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Executive Summary

Snohomish County has retained Northwest Hydraulic Consultants to prepare a Channel Migration Zone (CMZ) study to support the replacement of Bridge 581 that crosses over the Pilchuck River and is located in a section of the river where County code recognizes that channel migration is likely to occur. This report provides documentation of the CMZ delineation process and support for bridge design considerations related to channel migration.

Channel migration generally occurs via two processes that are considered in a CMZ analysis: bank erosion and avulsion. Bank erosion occurs when river flows have enough energy to erode the bank material and results in incremental movement of the channel toward the outside of bends (extension) or down-valley (translation). The composition of bank material and bank vegetation influences the susceptibility of banks to erosion. Avulsion is the process where the river suddenly shifts to a new channel location and often results from channel blockage related to large wood accumulation.

Aerial photographs and LiDAR topography data were used to understand historical channel migration patterns and rates. During a site visit, the condition and position of eroding banks were mapped, large woody debris and log jams inventoried, and surface grain size distributions determined. Bed load transport was computed using an empirical sediment transport function applied to the recent flow history.

The project reach of the Pilchuck River is very dynamic. Long-term historical aerial photograph records, observation of geomorphic features revealed in LiDAR topography, and field observations reveal both high rates of bank erosion and a propensity for floodplain-spanning avulsions. At sites of active erosion, meander migration rates range from 8 to 44 feet per year and bank heights range from 5 to 25 feet. Areas of unconsolidated, non-cohesive bank material are generally associated with the highest rates of erosion. One particularly important site of erosion occurs at River Mile (RM) 15.9, where erosion of the right bank results in the delivery of a large amount of sediment to the river channel. This sediment is causing bar growth and bank erosion downstream through the study area. Another noteworthy site of erosion is just downstream of the bridge at RM 15.1, where significant property loss has been occurring along the right bank for the past 6 years. Erosion at this site has been caused by a recent influx of sediment from upstream and a reduction in bank strength resulting from a loss of riparian vegetation.

The CMZ in the project vicinity was delineated using guidelines found in Section 2 of the Forest Practices Board Manual (DNR, 2004) assuming a design life of 75 years. The DNR manual defines the CMZ as the inclusive sum of three subcomponents: the Historical Migration Zone (HMZ), Avulsion Hazard Zone (AHZ), and Erosion Hazard Area (EHA), less areas disconnected by maintained infrastructure, termed the Disconnected Migration Area (DMA). The HMZ was delineated as the inclusive sum of all channels and active side channels visible in aerial photographs and maps from 1941 to 2011. The size and load of large wood in the study area indicates that local vertical fluctuations in channel elevation on the order of 6 feet above the top of bank elevation are likely in response to localized aggradation upstream of log jams. The avulsion hazard zone was delineated as the entire geomorphic floodplain since it is within 6 feet of the river top of bank elevation based on LiDAR mapping.
The rate of bank erosion, and therefore the appropriate width of the EHA, depends largely on the composition of the river bank. The glacial history of the study area has resulted in much variability in the floodplain and terrace materials that may be part of the river bank. Uncertainties regarding the extent of different types of materials represent a significant limitation of this analysis. Several different methods were used to define the erosion hazard buffer depending on the kind of geological material that was considered to be most likely present based on existing geological mapping, field observations, and best professional judgment. The reach average migration rate was determined to be 3.1 ft/yr, but localized erosion rates over short time periods can be very high. The reach average migration rate was used for areas mapped as alluvial terraces (shown in Figure 8), resulting in an erosion hazard buffer in that area of 230 feet. Because extremely fast erosion rates of the glacial outwash terrace (shown in Figure 2) to the west of the river are observed, an erosion hazard buffer of one-half meander amplitude (600 feet) was applied in areas where erosion of the outwash terrace was considered likely. The alternative, extrapolation of the high observed recent erosion rates, would result in an unreasonable erosion buffer width larger than the whole extent of valley expansion since the existing drainage network was established post-glaciation. In areas where high walls of glacial till migration, an erosion buffer width of 38 feet was applied. See Section 6.3 for additional detail regarding methods used to define the EHA.

Existing riprap and levees are observed to be ineffective long-term barriers to migration; therefore, there are no disconnected migration areas within the CMZ delineation extent except Highway 92. Relative CMZ hazard areas were delineated based on best professional judgment of likely future channel migration scenarios.

Due to site constraints, the proposed bridge will be constructed parallel to and directly upstream of the existing bridge. The present bridge length is 179’ and the proposed bridge will be approximately 200’. The area proposed for Bridge 581, including approach roadways, abutments, and any support piers, lies within the Pilchuck River CMZ. The right bank abutment lies within the moderate CMZ area, while the left bank abutment and approach roadway lie within the high hazard area. Local protection of the right bank abutment is most likely sufficient. Because extremely dynamic and difficult to predict channel migration is occurring upstream, it is not reasonable to design protection against all likely channel migration scenarios, but rather to plan on future bank protection once the specific threat is known. Significant sediment accumulation is occurring in the vicinity of the bridge, and so the low chord of the bridge should be placed high enough to account for this aggradation and continue to pass flood flows and the significant load of floating large woody debris.

The proposed bridge will not have an impact on the outside boundary of the CMZ. Changes to local hydraulics are uncertain and therefore erosion effects are not clearly discernible on the right bank, just downstream of the bridge.
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1) All references to left and right bank direction in this report are based on looking in a downstream direction along the Pilchuck River.

2) All elevations referenced in this report are in NAVD 88 vertical datum.

3) River Mile (RM) stationing in this report is based on GIS (LiDAR and aerial photograph) determination of the stream alignment measured as distance upstream from the confluence with the Snohomish River.
1 Introduction

Snohomish County (County) has retained Northwest Hydraulic Consultants (NHC) to prepare a Channel Migration Zone (CMZ) study to support the replacement of Bridge 581 over the Pilchuck River. Bridge 581 is located three miles southwest of Granite Falls, at approximately River Mile (RM) 15.2 near Lochsloy, Washington (Figure 1). The bridge is on 64th Street NE, providing access between Highway 92 and a farm on the east side of the river. The existing bridge was constructed in 1960 and partially rebuilt in 1988 to 1989 with additional portions rebuilt in 2010; it requires replacement related to issues with scour, debris accumulation on the bridge piers (bents) during floods, and related structural concerns. The proposed bridge will be constructed parallel to and directly upstream of the existing bridge. The present bridge length is 179' and the proposed bridge will be approximately 200'.

Bridge 581 is located within a section of the Pilchuck River where channel migration is likely per County Code SCC 30.62B.330. Migration of the Pilchuck River across the valley is a natural process, but it can affect structures within the river valley. As a result, a CMZ study is required to support bridge design. County code requires that the CMZ study follow the protocol detailed in Section 2 of the Washington Department of Natural Resources Forest Practices Board Manual (Title 222 WAC), Standard Methods for Identifying Bankfull Channel Features and Channel Migration Zones (DNR, 2004).

The objectives of this document are to:

1. Provide a CMZ study to meet County Code SCC 30.62B.330 requirements:
   a. Delineate the CMZ within the study area (a one mile long reach extending 0.5 miles upstream and downstream from Bridge 581);
   b. Analyze the effects of the CMZ on the proposed bridge replacement project;
   c. Analyze the effects of the proposed bridge on the CMZ; and
2. Assist the County with related CMZ, geomorphic, and hydraulic aspects of bridge design.

