Channel Migration and Scour Evaluation

Everett Delta Natural Gas Pipeline/Smith Island Restoration

Snohomish River, Washington

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INTRODUCTION

Williams Northwest Pipeline Company has constructed the Everett Delta Lateral Project, a 16-inch lateral from its main regional pipelines. From east to west, the pipeline crosses Ebey Slough, Steamboat Slough, Union Slough, and the mainstem Snohomish River along the approximate northern boundaries of Sections 14, 15, and 16 of Township 29N Range 5E. A general location map for the pipeline alignment is shown in Figure 1. The pipeline was placed by either Horizontal Directional Drilling (HDD) or trenching. Practically, the HDD can be placed at any elevation necessary to avoid expected scour depths. In the trenched portion of the alignment that runs parallel to 12th Street and then north to parallel I-5, the pipeline was placed at an approximate Top of Pipe (TOP) depth of 5 ft. The remaining trenched portion was placed at an approximate Top of Pipe (TOP) depth of 7 ft.

Snohomish County (the County) is planning the Smith Island Estuarine Restoration Project. The County is interested in determining any effect that the pipeline would have on the restoration actions and any effect that the restoration actions may have on the pipeline. These restoration actions include dike breaching and construction of dikes. A number of opportunities and specific projects for restoration of habitat in the vicinity of the pipeline alignment have been identified or are under development [Haas (2001), COE (2002), and Personal communication with A. Haas (2003)]. However, this report will address only the Smith Island Estuarine Restoration Project specifically.

This report will address the following issues:

1. How the breaching of dikes would affect the depths of Ebey, Steamboat, and Union Sloughs over the long-term.

2. The scour depths of the Snohomish River and distributary channels.

3. The likelihood that the Union Slough would migrate west and expose the pipeline on Smith Island where it was installed by trenching if the levee is breached on the left bank of Union Slough.

4. The risk of pipeline exposure, where it was installed by trenching, if portions of Smith Island are subject to tidal influence over the long-term.

5. The influence that the trenched pipeline would have on water movements within tidally influenced restored sites on Smith Island.

In the following sections, analyses and discussions are presented to address the above noted issues.
EXISTING CHANNEL CONDITIONS

The Snohomish River estuary has been highly modified by human actions (Hass and Collins, 2001). As shown on Figure 2, an extensive network of levees separates the major existing channels from the floodplain. The construction of the levees, coupled with major land use changes, has resulted in significant habitat loss since the 1850’s. These changes included the elimination of large areas of tidal marsh and blind tidal channels in the lower estuary.

The pipeline alignment crosses three major distributary channels and the mainstem Snohomish River channel. As shown on Figure 2, the channel crossings were accomplished by two HDD segments. The first crosses beneath Ebey Slough, Steamboat Slough, and Union Slough. The entrance and exit points of the HDD are located landward along the alignment from the existing levees. The second HDD segment crosses under the Snohomish River channel. The entrance and exit points for the Snohomish River HDD segment are located in or near existing developed areas along the river.

A hydraulic study to define the 100-year floodplain and floodway in the lower Snohomish River was recently completed for the Federal Emergency Management Agency (WEST, 2003). Results of that study are shown in Figure 3. The floodway designations were developed in consultation with representatives of both the City of Everett and Snohomish County. The existing channels are designated as floodways. Overbank areas along the pipeline alignment behind existing levees are designated as either density fringe or floodway fringe. Specifically, the areas surrounding the pipeline alignment on Smith Island are designated as density fringe. Areas designated as density fringe may be subject to limited developed subject to specific floodplain management criteria whereas areas designated as floodway typically cannot be developed.

The land areas surrounding the pipeline alignment that are within the floodway fringe can reasonably be expected to be developed in the future. Furthermore, if these areas were developed, it would be expected that they would be actively protected from channel migration. However, the floodway fringe could also be left undeveloped if purchased for use as a restoration or mitigation site. Additionally, the area surrounding much of the pipeline alignment east of I-5 is zoned Agri-10 and is thus unlikely to be extensively developed in the future. In this case, protection of these areas against channel migration would be unlikely.

