Santiam-Albany Canal Rehabilitation

Bank Stability Analysis

Final

Submitted to:
City of Albany

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Project Name

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Executive Summary

A systematic methodology to investigate key issues regarding bank stability along the Santiam-Albany Canal is presented in this document. Included in the contents are; 1) The geologic and pedologic setting for the project, 2) A discussion of the mechanisms and processes leading to canal bank failure, 3) The spatial distribution of bank failures and failure mechanisms in the reach context (OTAK 2008), 4) Implications of future canal dredging and operations on bank stability, and 5) Recommendations for stabilizing current canal bank failures and mitigation of the driving mechanisms for failure that will lead to long-term canal stability and self maintenance.

The canal is located in the Willamette lowland, a broad alluvial basin bordered on the west by Tertiary marine sedimentary and volcanic rocks of the Coast range, and on the east by the Tertiary and Quarternary volcanic rocks of the Cascade Range. Geologic processes occurring during the Quarternary Period have formed the underlying stratigraphy of the canal. The primary processes forming this stratigraphy are silt deposition from the glacial outburst floods emanating from the Columbia River Gorge and glacio fluvial sediment erosion and deposition of sands, gravels and cobbles from the South Santiam River. The end result of these processes is a discrete break in the erosional resistance of the canal bed in the vicinity of Tallman Rd. Upstream of this break the underlying geologic material is comprised of gravels and sands which are more erosion resilient than the underlying parent material downstream of this break, which is composed of silts and clays that are more susceptible to erosion.

Downstream of this geologic break, historic channel incision rates have been much greater with maximum incision depths in the range of seven to eight feet, compared to historic incision depths of one to two feet upstream of the break. Historic canal incision leading to bank over-heightening and over-steepening has been a primary mechanism of bank failure along the canal. Analysis of site specific data at the observed bank failure locations indicates threshold values for incipient bank failure of seven feet for bank height and 40 degrees for bank angle.

Local soil types also play an important role in bank stability. Using existing GIS based Natural Resource Conservation Service (NRCS) soils data, soil properties were examined for trends among the observed bank failure sites. The plasticity index (PI) is a measure of the range of moisture contents that encompass the plastic state. This range is related to the percentage of clay in the soil. Soils that have higher clay content generally have higher plasticity indexes. Higher clay content makes the banks more resilient to geotechnical and hydraulic erosion. There was a strong correlation between bank failure occurrences and soil PI. Bank failures are much less likely to occur in soils with a PI greater than 20. This is the suggested cutoff between medium and high plasticity soils. Local soil plasticity indexes should be taken into account during bank stabilization design. Projects planned in locations with soils having low plasticity indexes should generally incorporate more conservative designs

In addition to historic incision other key processes in bank stability are identified. A variety of data sources have been analyzed and interpreted to determine these key processes resulting in bank

instability issues along the Santiam-Albany Canal. The primary mechanisms of failure identified are:

- Channel incision leading to bank over-heightening
- Bank saturation due to overland drainage
- Gullying from overland runoff
- Impinging flow and hydraulic eddying from obstructions and debris
- Bend scour
- Undercutting and soil slump due to changes in bank vegetation and soil stratigraphy
- Failing infrastructure
- Bank wetting and drying
- Bank freeze/thaw
- Rodent burrowing
- Tree mortality
- Soil characteristics

Results of the data analysis of field observations indicate that 89 percent of the bank failures observed in the canal is geotechnical in nature. Only 2 percent of the failures are the result of scour and 5 percent are related to cantilever type failures, which can also be a result of hydraulic erosion of stratified soil layers that exhibit varying erosion resistance properties. In these failures a more easily eroded soil type may underlie a more resistant layer. Tension cracks are observed in 33 percent of the failures, these are another indicator of geotechnical failure. Only nine percent of the plane slip failures exhibited undercutting. Undercutting could be attributed to fluvial erosion. Results of these analyses indicate that geotechnical type bank failures are the dominant failure mechanism for the canal. These geotechnical failures are primarily due to over heightened and over steepened banks resulting from long term channel incision. However, failure in these banks can be triggered by other contributing factors such as bank saturation, tree surcharge and animal burrowing.

Overland drainage is also an important component of bank stability. Overland drainage conditions that promote continuous reaches of bank saturation are prone to failure. Saturated soils exist at approximately 50 percent of the field observed bank failure sites, and significant groundwater seepage exists at 17 percent of those sites. In some instances along the canal, overland drainage is allowed to flow directly into the canal. This creates a hazard of creating an overland gully that introduces significant amounts of sediment into the channel and creates localized bank stability problems. Field drainage should be intercepted and routed into the canal at approximately the operational water surface elevations to mitigate the instability at these locations.

Wetting and drying and freeze/thaw cycles greatly increase potential of failure in cohesive soil banks. Bank wetting and drying also causes swelling and shrinking leading to the development of fissures and tension cracks in the soil, thus creating a potential failure plane. Canal operations should be conducted to avoid canal bank wetting and drying. These operations should address both flow rate and hydraulic control structures.

Vegetation characteristics play an important role in canal bank stability. Vegetation can be both beneficial and detrimental for canal bank stability depending on the scenario. Bank roots generally reinforce stream banks and provide tensile strength to the stream bank soils. Nearly 70 percent of the bank failure locations had slope faces that were nearly devoid of significant vegetation needed to reinforce soil structure. This highlights the importance of having some form of vegetation present to stabilize the canal banks. The riparian area provides bank reinforcement and intercepts overland runoff that leads to bank saturation. The riparian corridor can also provide pollutant removal benefits improving water quality in the canal.

Bank vegetation can also be a detriment to canal stability. One problem in particular is the abundance of large trees that are reaching the end of their lifespan along the canal. These trees add excess surcharge (weight) to the bank. There are two different failure mechanisms that result from these trees:

1. The excess surcharge from the tree leads to a rotational slip failure leaving the tree rootball at the toe of the slope
2. The tree leaning into the canal creates a moment arm for bank failure toppling the tree into the canal.

Both of these mechanisms lead to bank failure that introduces both sediment and woody debris into the system. This has severe ramifications for both downstream capacity and flooding issues. These failures can also lead to flow impingement and hydraulic erosion of the opposing stream bank after the wood is introduced into the system, 16 percent of the major failure locations were related to impinging flow conditions. Isolated tree failures are a common failure mechanism along the canal and are prevalent along the entire length.

Nutria burrowing is common along the entire length of the canal. Burrowing has two negative consequences for bank stability:

1. Burrows create preferential conduits (piping) for overland flow to enter the bank and saturate soils.
2. Burrows disturb the soil structural integrity of the bank, thereby weakening the bank.

Burrows disturb root soil contact leading to increased tree mortality and increasing the incidence of tree failures. Nutria damage is certainly a nuisance and one of the causative factors of bank failure, but it is not a major driver of bank stability. However, Nutria burrows are conduits for **seepage flow out of the canal** increasing the likelihood of property damage adjacent to the canal, as well as flow loss when the canal operating flows are augmented.

All of the aforementioned failure mechanisms were identified on a reach by reach basis to address the spatial distribution of the mechanisms along the canal. This spatial distribution is presented in tabular format in the report. Prior to bank rehabilitation design, the driving bank failure mechanisms should be identified at the project site.