The CMZ was delineated based on a 75 year design life of the proposed new Bridge 581 structure.

1.1 Channel Migration

Channel migration is the movement of a river channel back and forth across its valley that occurs in meandering and braided rivers with wide valley bottoms and erodible river banks. The Pilchuck River in the vicinity of Bridge 581 is a meandering river, with wide sweeping bends and occasional split channels. Channel migration generally occurs via two processes that are considered in a CMZ analysis: bank erosion and avulsion.

Bank erosion occurs when a river’s discharge has enough energy to erode the bank material. Since much of the river’s energy is concentrated at the outside of meander bends, bank erosion often occurs there, resulting in migration of the river channel toward the outside of bends and translational movement of the channel down-valley. Erodible banks and high peak flows can result in relatively rapid channel migration during floods. Accumulations of large woody debris (e.g., log jams), accumulations of sediment, or other instream structures can also direct the
river’s energy toward banks and result in bank erosion. Bank protection, such as riprap or large woody debris structures, is sometimes constructed to reduce bank erosion. The CMZ analysis considers the potential for channel migration via bank erosion by mapping past locations and rates of bank erosion. This is achieved by analyzing historical maps and aerial photographs, considering current bank erodibility, and large woody debris and sediment accumulation potential. The CMZ analysis delineates a Historical Migration Zone (HMZ) where past migration has occurred and an Erosion Hazard Area (EHA) where future bank erosion is likely.

Avulsion is the process where the river suddenly shifts to a new channel location. Avulsions generally occur during peak flood flows, sometimes in response to a large log jam or obstruction in the river that diverts flow out of the former main river channel. Avulsions can result in split channels where the river flow is divided among several channels with vegetated islands between them. Over time, one of the split channels may become the main channel, and the others may only carry water during floods. Channel migration due to avulsions is more difficult to predict than migration due to bank erosion because the avulsion process is sporadic and often related to unpredictable accumulations of logs and debris in the stream during floods. The CMZ analysis uses historical aerial photographs and LiDAR data to delineate an Avulsion Hazard Zone (AHZ) that includes past avulsion paths and areas that have a high potential for future avulsions.

In addition to delineating the HMZ, EHA, and AHZ, the CMZ analysis considers areas of the river valley that are behind permanently maintained dikes, levees, or revetments. These are delineated as a Disconnected Migration Area (DMA).
2 Methods

2.1 Aerial Photograph, Historical Map, and Topographic Analysis

Historical channel positions were determined from aerial photographs and topographic maps that are listed in Table 1. Table 1 also lists major flood events that are likely to have caused significant channel changes. The channel position from the 1859 General Land Office (GLO) map includes areas outside of the fluvial valley where topography indicates no recent channel of Pilchuck River has been present. Because of this, the GLO is considered to only reliably indicate the gross channel form, and not any detail of the lateral position that can be useful in determining the HMZ. Aerial photographs and maps from 1941 to 2011, however, provide very good definition of positions the channel has occupied over the intervening 70 years.

Table 1: Historical Maps and Aerial Photographs used to Delineate Channel Positions and Relevant Peak Flow Events.

<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Source</th>
<th>Scale or Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1859</td>
<td>Surveyed Map</td>
<td>GLO survey</td>
<td></td>
</tr>
<tr>
<td>1941</td>
<td>Aerial photograph</td>
<td></td>
<td>1:34,600</td>
</tr>
<tr>
<td>1945</td>
<td>Peak flow: 10,500 at Granite Falls gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>Aerial photograph</td>
<td>Snohomish County</td>
<td>2 feet</td>
</tr>
<tr>
<td>1956</td>
<td>Topographic Map</td>
<td>USGS</td>
<td>1:24,000</td>
</tr>
<tr>
<td>1971</td>
<td>Visible Infrared</td>
<td>USGS</td>
<td>15 feet</td>
</tr>
<tr>
<td>1969</td>
<td>Aerial photograph</td>
<td>Snohomish County</td>
<td>2 feet</td>
</tr>
<tr>
<td>1974</td>
<td>Aerial photograph</td>
<td>Snohomish County</td>
<td>2 feet</td>
</tr>
<tr>
<td>1976</td>
<td>Peak flow: 8,510 at Granite Falls gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>Aerial photograph</td>
<td>Snohomish County</td>
<td>2 feet</td>
</tr>
<tr>
<td>1983</td>
<td>Aerial photograph</td>
<td>USGS</td>
<td>2 feet</td>
</tr>
<tr>
<td>1990</td>
<td>Aerial photograph</td>
<td>USGS DOQ</td>
<td>1 meter</td>
</tr>
<tr>
<td>1999</td>
<td>Peak flow: 11,200 at Snohomish gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Aerial photograph</td>
<td>NAIP</td>
<td>1.4 feet</td>
</tr>
<tr>
<td>2006</td>
<td>Peak flow: 11,100 at Snohomish gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Aerial photograph</td>
<td>Snohomish County (via USGS distribution)</td>
<td>1 foot</td>
</tr>
<tr>
<td>2009</td>
<td>Peak flow: 13,900 at Snohomish gage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Aerial photograph</td>
<td>NAIP</td>
<td>1 meter</td>
</tr>
<tr>
<td>2011</td>
<td>Aerial photograph</td>
<td>NAIP</td>
<td>1 meter</td>
</tr>
</tbody>
</table>

Detailed LiDAR elevation data flown in 2005 (PSLC, 2005) was also used to identify geomorphic features such as old channel locations, vegetation patterns, and detailed topographic information that is not visible on aerial photographs. The relative elevation above the river was determined by creating a valley-spanning surface of the river water surface elevation (at the time the LiDAR was flown) and subtracting this from the ground surface elevation. Because the
topography of river bars are clearly visible, it is inferred that the LiDAR was flown during a low-flow condition; therefore, elevations above the river determined by this procedure are subsequently called height above low-flow water surface. This procedure followed the methodology of Jones (2006).

2.2 Site Visit

NHC and Watershed GeoDynamics geomorphologists visited the project site on October 8, 2012 and walked the channel from approximately RM 14.7 to 16.5. On this date, the discharge of the Pilchuck River at Snohomish, WA (USGS gage 12155300) was low (56 cfs). Current bank conditions, substrate grain size characteristics, and major pieces of large wood and large wood jams were documented during the site visit.

Locations of bank protection and of actively eroding banks were documented on field maps and with a handheld GPS unit (Delorme PN-60w, typical positional accuracy within 9 feet using WAAS technology). The type and condition of bank protection was qualitatively evaluated. The current position of actively eroding banks was determined by walking along either the toe or top of bank and tracing a track with the handheld GPS unit. The stratigraphy of eroding banks, characteristics of eroding materials, and mode(s) of bank failure were noted.

The grain size distribution of actively transported sediment was determined from 100-stone random-walk Wolman pebble counts. Four counts were conducted on representative bar-heads away from the local hydraulic influence of large woody debris. Subsurface grain size distributions were not quantitatively evaluated but photos of the subsurface material were taken.

