Forest practices and regulatory Channel Migration Zones in the Skagit River Basin since the Forests and Fish Report

Gustav B Seixas and Curt N Veldhuisen

Skagit River System Cooperative

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Summary

- Identifying and buffering of Channel Migration Zones (CMZs) is required on non-federal forest lands in Washington State to safeguard riparian functions adjacent to migrating rivers.
- Recognition of regulatory CMZs is one of the more technically difficult aspects of the forestry rules. Identification of CMZs during permitting is a two-stage process involving an initial effort by the permit applicant followed by review by state agencies and Native American tribes.
- We used aerial photography, lidar-derived digital elevation models, and data from forest practice applications to assess trends in CMZ recognition and channel migration in the Skagit River basin since the 2001 update to the Forest Practices Rules.
- Of 25 timber harvest units we analyzed, CMZs were recognized in permitting of 18 sites (72%).
- Of these, channel migration occurred at 11 sites and migration did not occur at seven sites (the period of observation likely underestimates activity levels over the 140-year time frame that applies to the CMZ rule.
- Three sites did not receive CMZ recognition and experienced migration of the channel into the riparian forest.
- Bank erosion, not avulsion, was the dominant process by which migration occurred.
- Many of the sites that experienced channel migration were located on outer meander bends or were in channel reaches not confined by terraces or mountainous topography.
- Migration was episodic within the photo record and not clearly associated with periods in which large discharge events were recorded at Skagit River gages.
- We examined additional years of aerial photography dating back to 1937 at all sites that did not receive CMZ recognition; three sites exhibited channel movements in the record prior to 1998.

Introduction

In Washington State, riparian corridors along fish-bearing streams are protected from forest practices (primarily logging and road construction) in the Washington Forest Practices Rule (Washington Administrative Code 222) to provide ongoing ecological functions despite management activities on adjacent lands. River reaches that show potential for migration across their floodplains or erosion into adjacent hillslopes face additional restrictions to preserve riparian function despite future shifts in river position. (Alluvial fans also receive Channel Migration Zone (CMZ) protections; this report is focused on CMZs in post-glacial valley bottom environments, not alluvial fans.) Since the Forests and Fish Report (U.S.F.W.S. et al., 1999) and the 2001 revision of the Forest Practices Rules (WFPB, 2001), CMZs have been protected to ensure timber management does not diminish riparian processes critical to the maintenance of aquatic ecosystems such as supplying wood to stream channels and providing streamside shade.

Channel Migration Zones are defined as “the area where the active channel of a stream is prone to move and this results in a potential near-term loss of riparian function and associated habitat adjacent to the stream, except as modified by a permanent levee or dike. For this purpose, near-term means the time scale required to grow a mature forest” (WAC 222-16-010). The regulatory definition of ‘near-term’ is 140 years. Due to the possible erosion of the channel banks or avulsion of the stream into adjacent areas (Fig. 1), land managers are required to begin their riparian buffers at the outer edge of the CMZ, not at the channel margin in its current location (WFPB, 2004). However, predicting a river’s future position is challenging given the complex interactions between discharge, sediment supply, and large wood common to alluvial rivers (Abbe and Montgomery, 2003; Brummer et al., 2006). Therefore, CMZ delineation relies upon empirical data from available historical aerial photographs, topographic data, and field observations.

Not surprisingly, the CMZ rule has been among the most technically challenging of the Washington State Forest Practices Rules to implement. In the first 10 years after the Forests and Fish Report, at least two CMZ determinations were legally challenged (i.e. along the Greenwater and Quinault Rivers). Although the legal challenges were not directly questioning issues of technical implementation of the CMZ rules, they suggest a regulatory environment that may be subject to differences of opinion and interpretation. The official Board Manual used to guide application of the CMZ rule was expanded in 2004 (WFPB, 2004) and the resulting document is larger and more complex than similar Board Manual entries on other forest practice rules. Although 17 years have passed since CMZ rule implementation, we are not aware of any systematic effort to assess successes and potential pitfalls in CMZ recognition and delineation.

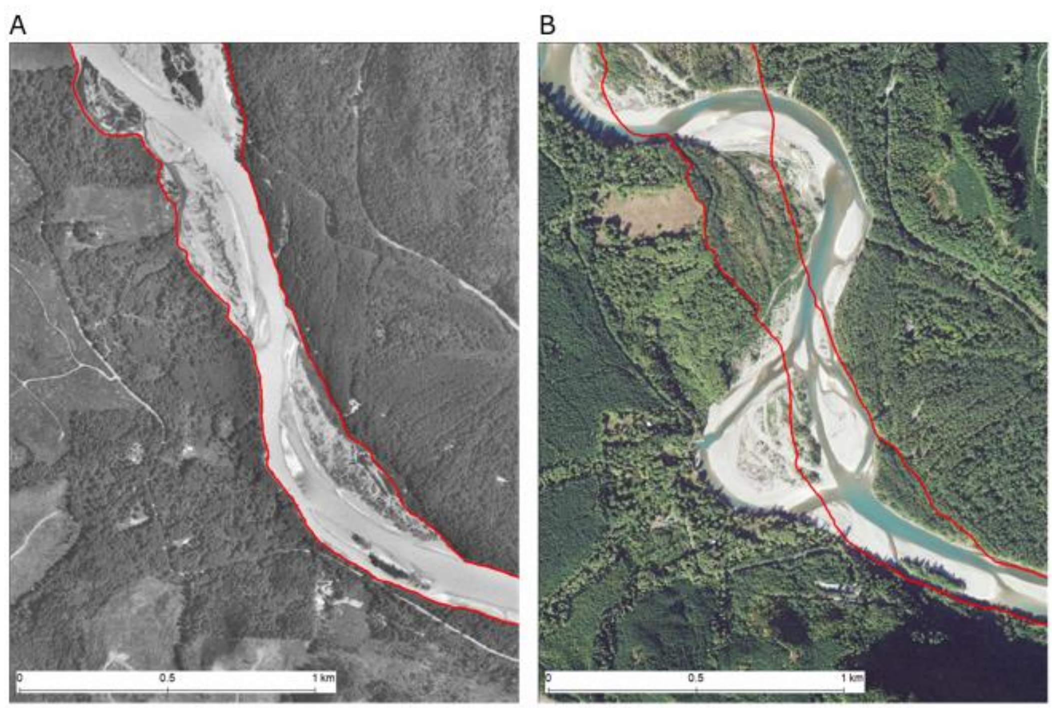

Figure 1. Aerial photographs showing channel migration in the Sauk River between A) 1998 and B) 2017. The location and scale are identical in both photos. The 1998 active channel envelope (see text) is mapped in red.

In this report, we retrospectively examine the regulatory process of recognizing CMZs in reaches that have experienced riparian logging since 2001 in the Skagit River basin, northwestern Washington State. In so doing, we address the following questions:

1) How well have the harvest layout and regulatory processes functioned to recognize CMZs?

2) Which geomorphic process (avulsion or bank erosion) is more likely to cause shifts in channel position, and is there a geomorphic process that is most likely to be overlooked by land managers and regulators when assessing potential channel migration hazards?