Bank rehabilitation measures need to identify and mitigate the driving mechanisms of bank failure as well as providing measures to treat the existing bank failure geotechnical instability problems. A discussion is provided in the text regarding recommendations for stabilizing current canal bank failures and mitigation of the driving mechanism causing failure. Summary points from these recommendations are:

- Incision can be halted through the use of gradient control structures that will serve to stabilize the existing canal bed profile and provide hydraulic control that will reduce erosive velocities and potentially induce deposition. These grade control structures should be placed in reaches with steep hydraulic gradients, which are presently showing degradational tendencies.
- Overland runoff from the agricultural lands generally flowing to the left bank of the canal should be controlled to minimize zones of bank saturation.
- Maintaining a riparian vegetative corridor is important for bank stability. The vegetation roots provide conduits for better drainage and the plant water transpiration mitigates long-term bank saturation.
- Impinging flow and hydraulic eddying conditions can be mitigated by removing canal debris and maintaining smooth transitions at the canal bankline.
- Most failure locations along the urban portions of the canal in Lebanon and Albany occur in areas where residential lawns extend up the edge of the canal. The lawn vegetation is not able to establish on the steep slope faces that are frequently inundated by canal waters. Relatively low cost bioengineering techniques that incorporate plant species tolerant of frequent inundation and rock toe protection could be utilized to stabilize these locations.
- Areas where current infrastructure elements are failing should be addressed in the long-term canal maintenance plan.
- The canal operating procedure should be implemented in a manner that limits large fluctuations in the water surface along the canal.
- Establishment of a riparian corridor along the canal banks is the only mitigation technique available for freeze/thaw problems.
- Nutria eradication and trapping programs have presently been implemented in the area and should be a permanent element of canal berm maintenance.
- Trees that are approaching the end of their life-span and are leaning at unstable angles should be removed from the canal banks to eliminate the excess surcharge they exert on the canal banks.

Introduction

The Santiam-Albany canal was initially dug in 1872-1873. Since that time, the earthen canal has withstood floods, wind storms, and decades of fluvial erosion. In its current state 135 years later, many sections of the 18.1 mile canal are exhibiting bank failure and stability problems. This memo addresses data analysis conducted to determine key issues regarding bank stability along the Santiam-Albany Canal. Included in the contents are; 1) The geologic and pedologic setting for the project, 2) A discussion of the mechanisms and processes leading to canal bank failure, 3) The spatial distribution of bank failures and failure mechanisms in the reach context (Otak 2008), 4) Implications of future canal dredging and operations on bank stability, and 5) Recommendations for stabilizing current canal bank failures and mitigation of the driving failure mechanisms that will lead to long-term canal stability and self maintenance.

Study Methodology and Objectives

A number of data sources were available to investigate canal stability. These included:

1. Historic and current longitudinal profile data
2. The current HEC-RAS hydraulic model
3. The GIS field assessment database
4. Geologic mapping of the areal extent of various soil types and subsurface geologic stratigraphy
5. Field data forms of major bank failure locations and the resulting database
6. Site reconnaissance

Although the data available is quantitative to some degree, no site specific measurements of soil properties influencing effective shear strength namely cohesion, internal friction angle, and bulk unit weight have been made; therefore, trends can be deduced regarding bank stability, but formal geotechnical stability analysis cannot be conducted due to insufficient data. The purpose of this document is to identify mechanisms of failure, the spatial distribution of these mechanisms, and suggestions for mitigation that would provide long-term stability to the canal.

Causes of bank failure are multi-faceted and often times inter-dependent. This document begins with a discussion of the geologic and pedologic setting of the canal. The geologic setting and underlying geologic stratigraphy play an important role in the stability and erosional tendencies of particular reaches of the canal. This section will be followed by a discussion of a variety of mechanisms that are causing both local and reach scale bank stability issues in the canal. Seventeen relatively homogenous reaches have been characterized for the canal (Otak, 2008); based on hydraulic, land use, stability, and geologic characteristics. The spatial distribution of the existing bank failures and the failure mechanisms operating in those reaches will be presented. Some failure mechanisms are common to the entire extent of the canal and some are reach specific. Canal dredging has been proposed for depositional reaches of the canal. These dredging activities will have direct repercussions on bank stability depending on the depth of dredging, current bank heights, backwater elevations and bank materials. If the dredging activities lead to bank instability, sediment from mass wasting will be introduced into the reach defeating the purpose of the initial dredging. Site specific dredging reach data and potential instability problems will be discussed.

The document will conclude with future recommendations for stabilizing the existing bank failures and potential approaches to mitigate the driving forces that are causing bank instability in the canal.

Project Setting

Physiography

Santiam-Albany canal is located in the southern Willamette Valley. The valley is located between the Coast Range on the west and the Cascade Range on the east. Along the canal course, the valley floor descends northwesterly, reflecting the underlying distribution of alluvial fan deposits. With the exception of local low-lying hills, relief in the area is generally low, ranging from an elevation of approximately 360 feet at the east end of the canal to an approximate elevation of 215 feet at the west end.

The Willamette River, located immediately west of Albany, is the principal river in the valley. It enters the valley south of Eugene and flows northerly approximately 190 miles to its confluence with the Columbia River near Portland. The other major rivers in the project area include the Calapooia River located near the west end of the canal, and the South Santiam River located at the east end of the canal. Water is diverted from the South Santiam River through head gates into the canal.

Land Use

In general, the canal alignment trends northwesterly across the southern Willamette Valley, extending from the City of Lebanon on the east to the City of Albany on the west. With the exception of the urban areas located at each end of the canal, most of the land use along the canal alignment is agricultural, with grass seed being the primary crop. Climate and soil conditions in Linn County provide the area with one of Oregon's most diversified agriculture areas, allowing a wide variety of specialty crops to be grown and leading the nation in the production of common and perennial ryegrass.

Lebanon is located on the east side of the valley at the base of the Western Cascade Range foothills. The city population is less than 20,000. The South Santiam River exits the foothills near Lebanon and flows northerly along the eastern edge of the city. Water for the canal is diverted from the South Santiam River through head gates that includes fish passage control structures.

Albany is located at the west end of the canal, near the confluence of the Willamette and Calapooia rivers. The city population is less than 50,000. Interstate 5 flanks the eastern side of Albany. The canal terminates at the Vine Street Water Treatment Plant (WTP), where the water is diverted, treated, and distributed for municipal use. Hydropower operations are planned to be reestablished at the Vine Street (WTP), hence there is a need to convey more water flow in the canal. Excess canal water drains into the Calapooia River.

Where the canal traverses agricultural land, access is generally good, except for areas with heavy growth of invasive vines and dense deciduous trees. The easement along the top of the canal is capable of providing access for vehicles and construction equipment. In the urban areas, access to the canal is limited due to residential and commercial development. Canal access in the urban areas can be gained in a canoe or similar watercraft; however, access to the easement along the top of the canal banks is likely to require walking through landscaped yards and may be constrained by fences, requiring permission from the property occupants.

