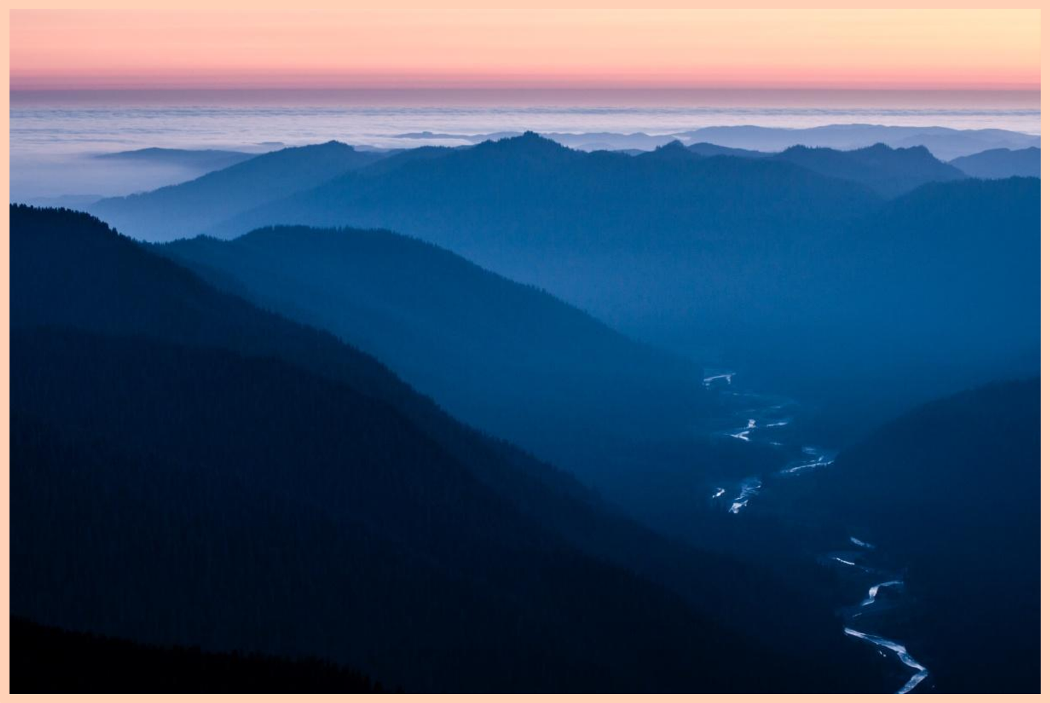

Screening Tools for Identifying Migrating Stream Channels in Western Washington

Geospatial Data Layers and Visual Assessments

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Cover Photo:
A view down the Queets River as it drains to the Pacific Ocean, by Nick Legg

Screening Tools for Identifying Migrating Stream Channels in Western Washington

Geospatial Data Layers and Visual Assessments

by

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Abstract

Lateral movement, or *migration*, of stream channels can threaten infrastructure and communities, while at the same time sustain floodplain health. Both the costs to human communities and the ecological benefits of migrating streams call for the identification and incorporation of channel migration into management decisions. Yet, few tools exist to rapidly identify migrating streams at landscape scales where spatial variability in channel migration is great. The Washington State Department of Ecology (Ecology) has developed two complementary tools for quickly assessing channel migration potential.

The first tool is a geographical information systems (GIS) layer called the Channel Migration Potential (CHAMP) layer. It contains stream networks of Western Washington (and much of Western Oregon) with associated data and information important for assessing channel migration activity. It also features information on channel characteristics such as stream flow and physical dimensions. This data layer's main feature is a classification of channel migration potential based on channel confinement and erosion potential. The layer was derived from existing statewide geospatial datasets and classified according to channel migration measurements by the High Resolution Change Detection (HRCD) project for the Puget Sound Region (Washington Department of Fish and Wildlife (WDFW), 2014). While the layer identifies the potential for channel migration, it does not *predict* channel migration rates. Thus, this data layer should be used to screen and prioritize stream reaches for further channel migration evaluation.

The second tool describes channel features that are diagnostic of channel migration activity and readily observed in aerial photographs. Thus, visual assessment can help refine the initial broad-scale assessments of channel migration potential using the CHAMP data layer. Together, these tools help plan and prioritize floodplain management actions such as Channel Migration Zone mapping, erosion risk reduction, and floodplain restoration.

Introduction

Lateral movement, or *migration*, of stream channels can threaten infrastructure and communities, while at the same time sustain floodplain health. The hazards of migrating channels are readily imagined, while their ecological benefits are less well known. For example, migrating channels enhance connectivity between channels and floodplains (Ward & Stanford, 1995), recruit wood to streams (Swanson, Lienkaemper, & Forest, 1978), build physical habitat on floodplains (Abbe & Montgomery, 1996), and create diversity in floodplain vegetation (Scott, Friedman, & Auble, 1996). These critical processes benefit aquatic species, and fuel biodiversity in streams and floodplains (Naiman, Bechtold, Beechie, Latterell, & Pelt, 2009; Ward & Stanford, 1995).

The ecological benefits and potential hazards of migrating streams make them valuable targets for floodplain restoration and flood risk reduction efforts. Migrating stream reaches offer opportunities for floodplain projects that achieve multiple benefits for traditionally opposing interests. The multiple benefit goal is the core principle of a new initiative called *Floodplains by Design*, which aims to align diverse interests in floodplain management (The Nature Conservancy, 2015; Washington Department of Ecology Floodplain Management Webpage, 2015). While channel migration can bring together opposing interests, few tools exist to assess channel migration activity across large areas. Spatial variability in channel migration processes across stream networks and watersheds makes it particularly challenging to incorporate channel migration into management decisions over these scales. The tools developed by Ecology and described in this document include geospatial data layers classified by channel migration potential, as well as visual assessment techniques that help identify migrating streams. They help facilitate planning and prioritization of floodplain restoration, preservation, and risk reduction projects on a landscape scale.

The tools can directly inform the mapping of Channel Migration Zones (CMZs): a step needed to incorporate channel migration into management decisions within individual floodplains. CMZs encompass the area that a stream channel is reasonably likely to move to within some future time-frame (Rapp & Abbe, 2003). In many ways, they act as templates for risk mitigation and floodplain restoration efforts. However, CMZ mapping requires effort and cost. Ecology has previously developed two CMZ mapping techniques with differing levels of effort and cost (see Ecology Publications 03-06-027 and 14-06-025). The more robust (but onerous) techniques should be applied in areas of the stream network with the greatest risk and habitat potential, whereas lower-cost methods are better suited for low risk streams. A primary goal for this work is to provide tools to strategically plan these CMZ mapping efforts across the landscape. This specific application of using the geospatial layer and visual assessment techniques to choose CMZ mapping approaches is discussed in the "Management Applications" section below.

This report describes two basic tools for identifying migrating channels across broad areas. The first tool is a geographical information systems (GIS) layer called the Channel Migration Potential (CHAMP) layer. The layer contains segmented stream networks of Western Washington (as well as most of Western Oregon) with associated data and information useful for assessing channel migration potential. It also provides information on channel characteristics such as stream flow and physical dimensions. The main feature of this data layer is a classification of channel migration potential based on channel confinement and erosion potential.

The layer was derived from existing statewide geospatial datasets and channel migration measurements from the High Resolution Change Detection (HRCD) project for the Puget Sound Region (WDFW, 2014). While the layer identifies the potential for channel migration, it does not *predict* channel migration rates. Thus, this data layer should be used to screen and prioritize stream reaches for further channel migration evaluation. The second major component describes channel features that are diagnostic of channel migration activity and readily observed in aerial photographs. Therefore, visual assessment can help refine initial the broad-scale assessments of channel migration potential using the CHAMP data layer.

The Channel Migration Potential (CHAMP) Layer

This section describes the general background and use of the CHAMP layer – the first tool described above. Because of the numerous steps involved in developing the CHAMP layer, the report’s appendix details data layer development. Inclusion in the appendix allows us to focus on the primary concepts and applications of the data in the main report, while also providing sufficient detail to understand the potential sources of error.

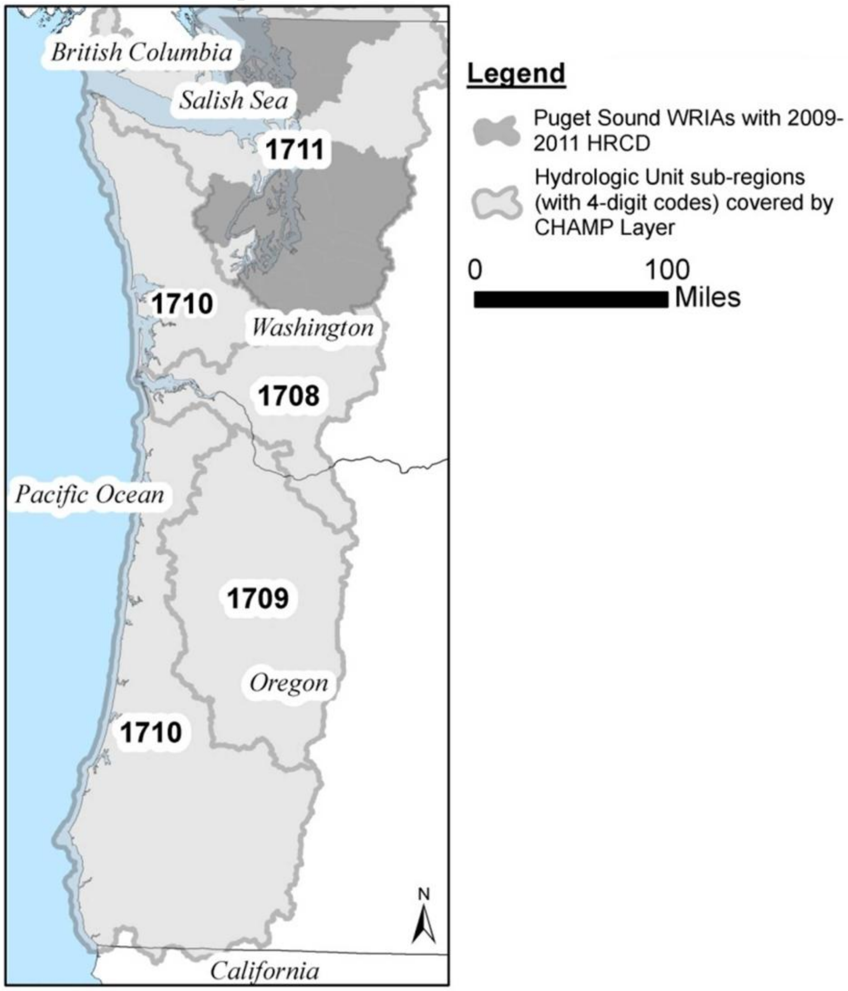

Figure 1. Overview map displaying the coverage of the CHAMP layer. HRCD data for the 2006-2009 period used to develop the erosion potential classification covers the Puget Sound Hydrologic Unit Sub-region (HUC 1711).