Profile plots of the thalweg elevations of the involved channels are shown in Figure 4, Figure 5, Figure 6, and Figure 7. The profile elevation data shown on the figures are taken from the hydraulic model developed for the lower Snohomish River and are mostly based on channel cross section surveys performed by Snohomish County in 1988 (Personal communication with Vaughn Collins, 2003). Additionally, the specific cross sections that were used to generate the profile plots do not necessarily occur at the same location as the pipeline alignment (see Figure 8). The approximate location of the pipeline alignment along each channel is shown on each figure.
The approximate minimum channel thalweg elevation data for the pipeline alignment are summarized in Table 1. As seen in the table and in Figure 4 through Figure 7, the minimum thalweg elevation is dynamic. The variation in channel elevation reflects the variability of both hydrology and sediment transport. To evaluate the maximum scour elevation potential, scour depth estimates should be subtracted from the minimum observed channel thalweg elevation.

### Table 1  Summary of minimum channel thalweg elevations in the vicinity of the pipeline alignment.

<table>
<thead>
<tr>
<th>Watercourse</th>
<th>Approximate Minimum Thalweg Elevation (ft, NGVD 1929)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snohomish County Survey (conducted in 1988)</td>
<td></td>
</tr>
<tr>
<td>Ebey Slough</td>
<td>-34</td>
</tr>
<tr>
<td>Steamboat Slough</td>
<td>-23</td>
</tr>
<tr>
<td>Union Slough</td>
<td>-13</td>
</tr>
<tr>
<td>Snohomish River</td>
<td>-37</td>
</tr>
</tbody>
</table>

**RESTORATION PLANS**

The pipeline crosses the proposed Smith Island Estuarine Restoration Project area west of Union Slough. In general, the proposed and specific restoration measures involve breaching of existing dikes and construction of new dikes to protect adjacent infrastructure. The project is intended to restore natural habitat-forming processes for proper ecosystem function over the long-term. This includes side channel formation, channel migration, and wood recruitment.

Plans for the planned restoration project were obtained from the County. The proposed project consists of construction of new dikes and cross dikes, filling the old borrow ditches adjacent to the existing dike, and breaching the existing dike in three locations. A schematic drawing for the project is shown in Figure 9. As seen on the schematic, the effects of remaining dikes and proposed cross dikes partially protect the pipeline from channel migration. It is noted that none of the proposed breaches are in the vicinity of the pipeline crossing.

**CHANNEL MIGRATION STUDY**

Available historic survey data and aerial photography for the pipeline crossing location were collected and reviewed. The data consisted of Digital Orthophoto Quadrangles (DOQ’s) (1990), printed orthophotos (1978, 1965), Digital Raster Graphics (DRG, digital versions of scanned USGS Quadrangles) (1956), and a digitized 1884 National Geodetic Survey map (Survey conducted in 1869). Orthophotos are aerial images that have been ortho-rectified so that they have the geometric properties of a map and therefore can be used to measure distances between objects. The printed orthophotos were scanned and merged using Adobe Photoshop 5.0. The final merged images from each of the five years were aligned together to the best possible extent in Photoshop using a combination of resizing and rotation. Unfortunately, the scanning process inevitably causes some
distortion to be introduced into the final digital image. Because of the distortion, the images cannot be aligned with 100% accuracy. A comparison of available data was conducted to define the locations and rates of historic channel migration. The results of the comparison are shown in Figure 10. As seen from the comparison of existing planform data, little change in the locations of the channels has occurred in the vicinity of the pipeline crossing.

Channel bank locations were analyzed using ArcView Geographic Information System (GIS), Version 3.2a, developed by the Environmental Systems Research Institute. Final aligned images from Photoshop were imported into ArcView and channel bank locations for the respective years were traced digitally. Comparisons could then be made between bank locations between each of the years by measuring distances between bank locations. A summary of maximum historic channel movements is presented in Table 2.

As seen from Figure 10 and Table 2, the observed migration distances are relatively minor over the 120 years of record. In general, no significant migration occurred beyond any existing levee. The project area has generally low hydraulic energy gradients that are strongly controlled by tidal base level. The construction and maintenance of the levee system tightly confined the river channels, practically limiting significant movement. It is also recognized that dredging and large woody debris removal have been on-going activities throughout the period of record (Haas and Collins, 2001). It is noted that the majority of dredging and removal of large woody debris has occurred on the mainstem.