Regional Geology

The canal is located in the Puget-Willamette Lowland, a structural depression that extends northward from approximately Eugene, Oregon to the Fraser River in southern British Columbia. Two major basins, separated by bedrock highland areas, comprise the lowland; these include the Puget South Lowland, located in southwestern British Columbia and Washington, and the Willamette Lowland, located in southwestern Washington and Oregon. The Willamette Lowland is a broad alluvial basin bordered on the west by Tertiary marine sedimentary and volcanic rocks of the Coast Ranges, and on the east by the Tertiary and Quaternary volcanic and volcaniclastic rocks of the Cascade Range.

Tectonic development of the project area is the result of oblique subduction of oceanic crust beneath the North American plate (Gannett and Caldwell, 1998; Conlon and others, 2005; Orr and others; 1992; Yeats and others, 1996). Subduction is occurring along the offshore Cascadia Subduction Zone. Development of the Cascade Range volcanoplutonic arc east of the Puget-Willamette Lowland began between approximately 43 and 35 million years ago in response to the subduction. During this time, the ancestral Pacific Ocean shoreline was located near the eastern edge of the Willamette Lowland. Uplift of the forearc basin and Coast Range to the west was also occurring during this time. The Coast Range consists primarily of Tertiary marine sedimentary rocks and intrusive rocks. Following uplift of the Coast Range, the Willamette Lowland became isolated from the ocean and sediments transported by rivers draining the Cascade and Coast Ranges began accumulating in the lowland.

Eruption and emplacement of the Columbia River Basalt Group occurred during the period from approximately 17 to 6 million years ago. These basalts entered the northern portion of the lowland through a gap in the Cascade Range and flowed as far south as Salem. In the lowland, the basalts are interpreted to overlie Eocene to Oligocene volcanic and marine sediments (Gannett and Caldwell, 1998). During and after emplacement of the basalt, uplift of the Coast Range continued and the basalts and underlying Eocene to Oligocene volcanic and sedimentary bedrock were distorted by faulting and folding to create five sedimentary basins within the Willamette Lowland (Conlon and others, 2005).

The canal is located in the northeastern portion of the southern Willamette Basin, one of the five basins in the Willamette Lowland. The other basins include (from north to south) 1) Portland Basin; 2) Tualatin Basin; 3) central Willamette Valley; 4) Stayton Sub-basin; and 5) southern Willamette Basin (Gannett and Caldwell, 1998; Woodward and others, 1998; Conlon and others, 2005). Narrow ridges underlain by the Columbia River Basalt Group separate the basins. These basins and tributary valleys are generally filled with over 1,400 feet of unconsolidated fluvial and lacustrine sediments. In the southern Willamette Basin where the canal is located, Conlon and others (2005) estimated the thickness of these sediments to be less than 500 feet. These deposits, which typically consist of clays and silts, are interpreted to have been deposited in low energy environments, including distal alluvial fans, low-gradient streams, and lakes (Conlon and others, 2005).

The Missoula Floods, a series of glacial outburst floods that originated in Montana approximately 13,000 to 15,000 years ago, had significant impacts on the geomorphology and depositional history of the Willamette Valley. Widespread inundation of the valley occurred during these floods. Up to 250 feet of silt, sand and gravel were deposited in the Portland Basin, and up to 130 feet of silt, known as the Willamette Silt, were deposited elsewhere in the valley (Woodward and others, 1998).

Following deposition of the Missoula Flood deposits, the Willamette River and its main tributaries (located principally on the eastern side of the Willamette Valley where they exit the western Cascade Range) created new floodplains by incising steep-walled drainage courses through the flood deposits. Modern floodplains in the valley are typically occupied by meandering and anastomosing streams and rivers that have deposited locally extensive sand and gravel deposits.

Stratigraphy

Previous studies in the Willamette Valley over the past 100 years have led to an understanding of the geologic processes, stratigraphic units, and local and regional landforms in the valley. Several of these published studies, including Allen and others (1986), Allison (1953), Allison and Felts (1956), Balster and Parsons (1968), Conlon and others (2005), Gannett and Caldwell (1998), and Woodward and others (1998) were reviewed during this study.

Recent studies of Quaternary deposits in the valley by O'Connor and others (2001) have improved chronologic control of the stratigraphic units, as well as presenting a conceptual model for the development of landforms that was lacking in previous studies. Based on the chronologic information (from tephra correlations and age-dating of organic and volcanic materials) and the current model of regional Quaternary environments, the updated stratigraphic nomenclature and Quaternary evolutionary model proposed by O'Connor and others (2001) have been adopted for this study.

Quaternary geologic units mapped in the area by O'Connor and others (2001) range in age from approximately 2.5 million years old to recent deposits laid down by the modern Willamette River and other principal rivers in the valley. Most of the Quaternary geologic units are generally interpreted to have been deposited within approximately the last 400,000 years or so (O'Connor and others, 2001).

Five major Quaternary stratigraphic units were mapped by O'Connor and others (2001) in the Willamette Lowland. Each stratigraphic unit records major geologic and environmental episodes that occurred in the lowland. In addition, the nature, distribution, and thickness of these units had an influence on the current topography and soil and groundwater characteristics. Basin-fill sediments in the Willamette Lowland consist primarily of clays and silts deposited in low-energy depositional environments including distal alluvial fans, low-gradient streams, and lakes (Gannett and Caldwell, 1998; Conlon and others, 2005). Coarse-grained deposits (e.g., sand, gravel, and cobbles) occur along the floodplains and channels of primary streams and rivers. The Quaternary stratigraphic units consist of (from youngest to oldest):

1. Holocene floodplain deposits;
2. Pleistocene sand and gravel deposits (post-Missoula Floods);
3. Missoula Flood deposits;
4. Pleistocene sand and gravel deposits (pre-Missoula Floods); and
5. Weathered terrace gravels.

Of these stratigraphic units, the Holocene floodplain deposits, post-Missoula Floods Pleistocene sand and gravel deposits, and Missoula Floods deposits have been mapped along the canal by O'Connor and others (2001). Holocene floodplain deposits occur at the east end of the canal near the South Santiam River. Post-Missoula Flood sands and gravels are a significantly widespread unit along the canal, occurring between approximately River Road Bridge in Lebanon and Langmack Road in rural Linn County. Missoula Flood deposits represent the most widespread unit, extending from approximately Langmack Road to the western end of the canal at the Vine Street WTP. A summary of the Quaternary stratigraphic units along the canal route, as mapped by O'Connor and others (2001), is provided below. The soil units identified by the Natural Resources Conservation Service (NRCS) that have developed on these deposits are also summarized below

In addition to the Quaternary units an outcrop of Tertiary Marine shale associated with the geologic development of the coast range has been field identified in the Albany area between canal stations 60+00 and 99+84, upstream of the Highway 99 crossing. This hardpan shale is highly resistant to erosion and has currently formed a knick zone within the reach. Figure 1 depicts the areal extent of these units in the project area and Table 1 characterizes the underlying geologic stratigraphy along the longitudinal profile of the canal utilizing the canal stationing adopted for the study.