Data description

The CHAMP layer is a vector-based (line) stream network layer divided into segments. Each segment contains a number of data attributes relating to stream, valley, and watershed characteristics (Table 1). Segment lengths scale roughly with stream size and discharge, i.e. segments increase in length in a downstream direction. With simple knowledge of symbology functions in the GIS program ESRI ArcGIS®, a user can map attributes as desired. Table 1 lists key attributes. Stream network lines extend downstream from points where predicted mean annual flow is 10 cubic feet per second (cfs) according to regression equations of Vogel et al. (1999). The subsequent discussion focuses on development of the channel migration classification (including the confinement and erosion potential classifications in Table 1).

Table 1. Key attributes of the CHAMP data layer and their geographic extents.

Attribute	*Extent*
Stream order	All of Western Washington*
Channel slope	All of Western Washington*
Drainage area	All of Western Washington*
Mean annual flow (predicted)**	All of Western Washington*
Channel width at mean annual flow (predicted)***	All of Western Washington*
Bankfull channel width (predicted)***	All of Western Washington*
Valley width	All of Western Washington*
Confinement	All of Western Washington*
Stream power index	All of Western Washington*
Percent alpine area in watershed area	All of Western Washington*
Mean land surface slope in watershed area	All of Western Washington*
Mean annual precipitation in watershed area	All of Western Washington*
Tributary junction drainage area ratio	All of Western Washington*
Eroded area per unit length (measured 2006-2009)	Puget Sound Region
Eroded area per unit length (measured 2009-2011)	Subset of Puget Sound Region****
Confinement classification	All of Western Washington*
Erosion potential classification	All of Western Washington*

* The data layer was developed by Hydrologic Unit "Sub-region" (with 4-digit codes). Portions of four Sub-regions cover Western Washington, including those identified as 1708, 1709, 1710, and 1711 (see Figure 1). The data layer also includes those areas of Hydrologic Unit Sub-regions extending outside of Washington into Oregon.
**Predicted using regression equations of Vogel et al. (1999)
***Predicted using regression equation developed in this study
****The subset of the Puget Sound region includes Watershed Resource Inventory Areas 1, 2, 3, 7, 8, 9, 10, 11, 12, 13, 15, and 16.

Classification of channel migration potential

The primary purpose for the CHAMP layer is to provide classifications of channel migration potential to aid and improve floodplain management across Western Washington. As noted above, the classification scheme is based on two sub-classifications of channel confinement and erosion potential. Each sub-classification has three categories, resulting in nine classes of migration potential in the full scheme. Though the layer does not cover Eastern Washington, existing data layers relating to channel migration are available for the Columbia Basin (T. Beechie & Imaki, 2014; Hall, Holzer, & Beechie, 2007). The general background, development steps, and results are described below. Additional technical detail on the development process is outlined in the Appendix.

Classification background

Channel confinement by valley walls

Again, one of two primary variables used in the classification scheme is channel confinement. Valley walls greatly limit the rate of channel migration on management timescales. Therefore, valley width and the degree that a channel is confined by valley walls indicate the maximum lateral extent that channels can migrate. A common measure for confinement is the ratio of valley width to bankfull channel width:

$$Confinement = \frac{Valley\ Width}{Channel\ Width}$$

The above equation produces confinement values of valley width in multiples of channel width. Confinement is classified according to definitions by Montgomery and Buffington (1998). The classes are shown visually in Figure 2 and are as follows:

- **Confined:** Valley width is less than 2x channel width
- **Moderately confined:** Valley width is between 2x and 4x channel width
- **Unconfined:** Valley width exceeds 4x channel width

In confined valleys, channels are likely constrained by valley walls with limited room to migrate laterally. Channels moderately confined by valley walls may move laterally, but the maximum lateral extent channels can migrate is still limited. Defining CMZ boundaries to encompass the entire valley bottom may be a low-cost and reasonable management option in confined and moderately confined valleys. Channels in unconfined valleys may occasionally impinge on valley walls, but are generally free to migrate.

Figure 2. Illustration of the channel confinement classification using valley cross-sections.

Erosion potential

Fundamentally, channel migration occurs when streamflow's erosive power exceeds the bank material's strength. It therefore follows that the erosive power of streams – known as stream power – is a major controlling factor on migration rates (Nanson & Hickin, 1986; Richard, Julien, & Baird, 2005). An index for stream power is one piece of information contained in the CHAMP layer, and it is the variable used to classify streams by erosion potential. Stream power index is the product of channel slope and stream discharge at a given stream segment, or:

$$Stream\ Power\ Index = Channel\ Slope\ x\ Stream\ Discharge$$

The equation above shows that stream power index (i.e. erosion potential) increases with either channel slope or stream discharge. Each stream segment's erosion potential is classified according to stream power index, based on findings that lateral erosion in the Puget Sound region is more likely in streams with higher stream power indices (these results are described below).

Three erosion potential classes were developed according to channel migration measurements made for the entire Puget Sound watershed by the High Resolution Change Detection (HRCD) project at the WDFW (2014). The HRCD data maps areas where land cover changed between 2006 and 2009 (years with available National Aerial Imagery Program high-resolution aerial photographs). WDFW classified each area of changed land cover by change agent (i.e. the cause of change). One category identifies forest removal as a result of fluvial action, or lateral erosion by stream channels. Figure 3 shows an example of stream erosion mapped by the HRCD project.

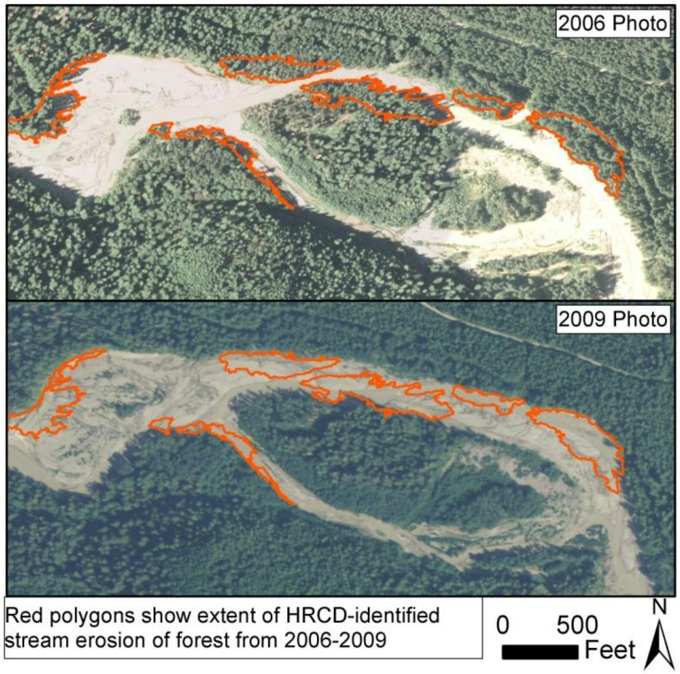

Figure 3. An example (Suiattle River, WA) of stream channel erosion between 2006 and 2009 measured by the HRCD project. Images are taken by the National Aerial Imagery Program (NAIP).

Ecology then measured the total area of the HRCD polygons in the vicinity of each CHAMP stream segment (detailed process described in the Appendix). The total eroded area divided by segment length is a metric for lateral erosion rate along each segment. Measured values of eroded area were then paired with stream power index for each segment in the Puget Sound region. These data suggest that streams of high stream power more readily migrated (e.g. eroded area per length was larger) between 2006 and 2009 (see the distribution of eroded area by stream power index in Figure 4). The three erosion potential classes defined according to the observations of eroded area and stream power are as follows:

- High Erosion Potential: The segment's stream power index falls in the high range where approximately 80% of the HRCD-measured erosion occurred from 2006-2009 in the Puget Sound region (Figure 4).
- Moderate Erosion Potential: The segment's stream power falls outside of the high erosion potential class, but is above the stream power where >95% of HRCD-measured erosion occurred in 2006-2009 (Figure 4).
- Low Erosion Potential: The segment's stream power falls in the low range where less than 5 percent of the HRCD measured eroded area occurred from 2006-2009 (Figure 4).

Figure 4 shows erosion potential class boundaries defined according the cumulative distribution of measured eroded area. The classification scheme was applied to the remainder of Western Washington due to roughly consistent physiographic and climatic characteristics. Greater detail on the classification steps is provided in the Appendix.

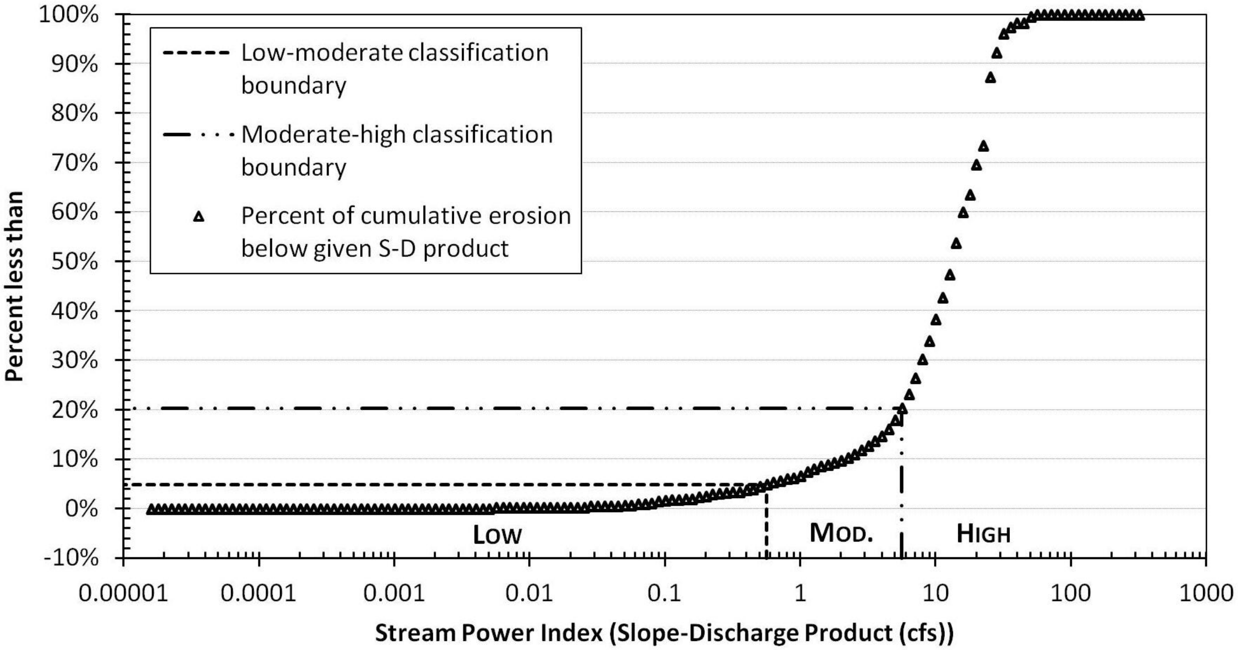

Figure 4. Cumulative distribution of observed lateral erosion by channels in the Puget Sound region as measured by the HRCD project . The graph also shows boundaries between classes of lateral erosion potential (boundaries fall at stream power indices of 0.56 and 5.62 cfs). The high erosion class encompasses 79.7% of the total measured 2006-2009 erosion in the Puget Sound (normalized according to the total distribution of observed stream power index). 95.1% of the measured erosion occurred above the stream power defining the low-medium class boundary.