### Table 2 Summary of historic channel migration.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Snohomish River</th>
<th>Union Slough</th>
<th>Steamboat Slough</th>
<th>Ebey Slough</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum Observed Difference (ft)</td>
<td>Rate of Change (ft/yr)</td>
<td>Maximum Observed Difference (ft)</td>
<td>Rate of Change (ft/yr)</td>
</tr>
<tr>
<td>1869-1956</td>
<td>660</td>
<td>7.6</td>
<td>422</td>
<td>4.9</td>
</tr>
<tr>
<td>1956-1965</td>
<td>135</td>
<td>15.0</td>
<td>363</td>
<td>40.0</td>
</tr>
<tr>
<td>1965-1978</td>
<td>no coverage</td>
<td>no coverage</td>
<td>132</td>
<td>10.2</td>
</tr>
<tr>
<td>1978-1990</td>
<td>no coverage</td>
<td>no coverage</td>
<td>100</td>
<td>8.3</td>
</tr>
</tbody>
</table>

It is noted that several factors likely affect the observed migration distances and rates of change stated in this report. Due to the scale and resolution of the scanned aerial photography used, it is difficult to estimate true bank locations and therefore bank locations were often estimated using a combination of the visible water edge and
vegetation. Also, differences in water surface elevations due to seasonal as well as daily
fluctuations will change the locations of the traced bank locations. Additionally, the
absolute accuracy of the 1869 survey map is unknown. It is further recognized that
differences in measured bank locations are also due to significant human influence. Fill
has been placed in many of the developed riparian areas along the lower Snohomish
River. Finally, it is noted that some variability in measured distances will arise due to the
inconsistencies associated with trying to align multiple scanned images from different
sources.

HYDRAULIC ANALYSIS
An existing hydraulic model of the Snohomish River was used to characterize the
existing hydraulic conditions of the pipeline alignment. The channel and overbank
hydraulic properties needed to perform scour calculations were obtained from a UNET
unsteady flow hydraulic model (USCOE 1997) developed for the Snohomish River Flood
Insurance Study (WEST 2003). The UNET model represents the Snohomish River,
Union Slough, Steamboat Slough, Ebey Slough, and the connector channel that runs
between Ebey Slough and Steamboat Slough. The model extends from Possession Sound
to well upstream of the area of interest.

To represent the Smith Island Estuarine Restoration Project, an additional hydraulic
model was developed by modifying the geometry of the existing conditions hydraulic
model to represent the removal of portions of the levee along Union Slough. Separate
models were considered due to the uncertain timing of future restoration efforts. The
extent of the assumed levee removal in the future condition hydraulic models is shown in
Figure 11. All the hydraulic models for existing and potential future conditions were run
with a downstream boundary condition of mean lower low water (-6 ft NGVD).

A summary of channel and overbank velocities for the 100- and 500-year floods is shown
in Table 3 and Table 4, respectively. As noted in the tables, “Storage Area” is a
floodplain area located landward of a levee that has ineffective flow conveyance potential
but can store floodwaters when the levee is overtopped. In general, the removal of a
portion of levee moderates the velocity of flow in the adjacent channel by allowing flow
within former storage areas. A slight increase in velocity in the Snohomish River
channel also occurs as a result of the assumed levee removals.

<table>
<thead>
<tr>
<th>Water Course</th>
<th>Analysis Condition</th>
<th>Mean Channel Velocity (ft/s)</th>
<th>Mean Overbank Velocity (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebey Slough</td>
<td>Existing</td>
<td>4.00</td>
<td>Storage Area</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>3.77</td>
<td>Storage Area</td>
</tr>
<tr>
<td>Steamboat/Union</td>
<td>Existing</td>
<td>6.12</td>
<td>Storage Area</td>
</tr>
<tr>
<td>Sloughs</td>
<td>No Smith Island Levee</td>
<td>3.73</td>
<td>2.24</td>
</tr>
<tr>
<td>Snohomish River</td>
<td>Existing</td>
<td>7.24</td>
<td>Storage Area</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>7.26</td>
<td>Storage Area</td>
</tr>
</tbody>
</table>
Table 4 Summary of hydraulic data for the 500-year flood.

<table>
<thead>
<tr>
<th>Water Course</th>
<th>Analysis Condition</th>
<th>Mean Channel Velocity (ft/s)</th>
<th>Mean Overbank Velocity (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebey Slough</td>
<td>Existing</td>
<td>4.59</td>
<td>Storage Area</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>4.53</td>
<td>Storage Area</td>
</tr>
<tr>
<td>Steamboat/Union Sloughs</td>
<td>Existing</td>
<td>6.38</td>
<td>Storage Area</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>4.15</td>
<td>1.50</td>
</tr>
<tr>
<td>Snohomish River</td>
<td>Existing</td>
<td>7.85</td>
<td>Storage Area</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>7.86</td>
<td>Storage Area</td>
</tr>
</tbody>
</table>

SCOUR ASSESSMENT
Scour along the channels in the Snohomish River estuary can be caused by floods, local scour around debris, channel migration, tides, or a combination of these factors. Scour potential due to floods can be reasonably estimated based on empirical relations. Local scour due to debris and channel migration are generally unpredictable for a specific location. Similarly, the formation of blind tidal channels may be due to a combination of flood impacts and tidal effects. Consequently, estimates of scour cannot be specific. Use of empirically-based equations that define envelope curves around a range of scour observations for similar conditions, coupled with appropriate margins to account for uncertainty is considered the most reasonable approach to estimating potential scour depths.