3) Are there predictors of channel migration, such as geomorphic setting or valley confinement, that could help to guide future CMZ recognition?

To address these questions, we used multiple years of aerial photography to map active channels and floodplains for the most dynamic rivers and streams in the Skagit River basin where they abut harvest units. We paired this before-after snapshot approach, which allowed us to assess whether migration had occurred, with inspection of the approved forest practices application (FPA) for each site, which enabled us to retroactively assess whether landowners and the regulatory team had recognized the channel migration hazard. Additionally, we examined geomorphic, topographic and hydrologic data to investigate possible physical predictors of channel migration. Although permit applicants are responsible for identifying CMZs near their proposed activities, their assessment is supported by a permit review process involving state regulatory agencies (Department of Natural Resources, Department of Ecology) and input from representatives of Native American tribes (including the authors of this report) and local governments. Our goal is not to highlight past oversights, but to identify any patterns in identification and application of CMZs with the intent of improving future CMZ implementation.

Study location

The Skagit River of northwestern Washington State, USA, is the largest river flowing into Puget Sound (Fig. 2). Including a small portion in Canada, the drainage area is approximately 8700 km^2. The low elevation areas included in this study are within the Western Hemlock forest climax zone (Franklin and Dyrness, 1973). Principal riparian tree species include red alder (*Alnus rubra*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) bigleaf maple (*Acer macrophyllum*), and Black cottonwood (*Populus trichocarpa*) (Haight, 2002). Positioned west of the Cascade Mountain crest, the region is characterized by a climate with cool, wet winters and dry summers. Large winter precipitation events occur episodically, with lowlands experiencing ~1000 mm/yr and the high mountains experiencing upwards of 5000 mm/yr on average (PRISM Climate Group, 2004). Repeated alpine and continental glaciations resulted in U-shaped valleys with extensive deposits of glacial and lacustrine sediments that line most alluvial channels (Waitt Jr, 1977; Heller, 1980; Riedel et al., 2010). Historically, glaciers contributed large volumes of sediment to Skagit River basin tributaries and the main stem, although downstream sediment transport of glacier-derived materials was limited to the Sauk River and its tributaries after the installation of the Skagit and Baker River dams in the early part of the 20th century. Landsliding and associated inputs of large volumes of sediment is a prevalent landscape process in all portions of the basin, contributing to channel aggradation, widening and movement (Beechie, 1998), though rates have declined since the 1990s in timberland areas (Veldhuisen, 2018).

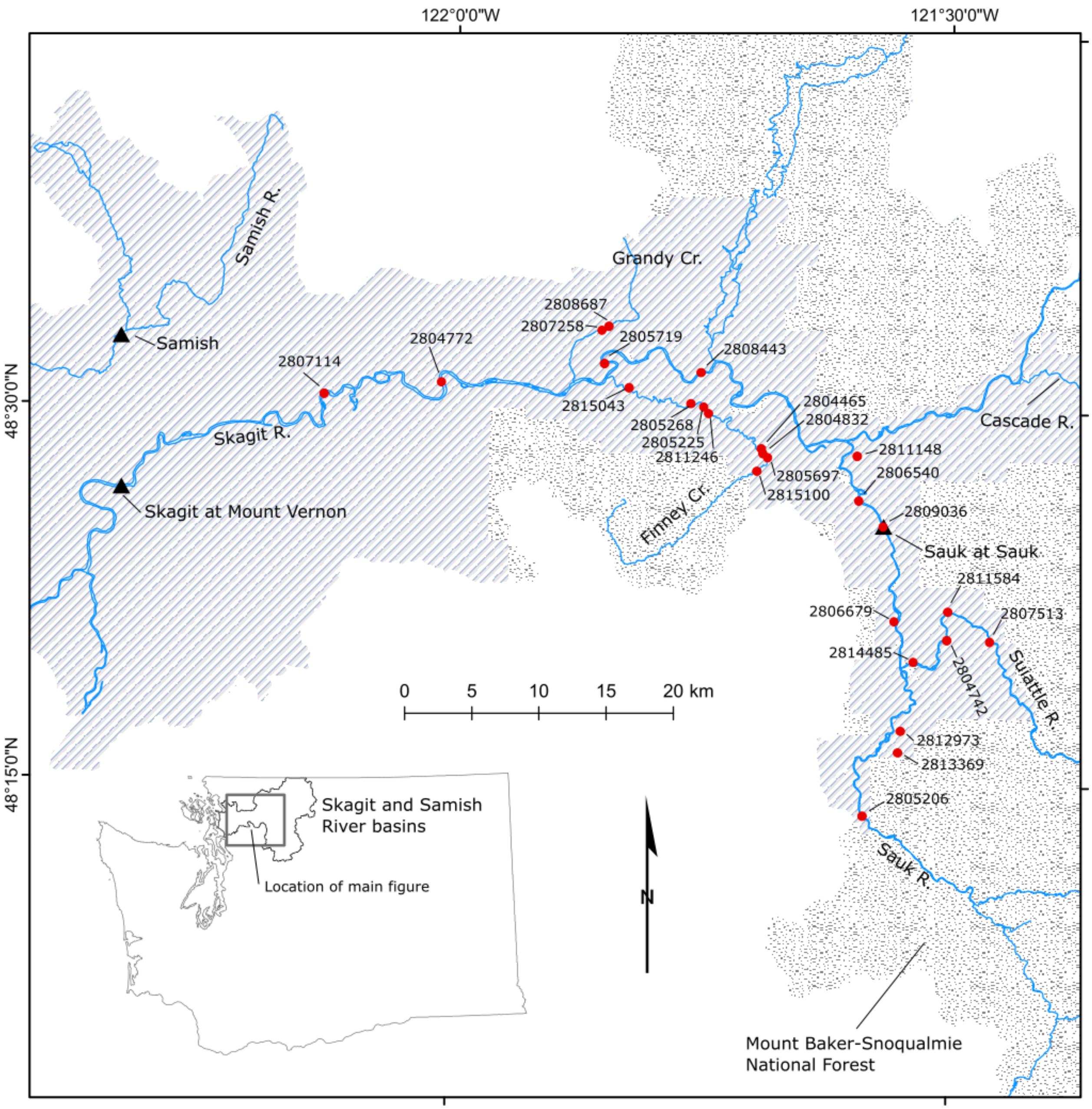

Figure 2. Location map showing outline of the Skagit and Samish River basins, the major creeks and rivers mentioned in the text (blue lines), approximate locations of FPAs used in the analysis (red points with adjacent FPA numbers for reference to appendix A), and locations of USGS river gages used in the hydrologic analysis (black triangles). National Forest Service land (gray stippled pattern) is governed by a different set of land management priorities and rules. Most of the land to the west of the National Forest and within the Skagit and Sauk River valleys (gray hatch pattern) is composed of commercial forestry, agricultural, or urban land uses and is subject to the state Forest Practices Rules.