Classification results and testing

The two-part classification scheme results in nine combinations of confinement and erosion potential (see Figure 5). As expected, the classification scheme distinguishes erosion measured from 2006 to 2009. Figure 5 shows that average erosion rate, as well as the number of migrating streams varies by class. Confined and low migration potential stream segments expectedly have low migration rates (as reflected by average eroded area and the percentage of segments with measured erosion shown in Figure 5). The highest erosion rates clearly occurred in unconfined stream segments with high erosion potential.

Erosion measured from 2006-2009 (used to *develop* classification)

EROSION POTENTIAL

CONFINEMENT	Low	Moderate	High
Confined	0.00 / 0.0 %	0.42 / 2.8 %	0.78 / 5.5 %
Moderately Confined	0.48 / 1.8 %	0.57/ 4.3 %	1.12 / 8.6 %
Unconfined	0.46 / 2.3 %	2.80 / 12.2 %	19.04 / 35.4 %

KEY: Mean eroded area (ft^2/ft) / % of segments with measured erosion (2006-2009)

Erosion measured from 2009-2011 (used to *test* classification)

EROSION POTENTIAL

CONFINEMENT	Low	Moderate	High
Confined	0.22 / 2.9 %	0.01 / 0.3 %	0.10/ 2.2 %
Moderately Confined	0.00/ 0.0 %	0.03 / 1.0 %	0.06 / 2.6 %
Unconfined	0.14 / 1.0 %	0.46 / 5.6 %	3.1 / 17.8 %

KEY: Mean eroded area (ft^2/ft) / % of segments with measured erosion (2009-2011)

Figure 5. Matrices of measured erosion (by the HRCD project) by migration class. The two matrices show measured migration from 2006-2009 and 2009-2011, which were used respectively to develop and test the classification scheme. Each class shows average eroded area (ft^2) per stream length (ft) and the percentage of stream segments with greater than zero lateral erosion measured.

Ecology tested the erosion potential classification scheme using a second mapping of high resolution land cover change from 2009-2011 (WDFW, 2014). At the time of this project's completion, high resolution change between 2009 and 2011 had been mapped for approximately 60 % of the Puget Sound region (for a subset of its Water Resource Inventory Areas[1] (WRIAs), see Figure 1). The lower matrix in Figure 5 shows the average eroded area in this later time period by class, allowing comparison with the 2006-2009 data (upper matrix) used to develop the classification. This comparison shows that absolute change was generally lower in the later period, a disparity that likely relates to the fewer number of years (two versus three years), and the series of large storms that caused flooding (and thus erosion) across the region from 2006-2009. However, the relative differences between classes show similar patterns in the two periods. This consistency corroborates the classification scheme's ability to map channel migration potential across the landscape.

The relatively high percentage of stream segments that had no measured lateral erosion (see Figure 5) indicates the level of variability in channel migration rates across the landscape. A

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[1] High resolution land cover change from 2009-2011 was mapped for WRIAs 1, 2, 3, 7, 8, 9, 10, 11, 12, 13, 15, and 16 at this project's completion date.

number of factors not accounted for in this classification cause variability in channel migration rates across space and time, including:

- The HRCD data measured change over two relatively short periods of time. During these short time periods, streams across the region experienced a variety of flood magnitudes. For instance, some streams classified as having high erosion potential may have had only small floods and in turn minimal lateral erosion during the measurement periods.
- Man-made structures such as roads, levees, and revetments limit lateral migration variably across the landscape. This underscores a few major considerations:
  - The CHAMP data layer may identify stream segments as having high migration potential that in fact do not currently migrate.
  - Man-made structures limit channel migration and should be considered in any channel migration study examining areas with human development. In many cases, portions of channel migration zones disconnected by man-made structures represent floodplain restoration opportunities.
  - A common approach to floodplain restoration is setting back levees to restore natural stream processes such as channel migration. With these goals in mind, levee setback projects should assess the streams natural tendency to migrate (absent of limiting man-made structures). The CHAMP layer provides one indication of natural migration potential that could be used in concert with studies of historical migration rates and floodplain landforms indicative of channel migration activity prior to construction of erosion-limiting structures.
- Channel migration rates depend on many factors such as local channel conditions (e.g. channel curvature and the presence of large wood), sediment supply, and vegetation, (Brummer, Abbe, Sampson, & Montgomery, 2006; Dunne, Constantine, & Singer, M.B., 2010; Hickin & Nanson, 1975; Micheli, Kirchner, & Larsen, 2004). A channel segment classified as having high migration potential may have limited migration due to other factors not captured in the classification. For a discussion of the landscape controls on channel migration, refer to Ecology publication 14-06-028 (Legg & Olson, 2014).

The points above demonstrate the CHAMP data layer’s primary function as a prioritization and screening tool, rather than a predictive one. Channel migration is a complex process dependant on multiple variables, and the visual assessment techniques (tool two) described later can help to further evaluate migration activity with minor effort.

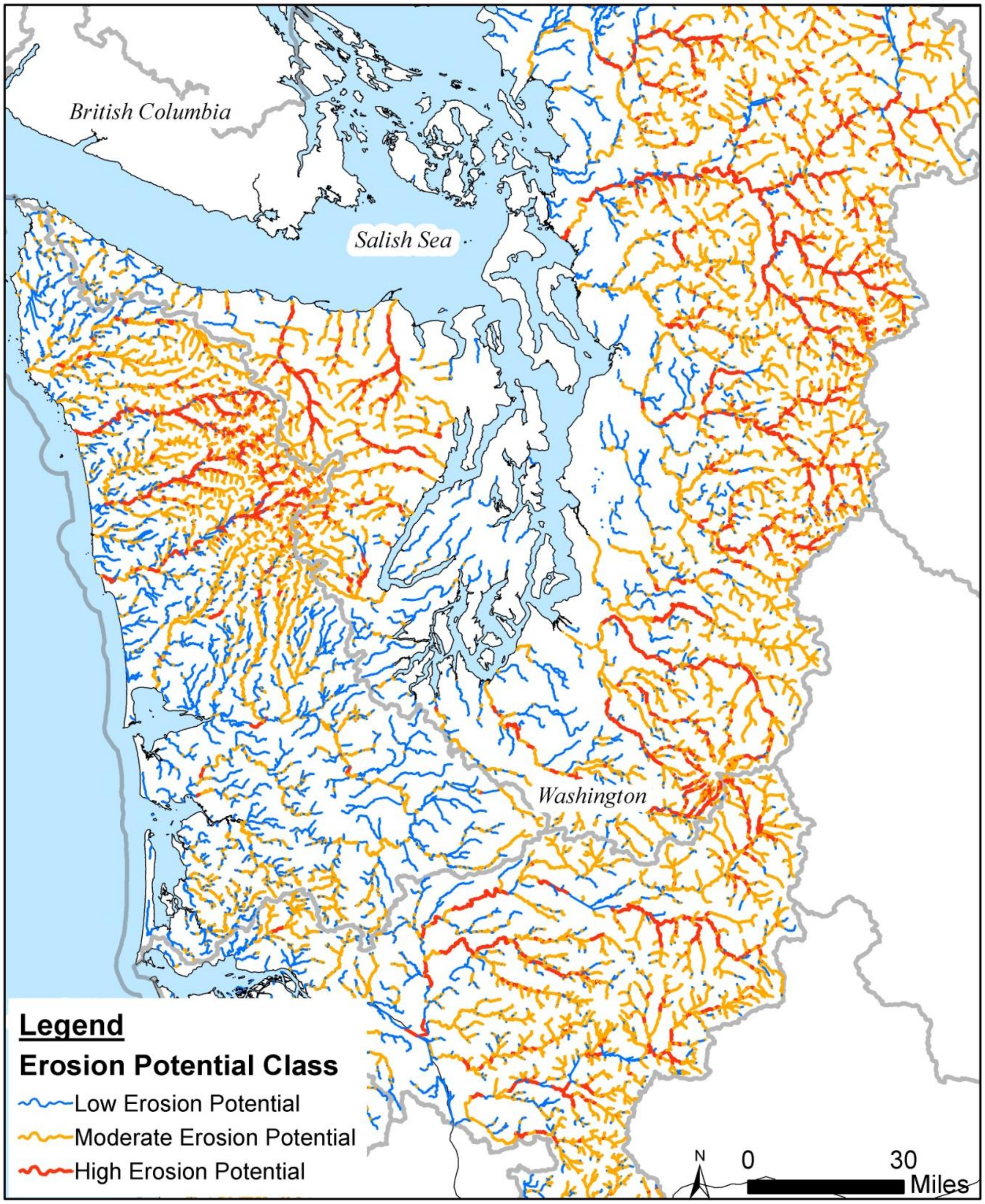


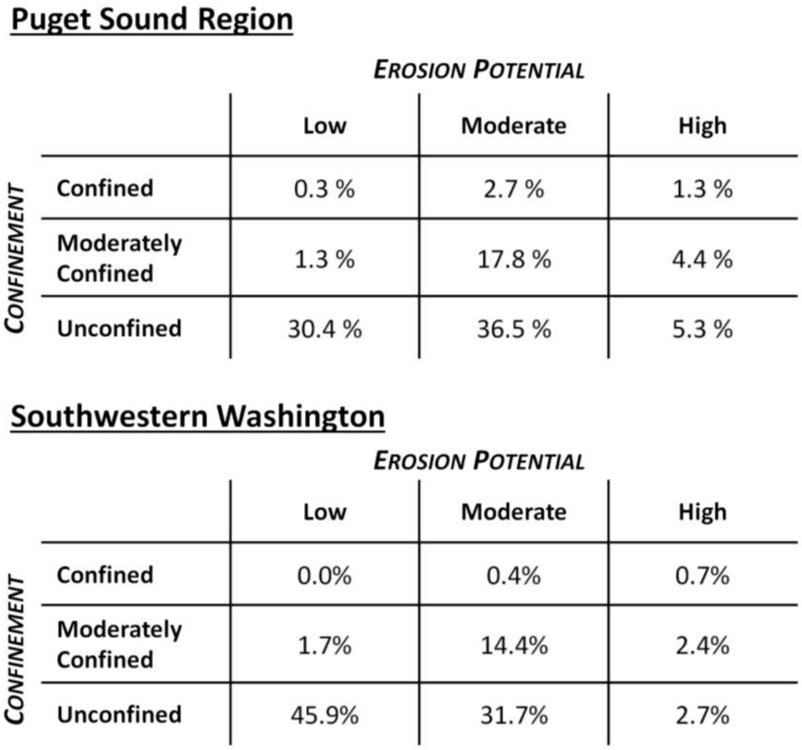
Figure 6. Stream network map of classified erosion potential in Western Washington.