The scour potential of the various watercourses due to floods was evaluated based on available topographic, hydraulic, and sediment size data. Empirical equations were applied to estimate the maximum potential scour depth for both the 100- and 500-year floods. It is noted that the Washington Department of Transportation specifies that stream crossings be designed to the 100-year flood and that the 500-year flood be used as a check for potential high flow damage (WSDOT 1997). The faster velocities and greater depths produced by the 100- and 500-year flows yielded conservatively large scour depths compared to lower flows. The lower flows, while useful for sediment transport analyses, may underestimate the scour depths that the pipeline may be subject to during the 100- and 500-year floods. Scour depths were calculated for the Snohomish River, and Ebey Slough. Because Union Slough and Steamboat Slough are hydraulically connected at high flows and because the two sloughs are captured by a single cross section in the UNET model, the scour calculations for Union Slough and Steamboat Slough were performed on the cross section that captures both slough channels. In other words, the scour depths are the same for Union Slough and Steamboat Slough. This will yield conservative scour elevations for Union Slough. For all water courses, the scour depths were computed based on data from cross sections located near the pipeline alignment.

Three scour equations found in “Computing Degradation and Local Scour, Technical Guideline for Bureau of Reclamation” (USBR 1984) were used. These are: the Lacey equation, the mean velocity method, and the competent or limiting velocity method.
Lacey’s equation:

\[ d_s = Z \left[0.47 \left(\frac{Q}{f}\right)^{1/3}\right] \]

where \( d_s \) is the depth of scour below the streambed, \( Z \) is a multiplying factor based on the bend condition of the channel, \( Q \) is the design discharge, and \( f \) is Lacey’s silt factor, which is based on the mean grain size of the bed material. For the calculations, \( Q \) was taken as the peak flow in each watercourse that resulted from the routing of the 100- and 500-year hydrographs through the UNET hydraulic model. Based on a geologic profile along the pipeline alignment shown in Figure 12 (Golder 2001), the bed material was assumed to be sandy silt. The bend condition of the Snohomish River, Union Slough, and Steamboat Slough was assumed to be “moderate” bends. Ebey Slough was assumed to have “severe” bends.

Mean velocity method:

\[ d_s = Z \left(d_m\right) \]

where \( d_s \) is the depth of scour below the streambed, \( Z \) is a multiplying factor based on the bend condition of the channel, and \( d_m \) is the mean depth from the hydraulic modeling. The bend conditions used were the same as those used in the computations for Lacey’s equation.

Competent or limiting velocity method:

\[ d_s = d_m \left[\left(\frac{V_m}{V_c}\right)-1\right] \]

where \( d_s \) is the depth of scour below the streambed, \( d_m \) is the mean depth from the hydraulic modeling, \( V_m \) is the mean velocity from the hydraulic modeling, and \( V_c \) is the competent mean velocity based on grain size of the bed material, the erodibility of the bed material, and depth of flow. The bed material was again assumed to be sandy silt, and the erodibility of the bed material was assumed to be “average.”

The scour depths were computed using these three equations for each of the watercourses, using the UNET model cross sections shown in plan view on Figure 8. The results of the scour calculations for the 100-year flood are shown in Table 5 and are shown in Table 6 for the 500-year flood. The calculated estimates of scour depths that are reported are the result of the equation that yielded the greatest scour depth. In general, estimated scour depths are 10 to 20 feet.
Table 5 Summary of estimated scour depth for the 100-year flood.

<table>
<thead>
<tr>
<th>Water Course</th>
<th>Condition</th>
<th>Channel Depth of Scour (ft)</th>
<th>Overbank Depth of Scour (ft)</th>
<th>Equation yielding reported scour depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebey Slough</td>
<td>Existing</td>
<td>12.7</td>
<td>Storage Area</td>
<td>Lacey</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>12.4</td>
<td>Storage Area</td>
<td>Lacey</td>
</tr>
<tr>
<td>Steamboat/Union Sloughs</td>
<td>Existing</td>
<td>13.1</td>
<td>Storage Area</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>13.0</td>
<td>7.6</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td>Snohomish River</td>
<td>Existing</td>
<td>13.4</td>
<td>Storage Area</td>
<td>Lacey</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>13.4</td>
<td>Storage Area</td>
<td>Comp. Vel.</td>
</tr>
</tbody>
</table>

Table 6 Summary of estimated scour depth for the 500-year flood.