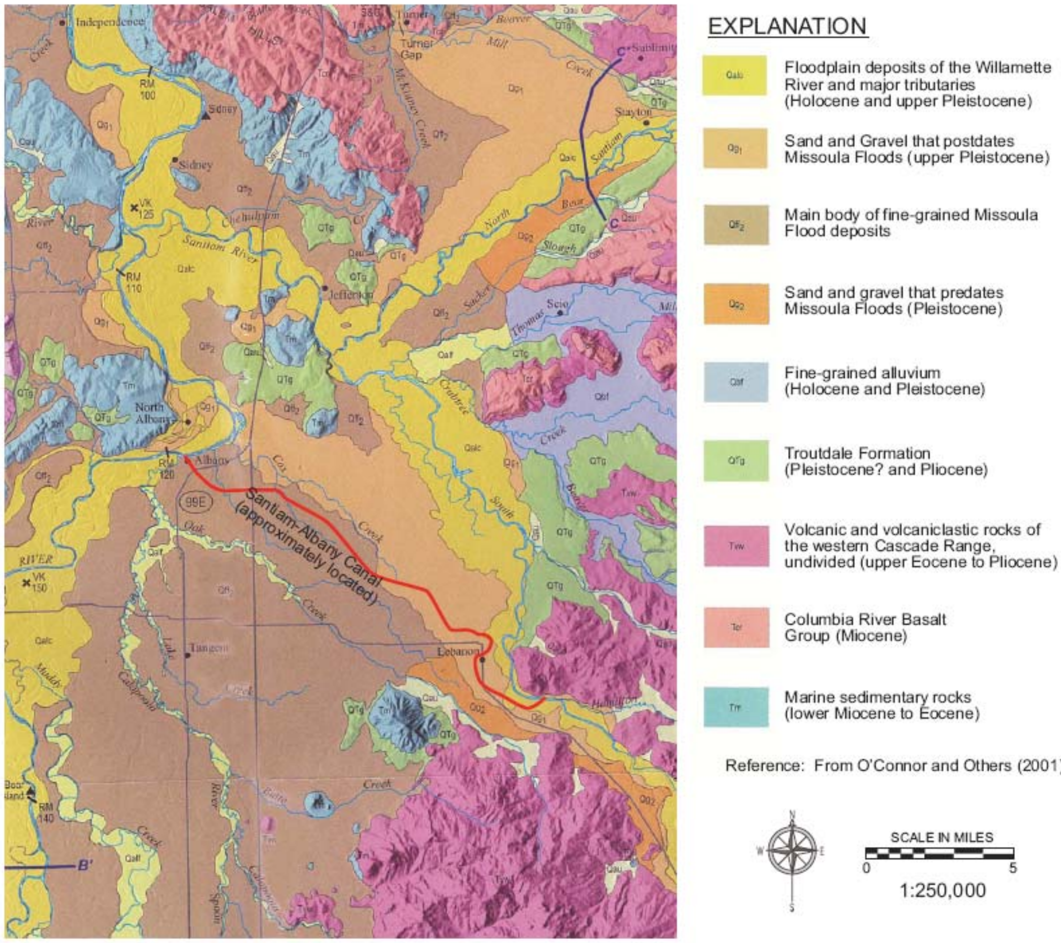


Figure 1: Arial Extent of Quaternary Geologic Units Along the Santiam-Albany Canal (adapted from O'Connor and Others 2001)

Table 1: Geologic Stratigraphy Changes Along the Longitudinal Profile of the Canal		
Canal Station-ft	**Description**	**Resilience to erosion**
Inlet- 866+47	Q_{alc}- Recent Holocene epoch alluvium (coarse gravels/cobbles)	Excellent
866+47 - 476+00	Qg_1- Pliestocene epoch glacio-fluvial sand and gravel deposits postdating the Missoula flood deposits	Good
476+00-99+84	Qff_s-Fine grained Missoula flood deposits from the Pleistocene epoch (interbedded silts and clays)	Poor
99+84-60+00	Tss- Tertiary Marine Sedimentary Shale and Mudstone (consolidated)	Excellent
60+00 – 0+00	Qff_s-Fine grained Missoula flood deposits from the Pleistocene epoch (interbedded silts and clays)	Poor

Holocene Flood Deposits (Qalc)

Along the canal, the Holocene deposits occur at the uppermost eastern end of the canal adjacent to the South Santiam River. They occur from the east end at the river to approximately River Road Bridge. The deposits are predominantly floodplain and channel sediments consisting of silt, sand, and gravel deposited by the South Santiam River. These deposits represent lateral and vertical accretion of overbank and channel deposits of the actively meandering South Santiam River. Gravel and sand deposits are the result of bedload transport along river channels, and the finer-grained sediments represent overbank deposits accumulated at higher elevations and greater distances from the main channels.

Soils that have developed on the Holocene flood deposits include the Camas, Chapman, Chehalis, Cloquato, and Newberg series. These soil series typically consist of very deep, excessively to well-drained soils that formed in mixed alluvium (U.S.D.A., 1987).

Pleistocene Sand and Gravel Deposits (Qg_1; post-Missoula Floods)

These sand and gravel deposits, deposited after the Missoula Floods occurred, are a thin, widespread unit that typically forms planar surfaces above the modern floodplain. They are a widespread unit along the canal, occurring from approximately River Road Bridge on the east to Langmack Road on the west. O'Connor and others (2001) suggested these deposits accumulated to form broad, alluvial fan deposits where major rivers, such as the Willamette and North and South forks of the Santiam Rivers, exit the western Cascade Range. During its history, it appears the South Santiam River had a more direct course from the alluvial fan apex near Lebanon to its confluence with the Willamette

River near Albany. Since that time, it has shifted its course northward. As the channel migrated northward, it stripped much of the fine-grained Missoula Flood deposits (Qffs) along a broad swath between Albany and Lebanon (O'Connor and others, 2001).

Missoula Flood Deposits

Deposits resulting from catastrophic glacial outburst floods that originated near Missoula, Montana mantle most lowland areas of the valley. A series of more than 40 floods occurred during the period from approximately 13,000 to 15,000 years ago. The flood deposits consist of multiple layers of clay, silt, and sand. Deposits are thickest in the northern portion of the valley and thin towards the southern valley.

O'Connor and others (2001) recognized three facies within the flood deposits based on stratigraphic distribution and grain size. These consist of primary fine-grained facies, younger fine-grained facies, and a coarse-grained facies. The primary fine-grained facies are the most widespread unit and are mapped along most of the canal alignment. A summary of the individual facies mapped by O'Connor and others (2001) is provided below.

Primary Fine-Grained Facies (Qff_s)

These deposits consist of interbedded clay, silt, and sand. They are the most widespread deposits along the canal, extending approximately from Langmack Road to the western end of the canal at the Albany WTP. These deposits are also the most widespread facies (Qff_2) of the main body of the flood deposits. These deposits exceed 100 feet in thickness in the northern Willamette Valley, but thin to less than approximately 30 feet in the southern portion of the valley.

Soil series that have developed on the primary fine-grained facies of the flood deposits include the Aloha, Amity, Dayton, Holcomb, Willamette, and Woodburn series (U.S.D.A., 1987). Soils of the Aloha series consist of very deep, somewhat poorly drained soils that formed in mixed alluvium or lacustrine silts. The Holcomb series consists of very deep, somewhat poorly drained soils that formed in stratified alluvium typically consisting of clay and silt. Soils of the Amity, Dayton, Willamette, and Woodburn series consist of very deep, somewhat poorly drained to well-drained soils that formed in silty glaciolacustrine deposits.