Landscape patterns of channel migration potential

Some general landscape patterns emerge from classifying Western Washington streams, which are relevant to management decisions at broad scales. Important points include:

- *Confined or low erosion potential streams* generally have minor erosion hazards and thus should in most cases require only limited channel migration analyses. These stream segments comprise a relatively large portion of stream networks, making up approximately 36% and 49% of the stream segments in the Puget Sound and Southwestern Washington regions, respectively (see Figures 6 and 7). The regional differences likely reflect differences in topography – for instance, the North Cascades are generally much higher in elevation than the southern Washington Cascades. Outside of the southwestern Olympic Range, coastal mountain ranges in the southwest Washington are relatively low in elevation. These topographic differences cause streams to be on average gentler with less erosive power.

- *Moderately confined streams* of moderate and high erosion potential are possible easy targets for CMZ mapping. Despite potentially high migration activity in these valleys, relatively small valleys limit the extent of eroded area over management timescales. The valley bottom area may act as a useful and low-cost estimate of CMZs, especially in areas with low development density. Moderately confined valleys of moderate and high erosion potential comprise 22% and 17% of stream segments in the Puget Sound and Southwestern Washington regions, respectively.
- *Stream erosion potential has broad landscape patterns.* Low erosion potential streams generally have small, lowland watersheds, as reflected by their small mean annual flows (averaging 59 cfs), and proportionally small alpine areas (averaging 0.7 % of watershed area). Moderate erosion potential streams have moderately-sized watersheds (with mean annual flow averaging 110 cfs) with proportionally larger alpine areas (averaging 8.4 % of watershed area). High erosion potential streams commonly flow from large mountainous watersheds. They have large mean annual flows (averaging 648 cfs) and the largest alpine areas (averaging 18.8 % of watershed area). High erosion potential streams emerging from the Cascades and Olympics are some of the largest rivers flowing across lowland areas of Western Washington.



Puget Sound Region

CONFINEMENT	EROSION POTENTIAL: Low	Moderate	High
Confined	0.3 %	2.7 %	1.3 %
Moderately Confined	1.3 %	17.8 %	4.4 %
Unconfined	30.4 %	36.5 %	5.3 %

Southwestern Washington

CONFINEMENT	EROSION POTENTIAL: Low	Moderate	High
Confined	0.0%	0.4%	0.7%
Moderately Confined	1.7%	14.4%	2.4%
Unconfined	45.9%	31.7%	2.7%

Figure 7. Regional stream network characteristics by channel migration class.

Errors and limitations

For documentation of errors associated with each attribute, refer to the Appendix. Generally, this data layer should be used to screen and prioritize stream reaches for further channel migration evaluation. The data resolution does not allow one to predict channel migration. The classification identifies stream segments for further examination, and those that likely require limited attention or analysis. The potential uncertainty involved in the classification approach is a reason for the visual assessment techniques (described below) being described along with the CHAMP data layer.

Other applications of the CHAMP layer

The CHAMP data layer has a number of attributes that can contribute to floodplain management across the state, and several are described below. The methods used to develop each of the data attributes are discussed in the Appendix.

Estimating stream discharge

Each stream segment has an associated estimate of mean annual flow using regression equations of Vogel et al. (1999). Their predictions were validated using measurements of mean annual flow and channel dimensions compiled from 135 stream gauges by Magirl and Olsen (2009).

Estimating channel width

Each stream segment has two estimates of channel width. The first is a prediction of channel width at mean annual flow using a regression equation relating mean annual flow (predicted by Vogel et al. (1999)) to measured width at mean annual flow (Magirl & Olsen, 2009). A regression equation for bankfull channel width was also developed for this study using a set of 179 measurements available through the Ecology Environmental Information Management System. The regression equation relates drainage area and mean annual precipitation (watershed average) to bankfull channel width for Western Washington.

Evaluating watershed characteristics

A number of attributes report physical characteristics of each segment's watershed, including:

- Watershed area: Watershed area is a fundamental metric for comparing streams.
- Mean annual precipitation: Mean annual precipitation averaged over watershed area.
- Watershed-average slope: Average slope is a metric for watershed ruggedness, and has been used as a surrogate for erosion rate and sediment supply (David R. Montgomery & Brandon, 2002).
- Percent of watershed classified as alpine area: This metric gives a sense of a stream's headwater environments, and has been used as a surrogate for sediment supply (T. Beechie & Imaki, 2014).

Evaluating habitat potential and type

Habitat potential and type relate to the form and physical processes occurring within a valley (David R. Montgomery, 1999). Channel migration is a physical process that creates physical heterogeneity important for aquatic habitat (Ward & Stanford, 1995), thus attributes relating to channel migration may correspond to habitat potential (Naiman et al., 2009). Valley width, confinement, and slope relate to the physical processes of disturbance and type of aquatic habitat present in a stream reach (David R. Montgomery, 1999).

Tributary junctions are loci of heterogeneity important to aquatic species (Benda et al., 2004). The ratio of tributary to main-stem drainage areas is reported for stream segments directly downstream of tributary confluences. This ratio indicates the size of a tributary relative to the main stem it flows into. Higher ratios indicate that the tributary stream is more likely to influence the physical form of the main-stem stream. Interactions between the two streams at confluences with high ratios may more readily create physical features important for aquatic species.

Visual Assessment of Channel Migration Activity

A channel’s form reflects its past movement as well as its tendency for continued lateral movement. This section describes two channel characteristics – channel width and pattern - that are indicative of a channel’s migration activity. Channel width and pattern are easily observed using widely available aerial imagery, allowing rapid identification of actively migrating stream reaches. These visual assessment techniques help to refine preliminary conclusions drawn from the Channel Migration Potential (CHAMP) layer. For example, they might allow identification of sections with relatively high migration activity within a series of CHAMP stream segments with the same channel migration classification.

Relative channel width

Local variations in a channel’s width correspond with a channels migration activity. Channel width increases in a downstream direction as watershed area and stream discharge increase – this systematic change in width is not the focus here. A stream’s *active channel* width also can vary over relatively short channel reaches where stream discharge is approximately constant. During the summer low flows when aerial photographs are typically taken, the active channel (outlined in light blue in Figure 8) is the area containing both wetted channel and adjacent gravel surfaces devoid of perennial vegetation (Church, 1992). This area is submerged and actively transports sediment during high stream-flows. The Cowlitz River example shown in Figure 8 suggests that the wider sections of the active channel (blue channel outline) roughly correspond with relatively high channel migration rates (as indicated by transect thickness). In wide sections of channel, relatively abundant gravel surfaces are present.

The correspondence between relative channel width and migration rate visible in Figure 8 holds true in a regional analysis of channel migration. Ecology studied controls on channel migration rates in a compilation of channel migration data from 13 streams across western Washington (Legg, unpublished work). These streams included the Cowlitz, Green, Nisqually, Nooksack (North, Middle, and South Forks), Pilchuck, Sauk, Skagit, Skykomish, Snoqualmie, Suiattle, and White Rivers. Average channel migration rate and active channel width were measured for stream segments (163 CHAMP segments) over 13 encompassing project reaches. Each project reach was thus divided into multiple segments. A strong positive correlation between relative migration rate and relative active channel width (see Figure 9) suggests that locally wide stretches of the channel tend to have large migration rates. Previous studies outside of the Puget Sound have also shown similar relationships, suggesting their applicability across Washington (Brice, 1982; Lagasse, Zevenbergen, Spitz, & Thorne, 2004).

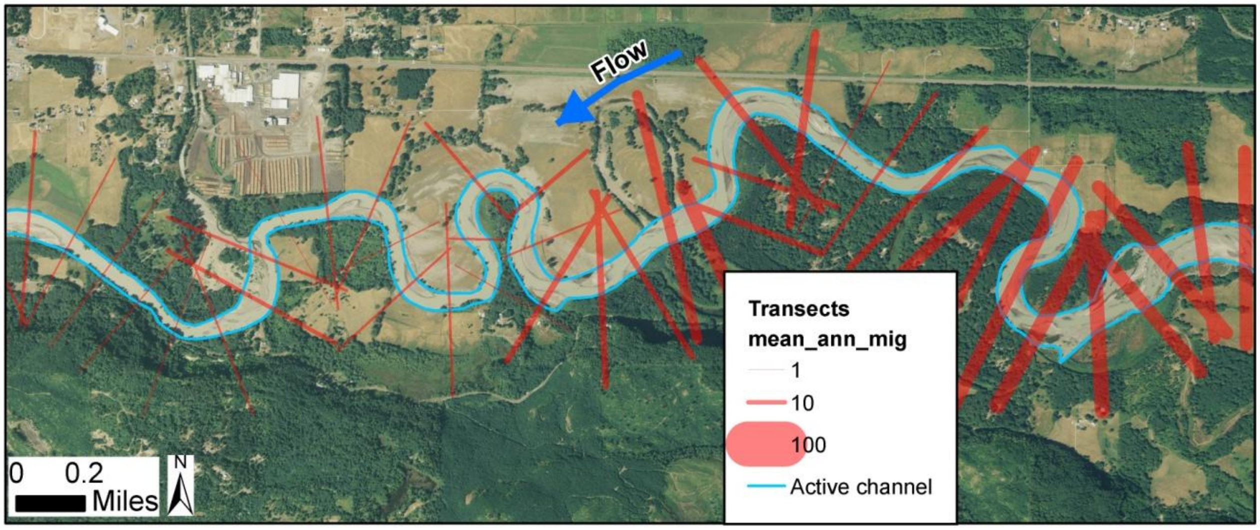


Figure 8. An aerial image of the Cowlitz River demonstrating the correspondence between active channel width and channel migration rate. Transect thickness scales with mean annual channel migration rate (ft/yr) measured between 1948 and 2011. Example transect widths for migration rates of 1, 10, and 100 ft/yr are shown in the example (transects widths may fall between these examples). The aerial photograph (NAIP) and active channel shown are from 2009. Channel mapping was completed by Geoengineers (2009).