2.3 Bed Load Transport

Bed load transport calculations were computed at four locations in or near the study reach. The Wilcock and Crowe (2003) sediment transport function was utilized as implemented in BAGS (Stream Systems Technology Center, 2009). A bed load transport rating curve was created for the range of flows recorded at the USGS gage for the Pilchuck River at Snohomish (12155300). Local hydraulic conditions were determined using available data. Valley cross sections were defined using LiDAR elevation data and assuming trapezoidal geometry below the water surface. The water surface slope was measured locally from the LiDAR data. Manning’s N values of 0.025 in the active channel and 0.06 in vegetated areas were applied. The grain size distribution of the bed was determined by the Wolman pebble counts described above.

Additionally, a morphologic estimate of bed load transport was made by estimating the volume of sediment deposited in a growing bar and eroded from the opposite bank at one location.
3 Project Setting

3.1 Geomorphic History

3.1.1 Glacial History

The geology, topography, and geomorphology of the Pilchuck River basin is greatly influenced by the last glacial interval which left behind a variety of sedimentary deposits associated with the glacier and runoff of glacial meltwater (Collins 1991, Booth 1989, Tabor et al. 2002). The Puget Lobe of the Cordilleran ice sheet moved into the Puget Sound area from Canada, reaching the Seattle area approximately 15,000 years ago. As the ice sheet moved south, it blocked many of the streams flowing off the Cascades and formed a series of lakes. Silt and clay were deposited in the lakes, forming what is locally called the Pilchuck Clay. As the glacier continued to move south over the area, cobble, gravel, and sand was deposited on top of the clay in deltas and alluvial deposits from rivers that drained the glacier. Up to 3,500 feet of glacial ice covered the Pilchuck River valley (only the top of Mt. Pilchuck remained exposed) and up to 50 feet of glacial till, a compact, poorly sorted mix of clay, silt, sand, and rocks was deposited under the ice. The till is significant along the present river bank because it is resistant to bank erosion, slowing the rates of channel migration where it is exposed.

As the last glacial maximum waned and the Puget Lobe melted, the Pilchuck River drainage gradually became ice free. Rivers flowing south from the melting ice carved wide meltwater channels and deposited large amounts of outwash (cobble, gravel, and sand) known as the Stillaguamish Sand on top of the till. The valley of the Pilchuck River downstream of the Bridge 581 site (downstream of approximately RM 14.5 on Figure 1) contained one of these large meltwater channels. The flow of the South Fork Stillaguamish River was diverted into the Pilchuck River valley west of the town of Granite Falls during this time and formed the broad, flat terrace underlain by outwash that Highway 92 presently follows between Granite Falls and Lake Stevens. The outwash is highly erodible and is forming many of the actively eroding banks seen during the site visit.

3.1.2 Post-Glacial River History and Valley Geology

Following the retreat of the ice sheet 14,000 years ago, the Pilchuck River established its current course and began incising and deepening its river valley. Areas mapped as alluvium (river deposits) on Figure 2 show areas where the river has been re-working the glacial deposits as it meanders across the valley. The shaded relief on Figure 2 also shows past river channel locations and the scalloped valley edges in the project vicinity between RM 14 to 18, where the river has eroded the glacial outwash terrace on the west side of the river.

Today, the river in the project vicinity has a meandering planform with local channel splits and some braided sections. Through the study area, the river has an average slope of 0.0028 with a range of local slopes between 0.001 and 0.0045. This compares to an average slope between RM 6 and RM 19 of 0.0031 (Figure 3). Both this planform and slope are indicative of relatively high bed load transport rates.
In the immediate vicinity of Bridge 581, the right valley wall is typically composed of a terrace of glacial outwash sand and the left valley wall geology includes glacial till, advance glacial outwash, and bedrock (Figure 2).

### 3.2 Basin Hydrology

Channel migration and bed load transport on gravel-bedded rivers such as the Pilchuck occur during peak flow (flood) events when the river has enough energy to erode banks and move the gravel and cobble substrate on the bed. Flows on the Pilchuck River have been recorded by the United States Geological Survey (USGS) at the Pilchuck River near Granite Falls Gage (USGS 12152500) from 1944 to 1980, and at the Pilchuck River near Snohomish Gage (USGS 12155300) between 1992 and the present. The basin area at the Granite Falls gage is 54 square miles, at the project site is 78 square miles, and at the Snohomish gage is 127 square miles. The USGS PKFQWin program was used to compute peak flow magnitudes using 37 years of peak flows at the Snohomish gage (Table 2). Note that the short period of record at this gage reduces confidence in the estimated magnitude of longer return interval floods (e.g., over 25 years recurrence interval).

Given the lack of sufficient data for direct computation of peak flows at the bridge site, NHC developed flood recurrence estimates for the bridge site by employing the USGS’s published regional basin area regression (Sumioka et al. 1998) to adjust gaged flood flow estimates from the Snohomish Gage to the project site. The basin is in USGS Region 2, which uses an exponent of 0.98 on the basin area ratio. The basin area ratio falls within the 50 to 150 percent range recommended for application of this approach.

**Table 2: Computed Peak Flows (cfs) at Pilchuck River USGS Gages.**

<table>
<thead>
<tr>
<th>Recurrence Interval (years)</th>
<th>Near Snohomish Gage 12155300 (127 sq mi)</th>
<th>Project Site (78 sq mi) (flood estimates scaled from Snohomish gage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>3,800</td>
<td>2,400</td>
</tr>
<tr>
<td>2</td>
<td>5,900</td>
<td>3,600</td>
</tr>
<tr>
<td>5</td>
<td>8,800</td>
<td>5,500</td>
</tr>
<tr>
<td>10</td>
<td>10,900</td>
<td>6,700</td>
</tr>
<tr>
<td>25</td>
<td>13,500</td>
<td>8,400</td>
</tr>
<tr>
<td>50</td>
<td>15,500</td>
<td>9,600</td>
</tr>
<tr>
<td>100</td>
<td>17,500</td>
<td>11,000</td>
</tr>
</tbody>
</table>

Figure 4 shows annual peak flows for the periods of record at both the Granite Falls and Snohomish gages. The period of 2007 through spring of 2012 has had a series of exceptionally high flows, including three of the highest flows on record at the gage near Snohomish; these three flows each have a recurrence interval between 10 and 25 years. These high flows have likely contributed to recent geomorphic instability in the project area that is described in the Historic Channel Migration section of this report.
These historical conditions do not necessarily represent predictions of future flows because changes to climate conditions can change the magnitude and frequency of future peak flows. Research by the Climate Impacts Group at the University of Washington suggests that winter precipitation events may be more intense within the next century (Salathé 2006).

3.3 Upstream Sediment Sources

Bank erosion and channel migration can be influenced by channel aggradation which occurs if upstream sediment supply is greater than the channel’s capacity to transport sediment. Upstream of Granite Falls, the Pilchuck River erodes outwash sand and gravel deposited by the receding Cordilleran ice sheet. In the upper valley (above RM 26), sediment comes from landslides along the valley walls and from steep tributary streams (Collins 1991). Large and unstable bars characterize much of the Pilchuck River channel below RM 25. The presence of these bars indicates a relatively high rate of bed load transport and could indicate that system-wide aggradation is occurring. Collins (1991) did not identify significant contributions of sediment from lowland tributaries. However, the field visit conducted for the current project showed abundant sediment sources along the channel for at least 1 mile upstream of Bridge 581 where channel migration and bank erosion mobilizes cobble, gravel, and sand material from alluvial and outwash terraces.