Methods

We included study sites that met four criteria: 1) each site had a timber harvest activity between July 2001 (the adoption date of the CMZ rule) and the summer of 2017; 2) each site was located on a floodplain, low terrace or adjacent hillslope of a migrating (or potentially migrating) channel; 3) the channel at each site had to be visible through the streamside forest canopy; and 4) sites could not be armored by engineered reinforcements. All sites are tabulated in appendix A. To compile the list of sites, we identified FPAs that had triggered CMZ concerns during the review process using archived FPAs and notes. To include sites where a regulatory CMZ may have been overlooked, we visually inspected each of the most active floodplains in the Skagit River basin (Skagit main stem, Sauk River, Suiattle River, Cascade River and Finney Creek) for harvested parcels using 2017 National Agricultural Imagery Service (NAIP) aerial photography and a GIS database of all harvest units (Skagit River System Cooperative data archives).

We scrutinized each FPA for documentation of considerations involved in CMZ recognition and riparian buffer design and classified each FPA based on whether a CMZ was recognized. For an FPA to be classified as 'CMZ recognized', there needed to be at least some consideration of CMZ delineation documented either in the harvest layout map, in the written portion of the application, or in the notes from the regulatory review. Few FPAs included CMZ reports from a qualified expert. For each site that had recognized a CMZ, we recorded whether the FPA applicant had recognized the CMZ or if the need for a CMZ was identified during the regulatory review process. All sites in our dataset should have received some form of CMZ recognition due to our inclusion criteria, even if it was a note regarding a field discussion during the review process. Therefore, we regarded CMZs not recognized during layout or the regulatory process as having been 'missed'.

Next, we used ESRI ArcMap (version 10.5) to map the outer margins of the active channel portion(s) of the floodplain adjacent to each harvest activity in 1998 and 2017, using aerial photography from those years. We identified the active channelized footprint using only information clearly visible on aerial photographs—light detection and ranging (lidar) digital elevation models are not available prior to 2006, requiring us to discount this potential source of information. We defined the 'active channel envelope' as the outer extent of the channelized portion of the landscape as defined by visible surface-resetting flows, including bars, islands, side channels and braids (Fig. 1). In other words, the active channel envelope was defined by the extent of channelized features devoid of vegetation or that contained water, similar to the historical migration zone commonly used in the CMZ delineation process (Rapp and Abbe, 2003) but including only the area visibly affected by flows in the photos we used (no other information was included, such as digital elevation models or field observations). The 1998 photo (Washington State Department of Natural Resources) represented the latest available data prior to the enactment of the Forests and Fish rules. The 2017 photo (NAIP) was the most recent data available. We chose to map the active channel envelope in 1998 for all sites, no matter the year of harvest, to keep the timescale of observation consistent between sites.

Using these maps of the active channel envelope, we classified each site as having experienced channel migration or having not experienced migration. We considered 'experienced migration' to include sites that had had measurable channel movement anywhere in the direction of the harvest unit. This means that an FPA judged to have experienced channel migration could have experienced a small (but measurable) level of erosion—the harvest boundary or riparian management zone did not have to be compromised in the period of record. Because we were only concerned with channel movement in the direction of the FPA, we did not record whether the channel width had changed over the period of record, although this information could be easily collected from the maps of the active channel envelope.

Additionally, we classified the migration mechanism at each site as either bank erosion or avulsion using visual interpretation of hillshade images of lidar data (USGS North Puget, 2017, and USGS Glacier Peak, 2015 acquisitions; 1 m resolution). Sites exhibiting bank erosion activity or potential had high banks and no visible side channels on the lidar hillshade (Fig. 3). Sites classified as containing avulsion activity or potential exhibited side channels or floodplains between the current channel and the harvest activity on the FPA (Fig. 3). Therefore, avulsion pathways included the historical migration zone; we did not attempt to assess whether avulsion channels were below the bankfull depth of the current channel. Sites classified as having both avulsion and bank erosion hazards exhibited the different types of migration mechanisms present in a longitudinal sense (i.e. an eroding high bank directly upstream of a low-lying floodplain with potential side channel or braid pathways). Due to the high-resolution of lidar imagery, we believe this method is more accurate than the methods recommended in the Forest Practices Board Manual (inspection of aerial photographs and topographic maps).

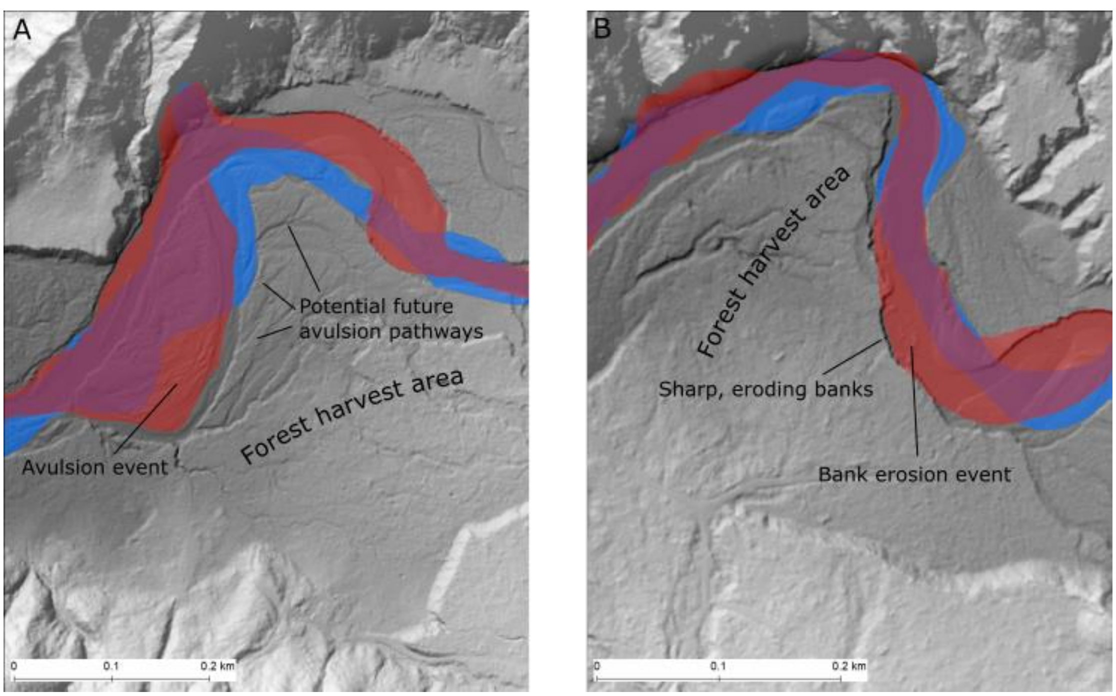

Figure 3. Example of A) avulsion and B) bank erosion hazards as seen on hillshade images of a lidar DEM. The avulsion zone in A is composed of multiple channel threads that cross the geologically-modern floodplain. In B, bank erosion is apparent in sharp banks. In both images the active channel envelope is mapped in 1998 (blue) and in 2017 (red).

To assess correlations between year of migration and regional hydrology, we mapped the active channel envelope on the FPA side of the river using each available NAIP photo year (2004, 2006, 2009, 2011, 2013, and 2015) for those sites that experienced migration, thereby establishing a timeline of channel migration and allowing us to identify years between which channel migration had occurred. Due to the gaps between the collection of NAIP imagery, we were not able to identify the timing of migration at finer resolution than two years.