Younger Fine-Grained Facies (Qff1)

These flood deposits consist of silt and sand that underlie surfaces eroded into Qff2 deposits. In general, these deposits are of limited extent, and have not been identified or mapped along the canal. They typically occur at elevations approximately 15 to 65 feet below adjacent surfaces underlain by the fine-grained facies of the Missoula Floods deposits. Soils developed on the younger fine-grained facies of the flood deposits are the same as those developed on the primary fine-grained facies. These include the Aloha, Amity, Dayton, Holcomb, Willamette, and Woodburn series (U.S.D.A., 1987).

Coarse-Grained Facies (Qff_c)

Coarse-grained flood deposits (Qff_c) have been recognized in the Willamette Valley near Wilsonville and Canby (O'Connor and others, 2001). These deposits are limited in extent and are not present along the canal. They typically occur as fan-shaped accumulations of sand, gravel, and boulders. Soils developed on the coarse-grained facies of flood deposits include the Willamette and Salem series. The Willamette series consists of very deep, well-drained soils that formed in silty glaciolacustrine deposits. Soils of the Salem series typically consist of very deep, well-drained soils formed in loamy alluvium over sandy and gravelly alluvium (U.S.D.A., 1987).

Pleistocene Sand and Gravel Deposits (Qg2; pre-Missoula Floods)

These unconsolidated deposits comprise the largest portion of the Pleistocene sand and gravel deposits (including the post-Missoula Floods sand and gravel deposits). They typically have a planar surface or subdued braided channel morphology. O'Connor and others (2001) reported the deposits generally consist of three to six feet of sandy silt overlying gravels and cobbles. The deposits also have a distinctive weathering profile that ranges from approximately six to ten feet thick (O'Connor and others, 2001). They are not present along the canal.

Soils developed on the pre-Missoula Floods sand and gravel deposits include the Awbrig, Briedwell, Clackamas, Coburg, Conser, Courtney, Dayton, Holcomb, Malabon, Oxley, Penga, Salem, and Sawtell series (U.S.D.A., 1987). The Awbrig, Briedwell, Clackamas, Coburg, Courtney, Malabon, Oxley, Salem, and Sawtell series consists of very deep, poorly to well-drained soils that formed in mixed alluvium weathered from volcanic and sedimentary bedrock. Soils of the Dayton series consist of very deep, poorly drained soils that formed in silty and clayey glaciolacustrine deposits.

Weathered Terrace Gravels (QT_g)

Weathered terrace gravels are the oldest Quaternary deposits identified in the Willamette Valley by O'Connor and others (2001). They have been identified or mapped in the project area. These gravels are interpreted to be as much as three to five million years old, but most of the unit is estimated to have been deposited between 0.5 and 2.5 million years ago (O'Connor and others, 2001). They represent weathered fluvial gravels and pediment surfaces that locally flank the valley floor. In general, the weathered terrace gravels consist of severely weathered to decomposed pebbles and cobbles enclosed in a red, clay-rich matrix.

Soils developed on the weathered terrace gravels include the Jory, Nekia, Salkum, and Veneta series (U.S.D.A., 1987). Soils of the Jory, Nekia, and Veneta series consist of moderately to very deep, well-drained soils that formed in colluvium and residuum derived from sedimentary and basic igneous bedrock. Soils of the Salkum series consists of very deep well drained soils formed in very strongly weathered ancient glacial drift.

Hydrogeology

Conlan and others (2005) identified seven regional hydrogeologic units in the Willamette Basin. These include (from youngest to oldest):

- High Cascade unit;
- Upper sedimentary unit;
- Willamette silt;
- Middle sedimentary unit;
- Lower sedimentary unit;
- Columbia River Basalt; and
- Basement confining unit.

Four of these units (upper sedimentary unit, Willamette silt, middle sedimentary unit, and the lower sedimentary unit) comprise the lowland between the Coast and Cascade Ranges. Along the canal, the upper sedimentary unit is the principal hydrogeologic unit. Infiltration of precipitation is principal recharge source in the Willamette Valley, with an estimated mean annual recharge of approximately 16 inches (Conlan and others, 2005). Most of the recharge occurs from November to April when most of the rainfall occurs and evapotranspiration is low. During the period from May to October, recharge is low and evapotranspiration is large. Groundwater extraction by pumping is also considerably higher from May to October.

A brief summary of the hydrogeologic units is presented below.

Upper Sedimentary Unit

This unit is exposed at the ground surface throughout its extent in the Willamette Lowland; however, it is not present in the Tualatin Basin. The upper sedimentary unit is the principal hydrogeologic unit along the canal. It extends from the ground surface to an estimated depth of approximately 40 feet.

It consists of unconsolidated late Pleistocene- to Holocene-age sands and gravels that make it the most productive aquifer in the Willamette Basin. It is capable of yielding groundwater at rates up to 10,000 gallons per minute (Conlon and others, 2005). South of the Portland Basin, the unit is equivalent to the post-Missoula Flood gravels and Holocene floodplain deposits of O'Connor and others (2001). Hydraulic conductivities range from 0.03 to 24,500 feet per day, and specific yields range from 0.003 to 0.2 percent (Conlan and others, 2005). Variations in the primary hydrogeologic parameters (e.g., conductivity, specific yield, transmissivity, etc.) of the upper sedimentary unit are likely to occur along the course of the canal due to lithologic changes, local groundwater pumping and recharge sources, bank seepage, and canal water infiltration.

Willamette Silt

The Willamette Silt unit consists of fine-grained sediments deposited by the Missoula Floods. Up to 40 beds of clay and micaceous silt, ranging from several inches to several feet thick, have been identified within the Willamette Silt. It generally occurs at the surface throughout most of the lowland south of the Portland Basin below an elevation of approximately 400 feet. In the southern Willamette Basin where the canal is located, the Willamette Silt is generally less than 20 feet thick (Conlon and others, 2005). Although groundwater yields are typically adequate for domestic use, the aquifer is typically not a preferred groundwater production unit.

Hydraulic characteristics of the Willamette Silt unit are poorly understood since few wells are developed in the unit. The few data available indicated the hydraulic conductivities in the central Willamette Basin ranged from 0.01 to 8 feet per day (Conlan and others, 2005).

Middle Sedimentary Unit

This unit consists primarily of slightly to moderately consolidated Pleistocene sands and gravels that underlie Missoula Flood deposits. These are late Pleistocene alluvial fan and braid-plain deposits that generally occur along the eastern and southern margin of the valley. It is typically unconsolidated in the upper section of the unit, but it becomes more consolidated and cemented with increasing depth.

The middle sedimentary unit is unconfined to semi-confined, with storage coefficients estimated to be greater than 0.001. Hydraulic conductivities range from 8 to 2,230 feet per day (Conlan and others, 2005).

Lower Sedimentary Unit

The lower sedimentary unit consists primarily of fine-grained distal alluvial fan sediments deposited by rivers and streams entering the Willamette Valley from the Coast and Cascade Ranges. Considerable amounts of sand and gravel also occur in the unit, particularly near its upper contact with the overlying middle sedimentary unit.