The physical mechanisms for the correspondence between local width and migration rate are likely two-fold. First, migrating channels leave un-vegetated gravel surfaces in their wake. These gravel surfaces make migrating channels wide relative to non-migrating streams of similar stream discharge. Floods can often prolong the germination time of perennial vegetation on these gravel bars. Second, local sediment deposition increases the abundance of gravel bars which in turn drives channel migration (Harrison, Legleiter, Wydzga, & Dunne, 2011; O'Connor et al., 2014). Gravel bars divert streamflow toward the opposite channel bank and enhance bank erosion and channel migration. Localized sediment deposition and channel migration can occur in response to longitudinal changes in channel slope or large woody debris jams (Brummer et al., 2006; D. R Montgomery & Buffington, 1997)

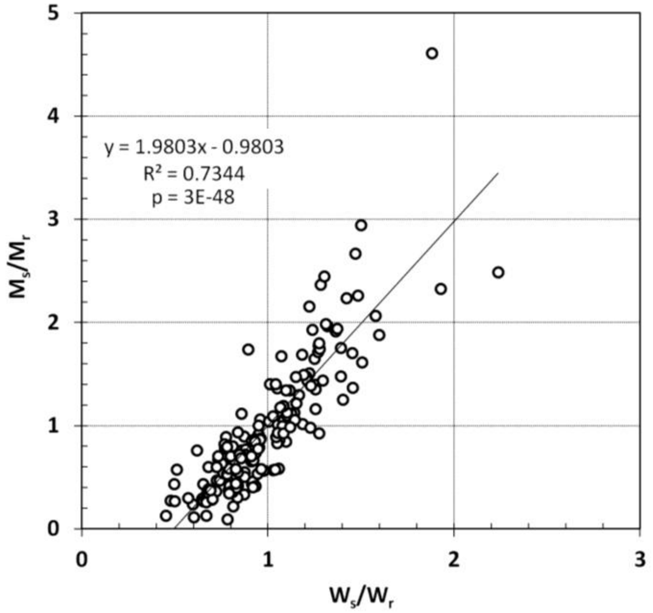


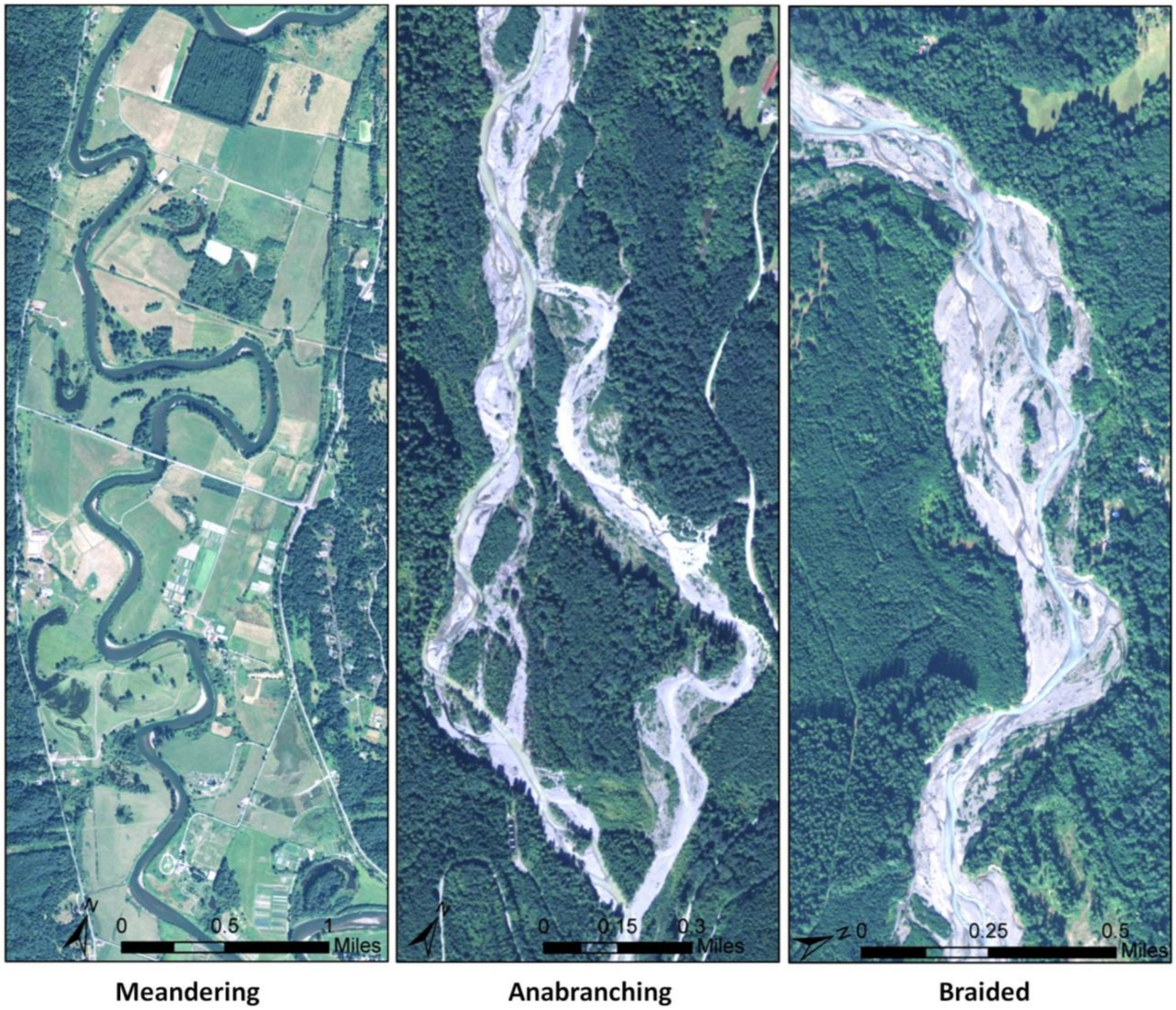
Figure 9. Scatter plot of relative active channel width (W_S/W_R) versus relative migration rate (M_S/M_R). Relative active channel width is the average channel width measured along a segment (W_S) divided by the average channel width measured along the encompassing channel reach (W_R). Relative width values over one mean the stream segment is wide relative to the reach-averaged channel width. Similarly, relative channel migration rate is the ratio of segment-average migration rate (M_S) to reach-average migration rate (M_R). The data shown are measured over 13 stream reaches divided into a total 163 segments in Western Washington.

Channel patterns and migration

Channels are commonly categorized by patterns which also broadly correspond with channel migration rates. A channel's pattern is its form as described from above. The four common channel pattern classes in unconfined valleys of Washington are straight, meandering, anabranching, and braided (T. J. Beechie, Liermann, Pollock, Baker, & Davies, 2006). Straight channels have low sinuosity and generally migrate the least of the four patterns. Meandering channels are single-threaded channels with sinuous courses (Figure 10). Anabranching channels have multiple active channels separated by forested islands with mature vegetation or forests (Figure 10). These forested islands typically remain dry during high flows. Braided channels have multiple intertwining channels that switch frequently around gravel bars. Gravel bars in braided streams commonly have immature vegetation, and are submerged during high flows despite being dry during low flows (Figure 10).

Each pattern is sustained by a unique set of channel migration processes that also broadly correspond with lateral movement rates (T. J. Beechie et al., 2006; Luna Bergere Leopold & Wolman, 1957). Straight channels generally migrate slowly through bank erosion. Meandering channels typically migrate at slow-to-moderate rates through a combination of bend migration and cutoff (cutoffs form oxbow lakes as visible in the meandering example in Figure 10). Anabranching channels migrate through bend migration and abrupt channel switching events (avulsions) around their forested islands. Anabranching channels typically migrate at moderate-to-high rates. Braided channels move laterally at rapid rates through frequent small avulsions.

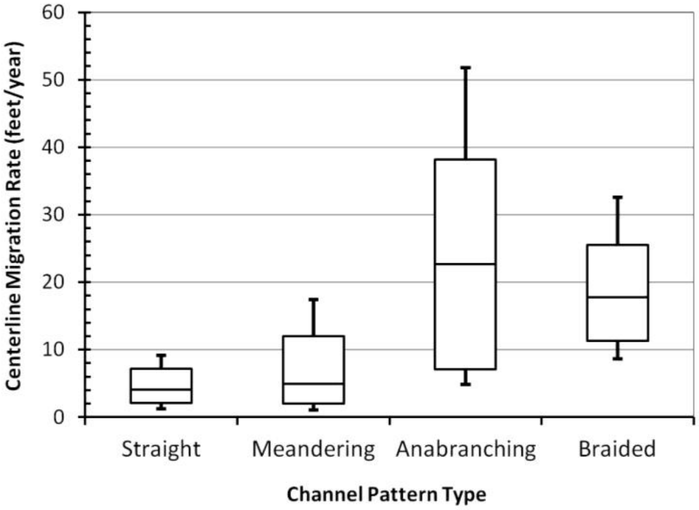
Figure 11 shows channel centerline migration rates measured in the Ecology study (mentioned above) of 13 streams in Western Washington.



Meandering **Anabranching** **Braided**

Figure 10. Aerial views of channel patterns in Washington. Aerial images of the meandering, anabranching, and braided channel patterns of the Snoqualmie, Middle Fork of the Nooksack, and Nisqually Rivers, respectively, were taken by the National Aerial Imagery Program in 2011.

Also see Ecology Publication 14-06-028, which elaborates upon the above description of channel migration processes and patterns (https://fortress.wa.gov/ecy/publications/SummaryPages/1406028.html).



** Boxes show 16th, 50th, and 84th percentiles*
Whiskers show 5th and 95th percentiles

Figure 11. Measured migration rates measured in 163 channel segments across 13 streams in Western Washington. Ecology measured channel migration during a technical study (Legg et al., unpublished data; mentioned in the main body text above). Kolmogorov-Smirnov tests revealed statistically significant differences in migration rates between single-threaded (including straight and meandering) and multi-threaded (including anabranching and braided) pattern types (p<0.001).

Summary – Using width and pattern to assess migration activity

Channel width and pattern are key channel characteristics for quickly assessing channel migration activity. The use of these characteristics depends in part on the assessment scale, as explained below. In either case, flagging migrating sections of stream in a GIS mapping program is a simple way to document the results of visual assessment.

Reach-scale visual assessments

At the reach-scale, channel pattern and relative width can be used together to assess relative migration activity along the reach of interest. For the purposes of this discussion, the reach-scale can encompass a stretch of channel over which stream discharge is approximately constant. Major tributary junctions (i.e. large changes in stream discharge) may represent reach boundary points. Over stretches of stream where stream discharge varies significantly, channel width will vary in response to discharge as well as channel migration activity (in these cases refer to the section below on “Large-scale visual assessments”).

Width and pattern can provide either redundant or independent information on relative channel migration activity. They will likely provide redundant information where active channel width and pattern both change along a reach. In a reach that transitions from braided to meandering pattern, for example, the braided portion of the reach will be wide relative to the meandering section. Relative widths of channels of different pattern are partially apparent in Figure 5. In the braided stream example, gravel surfaces are large relative to the wetted channel. Conversely, in the meandering stream, few gravel bars are exposed. Therefore, in a reach where channel pattern transitions from braided to meandering, a corresponding transition in width and migration activity would also be expected. However, along other stream reaches where the channel's pattern is classified consistently, width variations become the more important characteristic for evaluating relative migration activity. Figure 8 is one such example where the channel is consistently has a meandering pattern, but has varying migration rates that correspond locally to active channel width.

Large-scale visual assessments

Large-scale assessments cover multiple streams of varying size and discharge. At these scales, the primary focus becomes identifying migrating streams, rather than assessing relative migration activities. Channel pattern and width (e.g. abundant exposed gravel) remain important indicators of active channel migration. However, using pattern and width to compare relative migration activities of different streams (with different discharges) is difficult without taking measurements of channel migration.

Management Applications

The CHAMP and visual assessment tools can be applied for a number of purposes (e.g. general hazard assessment, habitat studies, and forest practices evaluations), but this discussion focuses exclusively on their use in choosing the Channel Migration Zone (CMZ) mapping techniques appropriate for a project area. CMZs are the most well-established and direct way of incorporating the hazards and benefits of migrating channels into floodplain management decisions. CMZs delineate the hazardous floodplain areas subject to lateral erosion, while also mapping potentially beneficial areas for aquatic species (Rapp & Abbe, 2003). Ecology has made available two levels of CMZ evaluations. The task of choosing the right CMZ method for a project is important for effectively utilizing limited resources.