Additionally, we used the lidar hillshades to classify the geomorphic and topographic setting of each site. We placed each site into categories for channel pattern, valley confinement, and geomorphic setting. Based on the sinuosity of the channel and whether the channel was single or multi-thread, we classified channels as meandering, island-braided, or straight following the definitions of Beechie et al. (2006) and Collins et al. (2003). We defined valley confinement as the ratio of floodplain width to bankfull channel width, with a ratio of four or higher defining an unconfined setting (Beechie et al., 2006). The streams we examined primarily occupied post-glacial valleys (Collins and Montgomery, 2011); accordingly, the valleys in 'confined' settings were commonly bordered by Pleistocene glacial or fluvial deposits of unknown (but likely low to moderate) shear strength and were still considered free to migrate. Moreover, a channel that abutted a terrace riser on one bank but had a large floodplain on the other side could still be classified as 'unconfined'. Geomorphic setting referred to the inside or outside of meander bends, or to sites that spanned the inside and outside of multiple meander bends.

To assess basin-scale hydrologic and geomorphic patterns, we examined daily discharge records from three long-term US Geological Survey river gages in the Skagit and Samish River basins and measured contributing area and slope at each FPA location using lidar and 10 m resolution DEMs (appendix B).

Results

We identified 25 sites for analysis that met our inclusion criteria (appendix A). Of these, four were on the Skagit River main stem, four were on the Sauk River, eight were on Finney Creek, four were on the Suiattle River, two were on Grandy Creek, two were on Dan Creek, and there was one on a Sauk River side channel. Regulatory CMZs were recognized in 18 of the 25 FPAs (72%; Fig. 4). Fourteen sites experienced channel migration and 11 did not. Of the seven FPAs for which no CMZ was recognized, three experienced migration and four did not experience migration (Fig. 4). We note that observation through the 19-year photo record is sufficient to confirm migration in some places but insufficient to rule out potential sporadic movement within the 140-year time frame pertaining to the CMZ rule.

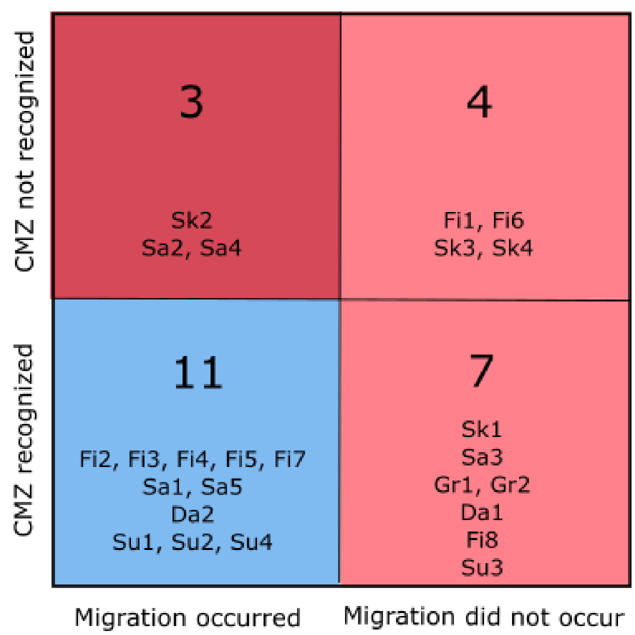

Figure 4. Matrix of observed channel migration and regulatory CMZ recognition results. The number of FPAs in each category is shown in large print with the site nicknames below (appendix A). Blue shading (lower left quadrant) represents FPAs with both CMZs and channel migration (the expectation of potential channel migration was met with the appropriate resource protection action). Deep red (upper left quadrant) indicates channel migration occurred but no CMZ was identified. Light red shading (right side) indicates migration has not occurred over the photo record.

After the adoption of the CMZ rule in 2001, CMZs were recognized immediately by some landowners and regulators (Fig. 5). However, in the early years there were also several CMZs that were 'missed' by landowners and regulators. By 2011, all potential CMZs in our dataset were recognized by either landowners or the regulatory process. We also note that the most recent two years of the record are characterized solely by landowner recognition, perhaps indicating increasing familiarity with the CMZ rules.

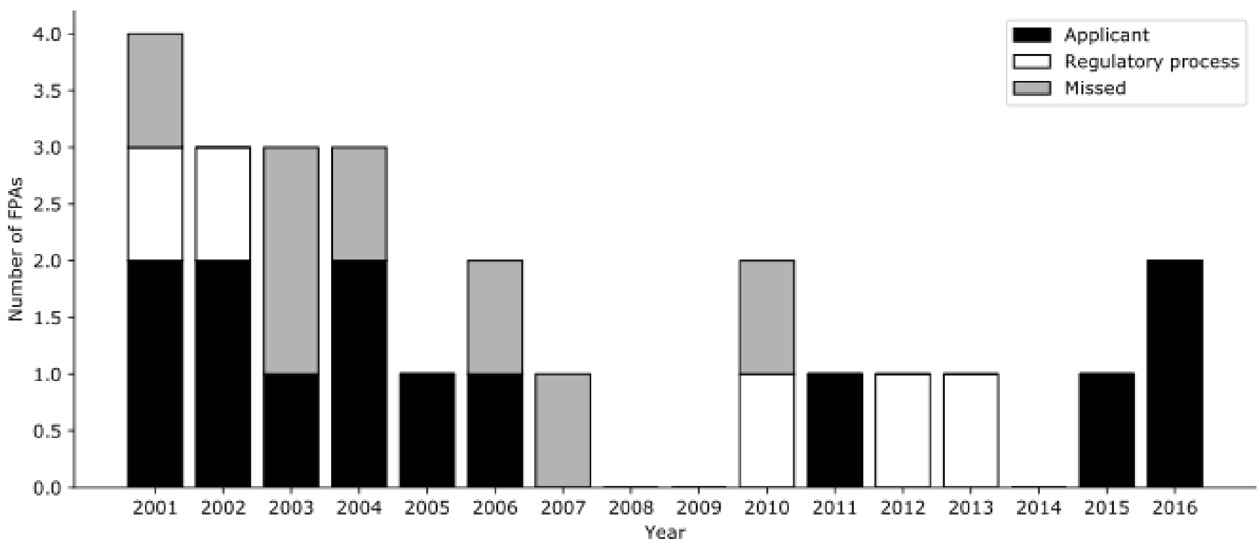

Figure 5. Timeline of CMZ recognition split into identification categories: CMZ recognized by the applicant, CMZ recognized by the regulatory process, and CMZ not recognized.

Channel migration was episodic across the 19 years of the photo record. At most sites that experienced migration, a single photo year exhibited the highest level of channel change, allowing us to assign a primary migration year for each site. At least one site experienced migration in each photo year we examined; migration was most commonly noted in 2004 and was least present in photos from 2011 to 2015 (Fig. 6).