The lower sedimentary unit is a confining unit, with local productive sand and gravel layers of sufficient thickness to provide moderate to high well yields. However, in the southern Willamette Valley the well yields are less than 20 gallons per minute (Conlan and others, 2005).

Columbia River Basalt

The Columbia River Basalt unit consists of a series of Miocene flood-basalt lava flows. Water-bearing zones in the basalt are typically sub-horizontal, tabular interflow zones separated by low-permeability basalt flows that act as confining layers. As a result, well yields can be highly variable, typically ranging from 20 to 1,000 gallons per minute.

Basement Confining Unit

The basement confining unit forms the floor of the Willamette Valley and includes Tertiary marine sedimentary rocks and Eocene volcanic rocks of the Coast Range and volcanic and volcaniclastic rocks of the Western Cascades. It has low permeability, low porosity, and low well yield (generally less than five gallons per minute; Conlan and others, 2005). Hydraulic conductivities are estimated to range from 10^{-5} to 10^{-2} feet per day; storage coefficients range from 5×10^{-5} to 3×10^{-3} (Conlan and others, 2005).

Relationship Between Soil Type and Observed Bank Failures

NRCS soils data polygons were overlayed with the GIS layer for the canal centerline to determine the changes in soil type along the longitudinal profile of the canal. Soils range from clay loam to gravelly silt loam. The NRCS soils database also has information on the plasticity index, erodibility parameters and saturated hydraulic conductivity. These parameters were calculated on a depth weighted basis for each soil type along the canal. The plasticity index (PI) is a measure of the range of moisture contents that encompass the plastic state. This range is related to the percentage of clay in the soil. Soils that have higher clay content generally have higher plasticity indexes. Higher clay content makes the banks more resilient to geotechnical and hydraulic erosion. The available erodibility parameters in the database are Kw and Kf. Both of these parameters refer to the susceptibility of a soil to sheet and rill erosion. Kw refers to the whole soil and Kf refers to the fine grained portion of the soil. This K factor is one of six factors used in the Universal Soil Loss Equation (USLE) to predict average annual rates of soil loss by sheet and rill erosion. K factors can range from 0.02 to 0.69 with higher values indicating greater potential for erosion. Summary data for the soil types occurring along the canal, as well as the frequency of bank failure occurrence by soil type are presented in Table 2. A parameter to estimate the relative rate of bank failure occurrence within a given soil type was created. This parameter is presented in Table 2 as the Soil Failure Frequency Ratio (SFFR). The SFFR for a given soil is calculated as:

$$SFFR = \frac{\%\,of\ all\ failures\ occurring\ in\ a\ given\ soil}{\%\,of\ total\ canal\ length\ occupied\ by\ a\ given\ soil}$$

A higher SFFR indicates greater susceptibility for bank failure occurring within the given soil type.

The SFFR values for each soil are plotted as a function of the Plasticity Index (PI) in Figure 2. This shows a strong correlation between bank failure occurrences and soil PI. Bank failures are much less likely to occur in soils with a PI greater than 20. This is the suggested cutoff between medium and high plasticity soils proposed by Burmister (1949) (Table 3). Local soil plasticity indexes should be taken into account during bank stabilization design. Projects planned in locations with soils having low plasticity indexes should generally incorporate more conservative designs. The river stationing as well as the geotechnical properties of various soil layers occurring along the canal is presented in Appendix A.

Table 2: Summary Data for NRCS Soil Types Located Along the Santiam-Albany Canal

NRCS Soil #	Soil Name	Length -ft	% of Canal Total Length	% of all failures	PI-weighted average	Kf-weighted average	Kw-weighted average	Ksat (in/hr)	Soil Failure Frequency Ratio (SFFR)
23	Clackamas gravelly silt loam	5427	5.8%	0%	15	0.36	0.14	0.58	0.0
29	Courtney gravelly silty clay loam	1477	1.6%	0%	18	0.3	0.14	2.82	0.0
98	Waldo silty clay loam	985	1.0%	0%	22	0.27	0.27	0.46	0.0
46	Holcomb silt loam	2760	2.9%	0%	22	0.34	0.34	0.62	0.0
28	Conser silty clay loam	2297	2.4%	0%	23	0.35	0.35	0.44	0.0
7	Awbrig silty clay loam	512	0.5%	0%	29	0.34	0.34	0.44	0.0
19	Chapman loam	455	0.5%	1%	8	0.3	0.3	1.66	2.1
8	Bashaw silty clay	3292	3.5%	1%	49	0.18	0.18	0.03	0.3
63	Malabon silty clay loam	11958	12.7%	2%	20	0.27	0.27	0.66	0.2
87	Salem gravelly silt loam	2628	2.8%	3%	8	0.26	0.13	25.76	1.1
26	Coburg silty clay loam	8040	8.5%	4%	18	0.35	0.35	0.65	0.5
73	Fine sandy loam	14700	15.6%	11%	1	0.24	0.17	9.06	0.7
27	Concord silt loam	12014	12.8%	11%	11	0.43	0.43	0.58	0.9
33	Dayton silt loam	10543	11.2%	13%	18	0.43	0.43	0.79	1.2
3	Amity silt loam	8738	9.3%	18%	9	0.47	0.47	1.14	1.9
106a	Woodburn silt loam	8244	8.8%	35%	10	0.4	0.4	1.18	4.0

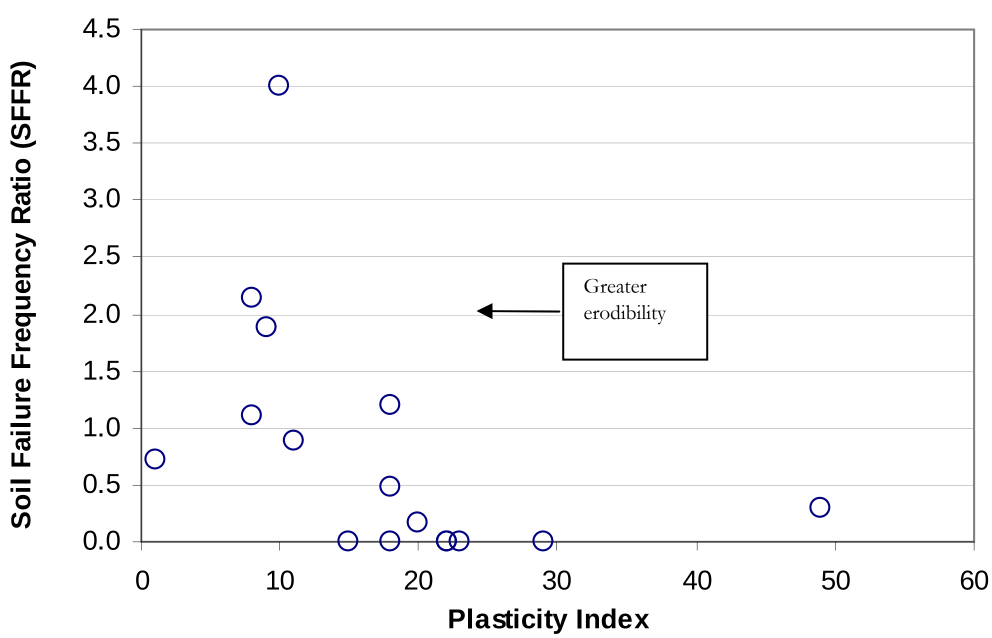


Figure 2: SFFR As a Function of Soil Plasticity Index (PI)

Table 3: Qualitative Plasticity Index/Soil Descriptions (from Burmister 1949)	
PI	**Description**
0	Nonplastic
1 - 5	Slightly plastic
5 - 10	Low plasticity
10 - 20	Medium plasticity
20 - 40	High plasticity
> 40	Very high plasticity

SFFR values were also plotted as a function of erodibility factors Kf and Kw. Susceptibility to erosion increases with increasing Kf and Kw values. This trend is evident in Figure 3. The local Kf and Kw values should be checked at proposed bank stabilization sites, if these values are high (0.25) then it may be advisable to incorporate more conservative bank stabilization designs and incorporate more rigorous site erosion control practices.

