quality orthophotographs were available for the 2002-11 period (-). • Lack of stereo vision was offset by other topographical information (contour maps, LiDAR hill-shades) (-)
Reduced detection due to forest cover: Moderate Effect • Buffer use expanded in the 1990s, preferentially obscuring view of most landslide-prone terrain (+) • Because only a modest proportion of landscape (<10%) has been logged under new rules (Figure 5), most of landscape is yet unaffected (-)

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Appendix 1. Landscape, hydrologic and geologic information for Skagit inventory areas.

Inventory Area	Area[1] (mi^2)	Elevation range[2] (feet)	Mean annual precipitation[3] (inches)	Generalized Lithology (W. Lingley, additional notes below)
Nookachamps	49	20 - 4000	34 - 140	Heterogeneous metamorphic and sedimentary rock, glacial outwash, landslide deposits
Hansen	45	50 - 4040	44 - 116	Phyllite, glacial outwash
Finney	33	140 - 4280	64 - 110	Phyllite, glacial outwash
Jackman	22	200 - 4380	66 - 86	Meta-sedimentary and meta-volcanic rock, glacial outwash, landslide deposits
Sauk Prairie	51	400 - 3780	68 - 92	Phyllite and heterogeneous metamorphic rock
Jordan	42	320 - 4480	64 - 98	Heterogeneous metamorphic rock, intrusive igneous rock (granodiorite)

1 – Area values are for managed forest land, excluding lowlands under non-forestry land uses

2 – Majority of all inventory areas are within the middle of the elevation range, ~500’ to 3,000’

3 – Range across inventory area, from PRISM model using precipitation data from 1960-90

Other geology notes:

- Uplands in much of the land in this study is blanketed with a veneer of relatively stable glacial till.
- Lowlands are mostly covered with glacial lodgement till, lacustrine clay, and outwash, or covered with volcanoclastic debris flow deposits (lahar).
- While all inventory areas have abundant landslide deposits, older deep-seated and highly unstable landslide deposits cover larger portions of the Nookachamps and Jackman areas.

Appendix 2. Additional information on landslide data collection from aerial photographs

Imagery from prior to 1998 were mainly 1:12,000 scale aerial photographs viewed as stereoscopic pairs. These were augmented with color and black/white digital (non-stereo) ortho-photography and 1:8,000 stereo-images where available. About 15% of all landslides were confirmed in the field. Several steps are employed herein to minimize biases among interpreters. First, anomalies having lower certainty of actually being landslides were eliminated (e.g., landslides rated as "*Questionable*" by the Landslide Hazard Zonation teams). Second, all landslides smaller than 1,000 ft^2 were excluded, because small failures cannot be mapped with consistency owing to issues of photo quality and vegetation, which vary among data sets. Third, the inventory is limited to shallow landslides, which create scarps more consistently visible than those of deep-seated landslides, which commonly move slowly and may not create conspicuous canopy openings.

To compare the ability to detect subtle landslides on orthophotographs with detection using stereo-photographic pairs, landslides in the Hansen watershed identified using high-quality 2013 color stereo-pairs were compared with landslides in the same area mapped using 2011 orthophotographs. Although most landslides were visible on both images, two additional landslides were visible using the 2013 images. This was attributed to the superior resolution, rather than stereographic perspective. In fact, the 2013 photos were noticeably higher quality than earlier stereographic pairs used for Watershed Analyses and Landslide Hazard Zonation studies.

Further protocol information is provided in the Landslide Hazard Zonation manual (UPSAG 2006), the LHZ reports, and the mass wasting module reports from the Watershed Analyses. All are listed in the references to this report.

We assume that, given rapid natural revegetation, landslides predating the earliest available photography will be uniformly distributed among watersheds and time. In our experience, the earliest visible landslides probably predate the earliest photo by a decade or less in all Skagit basin watersheds, older slides being hidden under reestablished vegetation.