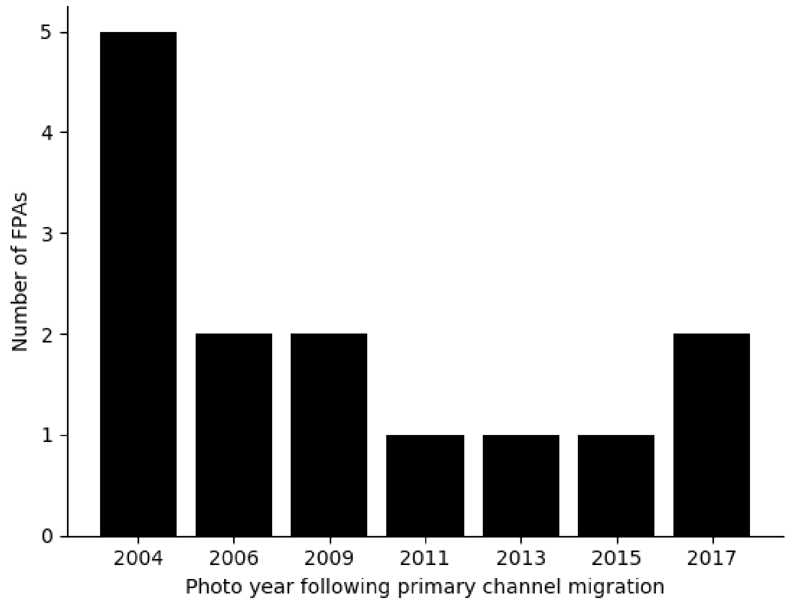

Figure 6. Photo year following the main episode of channel migration detected for each FPA that experienced channel migration.

The most common migration process at sites that experienced migration was bank erosion (13 FPAs) (Fig. 7 left panel). Only one site avulsed. At the sites that did not exhibit channel movement, bank erosion hazards were present at seven FPAs and avulsion hazards were present at three FPAs (Fig. 7 right panel), while both bank erosion and avulsion hazard potential were present at one FPA.

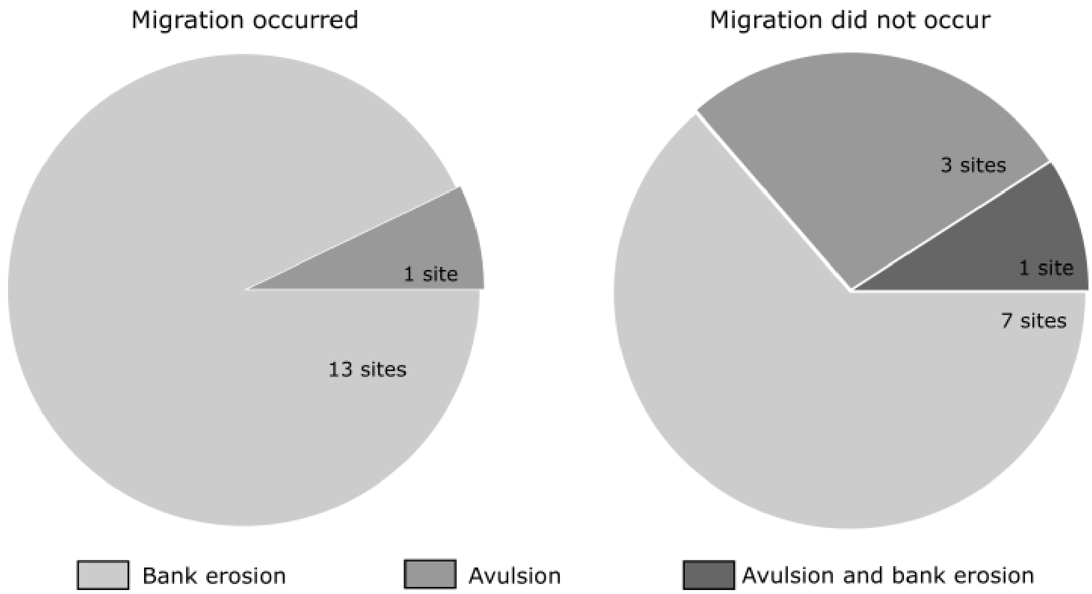

Figure 7. The distribution of migration process for sites at which migration occurred (left), and sites at which no migration occurred (right). In the right panel, migration process is meant to imply the potential process by which channel movement could threaten the CMZ should the channel migrate.

The meandering channel pattern category was most common both in sites in which migration occurred and sites in which no migration occurred (Fig. 8). For sites in which migration occurred, island-braided channels were the second-most common while straight channels were the least common. At sites at which no migration occurred, island-braided and straight channels were each represented by one FPA. Unconfined channels were more common at sites in which migration occurred; in the no migration set, confined channels were slightly more common than unconfined channels (Fig. 8). The geomorphic setting 'outer meander bend' was most common and the setting 'inner bend' was least common at sites with migration; for sites at which migration did not occur, 'inner bend', 'outer bend' and 'inner and outer bend' were equally common while straight channels were the least common (Fig. 8).

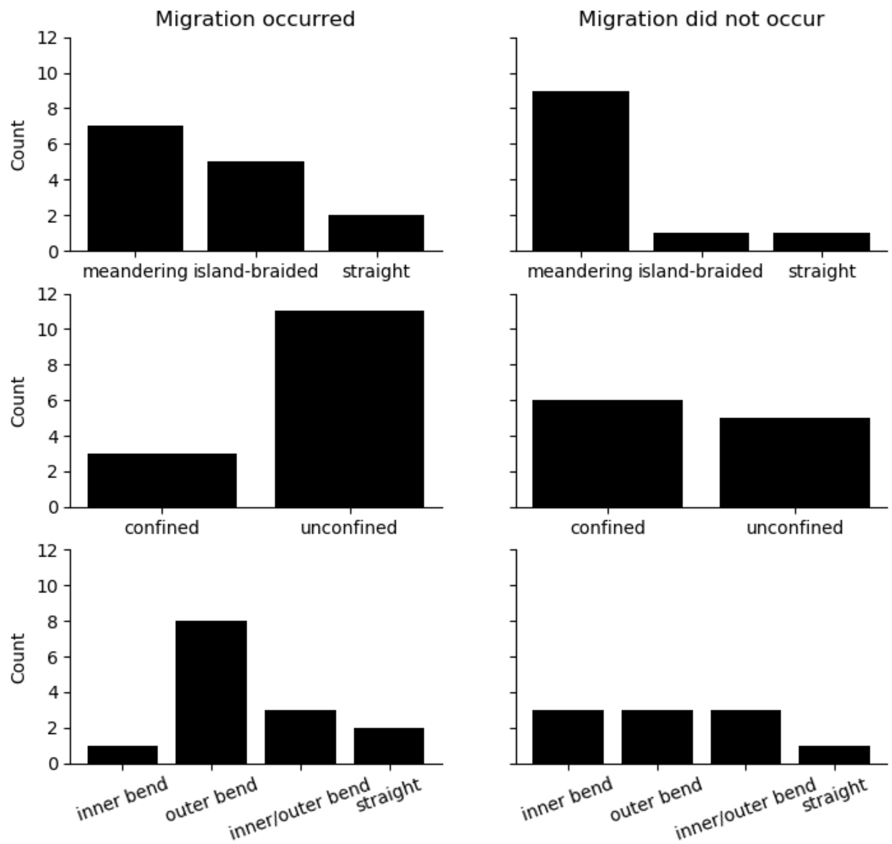

Figure 8. Bar charts of channel type, valley confinement, and geomorphic setting. The geomorphic setting 'inner/outer bend' indicates site at which the harvest activity spanned an inner and an outer meander bend.