3.4 Large Woody Debris

Large woody debris, which include trees, logs, root wads, and log jams, can affect channel migration by either protecting banks (if the wood diffuses flow against the bank) or increasing bank erosion and avulsion hazard if a log jam blocks the channel and directs flow toward the banks. Large wood is supplied to the Pilchuck River channel where bank erosion or landsliding in areas of mature forest causes trees to topple into the river channel. This wood can be transported downstream during floods or can be stored within the channel. In the project vicinity, large wood is present as individual pieces; these have only very local effects on channel morphology and are lodged against banks or on river bars. Several significant log jams are present. These result in upstream aggradation and/or bank erosion along the sides of the jams. Montgomery et al. (2003) describe how the formation of large wood jams in lowland forested streams can cause the bed to aggrade to the level of two stacked logs above the bankfull elevation, which can result in avulsions spanning floodplain areas that are lower than this level. On the Pilchuck, tree diameters of three feet and greater are present. Therefore, the area of the valley in the project vicinity that lies within six feet above the bankfull elevation (the height of two stacked three foot logs) may be occupied by an avulsed stream channel if a large wood jam caused enough aggradation to redirect the river.

Abundant large woody debris is present in the study area. Five log jams were observed during the site visit (Figure 5 and Photo 8), as well as several individual pieces of wood with diameters of 2 to 3 feet, lengths greater than 35 feet, and large root wads. Much of this wood appears to have been recruited from the floodplain in the vicinity of the project area by recent channel migration. A channel-spanning jam near RM 15.5 has caused local upstream aggradation, rapid bank erosion of a mature forested area (leading to additional wood input), and evidence of a potential future avulsion into the area behind the levee at this site. These observations confirm
the local relevance of research by Montgomery et al. (2003) regarding the role of large woody debris in channel avulsion hazards.

Individual pieces of large woody debris are also present in the vicinity of Bridge 581, including several pieces immediately upstream of the bridge and individual pieces and a small jam on the right bank just downstream of the bridge. Several pieces downstream of the bridge are lodged near the right bank and likely provide some bank protection for this eroding bank. Unconfirmed reports suggest that these may have been dragged into this position by adjacent property owners.
4 Sediment Characterization and Transport

4.1 Bed Sediment Characteristics

Collins (1991) conducted a bed load transport study on the Pilchuck River below RM 7. Grain size distribution data were collected as part of the current study to supplement Collins’ data. At RM 9.8 (approximately 5.5 miles downstream of the study area), a river-bar bulk sample indicated a D$_{10}$ (10 percent of the particles are smaller than the D$_{10}$) of <2mm, D$_{50}$ (the median grain diameter) of 19.5 mm, and a D$_{90}$ (90 percent of the particles are smaller than the D$_{90}$) of 115 mm.

Results of Wolman pebble counts from the project area are shown in Figure 6. All four sampled bars showed significant armor layer development. The D$_{10}$ of these samples ranged from 10 to 14 mm, the D$_{50}$ from 27 to 54 mm, and the D$_{90}$ from 58 to 104 mm. Subsurface sediment in these bars contained very high sand fractions (Photos 12 to 16).

There is an abrupt and dramatic fining of the bed material just downstream of the eroding bank at RM 15.9 (compare counts 16.45 and 15.76, which are from either side of this change). The D$_{50}$ decreases from 55 mm to 27 mm and D$_{90}$ decreases from 104 mm to 58 mm. Additionally, the proportion of sand on the surface of the bed also increases markedly (e.g., Photos 8 and 16). This is likely a result of a very large input of fine gravel and sand at RM 15.9, the site of a rapidly eroding right bank. The grain size distributions gradually coarsen downstream from this location, perhaps indicating mixing of sediment derived from the eroding bank at RM 15.9 and pre-existing streambed material.

Significant aggradation is occurring in this area as is supported by the abrupt change in grain size distribution, rapid growth of large bars, a very “loose” character of bed and bar sediment, and observation of buried root collars of bank and floodplain trees between RM 15.9 and RM 15. Bar surfaces at RM 14.75 and 15.6 lie at elevations above the surrounding floodplain, indicating local aggradation. This aggradation is likely a consequence of the large sediment input to the river at RM 15.9. There may also be reach-scale aggradation caused by a large-scale disequilibrium in hydrology and/or sediment supply.

4.2 Bed Load Transport and Historical Aggradation

Survey data confirm that local aggradation is occurring. Thalweg profile comparisons between the recent survey used to develop the HEC-RAS model provided by Snohomish County and the bed profile published in the 1983 FEMA Flood Insurance Study (FEMA 1983) show that the bed has aggraded on average 2.3 feet within approximately one-quarter mile on both sides of the bridge (Figure 7).

Bed load transport calculations suggest that this local aggradation is the result of a large input of sediment caused by bank erosion at RM 15.9. By comparing the volume of sediment deposited in the bar at RM 15.9 with the volume of sediment eroded from the terrace at that location, it is possible to estimate the minimum values of bed load transport to, and away from, the eroding bank at RM 15.9. The difference in these values illustrates the change in the sediment transport rate resulting from the input of relatively fine sediment at the eroding bank.
Over the past five years, approximately 3,100 cubic yards of sediment have been deposited in a bar in this area and approximately 12,500 cubic yards of sediment have eroded from the river bank. Comparing these volumes indicates that the bed load transport rate has increased in the downstream direction by a factor of four at the site of the eroding bank.

Estimates of bed load transport calculated from channel hydraulics using the Wilcock and Crowe (2003) sediment transport function produce very similar values to the morphologic estimates (Table 3). Furthermore, the downstream reduction in sediment transport capacity between RM 15.75 and 15.1 explains the aggradation in this area because the rate of bed load transport into the reach is significantly greater than the rate of bed load transport out of the reach.

Table 3: Bed Load Transport Estimates.

<table>
<thead>
<tr>
<th>Cross Section Location (RM)</th>
<th>16.2</th>
<th>15.75</th>
<th>15.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble Count Sample</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Transport Rate (yd³/yr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1992-2012 flows)</td>
<td>1,800</td>
<td>6,900</td>
<td>2,100</td>
</tr>
<tr>
<td>Transport Rate (yd³/yr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2007-2012 flows)</td>
<td>3,400</td>
<td>10,000</td>
<td>3,200</td>
</tr>
<tr>
<td>Morphologic Estimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of Transport Rate (yd³/yr)</td>
<td>3,100</td>
<td>13,000</td>
<td>N/A</td>
</tr>
<tr>
<td>(2007-2012)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The estimates of bed load transport at RM 16.2 and 15.1, which are away from the strong local influence of the sediment input at RM 15.9, compare well to that of Collins (1991) who estimated 1,000 to 2,000 yd³/yr average annual bed load transport downstream at RM 7.
5 Current Bank Conditions and Historical Channel Migration

5.1 Topographic Indication of Historical Migration

The LiDAR data were used to produce a map of relative elevation above the river water surface (Figure 8). Well preserved alluvial features that span the Pilchuck River Valley are located on a relatively flat floodplain and show both recent, historic, and relic channel locations. Fluvial features visible in the project reach include meander scroll bars, active and inactive side channels, and depressions indicating historical channel positions. The area that includes these features is considered the geomorphically active floodplain. There are alluvial terraces in places on the margins of this floodplain. These terraces are typically about 10 feet above the Pilchuck River low flow water surface. Above these alluvial terraces to the west of the river, there is a large, low-relief glacial outwash terrace, which was described in the Glacial History section of this report.