<table>
<thead>
<tr>
<th>Water Course</th>
<th>Condition</th>
<th>Channel Depth of Scour (ft)</th>
<th>Overbank Depth of Scour (ft)</th>
<th>Equation yielding reported scour depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebey Slough</td>
<td>Existing</td>
<td>15.8</td>
<td>Storage Area</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>15.8</td>
<td>Storage Area</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td>Steamboat/Union Sloughs</td>
<td>Existing</td>
<td>15.5</td>
<td>Storage Area</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>15.5</td>
<td>6.9</td>
<td>Mean Vel.</td>
</tr>
<tr>
<td>Snohomish River</td>
<td>Existing</td>
<td>18.1</td>
<td>Storage Area</td>
<td>Comp. Vel.</td>
</tr>
<tr>
<td></td>
<td>No Smith Island Levee</td>
<td>18.2</td>
<td>Storage Area</td>
<td>Comp. Vel.</td>
</tr>
</tbody>
</table>

**RISK ANALYSIS**

In the preceding section the scour potential along the various portions of the pipeline alignment was examined. The results of that analysis defined the minimum burial depth required to avoid potential scour impacts for the existing channel locations. However, it is recognized that the long-term risk of scour affecting the pipeline alignment will be dependent on the potential for the involved channels to migrate during its service life, which is assumed to be 50-years. Scour related impacts to the pipeline could occur if any of the channels were to migrate into the overbank areas where burial depths are significantly shallower. In view of that, an understanding of the migration potential of the involved channels can be used to characterize the potential risk of scour impacts.

In general, channel migration is a natural characteristic of all geologically unconfined watercourses formed in transportable sediments. Typically, the type, magnitude, and rate of channel migration are reflective of a dynamic equilibrium that is characteristic of the involved geomorphic setting and channel type. The magnitude and rate of channel migration reflects changes in hydrology, hydraulics, and sediment transport. Such
changes may occur due to both natural and man-made influences. Because the pipeline is installed entirely underground at a depth designed to not be exposed by scour, the pipeline will not affect the hydrology, hydraulics, or sediment transport characteristics of the involved watercourses.

Extrapolation of historic channel migration rates is commonly used to predict potential future channel locations. As previously presented, the historic channel migration information indicates that the channels in the project area have not migrated significantly over a period of at least 120 years. This apparent stability in the channel locations is attributed to several factors. First, the broad, flat Snohomish River valley has a size and gradient that has been inherited from prior glacial activity. This low gradient river is incapable of transporting all of the sediments delivered to it by tributaries. Consequently, the river valley is a site of long-term storage of sediments supplied from upstream and overall slow aggradation occurs in the estuary. Second, Puget Sound exerts a strong base-level control on the hydraulic conditions in the project area, moderating flow velocities and the potential for significant bank erosion and channel migration. Third, the channels have been strongly influenced by the construction and maintenance of an extensive levee system, active management of large woody debris in the channels, and dredging. Last, a number of transportation corridors, bridges, and other developments have been constructed that effectively control the location of the channels.

In general, the pipeline alignment is located in a depositional environment where long-term lateral channel migration would typically be expected. Under natural conditions, overbank sediment deposition would occur during floods and bed load deposition within channels would cause them to shift laterally. However, the existing channels are leveed which artificially increases stage and velocity, confines floods of low return periods, limits the ability for overbank sediment deposition, and generally mutes the potential for dynamic change. It is noted from the channel elevation data presented in Table 1 that significant changes in the minimum elevation of the involved channels do occur. In fact, dredging of the mainstem Snohomish River is conducted for maintenance of a shallow draft navigation channel. As part of that navigation project, a sedimentation basin is maintained upstream of the Interstate 5 bridge (Personal communication with Hiram Arden, U.S. Army Corps of Engineers, 2003).

A primary reason for the slow rate of channel migration in the project area is believed to be the overfit nature of the river relative to its glacially formed valley. The size and gradient of the Snohomish River valley was not developed by modern hydrologic conditions. The broad, flat, low gradient valley was produced by voluminous glacial meltwater issuing from beneath the ice sheet or subaerial rivers formed during ice sheet retreat (Booth et al, 2003). As a result of its overfit condition, the modern watercourses have limited sediment transport ability. The existing channels in the project area cannot deliver coarse sediments such as cobbles and gravels to the estuary.