The discharge records at two gaging stations in the Skagit River basin showed similar patterns in daily flow between 1998 and 2017 (Fig. 9A, B). The largest peaks at the gages occurred in October 2003 and November 2006. The Samish River gage (Fig. 9C) showed a different pattern: the largest event occurred in January 2009. The differences in discharge patterns between the Skagit and Samish River gages reflect the snow-dominated hydrology of the Skagit basin tributaries versus the primarily rain-dominated Samish basin, as well as spatial variation in precipitation intensity. Any potential correlation between number of migration events and peaks in the discharge record is obscured by the varying length of time between photo sets in the available record.

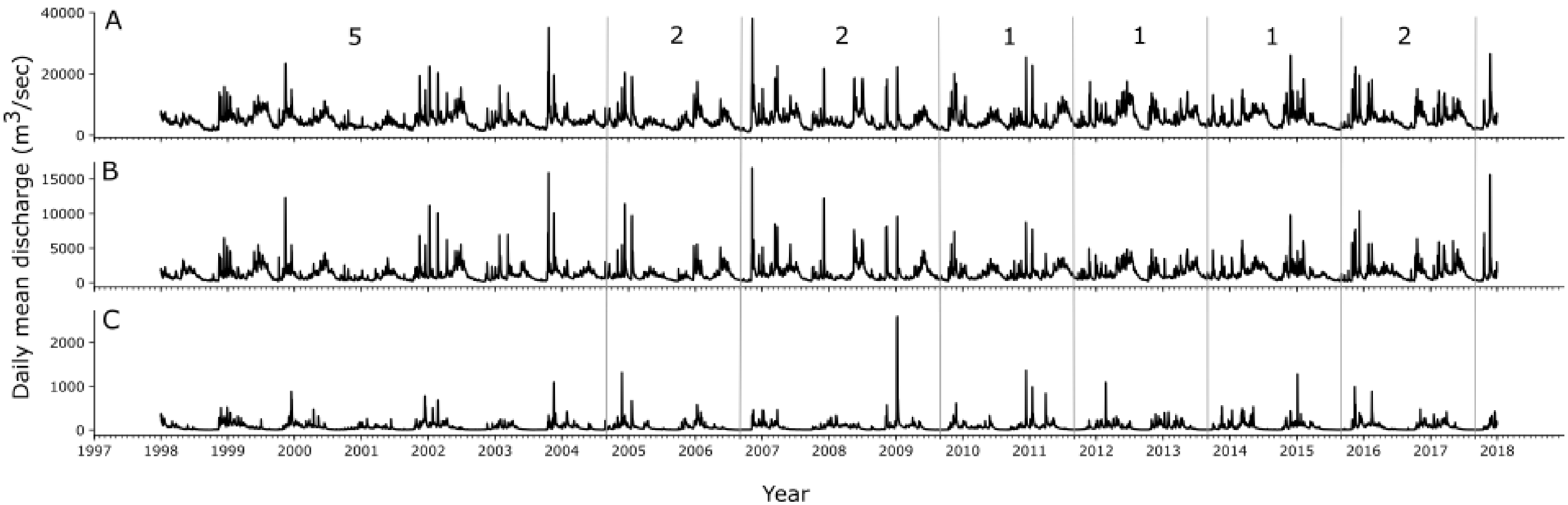

Figure 9. Mean daily discharge at three USGS gages in the Skagit and Samish River basins. A) Skagit River at Mount Vernon (lower Skagit basin); B) Sauk River at Sauk; and E) Samish River. Vertical grey lines represent the approximate date of each aerial photograph used in the analysis; the count of each FPA that experienced migration in each time period is shown at the top of the figure.

The occurrence of migration is not well stratified on a plot of channel gradient versus contributing drainage area (Fig. 10).

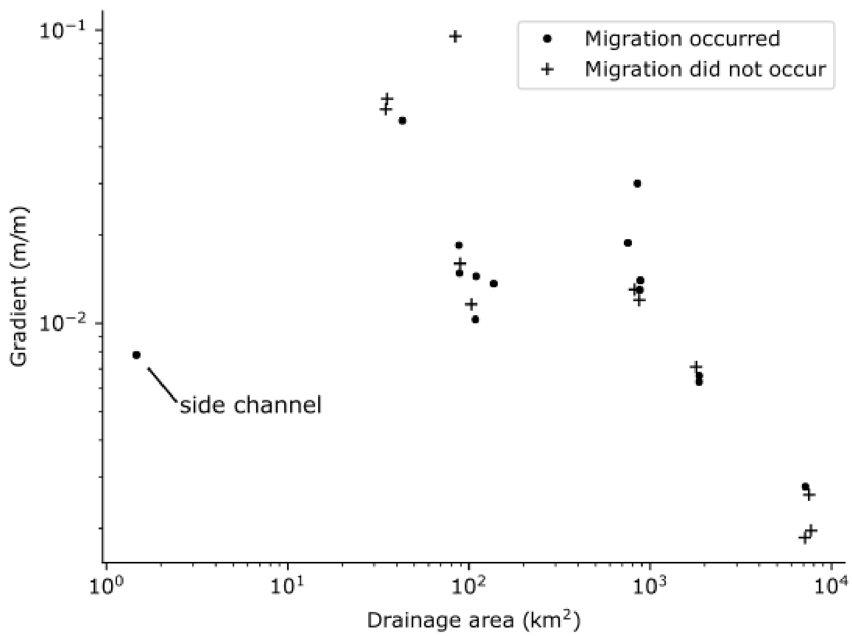

Figure 10. Channel gradient versus contributing drainage area for all study sites, stratified by migration status. The point marked 'side channel' was a side channel to the Sauk River; it had a very low slope but was effectively cut off from upstream drainage area due to the mechanics of our flow accumulation algorithm (appendix B).

Discussion and conclusions

Our results demonstrate that, between 1998 and 2017, channel migration occurred in the vicinity of a forest practices activity in 56% (14/25) of all cases identified as being vulnerable to channel movement (Fig. 4). Of these, three FPAs were not recognized by the landowner or regulatory agencies as needing CMZ prescriptions. To investigate the reasons for the missed recognitions we assessed in detail each FPA that did not have a CMZ recognized by the landowners or regulators. According to the additional aerial photographs we consulted (photo years 1937, 1944, 1949, 1953, 1969 and 1974), three sites (Sk2, Sa2 and Sk3) had clear evidence of historical channel migration in the direction of the forest practices activity prior to 1998. Three sites (Sk4, Sa4, Fi6) demonstrated no evidence of migration, indicating these sites may indeed be stable over long timescales. One of the latter sites (site Sa4) experienced migration between 1998 and 2017, although migration was limited to approximately 10 m. This site serves to remind us that channel migration can occur at any time, even in places in which no photo evidence for movement was available. The photo evidence for channel migration at site Fi1 was ambiguous due to clear orthorectification errors at that location in the 1944 photo; however, channel widening was clearly evident. Further, we caution that sites categorized as non-migrating in the right half of figure 4 are only tentatively placed: they may become vulnerable to channel migration if conditions become favorable. However, seven of those FPAs—those occupying the lower right quadrant—would switch from red to blue with a presumably benign result because channel migration was considered in the harvest layout. The FPAs in the upper right quadrant may provide reduced riparian function if migration occurs due to lack of CMZ protection.