5.2 Current Bank Conditions

Figure 5 shows bank conditions within the project area that were mapped during the field visit in October 2012, including bank protection (riparp) and actively eroding banks. Five stretches of riprap revetment were observed within the study area. These typically consist of loose 2 to 3 foot angular boulders. All appeared to be functioning except about 40 feet of the revetment at RM 16, which has local failures (Photo 1). Collins (1991) mapped approximately 500 feet of riprap on the outside of the bend downstream of RM 16. No trace of this riprap was visible during the site visit.

Areas of eroding banks are also shown in Figure 5. Five sites of moderate or extreme active erosion were noted between RM 15 and 16. Table 4 lists these erosion sites along with information on the composition of the eroding bank and rates of bank erosion. Photos 2 through 11 show these eroding banks. All of the locations of active bank erosion occur in areas with unconsolidated bank materials, and the presence of non-cohesive bank materials appears to be related to the highest rates of bank erosion. Short-term bank erosion rates (defined as the rate of bank erosion during the most recent period of active erosion) range from 8 to 44 ft per year. Long-term rates of bank erosion (defined as the erosion rate occurring over the whole period of aerial photograph record, except at RM 15.9 where the most recent period of extremely rapid erosion has been excluded) range from 1.2 to 11 ft/yr. The pattern of historical movement at each of these locations is described in the next section.

The right bank at RM 15.2, just downstream of the existing Bridge 581 structure, includes a 30 ft long exposure of glacial till. Without significant subsurface exploration, it is not possible to determine the extent of this till body. It locally limits channel migration to the west, and if it is laterally extensive beneath the outwash sand terrace, it would likely act as a systematic barrier to channel migration.
Table 4: Sites of Moderate to Extreme Active Bank Erosion.

<table>
<thead>
<tr>
<th>River Mile and Bank (photo numbers)</th>
<th>Length</th>
<th>Bank Height</th>
<th>Bank Stratigraphy</th>
<th>Short-Term Erosion Rate(s) (period)</th>
<th>Long-Term Erosion Rate (period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1 RB (2-4)</td>
<td>420 ft</td>
<td>7 ft</td>
<td>Cohesive clayey silt and cohesive gravel</td>
<td>9 ft/yr (2007-2012)</td>
<td>1.2 ft/yr (1941-2012)</td>
</tr>
<tr>
<td>15.2</td>
<td>Location of existing Bridge 581.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.4 RB (5-6)</td>
<td>550 ft</td>
<td>9 ft</td>
<td>Cohesive clayey silt and cohesive gravel</td>
<td>11 ft/yr (2007-2012), 40 ft/yr (2011-2012)</td>
<td>2.5 ft/yr (1941-2012)</td>
</tr>
<tr>
<td>15.5 LB (7-8)</td>
<td>550 ft</td>
<td>6 ft</td>
<td>Non-cohesive sandy silt, local gravel</td>
<td>40 ft/yr (2007-2012)</td>
<td>11 ft/yr (1990-2012)</td>
</tr>
<tr>
<td>15.7 LB (9)</td>
<td>500 ft</td>
<td>5 ft</td>
<td>Gravel and cohesive silty sand</td>
<td>8 ft/yr (2007-2012)</td>
<td>1.7 ft/yr (1941-2012)</td>
</tr>
<tr>
<td>15.9 RB (10-11)</td>
<td>850 ft</td>
<td>15-25 ft</td>
<td>Sandy gravel with coarse sand lenses, few cobbles</td>
<td>44 ft/yr (2007-2012)</td>
<td>1.5 ft/yr (1941-2007)</td>
</tr>
</tbody>
</table>

5.3 Pattern of Historical Migration

The pattern of historical channel movement in the study area is characterized by meander migration resulting from bank erosion on the outside of meander bends and occasional avulsion and chute cutoff events triggered by large wood jams. Historical channel positions are shown in Figure 9.

There are three distinct sites of active channel migration over the past decade in the one mile long CMZ delineation reach, and one very significant area of migration just upstream of this reach. The downstream-most site is in the vicinity of RM 14.75, downstream from Bridge 581. Here the active channel (defined as the extent of unvegetated bars and the wetted channel) has narrowed as a consequence of stabilization of the right bank point bar by vegetation. Sometime between 1990 and 2006, a log jam developed on the left bank at RM 14.85. During this same time period a side channel developed on the left bank, reconnecting to the main channel near RM 14.25. Between summer 2006 and summer 2007, a large log jam developed across the head of this side channel. This jam likely prevented a full scale avulsion; since 2007, this side channel has remained in place but relatively small.

Just downstream of the bridge, at approximately RM 15.1, a significant bar developed on the left bank sometime between 2007 and 2009, probably as a consequence of increased local sediment supply and aggradation. Flow around this bar has widened the channel, eroding as much as 45 feet of the river’s right bank between 2007 and 2012. In this area, riparian vegetation was cleared in the 1980s and 1990s, likely increasing the susceptibility of the bank to erosion. This zone of active erosion appears to extend along approximately 420 feet of the channel (Photo 3). The bank is composed of cohesive clayey silt and cohesive gravel (Photo 2). A small log jam may be protecting parts of the bank in this vicinity (Photo 3), but some flow
does travel over and behind the log jam causing bank erosion. The upstream extent of rapid erosion directly corresponds to the limit of glacial till in the bank at RM 15.2 (Photo 4). Continued erosion at this site will likely erode portions of the adjoining properties that lie on the river’s floodplain. Whether structures at this site are threatened depends on the subsurface geological material beneath the outwash terrace surface. If the till that is exposed in the river bank at RM 15.2 extends through the area, the structures are likely protected from erosion in the near future. Conversely, if the area is underlain by glacial outwash sand and gravel, extremely rapid erosion of the terrace surface similar to what has occurred at RM 15.9 is possible.

Upstream of the bridge, between RM 15.3 and 15.75, large point bars have grown on both banks since 1990. During the same time, the sinuosity of the river has increased and the active channel has widened from approximately 115 ft to a range of 140 to 250 ft. The largest movement occurred at RM 15.5, where the left bank has eroded 275 ft since 1990. Here the bank is composed of non-cohesive sandy silt with local gravel (Photos 7 and 8). The principal driving force for channel migration in this area is deposition of a large volume of sediment in a series of point bars. Erosion in this area has destroyed at least 175 lineal feet of levee on the left bank between 2005 and 2012 (Figure 9) and provided large woody debris to the channel that is exacerbating aggradation and bank erosion. At RM 15.5, the eroding bank is perpendicular to the levee, while downstream (in the vicinity of RM 15.25) the channel bank is parallel to the levee and appears more stable. This levee does not act as a barrier to migration when attacked head on, but may reduce channel migration when the levee is parallel to the channel bank. The past flood season appears to have accelerated erosion on the right bank at RM 15.4. This is likely the result of changing geometry at an upstream bend that now directs the flow against an unprotected bank rather than against riprap. Continued rapid channel migration and bank erosion is likely in this vicinity.