Along the upstream tributary Snoqualmie River, which has the same overfit morphology as the Snohomish River valley, it has been noted that little change has occurred in the location of the river or oxbows over a 130-year period of record (Collins et al, 2003).
Most oxbows along the Snoqualmie River that were in existence in 1870 are still present, indicating that a geologically similar watercourse migrates slowly and avulsions of the channel occur infrequently. This observation of upstream channel migration characteristics provides some specific evidence that the natural potential for channel migration in the project area may be equally slow.

The flat gradient and broad nature of the underfit river and tidal control from Puget Sound creates a low energy environment where only fine sediments (sands, silts, and clay) can typically be transported. Hydraulic analyses demonstrate that shear stresses that could act on the banks of the channels are relatively low even for extreme flood events. Calculated average shear stresses ranged from 0.6 lb/sq ft in the main channel of the Snohomish River for the 500-year flood to 0.2 lb/sq ft in Ebey Slough for the 100-year flood. Although the identified shear stresses are large enough to erode the sandy silt-sized sediments (FHWA 1986) found in the project area, most types of vegetation can resist shear stresses of this magnitude (FHWA 1986). Accordingly, most riparian and floodplain vegetation would be expected to resist erosion. Smaller more frequently occurring flows are more strongly influenced by tidal effects, resulting in lower shear stresses on the channel and bank erosion potential.

Another important influence on channel migration potential is the effect of large woody debris. Large wood has been shown to be a dominant influence on the geomorphology of large western Washington Rivers (Collins et al., 2002). Debris jams can create channel avulsions resulting in multiple channels, floodplain sloughs, and distributary channels. Large jams are thought to have had a dominant influence in the past in lower-gradient rivers on the routing of water, sediment, and wood and on floodplain formation and maintenance. Jams increase flooding, deposition of sediments in overbank areas, and recharge of floodplain wetlands. Channel plugging jams may have also been important to the evolution of estuarine sloughs and marshes.

The potential significance of woody debris influences on channel migration conditions during the 50-year service life of the pipeline may be limited due to the current conditions of riparian forests and the affects of the historic management of wood debris. Major jams on the Snohomish River that can provide a significant regulating effect on the export of wood debris no longer exist and riparian forests have been significantly reduced or altered (Collins et al 2003). These conditions have created a general deficit of recruitable large woody debris. It is also recognized that the volume and size of wood available in the existing riparian forest is significantly smaller today than in the mid-19th century. Additionally, it has been hypothesized that future export of the depleted wood debris supplies to the Snohomish River may actually increase as the remaining relict large debris in the system decays (Collins et al, 2002). If true, this would further dilute the influence of the remaining depleted woody debris supply. Even with active conservation and restoration efforts in the basin, a significant deficit of large woody debris can be expected to extend well into the future. Consequently, significant impacts to overall channel migration characteristics and the scour potential for the pipeline during its 50-year service life due to large wood debris accumulations similar to those observed by early European settlers of the area are not expected. However, because of the random
nature of natural woody debris accumulation, it is recognized that there will always be at least a low risk that woody debris could locally influence channel migration conditions in the vicinity of the pipeline alignment.

In the following sections discussions of risk due to channel migration for the specific segments of the pipeline alignment are presented:

**Trenched pipeline installation located east of Ebey Slough**
This portion of the pipeline alignment is located in the floodplain parallel to the existing Ebey Slough channel. Ground elevations along this segment of the alignment generally range from about 3 to 10 ft NGVD. Near Sunnyside Boulevard, along the floodplain boundary, ground elevations rise rapidly from 10 to 30 ft NGVD. The alignment along this segment crosses the apparent remnant of a blind tidal channel. In general, the channels are less than 5 ft in depth. Under existing conditions, there is no significant risk of channel migration affecting this segment of the pipeline since it is protected by an existing levee. No significant channel migration has occurred in this area over the 120-year historic record.

Any future planned levee breach along Ebey Slough as part of future restoration efforts was not analyzed as part of this study. Only the planned levee breaches that are part of the Smith Island Estuarine Restoration Project were addressed in this study.