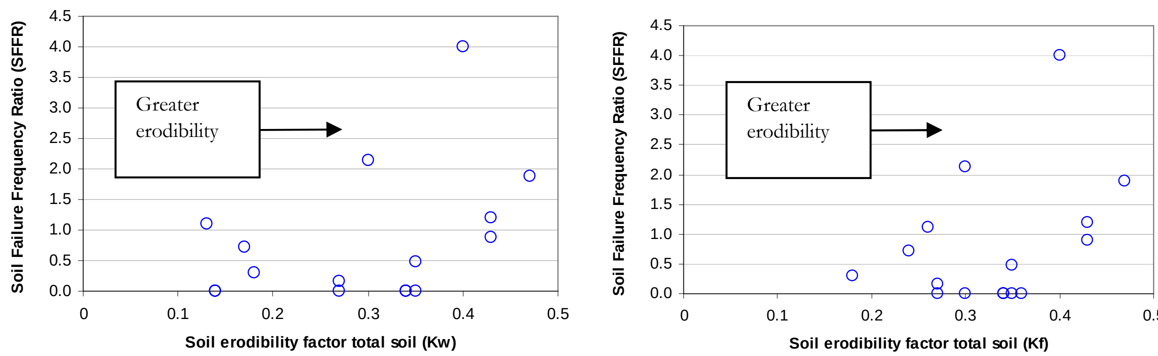


Figure 3: SFFR As a Function of Soil Erodibility Kf and Kw.

Processes and Mechanisms of Bank Failure and Channel Instability in the Canal

This section will discuss the primary mechanisms and drivers leading to the presently observed canal bank instability. Bank instability can result from a myriad of causes. These are:

- Channel incision leading to bank over-heightening
- Bank saturation due to overland drainage
- Gullying from overland runoff
- Impinging flow and hydraulic eddying from obstructions and debris
- Bend scour
- Undercutting and soil slump due to changes in bank vegetation and soil stratigraphy
- Failing infrastructure
- Bank wetting and drying
- Bank freeze/thaw
- Rodent burrowing
- Tree mortality
- Soil characteristics

Each of these potential causes of bank instability will be discussed in the following sections. These discussions will be coupled with examples from the field data observations made in the winter of 2006-2007. Additionally, quantitative analysis of the field measured "major" bank failures database will be discussed to provide insight into the hydraulic, geometric, topographic, vegetative, hydrogeologic, and land use characteristics associated with these failures.

Long-term Reach Scale Erosional and/or Depositional Characteristics and Subsequent Effects on Bank Stability and Canal Hydraulics

Channel stability for the canal can be broadly categorized into bank stability and bed stability. Instability of the canal bed can take place through either erosion or deposition. Both processes can have negative consequences; bed erosion can lead to increased bank heights and geotechnical instability; whereas, sediment deposition can lead to capacity loss, flooding issues, and costly dredging activities. The consequences of the erosion and bank failure within an upstream reach are manifested through increased sediment and debris loads that have the potential to be depositional problems in the downstream reaches. Therefore, bed and bank stability within the range of equilibrium is ideal for long-term canal self-maintenance.

A simple method to investigate long-term channel stability is to compare historic and current longitudinal profile data. These data for the Santiam-Albany canal were made available from Pacific Water Resources (PWR) (Figure 4). Canal bed profiles were available for the following time periods:

1. Original conditions (assumed ~1873)
2. 1890, and
3. 2007

The historical longitudinal profiles provide insight into the erosional characteristics of the canal. All reaches available for comparison (stations 61+88 to 643+00) have degraded or incised historically. From a geomorphic perspective, this occurs due to the relatively clear water diverted into the canal from the South Santiam River, and the lack of channel sinuosity which is common in canal design. Energy in alluvial channels is utilized to perform work against friction at the channel boundary, against internal friction, in transporting the sediment load, and in eroding the channel boundary. In the Albany-Santiam canal there is essentially no sediment load supplied to the channel from upstream and clear water scour results. Canal design typically involves following the steepest gradient available in the valley (valley slope) and lateral constraint to maximize agricultural land use. By contrast natural streams typically adjust their gradient over time through planform change (meandering). If this mechanism is not available (i.e., from linear canal design), gradient adjustment occurs via channel incision (i.e., lowering the elevation of the thalweg). This is the case for the Albany-Santiam canal. The resulting channel degradation has direct consequences for reach stability and subsequently, bank stability because bank heights and angles are raised above critical failure thresholds. Canal hydraulic reaches have been delineated and discussed in previous technical memoranda (Otak February 26,2008). Table 4 depicts the reach average degradation rates calculated along the canal. The degradation rates range from 1.5 to 7.5 feet along the canal profile.

Table 4: Historic Canal Incision Rates from 1873 to 2007

Reach	Intermediate River Station	Elevation Change
	(ft)	(ft)
8	58,709	-1.8
9	50,565	-1.5
10	45,189	-3.4
11	34,687	-6.0
12	25,151	-7.5
13	19,427	-5.7
14	13,101	-2.2
15	8,075	-2.8