Just upstream of the CMZ delineation reach, in the vicinity of RM 15.9, the river has eroded into the outwash terrace and widened significantly. Over the 70 year period of the aerial photograph record, the river has migrated gradually to the west at this bend. Between 1941 and 2007, the average annual rate of migration was approximately 1.5 feet.

Since 2007, this rate of migration at RM 15.9 has increased dramatically. Between summer 2007 and fall 2012, the left bank point bar at RM 15.9 has grown and the active channel has widened from 130 to 375 feet, and up to 245 feet of the right bank eroded (rapid bank erosion is ongoing). This yields a local maximum migration rate of approximately 44 ft/year. During the February 22, 2012 flood event, a home at this location collapsed into the river due to bank migration (Photo 11). It appears as though the rate of bank erosion at this site accelerated when the channel intersected the outwash sand terrace, the surface of which lies 15 to 20 feet above the channel. The bank in this terrace is composed of easily eroded, non-cohesive sandy gravel with coarse sand lenses and few cobbles (Photo 10). It has a high, steep scarp above the channel, which prevents vegetation from stabilizing the bank (Photo 11). Failure of the riprap mapped by Collins (1991) at this location may have initiated channel migration, but the timing of this riprap failure is unknown. Currently, no natural factor is limiting continued rapid erosion at this site. It will likely remain a significant local sediment source. Highway 92 and the home downstream of the property that collapsed into the river on February 22 are at risk if bank...
erosion continues at recent rates. Two additional homes upstream of the property that collapsed into the river are also threatened by bank erosion.

5.4 Average Rate of Historical Migration

The reach-averaged bank erosion rate for the Bridge 581 CMZ delineation reach was calculated by dividing the total eroded floodplain area determined from the aerial photograph record by the length of bank edge adjacent to the floodplain, and then by the number of years of photo record. These values were determined based on data collected on the river between RM 13.7 and 16.75. This reach includes and extends beyond the one-mile long project reach and includes an area where the river character is generally similar to the project area. Values used in this calculation and resulting erosion buffers are shown in Table 5. The result is an average bank erosion rate of 3.1 ft/yr. The highest observed bank erosion rate occurred in the vicinity of RM 15.9 where the river migrated an average of 44 ft/yr between 2007 and 2012 through an outwash sand terrace. In contrast, at a more stable location (where the bank is most likely stabilized by riprap upstream), the stream has migrated 95 feet over 70 years (average rate of 1.4 ft/yr). This shows that the local channel configuration, bank lithology, and bank condition have a strong influence on bank erosion rates in the study area.

**Table 5: Values used to Calculate Average Bank Erosion Rate between RM 13.7 and 16.75.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1941 Active Channel Area</td>
<td>2,131,189 ft²</td>
</tr>
<tr>
<td>2011 HMZ Area</td>
<td>5,280,544 ft²</td>
</tr>
<tr>
<td>Eroded Area (1941-2011)</td>
<td>3,149,355 ft²</td>
</tr>
<tr>
<td>Erodible Length</td>
<td>14.650 ft</td>
</tr>
<tr>
<td>Average Erosion Rate</td>
<td>3.1 ft/yr</td>
</tr>
</tbody>
</table>

The CMZ in the project vicinity was delineated using guidelines found in Section 2 of the Forest Practices Board Manual (DNR, 2004). The DNR manual defines the CMZ as the inclusive sum of three subcomponents: the Historical Migration Zone; Avulsion Hazard Zone; and Erosion Hazard Area. Areas within the CMZ that are disconnected by maintained infrastructure (the Disconnected Migration Area) are removed from the CMZ. The following sections present the rationale used to define each individual subcomponent and maps showing the extent of the CMZ within the study area.

5.5 Historical Migration Zone

The Historical Migration Zone was delineated as the inclusive sum of all channels and active side channels visible in aerial photographs and maps from 1941 to 2011. In some cases, slight adjustments (<30 ft) to the marginal position were made where present-day LiDAR topography indicated the true historical channel margin was different than the position based on aerial photograph interpretation. Inconsistencies result from small georeferencing inaccuracies or
slight misinterpretation of the bank line that may occur where it is obscured by trees. Figure 9 shows the positions of historical channels and extent of the HMZ.

5.6 Avulsion Hazard Zone

Avulsions visible in the aerial photograph record and relic abandoned side channels shown on the LiDAR data indicate that avulsions are an important mechanism of channel migration in the study area. As described in the introduction, large bars along the Pilchuck River downstream of Granite Falls and the general downstream reduction in gravel transport rates estimated by Collins (1991) indicate system-wide aggradation may be occurring. Local aggradation of 2.3 feet has occurred at the bridge site over the past three decades. In addition, the effect of large wood and local sediment sources may also affect the study reach. The size of existing large wood in the study area indicates that local vertical fluctuations in channel elevation on the order of 6 feet are likely (Raup and Abbe, 2003). The avulsion hazard area was therefore delineated as the entire geomorphic floodplain surface, which generally lies at about the bankfull elevation and within 8 feet of the low-flow water surface (Figure 10). An important site of potential future avulsion is at RM 15.45, where a sharp river bend and a growing large wood jam have contributed to the growth of a large bar, and where a relic channel exits the left bank of the river at an elevation approximately 2 feet below the bankfull elevation. Channel scouring and accumulations of debris along this channel indicate that it has recently conveyed a significant amount of flow with moderate velocity. Current hydraulic conditions and observations of past flooding confirm this avulsion hazard. A HEC-RAS hydraulic model provided by Snohomish County shows concentrated flow along avulsion path 1 (Figure 8, inset) during a flow of 5,200 cfs and concentrated flow along avulsion path 2 during a flow of 7,700 cfs. These paths represent low areas where avulsions would be most likely over the short-term.

5.7 Erosion Hazard Area

The Erosion Hazard Area is shown in Figure 10. The reach average migration rate was determined to be 3.1 ft/yr (Table 5), but localized erosion rates over short time periods can be very high (up to 44 ft/yr, Table 4). The pattern of historical migration indicates that bank erosion rates through the outwash terrace may be comparable to, or higher than, bank erosion across the active geomorphic floodplain. Generally, alluvial terraces appear to be somewhat resistant to erosion. Till and bedrock, where present, is very resistant to bank erosion. Determination of erosion hazard buffers was based on observed erosion rates extrapolated over the 75 year design life for the bridge.

Because the entire geomorphic floodplain was determined to lie within the AHZ, which lies inside of the EHA, no erosion buffer distance was delineated within the floodplain. Where migration would be moving into alluvial terraces, the reach average migration rate is comparable to observed erosion rates at terrace edges and there appears to be a reasonable basis for determining the erosion hazard in this surface over a 75 year time period. Therefore, an erosion buffer of 230 feet was applied outside of the HMZ or AHZ in alluvial terraces.