**HDD pipeline installation under the distributary channels**
The portion of the pipeline installed by HDD under the distributary channels of the Snohomish River was placed at a depth that is 45 feet below the lowest observed channel thalweg elevation (see Table 1) in order to avoid potential scour. As shown in Table 6, the calculated maximum scour depth for the 500-year flood along distributary channels was determined to be 15.5 feet. By placing the pipeline at a depth that is 45 feet below the lowest observed channel thalweg elevation, the HDD was placed nearly 30 feet below the maximum estimated scour depth for the 500-year flood and there will be no significant risk of impacts due to channel migration or associated scour.

Of greater significance are the entry and exit points to which the sloped portions of the HDD are tied. Both the entry and exit points are located landward of existing levees. Under existing conditions, it is judged that no significant risk of channel migration affecting the HDD entry and exit points exists since they are protected by levees. If the levee along Union Slough is breached as part of the Smith Island Estuarine Restoration Project, the risk of channel migration would increase, as there would be fewer man-made impediments to channel migration. Also, the blind tidal channels would again be subject to tidal action. However, it should be noted that none of the proposed levee breaches are in the vicinity of the pipeline alignment. Additionally, it should be recognized that the same geomorphic setting would still control the Union Slough channel. The extremely low gradient of the valley and tidal control on the hydraulics of flow would still strongly control the potential for dynamic channel movement. The breaching of levees would increase the frequency of overbank flooding and overbank sediment deposition. As
observed on the morphologically similar upstream tributary Snoqualmie River (Booth, 1994), increased overbank sediment deposition may ironically result in natural levee development along the channel. Natural levee formation has been documented in the Snohomish Estuary on Otter and Spencer Islands near the project site (Communication from Craig Garric, Snohomish County, 2007). Restoration efforts would also be expected to promote the rapid reestablishment of riparian and floodplain forest. Woody vegetation along the banks and floodplain would increase hydraulic roughness on the floodplain, promote sediment deposition from overbank floods, and generally increase resistance to bank erosion and channel migration.

Additionally, the location of the entry/exit point of the HDD pipeline west of Union Slough will be behind an approximately 3,500 foot section of levee that is not proposed to be breached. Considering the geomorphic setting, long record of insignificant channel migration or dynamic channel movement in the project area, current deficit of large woody debris within the river system, and potential restoration influences, the risk of impacts due channel migration and scour along this segment of the pipeline alignment is judged to be low during its 50-year service life.

**Trenched pipeline installation between Union Slough and I-5**

Under existing conditions, there is no significant risk of channel migration affecting this segment of the pipeline since it is protected by an existing levee. However, the Smith Island Estuarine Restoration would breach the levees upstream and downstream of the pipeline alignment. If the levee along the west bank of Union Slough is breached, the risk of channel migration to the pipeline segment between Union Slough and I-5 will increase. The pipeline runs southwest from the levee along the west bank of Union Slough for approximately 1,900 feet before crossing under a proposed cross dike. The pipeline alignment in this area has relatively low ground elevations and crosses the upstream end of at least one remnant blind tidal channel.

The proposed levee breaches are located approximately 1,000 feet north (downstream) of the trenched pipeline and 2,500 feet south (upstream) of the trenched pipeline. Under this levee breaching plan, the Union Slough distributary channel would have to migrate to the west or another distributary channel would need to form to the west of Union Slough for the trenched pipeline to be affected. Westward migration of Union Slough in the vicinity of the trenched pipeline would be severely limited by the 3,500-foot section of levee that will remain in place under the restoration plan.

In summary, the risk of channel migration affecting the pipeline alignment between Union Slough and I-5 if existing levees are breached is considered to be low. The risk is minimized by the proposed locations of levee breaching and the existing infrastructure that control the potential location and magnitude of flow along the left overbank of Union Slough. Additionally, as previously described, the general risk of dynamic channel migration is low due to the general geomorphic setting of the project. It is noted that some risk will exist once the levees are breached and maintenance of the levees left in
place ceases. However, during the design life of the pipeline, the risk due to channel migration is considered to be low.

**Pipeline installation west of I-5**

The portion of the pipeline located to the west of I-5 is considered to have an insignificant risk of being influenced by the migration of the Snohomish River. The trenched portion of the pipeline in this area is located in a relatively urbanized setting in close proximity to important existing infrastructure. Significant dynamic channel migration in this setting would likely not be acceptable due to the potential impacts to the infrastructure. Additionally, the HDD portion of this pipeline segment can be constructed to any elevation necessary to avoid potential scour effects. The HDD portion under the main channel of the Snohomish River was placed at a depth that is 32 feet below the lowest observed channel thalweg elevation (see Table 1) in order to avoid potential scour. As shown in Table 6, the calculated maximum scour depth for the 500-year flood along the Snohomish River was determined to be 18.2 feet. By placing the pipeline at a depth that is 32 feet below the lowest observed channel thalweg elevation, the HDD was placed nearly 14 feet below the maximum estimated scour depth for the 500-year flood and there will be no significant risk of impacts due to channel migration or associated scour.