The two primary methods of CMZ mapping are referred to as *planning-level* and *detailed-level* assessments. These two methods have distinct effort and cost-levels, but also provide different levels of information. Key elements of each are described below:

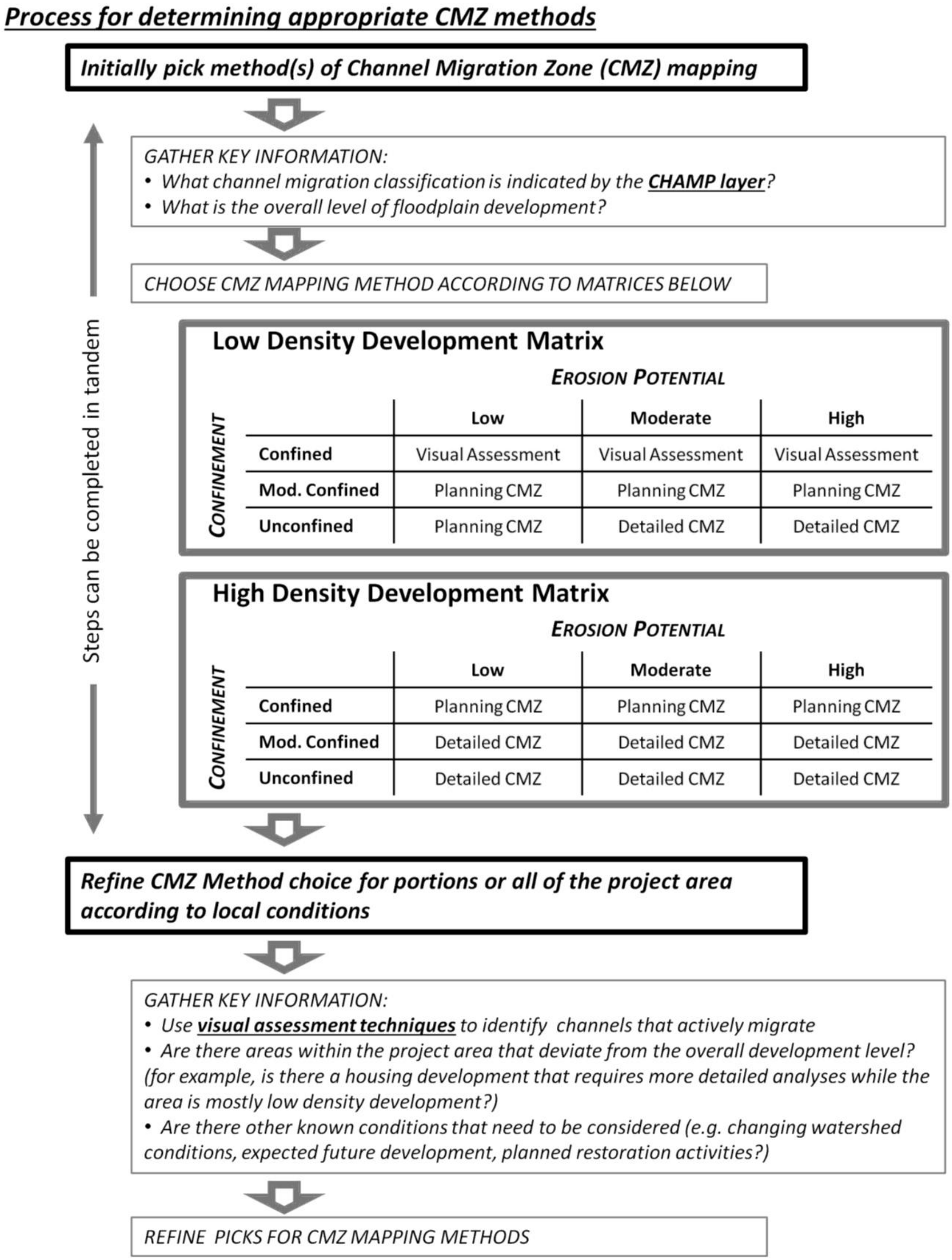
- *Planning-level CMZ mapping:* This approach is the lower-cost option, and is described in Ecology publication 14-06-025 (Olson, Legg, Abbe, Reinhart, & Radloff, 2014). Its lower effort and cost per stream mile means that CMZs delineated using this technique are generally more conservative in nature, and that they will generally be wider than CMZs mapped using the detailed CMZ methods (following the precautionary principle). Planning-level methods use features and characteristics of valley bottoms which indicate the extent of past migration. This evidence of past migration then serves as a basis to define the CMZ to encompass future migration. Planning-level methods are generally more feasible on streams with low-density development, or in relatively confined valleys where the channel is likely to erode a large proportion of its valley bottom on management timescales (100 or 500 year design lives are common for CMZs).
- *Detailed-level CMZ mapping:* This approach is the higher-cost option, and is described in Ecology publication 03-06-027 (Rapp & Abbe, 2003). Detailed analyses involve mapping

historical channel positions as well as measuring historical channel migration rates, which are in turn used to project the areas likely to be eroded by the channel in the future. These analyses provide a relatively robust picture of a channel's movement through time, and the eroded areas expected in the future. These methods are more suitable for areas with greater development density or expected high habitat potential.

The CHAMP data layer and visual assessment techniques help to pair channel reaches with the appropriate CMZ techniques using a decision process outlined in Figure 12. In general, the CHAMP layer provides a first idea of channel migration potential, and an initial assessment of the CMZ mapping techniques appropriate to a particular stream reach. Visually assessing channels for active migration is an important next step for refining initial choices of CMZ mapping approaches. In many cases, it makes more sense to use visual assessment techniques and the CHAMP layer in concert in a GIS system. Using this approach, the CHAMP layer (and corresponding matrices in Figure 12) give a base pick for the appropriate CMZ mapping approach, and then those picks are refined according to observations of channel migration activity.

Figure 12 identifies development level as important factor in choosing CMZ mapping techniques, particularly from a hazards perspective. When assessing the development level, it is important to consider both developments in the floodplain, valley bottom, and adjacent to valley slopes. Development adjacent to valley slopes (particularly on and above) can be at risk of slope failure (landslides) induced by the channel eroding at the base of valley walls.

The matrices in Figure 12 identify possible CMZ mapping approaches according to the CHAMP channel migration classification. The matrices show that greater levels of analyses are generally needed for areas with greater development density. It is important to recognize that these are only suggestions and that any number of factors may play into a decision for CMZ mapping. This need to incorporate local conditions and constraints in to management decisions will always be present; therefore, the decision process outlined above and in Figure 12 should be considered a framework rather than a rigid process.



Process for determining appropriate CMZ methods

Initially pick method(s) of Channel Migration Zone (CMZ) mapping

GATHER KEY INFORMATION:
- What channel migration classification is indicated by the **CHAMP layer**?
- What is the overall level of floodplain development?

CHOOSE CMZ MAPPING METHOD ACCORDING TO MATRICES BELOW

Low Density Development Matrix

CONFINEMENT	EROSION POTENTIAL: Low	Moderate	High
Confined	Visual Assessment	Visual Assessment	Visual Assessment
Mod. Confined	Planning CMZ	Planning CMZ	Planning CMZ
Unconfined	Planning CMZ	Detailed CMZ	Detailed CMZ

High Density Development Matrix

CONFINEMENT	EROSION POTENTIAL: Low	Moderate	High
Confined	Planning CMZ	Planning CMZ	Planning CMZ
Mod. Confined	Detailed CMZ	Detailed CMZ	Detailed CMZ
Unconfined	Detailed CMZ	Detailed CMZ	Detailed CMZ

Refine CMZ Method choice for portions or all of the project area according to local conditions

GATHER KEY INFORMATION:
- Use **visual assessment techniques** to identify channels that actively migrate
- Are there areas within the project area that deviate from the overall development level? (for example, is there a housing development that requires more detailed analyses while the area is mostly low density development?)
- Are there other known conditions that need to be considered (e.g. changing watershed conditions, expected future development, planned restoration activities?)

REFINE PICKS FOR CMZ MAPPING METHODS

Figure 12. Process for choosing the appropriate CMZ mapping methods for a project area.

Other Ecology Publications on Channel Migration

Rapp, C.F., and Abbe, T.B., 2003, *A Framework for Delineating Channel Migration Zones*: Ecology Publication 03-06-027. https://fortress.wa.gov/ecy/publications/summarypages/0306027.html

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Legg, N.T., and Olson, P.O., 2014, *Channel Migration Processes and Patterns in Western Washington: A Synthesis for Floodplain Management and Restoration*: Ecology Publication 14-06-028. https://fortress.wa.gov/ecy/publications/SummaryPages/1406028.html

Legg, N.T., Heimburg, C., Collins, B.D., and Olson, P.O., 2014, *The Channel Migration Toolbox: ArcGIS® Tools for Measuring Stream Channel Migration*: Ecology Publication 14-06-032. https://fortress.wa.gov/ecy/publications/SummaryPages/1406032.html

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Appendix

The appendix describes the processing steps used to generate the CHAMP layer. The CHAMP layer (line) contains up to 28 attributes. The full list of attribute names, field names, and extents are shown in Table A 1 below. At the beginning of each appendix sub-section, a table lists the attributes generated using the methods described in that corresponding section.

Table A 1. Table of attributes and their field names.

Attribute	*Field Name*	*Extent*
Unique segment ID	hydroid	All of Western Washington*
Unique ID of upstream segment	up_hydroid	All of Western Washington*
Unique ID of downstream segment	dn_hydroid	All of Western Washington*
Node number of upstream segment endpoint	up_node	All of Western Washington*
Node number of downstream segment endpoint	down_node	All of Western Washington*
Segment length (ft)	seg_lth_ft	All of Western Washington*
Elevation at upstream segment endpoint (ft asl)	elev_up_ft	All of Western Washington*
Elevation at downstream segment endpoint (ft asl)	elev_dn_ft	All of Western Washington*
Hydrologic Unit (12-digit) name	HUC12name	All of Western Washington*
12-digit Hydrologic Unit Code	HUC12	All of Western Washington*
Stream order (Strahler method)	str_ord	All of Western Washington*
Channel slope (ft/ft)	slope_tan	All of Western Washington*
Drainage area (mi^2)	wshedarea	All of Western Washington*
Mean annual flow (predicted, cfs)**	maf_cfs_v	All of Western Washington*
Channel width at mean annual flow (predicted, ft)***	cwid_ftmaf	All of Western Washington*
Bankfull channel width (predicted, ft)***	cwid_ft_bf	All of Western Washington
Valley width (ft)	vwidth_ft	All of Western Washington*
Confinement (multiples of channel width)	vwidth_bfw	All of Western Washington*
Stream power index (cfs)	sl_x_dis	All of Western Washington*
Percent alpine area in watershed area	pct_alp	All of Western Washington*
Mean land surface slope in watershed area (deg.)	bavg_slp	All of Western Washington*
Mean annual precipitation in watershed area (in)	baprec7100	All of Western Washington*
Tributary junction drainage area ratio	trib_da_rat	All of Western Washington*
Below HRCD resolution	b_hrcd_res	Puget Sound Region
Eroded area per unit length (measured 2006-2009, ft^2/ft)	er_pl_0609	Puget Sound Region
Eroded area per unit length (measured 2009-2011, ft^2/ft)	er_pl_0911	Subset of Puget Sound Region****
Confinement classification	conf_class	All of Western Washington*
Erosion potential classification	eros_class	All of Western Washington*
Full migration classification name	mig_class	All of Western Washington*

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* The data layer was developed by Hydrologic Unit "Sub-region" (with 4-digit codes). Portions of four Sub-regions cover Western Washington, including those identified as 1708, 1709, 1710, and 1711 (see Figure 1). The data layer also includes those areas of Hydrologic Unit Sub-regions extending outside of Washington into Oregon.