The migration rate in the only observable intersection of the outwash terrace and channel has been 40 ft/yr. Extrapolating this rate over 75 years would yield an erosion buffer distance of
Currently, channel migration was not observed in the vicinity of RM 15.5. This area was mapped as a disconnected migration area. Typically active valley bottom widths in the vicinity of the project site are 1,000 to 1,500 feet. This width represents the whole extent of valley expansion since the existing drainage network was established post-glaciation. On this basis, it is not reasonable to extrapolate very high short-term erosion rates. Rather than an extrapolated erosion rate, an erosion hazard buffer of one-half meander amplitude (600 feet) was applied in areas where erosion of the outwash terrace was considered likely. One-half meander amplitude was chosen because a greater increase in sinuosity and accompanying decrease in the local slope would likely trigger avulsion across the low-lying floodplain.

Meander bends where the stream intersects thick till deposits were observed to be slowly eroding. This erosion is not detectable over the 70-year aerial photograph record and has likely been on the order of 0.5 ft/yr or less. Applying this average rate to the 75 year time period yields a buffer width of 38 feet. Landslide hazards associated with channel migration and slope- undercutting exist upslope from the edge of the EHA in these areas.

A 30 ft long exposure of glacial till was observed on the right bank downstream from the edge of the riprap at Bridge 581. Without significant subsurface exploration, it is not possible to determine the extent of this till body. None of seven well logs ranging in depth from 21 to 105 ft in the Washington Department of Ecology Database (DOE 2013) located in the project vicinity between Pilchuck River and Highway 92 describe material that would likely be till; which indicates that the unit is not likely laterally extensive. If it is laterally extensive beneath the outwash sand terrace, it should act as a barrier to channel migration. If till is not laterally extensive, extremely rapid rates of erosion like those observed in the vicinity of RM 15.9 are possible along the glacial outwash terrace to the west of the Pilchuck River.

5.8Disconnected Migration Area

The area to the northwest of State Highway 92 was mapped as a disconnected migration area. Currently, the highway is threatened by active erosion at RM 15.9 and has no bank protection scheme in place, but it meets the criteria defined in DNR (2004), such that future maintenance limiting channel migration can be expected.

No other disconnected migration areas, defined as areas behind permanently maintained levees or dikes or structures supporting public right-of-way and receiving regular maintenance, were mapped in the project vicinity. Existing riprap at RM 16 and levees across the floodplain have not been long-term barriers to channel migration. As shown in Figure 9, historical channel migration between 1990 and 2012 has eroded portions of the left bank levee in the vicinity of RM 15.5. This levee is composed of silt with riprap facing on the channel side. At RM 15.5, the river channel migrated directly into the upstream end of the levee, resulting in breaching and erosion of the head of the levee. In contrast, between RM 15.2 and 15.4, where the river runs parallel to the levee, the levee has successfully constrained channel migration. If bank protection were to be put in place that keyed the levee head into an area outside of the high migration hazard area, the levee would likely continue to resist erosion in the future.
5.9 Relative Channel Migration Zone Hazard Areas

Relative CMZ hazard areas were delineated based on best professional judgment of likely future channel migration scenarios given the current channel configuration, surface topography, geological mapping, vegetative cover, and large wood loading. Three CMZ hazard areas are mapped in Figure 11. Extreme hazard areas are areas where extrapolation of current processes into the near future (1 to 20 years) indicates channel migration is considered likely within that time period. High hazard areas are areas where conditions such as low lying topography and/or easily erodible banks indicate that no significant obstacle exists to prevent channel migration but where specific channel occupation over a decadal timescale cannot be predicted from the current channel configuration. Moderate hazard areas are areas where application of the DNR (2004) CMZ delineation protocol necessitates inclusion in the CMZ but where some significant obstacles to channel migration may exist.
6 Conclusions

The observations and analysis presented in this report show that the Pilchuck River is very dynamic in the study area. Long-term historical aerial photograph records, observation of geomorphic features revealed in LiDAR topography, and field observations reveal both high rates of bank erosion and a propensity for floodplain-spanning avulsions.

The Avulsion Hazard Zone was delineated to include the entire geomorphic floodplain. This was determined both from observation of historical avulsions and on the basis of potential aggradation heights associated with reach-wide aggradation and the influence of large wood jams. Different erosion hazards were determined to exist in three separate geomorphic environments, and so different erosion hazard buffers were applied along the stream. In alluvial terraces, where somewhat erosion resistant geological materials are present and where vegetative structure may stabilize banks, a buffer width equivalent to the reach-average historical migration rate was applied. In the glacial outwash terrace to the west of the river, where geological materials are observed to be very erodible and where unconstrained historical migration rates have been very high, an erosion hazard buffer of one-half a typical meander amplitude for the reach was applied. Finally, slow erosion was observed where the stream intersects thick deposits of glacial till. Here, an erosion rate of less than 0.5 feet per year is indicated by the historical photo record and a buffer width based on that rate was applied.

Relative CMZ hazard areas were delineated based on best professional judgment of likely future channel migration scenarios and potential obstacles to channel migration. Extreme, high, and moderate future channel migration hazard areas were mapped.

6.1 Implications for Bridge Design

6.1.1 Impact of Channel Migration on the Proposed Bridge

The area proposed for Bridge 581, including approach roadways, abutments, and any support piers, lies within the Pilchuck River CMZ. The location of the right bank abutment is mapped in the moderate hazard area because it lies on erosion resistant glacial till. Placement of local bank protection in the immediate vicinity of the abutment should provide adequate defense against future channel migration assuming till is continuous subsurface. The left bank abutment and approach roadway lie within the extreme hazard area. Here, avulsion of the channel upstream or reconfiguration of the channel geometry through meander migration and/or formation will likely cause the channel to interact with bridge support structures or their protection features. Currently, riprap along the left bank holds the channel in place, but downstream progression of bank erosion at RM 15.4 to 16 could cause the riprap to fail. Because of this, substantial bank protection may be warranted to protect the left bank abutment. Extremely dynamic and difficult to predict channel migration is occurring upstream, and so it is not reasonable to design protection against all likely channel migration scenarios. Rather, it seems prudent to tie protection of the left bridge abutment into existing upstream revetment to protect it against a scenario where a meander grows on the right bank upstream of the bridge. Because it is uncertain how the upstream channel will develop, it may be best to
wait to design any further protection of the right bank abutment until the specific erosion threat is clear.

There is also the possibility of an avulsion occurring upstream (especially at RM 15.5) that could cause formation of a new channel cutting across the left bank approach roadway. At this time, this is not an event that is possible to forecast, but the possibility should be considered in the overall plans to maintain access across Pilchuck River at the Bridge 581 site.

Aggradation is likely to continue at the bridge site in the near future. It is possible that another 2 to 4 feet of sediment may accumulate in the channel, which could reduce the hydraulic capacity of the bridge opening. The low chord of the bridge should be placed high enough to account for this aggradation and continue to pass flood flows and the significant load of floating large woody debris.