**CONCLUSIONS**

Based on the analysis and information presented in the prior sections, the following conclusions to the issues mentioned in the introduction to this report have been made:

1. Breaching dikes will reduce the flow within the main channel of Ebey, Steamboat, and Union Sloughs during commonly occurring floods. As shown in Table 3, this effect is also evident in the hydraulic results for the 100-year flood. Based on Lane’s relationship (Lane, 1955):

   \[
   Q_S \sim Qs D_{50}
   \]

   Where
   
   - \( Q \) = water discharge,
   - \( S \) = channel slope,
   - \( Qs \) = sediment discharge, and
   - \( D_{50} \) = median sediment size.

   The reduction in flow will result in a corresponding reduction in sediment transport. As commonly occurring flows would be influenced, it would be expected that on average less sediment would be transported downstream and more sediment would be deposited within the main channel of these watercourses. Over the long-term this will result in bedform formation, reduced flow depth and channel capacity, side channel formation, and increased channel migration. It is noted that in the near-term, during a transitional period that may last for several years, this may not be the case.
2. In general, the scour depths of the Snohomish River and distributary channels range from 10 to 20 feet. By placing the pipeline at a depths that are a minimum of 32 feet below the lowest observed channel thalweg elevation for the mainstem Snohomish River and 45 feet below the lowest observed channel thalweg elevation for the distributary channels (Table 1), the HDD was placed nearly 14 feet and 30 feet, respectively, below the maximum estimated scour depth for the 500-year flood and there will be no significant risk of impacts due to channel migration or associated scour.

3. Along the left bank of Union Slough, the pipeline was placed at an approximate Top of Pipe (TOP) depth of 7 ft. The existing levee system has controlled the position of Union Slough. No historic migration of the channel along the trenched installation on Smith Island has occurred. If the levee is breached, but not removed, and maintained, it would be expected that the levee would continue to exert significant lateral migration control on the main Union Slough channel location. The Smith Island Estuarine Restoration Project includes this specific action. In this case, a scour depth based on overbank hydraulic conditions would be considered more appropriate than a scour depth based on channel hydraulics. As shown in Table 5 and Table 6, the estimated overbank scour depths along Union Slough range from 6 to 8 ft.

4. If the levees are breached but maintained, the levees may prevent significant channel migration. Scour in areas protected by breached levees would be subject to both floods and tides. Scour due to floods in overbank areas for the 100-and 500-year floods were defined in Table 5 and Table 6 and are expected to range from 6 to 8 feet in depth. Scour action due to tides may form blind tidal channels over time. The depths of remnant blind tidal channels defined from topographic mapping of the area are observed to be less than 5 ft in depth. The pipeline installation has a TOP depth of 7 ft below the minimum elevation of the remnant channels.

5. There are no above ground features of the trenched pipeline and there are no permanent maintenance roads. Trench backfill in most cases consists of excavated native soils. Available geotechnical information shows the area to be consistently estuarine deposits comprised of silt, sandy silt, and clayey silt (Golder, 2001) to depths of 20 to 30 ft below ground surface as shown on Figure 12. The trench backfill should be compacted to match the native overlying soils. The pipeline is not expected to significantly influence water movements in the tidally influenced sites.
Figure 1 Location map.
Figure 2 Levee locations in project area.
Figure 3 FEMA 100-year floodplain and floodway boundaries.
Figure 4 Thalweg Profile for Ebey Slough

Note: Thalweg data shown is based on Snohomish County 1988 survey.
Steamboat Slough Thalweg Profile

Maximum Scour Depth = 15.5 ft

Note: Thalweg data shown is based on Snohomish County 1988 survey.

Figure 5 Thalweg profile for Steamboat Slough
Figure 6 Thalweg profile for Union Slough.
Figure 7 Thalweg profile for the Snohomish River

Note: Thalweg data shown is based on Snohomish County 1988 survey.

Maximum Scour Depth = 18.2 ft
Figure 8 Hydraulic model cross sections used to perform scour calculations.
Figure 9 Smith Island Estuarine Restoration Project
Figure 10  Historic channel locations.
Figure 11 Extents of levee removal in hydraulic modeling.
Figure 12 Soil types in vicinity of tidally influenced restored sites.
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