**Predicted using regression equations of Vogel et al. (1999)

***Predicted using regression equation developed in this study

****The subset of the Puget Sound region includes Watershed Resource Inventory Areas 1, 2, 3, 7, 8, 9, 10, 11, 12, 13, 15, and 16.

Raster processing

Processing of raster datasets was required as an initial step in the CHAMP development process. Table A 2 lists the raster data used

Table A 2. Primary raster data used in CHAMP development

Data type	*Source*	*Description of Use*
Elevation (30 m resolution digital elevation models (DEMs))	National Hydrologic Dataset Plus version 2 (unfilled DEMs)	Topographic measurements and generation of hydrologic rasters
Mean Annual Precipitation (800-m resolution grids, 1961-1990 averages)	PRISM Climate Group	Used for calculation of watershed mean annual precipitation needed for regression predictions of mean annual flow using regressions developed by Vogel et al. (1999).
Mean Annual Precipitation (800-m grids, 1971-2000 averages)	PRISM Climate Group	Used for calculation of watershed mean annual precipitation needed for development of bankfull width regressions.
Mean Annual Temperature (800-m grids, 1961-1990 averages)	PRISM Climate Group	Used for calculation of watershed mean annual temperature needed for regression predictions of mean annual flow using regressions developed by Vogel et al. (1999).
Land cover grids (2011)	National Land Cover Database 2011 (USA)	Used to delineate alpine areas

Note that climatologic grids were not available north of the US-Canada border, so related attributes in watersheds spanning the international border will be under-predicted. However, the number of stream segments affected by this error is small relative to the entire dataset.

Generating stream networks

Table A 3. Attributes generated during stream network generation

Attribute	*Field Name*
Unique segment ID	hydroid
Unique ID of upstream segment	up_hydroid
Unique ID of downstream segment	dn_hydroid
Node number of upstream segment endpoint	up_node
Node number of downstream segment endpoint	down_node
Stream order	str_ord
Drainage area	wshedarea

Stream network lines were delineated using standard ESRI ArcGIS flow direction and flow accumulation tools. These tools were applied on raw 30-m resolution Digital Elevation Models (DEMs) obtained from the National Hydrography Dataset Plus (v2). Note that the DEMs used here were the raw versions, and not the “hydro-enforced” DEMs produced for the National Hydrologic Dataset. Note that NHD stream network lines were not used for this layer because of the need to make measurements of valley width. Due to the hydro-enforcing process, NHD streams do not always follow the lowest elevation points along valleys, which would have caused problems for our valley width measurements (discussed below). Stream network lines were extracted downstream of points where mean annual flow was predicted as 10 cubic feet per second (cfs) by the Vogel et al. (1999) regression equations. These processing routines were performed separately by Hydrologic Unit "Sub-regions" identified by 4-digit codes.

Generating watershed-based attributes

Table A 4. Watershed-based attributes included in the CHAMP layer.

Attribute	*Field Name*
Percent alpine area in watershed area	pct_alp
Mean land surface slope in watershed area	bavg_slp
Mean annual precipitation in watershed area	baprec7100

A number of CHAMP fields describe watershed characteristics such as mean average precipitation averaged over a watershed area. These values were initially generated using ArcGIS Flow Direction (used in stream network generation) and *Weighted* Flow Accumulation tools. Flow accumulation weighting is an option in the Flow Accumulation tool (ESRI ArcGIS). The weighting option totals drainage area values according to the input weighting raster. The following rasters were generated using weighted flow accumulation (and other processing steps described):

- Watershed-averaged mean annual precipitation [baprec7100]: Flow accumulation weighted by a raster of mean annual precipitation divided by standard flow accumulation raster (watershed area) using raster math. Note that this operation was completed for PRISM temperature averages for both 1961-1990 and 1971-2000 (see Table A 2). The 1961-1990 data was used for prediction of mean annual flow according to regression equations by Vogel et al. (1999). The 1971-2000 data was used for prediction of bankfull channel width (described below).
- Watershed-averaged mean annual temperature: Flow accumulation weighted by a raster of mean annual temperature divided by standard flow accumulation raster (watershed area) using raster math. This operation was completed for PRISM temperature averages for 1961-1990. Mean annual temperature is not included as a data attribute, but was used to calculate mean annual flow according to regression equations developed by Vogel et al. (1999).
- Percentage of watershed classified as alpine area: Flow accumulation weighted by raster of alpine and non-alpine areas divided by standard flow accumulation raster (watershed area) using raster math.
- Watershed average slope: Flow accumulation weighted by slope raster divided by standard flow accumulation raster (watershed area) using raster math. The slope raster was generated using ESRI ArcGIS Spatial Analyst Tools.

Once generated in raster form, the attributes listed in Table A 4 were extracted to CHAMP segments using the ArcGIS "Extract Multi-Values to Points" Tool.

Note that the alpine area raster used to measure percent alpine area was derived using methods of Beechie and Imaki (2014) using land cover data. This process involved first merging areas identified as barren, ice, and unvegetated by the US National Land Cover Dataset (2006) in the

United States. These areas above elevations of 2000 meters above sea level were classified as alpine area.

Vector processing - Segmenting the stream network layer

Table A 5. Simple attributes generated for each stream segment.

Attribute	*Field Name*
Segment length	seg_lth_ft
Elevation at upstream segment endpoint	elev_up_ft
Elevation at downstream segment endpoint	elev_dn_ft
Channel slope	slope_tan

The raw line layer produced from the stream network generation routine in ArcGIS above was divided into individual line shapes extending between tributary junctions (e.g. individual lines represented stream network links). These link lines were further sub-divided into the final CHAMP line segments. Line segment length was scaled according to predicted channel width at mean annual flow. According to regression equations discussed below, Ecology calculated each link's channel width according to its watershed area, watershed-average precipitation, and watershed-average temperature (extracted at the link's midpoint). Segment lengths were then defined as 60.5 times predicted channel width (predicted for the link). This spacing was defined with the goal of including multiple meander wavelengths in each segment. Meander wavelength, according to Leopold and Wolman (1960), is approximately 11 times channel width. Thus, segments of the defined length should include approximately 5.5 meander wavelengths. This approach of defining segment length by multiples of channel width is similar to methods by Clarke et al. (2008).

Note that elevations at segment endpoints (see Table A 5) were extracted to CHAMP segments using the ArcGIS "Extract Multi-Values to Points" Tool. Segment slope was then calculated as the change in elevation divided by segment length.

Analyses, processing, and calculations for individual attributes

The text below describes data and GIS analyses required to generate many of the attributes in the CHAMP layer.

Mean annual flow and channel dimensions

Table A 6. Attributes related to mean annual flow and corresponding channel dimensions.

Attribute	*Field Name*
Mean annual flow (predicted)**	maf_cfs_v
Channel width at mean annual flow (predicted)***	cwid_ftmaf

The CHAMP data layer extends upstream to points in the drainage network with predicted mean annual flows of 10 cubic feet per second (cfs). The CHAMP layer was developed in the Shorelands and Environmental Assistance Program of the Washington Department of Ecology. The program's jurisdiction in fluvial systems extends to points in the drainage network with mean annual flows of 20 cfs. Mean annual flow was therefore a logical basis for and useful attribute within the CHAMP layer.

Regression equations developed by Vogel et al. (1999) provided a simple means to predict mean annual flow, with one equation applying for the entire Pacific Northwest. Their equation predicts mean annual flow based on watershed area, mean annual precipitation, and mean annual temperature. Precipitation and temperature values are averaged across watersheds. According to the methods of Vogel et al., Ecology used rasters of mean annual precipitation and temperature from 1961-1990 available from the PRISM climate group (Daly et al., 2000). Ecology first tested the regression equation with a set of mean annual flow measurements compiled by Magirl and Olsen (2009). Regressing measured (MAF_M) to predicted mean annual flow (MAF_P) revealed a strong correlation with little bias ($MAF_M = 0.99 * MAF_P$; $R^2 = 0.97$). The Magirl and Olsen data set also had associated measurements of flow width (ft) and hydraulic depth (e.g. average flow depth), allowing development of two additional regression equations between these channel dimensions and predicted mean annual flow. The regression equation relating predicted mean annual flow (cfs) to channel width (W_{MAF}, ft, [cwid_ftmaf]):

$$W_{MAF} = 4.09 * MAF_P^{0.478} \ (R^2 = 0.87, p = 3.5 * 10^{-114})$$

According to Newman's (1993) methods for correcting regression bias in log-transformed data, a bias correction factor of 1.04 should be applied to the above equation (resulting in a coefficient of 4.25). The regression equation relating predicted mean annual flow (cfs) to hydraulic depth (D_{HMAF}, ft):

$$D_{HMAF} = 0.23 * MAF_P^{0.370} \ (R^2 = 0.64, p = 7.58 * 10^{-60})$$

A bias correction factor of 1.09 should be applied in a similar fashion as above. Note that hydraulic depth is not included as an attribute in the final CHAMP data layer, but it was used in automated measurement of valley width (discussed below).

Bankfull channel width

Table A 7. Attribute field name containing predicted bankfull channel width.

Attribute	***Field Name***
Bankfull channel width (predicted)***	cwid_ft_bf

Bankfull channel width is the most commonly used dimension of channel size. The bankfull channel is that which commonly carries an approximate 1.5- to 2-year recurrence interval flood in the Pacific Northwest, or more generally the most geomorphically effective flow (Castro & Jackson, 2001). Prior to this study, only regression equations developed using small datasets were available to predict bankfull width in Western Washington. Ecology developed a regression equation using 179 channel measurements distributed across Western Washington available through Ecology’s Environmental Information Management System (measurements made by Ecology’s Biological Monitoring and Status and Trends Monitoring Programs). The regression equation relates watershed area (A, mi^2) and mean annual precipitation (watershed average, P, inches per year) to bankfull channel width (W_{BF},ft):

$$W_{BF} = 0.91 * A^{0.381} * P^{0.634}\ (R^2 = 0.83;\ p = 2.66 * 10^{-68})$$

A bias correction factor of 1.16 (as calculated using Newman’s (1993) procedure) should be applied to the above equation. The above equation appears to have the greatest relevance at bankfull widths below about 250 feet. At widths greater than 250 feet, the equation consistently over-predicted the few measurements available.