Complicating regulatory application of CMZs is the observation that alluvial rivers adjust their gradient, width, depth, roughness, channel pattern and position to accommodate spatial or temporal shifts in transport capacity or sediment supply (Leopold et al., 1964; Abbe and Montgomery, 1996; Montgomery and Buffington, 1997; Beechie et al., 2006; Brummer et al., 2006; Pfeiffer et al., 2017). Due to the stochastic nature of sediment supply and discharge (Benda and Dunne, 1997) and the spatially-variable local condition of bank and floodplain vegetation, alluvial environments can be highly dynamic (or relatively stable) over timescales of days to years to centuries. However, our results suggest at least some qualitative relationships between channel migration in the Skagit River basin and geomorphological and hydrological conditions. For example, there were clear associations between channel migration and FPAs situated on outer meander bends and in reaches unconfined by terrace deposits or mountainous topography. However, migration status was not well stratified on a plot of channel gradient versus contributing drainage area (Fig. 10). Channel migration is driven by the ability of a channel to erode its banks, not its bed. Steep channel slopes for a given drainage area, which may be important for the analysis of vertical incision (Whipple and Tucker, 1999) may be unrelated to lateral channel movements. Thus, our data are consistent with the idea that channel migration is driven by sediment transport dynamics, discharge and large wood (Brummer et al., 2006).

There was no clear correlation between the number of FPAs that experienced migration and peaks in the discharge record, although the years preceding 2004 had the largest number of migration events at sites in our dataset (Figs. 6, 9) and this time frame included the 2003 storm (second largest in the analysis period). However, 1998-2004 (six years) is a longer window than the two- to three-year windows between later NAIP photo sets. In addition, we note that the photo period that includes the 2006 storm (storm of record in the analysis period) accounts for only two migratory FPAs. The apparent lack of correlation between the largest storms and channel migration events at forest practices sites is likely due to the small dataset examined here. We suspect that channel migration is correlated with discharge at the landscape scale although the nature of our dataset precludes making that association here.

Interestingly, bank erosion was by far the most common migration process affecting the sites in our dataset (Fig 7). Only one site experienced avulsion. Additionally, bank erosion potential was also more common than avulsion potential at sites that did not experience channel migration. This contrasts with evidence that suggests that avulsion was a much more frequent channel migration process prior to European-American colonization in post-glacial settings similar to the rivers we examined here (Collins et al., 2003). We suspect the common occurrence of bank erosion to reflect the dominance of meandering channels on the modern Skagit basin landscape, which in turn reflects geomorphic processes and response to topography, confinement and land use. More concretely, avulsion hazards only occur where potential avulsion pathways exist (i.e. portions of the floodplain that are at or below the elevation of the current channel or steeper or less impeded flow pathways). Bank erosion may occur anywhere the channel abuts a terrace or hillslope at or above the elevation of the channel banks. The latter situation may be more common in the Skagit basin in areas subject to forest practices. Additionally, it is possible that foresters and regulatory bodies overestimate the resistance of glacial terraces and floodplain features to erosion, deeming a river isolated from a forested terrace when in fact the river is able to undercut and erode the terrace toe. The result of this overestimation may be the lack of an analysis of erosion hazards. Additionally, rates of bank erosion may have increased since before European-American colonization due to riparian logging practices that removed old growth forests from channel banks. Channel bank erosion is correlated with the ability of a river to incise beneath the rooting depth of floodplain vegetation (Beechie et al., 2006); the old growth riparian forests composed of much larger cedar, spruce and hemlock than exist today may have been able to more effectively reduce the rate of lateral migration due to increased root depth and strength.

Nevertheless, the above observations do not explain why so few of the avulsion-prone reaches in our dataset experienced channel migration (20%). There are four possible reasons for this result. First, our sample size of avulsion-prone reaches is small, suggesting there could be an element of chance limiting our ability to encapsulate the true rate of avulsions in forested lands across the landscape. This is consistent with the possibility that landowners preferentially avoid avulsion-prone reaches for logging and road-building activities due to the easily-identifiable risks.

Second, historical removal of large wood may have led to widespread channel incision and disconnection from side-channels and low-lying floodplains (Collins et al., 2003). Logjams (including, in some cases, channel-spanning logjams) were common features of Puget Sound rivers prior to European-American colonization (Collins et al., 2002, 2003), and these large accumulations were able to increase upstream water surface elevations and cause avulsion of river reaches into side channels and across floodplains (Brummer et al., 2006). Today, large jams are scarce in the Skagit River basin due to historical removal of large wood and early riparian logging practices that reduced the quantity and size of riparian trees prior to the current regulatory regime.

Third, a reduction in sediment supply may have caused lower rates of aggradation, i.e. higher potential rates of relative incision with the net effect being similar to that of diminished quantities of large wood. Veldhuisen (2018) compiled timeseries data on shallow landslide frequency from previously-published inventories and aerial photographs and found a strongly diminished rate of landsliding between 2002 and 2011 when compared to the peak in the 1980s and 1990s. The inventory areas used in that study to assess temporal trends in shallow landslide frequency overlap strongly with the locations of the FPAs cited here; furthermore, we note that the decade of diminished shallow landslide activity corresponded with most of the period of record used in this study. This mechanism is consistent with an observed reduction in sediment delivery to Skagit Bay in recent decades (Hood et al., 2016). We speculate that the reduction in landsliding documented in upland portions of the landscape may have had tangible effects in mainstem rivers downstream by reducing the rate of channel switching and avulsion in several of the largest Skagit basin rivers. While the small sample size of our dataset makes the specific relationship between avulsion rates and forest harvest sites difficult to assess with confidence, we posit that diminished large wood and sediment may have worked in tandem to decrease the likelihood of avulsion at our study sites. Moreover, the continued legacy of wood removal due to clearing of stream channels in the late 1800s and early- to mid-1900s set the stage for quick sediment conveyance after the peak of sediment delivery in the 1980s and 1990s (Veldhuisen, 2018). This sediment supply connection may not affect the rate of bank erosion to the same degree if bank erosion is driven more by trends in discharge.

Fourth, it is possible our methods overestimated the potential for avulsion. At all sites, we used lidar hillshades to characterize avulsion hazards using the presence of side channels and apparent low-lying areas as evidence supporting avulsion as the erosion process (or potential erosion process). While it is possible some sites were further incised below the elevation of potential avulsion pathways than was readily apparent on the hillshade image, we suspect this situation to have been rare due to the high resolution of the lidar datasets we used. Side channels that have become ‘perched’ on abandoned terraces should not long retain the characteristics that result from active flow such as clearly-defined banks.

We purposefully did not record data on the efficacy of each CMZ in providing streamside shade and wood recruitment where one had been delineated. This was because our focus was on patterns of channel migration in relation to CMZ recognition; our intent was not to perform an audit of the delineation of individual CMZs, in part because retroactive judgement of the performance of a CMZ could change at any time after a large storm or large wood- or sediment-related avulsion event. Moreover, we did not want to highlight CMZs that had failed to protect riparian function, opting instead for a landscape-scale approach that would elucidate patterns in channel migration.