6.1.2 Impact of the Proposed Bridge on Channel Migration

Although it is not possible to make specific conclusions regarding the impact of the proposed bridge on channel migration without detailed plans for the bridge and associated bank protection, the following discussion assumes a proposed bridge design that completely spans the existing river channel and has substantial bank protection for the bridge abutments. Because this reach of the Pilchuck River is very dynamic, the limited bank protection that would be added in the immediate vicinity of a new bridge would not change the outside limits of the CMZ. Without significant river training, it appears that the river has the capacity to avulse or erode around these abutments within decades if large floods occur. Because the right bank at the bridge site is composed of till, which already locally limits channel migration, any protection on the right bank will have little effect on future channel migration. Depending on the extent of bank protection on the left bank, that protection may limit migration.

Removing the existing mid-channel bridge piers would likely change the hydraulics at the site of the eroding bank at RM 15.1. It is difficult to determine the direction of this change. Currently, bars form in the lee of the bridge piers. These may contribute towards deflection of the flow toward the right bank. Conversely, the existing bridge piers may dissipate some energy from the flow and provide some protection of that bank. Snohomish County SWM will be preparing further hydraulic modeling for the Bridge 581 project during 2013, and a summary report will be available when that work has been completed.

Overall, without (unlikely and possibly ill-advised) inclusion of a reach-wide bank protection program associated with the bridge, construction of a new Bridge 581 will not change the limits of the CMZ or its individual subcomponents; although, specific design elements could change the boundaries of the relative hazard areas in the immediate vicinity of the bridge.

6.1.3 Large Woody Debris Loading

Large woody debris loads are relatively high in the Pilchuck River during large flood events. County staff report that debris is frequently lodged on the upstream side of the current bridge pier, requiring monitoring and removal during large floods. Existing log jams and active channel migration into mature wooded areas within 0.5 miles upstream of the bridge suggest that input
and transport of wood large enough to affect bridge piers will continue, and possibly increase in the future. Design of the bridge structure to minimize trapping of debris by eliminating or minimizing piers and providing adequate clearance is suggested to reduce continued maintenance issues associated with debris.
7 Study Limitations

The CMZ study utilized existing information, including approximately 60 years’ record of historical aerial photographs and hydrology, existing surficial geologic mapping, and observations of current (2012) channel and bank conditions to predict future channel migration hazards. Limitations of the study include:

- Local bank erosion susceptibility and rates are controlled in part by the resistance of the bank to erosion. Glacial stratigraphy is extremely variable over short distances; lenses of resistant till or susceptible silt/sand/outwash that are not shown on current mapping can influence future bank erosion rates.
- Changes in watershed conditions may alter rates of sediment and large woody debris input upstream of the bridge, changing predictions of future aggradation rates or debris loading.
- Changes to climate conditions can change the magnitude and frequency of future peak flows. Research by the Climate Impacts Group at the University of Washington suggests that winter precipitation events may be more intense within the next century (Salathé 2006). More intense or frequent flood events could increase rates of channel migration.
Glossary

abutment  The structure beneath the point where the bridge slab joins the approach roadway; designed to carry the loading conditions present in bridge structures.

aggradation  An increase in land elevation due to the deposition of sediment.

AHZ  Avulsion Hazard Zone: the part of the CMZ where the channel may shift suddenly.

alluvial  Sediment deposited by flowing water or landforms resulting from that deposition.

avulsion  The process where the river suddenly shifts to a new channel location.

BAGS  Bedload Assessment For Gravel Bedded Streams: a US Forest Service visual basic application that can be used for sediment transport modeling.

bed load  The part of a river's sediment load that moves in traction or saltation along the bed. Usually composed of sand, gravel, and cobbles.

channel migration  The movement of a river channel back and forth across its valley.

CMZ  Channel Migration Zone. For the purposes of this report, the area where the channel may be reasonably predicted to migrate over the 75 year life of the proposed bridge. Delineated according to the criteria defined by DNR (2004).

DMA  Disconnected Migration Area: areas that are within the CMZ but protected by maintained dikes, levees, or public infrastructure.

EHA  Erosion Hazard Area: the area where future bank erosion is likely.

empirical sediment transport function  A mathematical equation derived from observation of sediment transport under various conditions that predicts sediment transport rates by factors such as water velocity (shear stress) and the size of the sediment.

floodplain  The area inundated by flood flows.

geomorphic  Having to do with the shape of the earth surface or processes that formed those shapes.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>geomorphic</td>
<td>The relatively flat area adjacent to the channel system that is low-lying (at approximately the elevation of the river's banks) and displays</td>
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<tr>
<td>floodplain</td>
<td>geomorphic features typical of channel erosion and depositional processes.</td>
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<td>HMZ</td>
<td>Historical Migration Zone: the area where the river channel has migrated since approximately 1900.</td>
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<td>LiDAR</td>
<td>Light Detection And Ranging: an optical remote sensing method that produces high resolution topographic surfaces.</td>
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<tr>
<td>morphology</td>
<td>Having to do with the shape of the earth surface or based on changes in the shape of the earth surface.</td>
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<tr>
<td>riprap</td>
<td>A loose assemblage of angular rock placed to protect against erosion.</td>
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<tr>
<td>RM</td>
<td>River Mile, measured as distance upstream of Pilchuck River's mouth.</td>
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<tr>
<td>SWM</td>
<td>Surface Water Management Division</td>
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</tbody>
</table>
References


Figure 4: Annual Instantaneous Peak Flows at Pilchuck River Gages.
Riprap shown in this position by Collins (1991)

Bar 1 ft higher than left bank floodplain

Large wood jam across low flow channel

Indications of flow 1.5 ft deep in side channel

Count 4

Count 3

Count 2

Large wood jam across low flow channel

Bar slightly higher than right bank floodplain

Bridge 531
Figure 6: Observed Surface Grain Size Distributions on Bar Heads.
Figure 7: Thalweg Elevation Comparison Showing Aggradation between the Late 1970s and Current Conditions.
Photo 1: Failed riprap on right bank at RM 16.

Photo 2: Stratigraphy of eroding bank at RM 15.1. Cohesive clayey silt overlays cohesive gravel.
Photo 3: View looking downstream toward eroding bank at RM 15.1.

Photo 4: The upstream edge of very active erosion at RM 15.1 directly corresponds to the limit of exposed till in the river bank (visible in this photo just to the left of blackberry vines).
Photo 5: Stratigraphy of eroding bank at RM 15.4. Cohesive gravel overlays cohesive clayey silt.

Photo 6: Overview of eroding bank at RM 15.4.
Photo 7: Stratigraphy of eroding bank at RM 15.5 with both dominant non-cohesive sandy silt and local gravel.

Photo 8: Overview of eroding bank at RM 15.5. A large wood jam lies along the bank, but has not protected it from erosion. Also note the high proportion of sand in the foreground bar.
Photo 9: View looking upstream toward moderately eroding bank at RM 15.7.

Photo 10: The eroding bank at RM 15.9 is composed of non-cohesive, easily erodible sandy gravel.
Photo 11: Overview of eroding bank at RM 15.9. Note remnants of a house destroyed by channel migration in the February 2012 flood event.

Photo 12: Bar surface and subsurface at location of pebble count 1.
Photo 13: Bar surface and subsurface at location of pebble count 2, note significant fining of armor layer relative to bar at location of pebble count 1.

Photo 14: Bar surface and subsurface at location of pebble count 3.
Photo 15: Bar surface and subsurface at location of pebble count 4.
Photo 16: Bar at RM 15.4. Note the high proportion of sand on the bar surface.