Valley width measurement

Table A 8. CHAMP fields related to valley width

Attribute	*Field Name*
Valley width	vwidth_ft
Confinement*	vwidth_bfw
Confinement classification*	conf_class

*The confinement calculation and classification are described in the main body of the report.

For each CHAMP stream segment, valley width was measured using the following procedure in ArcGIS:

1. Using the Transect Generation Tool (part of the Channel Migration Toolbox developed at Ecology; see Ecology publication 14-06-032 (2014)), transects were drawn perpendicular to the stream network at a spacing of 0.5 times channel width at mean annual flow (typically 10 transects per stream segment).
2. A point was created at the intersection of each transect with the stream network.
3. The ground elevation was extracted at each point from the 30-meter DEM.
4. A vertical height, h, of 8.5 (see discussion below and Figure A 1) times channel depth at mean annual flow was added to the elevation (extracted in previous step) of each point.
5. An elevation raster was interpolated according to the elevated values calculated in the previous step (see Figure A 1). This step essentially created a smooth surface that intersected the actual valley wall at some distance from either side of the stream line. These two intersection points are referred to as VWa and VWb in Figure A 1.
6. At each transect generated (see Step 1 above), the distance between intersection points VWa and VWb was measured as valley width (Figure A 1).
7. Transect valley width measurements (usually 10) were averaged for each stream segment.

Ecology arrived at the height value (h) of 8.5 multiples of channel depth (see step 4 above and Figure A 1) through a trial and error calibration process. We first manually measured valley width at 50 randomly selected points in ArcGIS. At multiple values of h (in multiples of channel depth), Ecology compared manually measured valley widths to those measured using the above automated routine. The height value of 8.5 times channel depth compared well with manual measurements. At this value, linear regression produced a regression line with a slope of 1.00

(R^2= 0.95) between manual and automated measurements, suggesting a good agreement between the two.

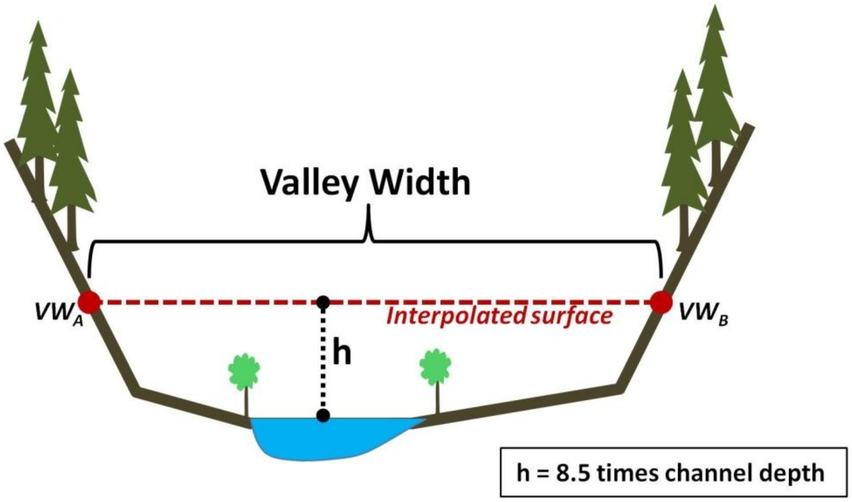

Figure A 1. Cross-sectional illustration of the main elements of the GIS routine used to measure valley width.

Merging of High Resolution Change Detection Data with the CHAMP layer

Table A 9. Attributes containing information on erosion measurements made by the HRCD project.

Attribute	*Field Name*
Below HRCD resolution	b_hrcd_res
Eroded area per unit length (measured 2006-2009)	er_pl_0609
Eroded area per unit length (measured 2009-2011)	er_pl_0911

The High Resolution Change Detection (HRCD) project (WDFW, 2014) mapped polygons across the landscape where land cover had changed between consecutive NAIP aerial images. The process of associating these areas of change with adjacent CHAMP segments involved the following steps:

1. Buffers were generated around each stream segment. The buffers were divided by lines approximately perpendicular to the stream line. Buffer widths were scaled to channel width in order to minimize problems with buffers over-reaching into adjacent streams.
2. A vector-based geoprocessing routine allowed measurement of the changed land cover area (as a result of fluvial erosion) within each buffer polygon.
3. Measured area of land cover change was then joined to stream network segments, and normalized to segment length.

The above processing routine was performed separately by stream order to minimize buffer overlap problems at tributary junctions. However, tributary junctions are likely to have the greatest errors where buffers of small streams overlap areas eroded by the larger stream.

Erosion potential classification

Table A 10. Attributes related to the erosion potential classification.

Attribute	*Field Name*
Below HRCD resolution	b_hrcd_res
Erosion potential classification	eros_class
Full migration classification name	mig_class

The erosion potential classification was based on observations that HRCD measured change tended to be greater on stream segments with high stream power index. Prior to developing this classification scheme, Ecology removed stream segments classified as confined (confinement values of less than 2x channel width), and those segments that appeared to be below the resolution of the HRCD data. Detected change abruptly fell to zero at streams of predicted bankfull width of about 21 feet. The HRCD mapping process filtered out changed polygons below about 1/20th acre (a ~52-foot diameter circle) in area. Because areas eroded by fluvial action are likely oblong in shape, it seems likely that the observed threshold in stream size is related to the resolution of the HRCD data. Ecology therefore eliminated streams less than predicted bankfull widths of 21 feet from the classification analysis. In total, 1806 of 21898 stream segments in the Puget Sound region were removed from the classification analysis as a result of either being confined or below the 21-foot bankfull width threshold. Streams narrower than 21 feet may migrate in reality, but were simply removed due to being below the resolution of the HRCD process. Note that the field [b_hrcd_res] indicates the stream segments below the HRCD resolution.

A relationship between eroded area and stream power is partially visible in Figure A 2A, where the individual erosion measurements (grey dots) appear to increase toward high stream power indexes (slope-discharge products). However, the visual clustering apparent in the individual erosion measurements (grey dots) is to some degree obscured by the fact that stream power is unevenly distributed. The blue squares in Figure A 2A show the cumulative distribution of stream power index. Comparing the cumulative stream power distribution to the individual erosion measurements explains why the density of grey dots appears to increase toward a stream power index value of about 3, and then decrease in density toward higher stream powers. To remove the effect of the stream power index distribution, Ecology binned (logarithmic bins with widths of 0.05) and averaged the erosion data, which results in the black triangles shown in Figure A 2A. Despite having low average values due to a high proportion of low migrating reaches, the binned data (black triangles) make apparent the peak in erosion rates at the upper range of stream power. The cumulative distribution of the binned erosion values are shown in Figure A 2B.

Ecology defined classifications based on the distribution of bin-averages shown in Figure A 2B. The “high” erosion potential class defines the uppermost region of stream power index that contained 79.7 % of the observed erosion (according to bin averages). The “moderate” erosion potential class falls outside of the high class, but where greater than 95.1% of observed erosion occurred.

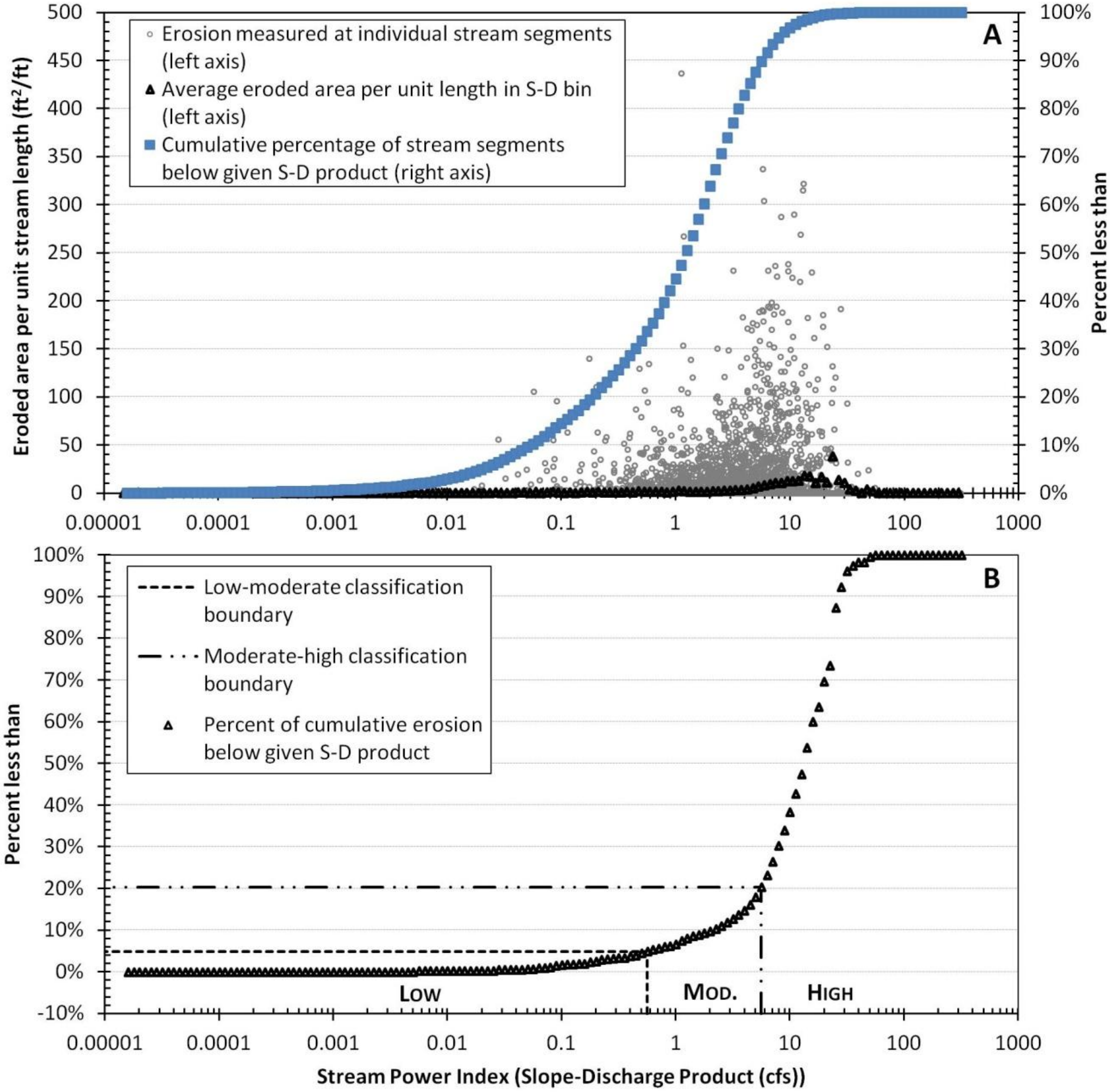

Figure A 2. Measured area eroded by fluvial action by the HRCD project, graphed relative to stream power index. Stream power index is the product of slope and discharge (S-D product). Graph A shows individual measurements of erosion (grey dots), the cumulative distribution of stream power index in the Puget Sound (excluding confined and stream segments below the resolution of the HRCD data), and binned averages of erosion (black triangles). The cumulative distribution as defined by the binned averages is shown in graph B, and was used to define erosion potential classifications as shown.