However, we can draw some general conclusions about CMZ protections in the Skagit River basin since the Forests and Fish Report. First, channel migration appears to occur most commonly at the outer edges of meander bends and along unconfined channels (both expected results). Second, the potential for bank erosion appears to have been under-recognized by many land managers and regulators. Bank erosion affected over 90% of the sites that experienced channel migration between 1998 and 2017, indicating this process is capable of altering riparian areas on timescales much shorter than timber harvest cycles (the above statement refers only to bank erosion hazard recognition, not calculation of historical migration rates). Also, all avulsion hazards in our dataset were recognized. Finally, the regulatory process appears to have been successful at identifying the majority of the locations where CMZ delineations should be required, especially later in the period of study (e.g. Fig. 5). Land managers identified most of the CMZs, but regulators identified a significant number as well (Fig. 5, appendix A). While we are encouraged by the lack of ‘missed’ CMZs since 2010, we caution that over

25% of the sites in our study had no CMZ recognized. We suggest that increased awareness of the potential for bank erosion may help mitigate the oversight of CMZ delineation in the future. Finally, we recommend that the full historical record of aerial photographs be reviewed by land managers and regulators during the forest practice application process for all proposals near known migrating rivers.

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Appendix A: Site characteristics

Nickname	FPA #	FPA Year	Stream name	Area (km^2)*	Gradient (m/m)	BFW (m)	CMZ recognized?	Migration occurred?	Migration process	Photo year**	CMZ recognized by:	Channel pattern	Confinement	Geomorphic setting
Fi1	2804465	2001	Finney Creek	89.28	0.0160	184.67	No	No	Bank erosion			meandering	confined	inner and outer meander bend
Su1	2804742	2001	Suiattle River	874.81	0.013	53.7	Yes	Yes	Bank erosion	2004	applicant	meandering	unconfined	outer meander bend
Sk1	2804772	2001	Skagit River	7517.89	0.0026	50.00	Yes	No	Avulsion		Regulatory process	meandering	unconfined	inner meander bend
Fi2	2804832	2001	Finney Creek	88.51	0.0148	32.00	Yes	Yes	Bank erosion	2017	Applicant	meandering	confined	outer meander bend
Sa1	2805206	2002	Sauk River	753.10	0.0188	68.67	Yes	Yes	Bank erosion	2006	Regulatory process	meandering	confined	inner meander bend
Fi3	2805225	2002	Finney Creek	108.51	0.0103	36.33	Yes	Yes	Bank erosion	2009	Applicant	meandering	unconfined	outer meander bend
Fi4	2805268	2002	Finney Creek	109.51	0.0145	47.00	Yes	Yes	Avulsion	2004	Applicant	island-braided	unconfined	outer meander bend
Fi5	2805697	2003	Finney Creek	87.83	0.0185	32.00	Yes	Yes	Bank erosion	2011	Applicant	straight	unconfined	straight
Sk2	2805719	2003	Skagit River	7171.14	0.0028	124.33	No	Yes	Bank erosion	2006		meandering	unconfined	outer meander bend
Sa2	2806540, 2806178	2003/2004	Sauk River	1860.98	0.0066	213.00	No	Yes	Bank erosion	2009		island-braided	unconfined	outer meander bend
Sa3	2806679	2004	Sauk River	1792.48	0.0071	128.67	Yes	No	Avulsion and bank erosion		Applicant	meandering	unconfined	inner meander bend
Sk3	2807114	2004	Skagit River	7714.99	0.0020	189.00	No	No	Bank erosion			island-braided	unconfined	outer meander bend
Gr1	2807258	2004	Grandy Creek	35.36	0.0583	31.67	Yes	No	Bank erosion		Applicant	meandering	confined	inner and outer meander bend
Su2	2807513	2005	Suiattle River	851.33	0.03	48.4	Yes	Yes	Bank erosion	2013	Applicant	meandering	confined	outer meander bend
Sk4	2808443	2006	Skagit River	7141.77	0.0019	156.00	No	No	Bank erosion			meandering	confined	outer meander bend
Gr2	2808687	2006	Grandy Creek	34.80	0.0537	22.67	Yes	No	Bank erosion		Applicant	meandering	confined	inner and outer meander bend
Sa4	2809036	2007	Sauk River	1858.71	0.0063	104.67	No	Yes	Bank erosion	2004		straight	unconfined	straight
Sa5	2811148, 2811282, 2811384	2010	Sauk River sidechannel	1.46	0.0078	29.67	Yes	Yes	Bank erosion	2015	Regulatory process	island-braided	unconfined	outer meander bend
Fi6	2811246	2010	Finney Creek	102.99	0.0116	24.33	No	No	Bank erosion			straight	confined	straight
Su3	2811584	2011	Suiattle River	870.0	0.012	59.5	Yes	No	Bank erosion		Applicant	meandering	confined	inner meander bend
Da1	2812973	2012	Dan Creek	819.19	0.0130	115.00	Yes	No	Avulsion		Regulatory process	meandering	unconfined	inner and outer meander bend
Da2	2813369	2013	Dan Creek	42.92	0.0491	23.00	Yes	Yes	Bank erosion	2004	Regulatory process	meandering	unconfined	inner and outer meander bend

Su4	2814485	2015	Suiattle River	881.74	0.014	62.33	Yes	Yes	Bank erosion	2004	Applicant	Island-braided	Unconfined	Inner and outer meander bend
Fi7	2815043	2016	Finney Creek	136.78	0.0136	57.00	Yes	Yes	Bank erosion	2017	Applicant	island-braided	unconfined	inner and outer meander bend
Fi8	2815100	2016	Finney Creek	84.01	0.0951	26.33	Yes	No	Avulsion		Applicant	meandering	unconfined	outer meander bend

* Contributing drainage area to approximate midpoint of reach.
** Photo year following largest episode of migration.

Appendix B: Methods for computing contributing drainage area and slope

We measured topographic attributes at our sites using lidar and one-arcsecond resolution DEMs. We computed contributing drainage area using the D8 flow accumulation of a one-arcsecond resolution (~25 m) DEM (included the portion of the Skagit River basin above Ross Dam). The D8 accumulation algorithm sends all flow from each cell into one neighboring cell following the path of steepest descent; therefore, no flow is split and natural features of alluvial rivers such as side channels and braids are not treated correctly. One of our sites (Sa5) was affected by this feature of the flow accumulation routine.

We measured channel gradient using bare earth lidar DEMs. For each site, we extracted the thalweg cells of the DEM within an approximately 1 km long reach of channel centered on the FPA; In this context, thalweg is the flow pathway found by the D8 algorithm after the DEM has been filled using the priority flood algorithm of Barnes et al. (2014). In low gradient rivers such as the Skagit River main stem, this technique may underestimate slope if the digital thalweg meanders back and forth across the true thalweg. We made no attempt to quantify this source of error. Channel gradient is the slope of a linear regression of channel surface elevations against along-channel distance using all thalweg cells.