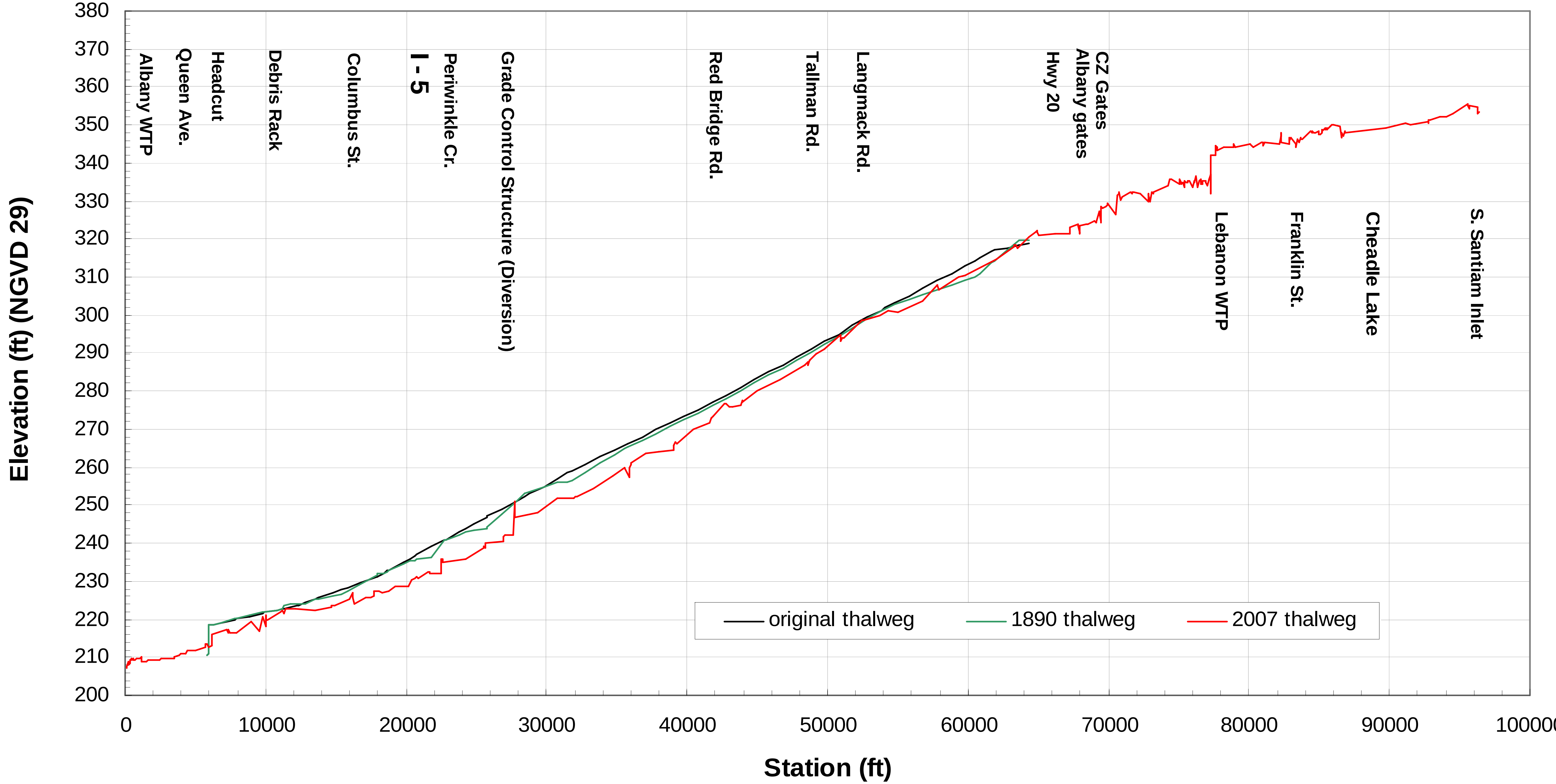
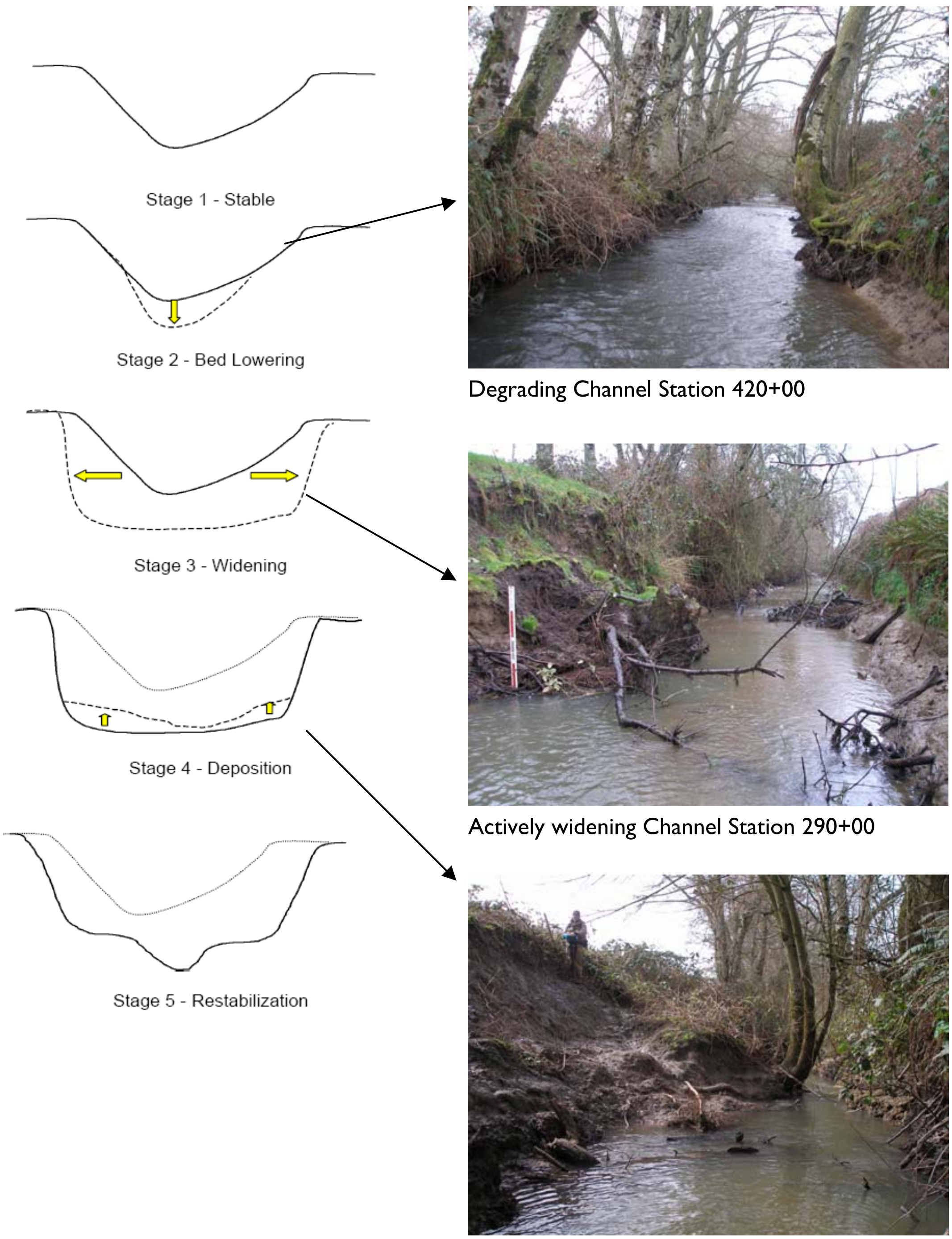


Figure 4: Historic and Current Longitudinal Profiles of the Santiam-Albany Canal

Canal Geomorphology

Space for time substitution (Schumm et al. 1984) indicates a sequence of morphological changes that will occur in incised channels (Figure 5). The well-documented sequence is termed the channel evolution model (CEM). In the case of the canal, Stage 1 would be the original canal digging in 1873. Due to reasons described in the preceding discussion, the canal began to degrade or incise. This would be considered Stage 2. During Stage 2 of the channel evolution, process sediment transport capacity within a reach is at a maximum. Once a critical stability threshold for bank height is exceeded, Stage 3 begins where channel widening is the dominant process. As the channel widens, bed shear stress and erosive velocities are reduced. This reduced reach transport capacity is coupled with increased sediment supply from the failing banks upstream and the dominant channel process is deposition for Stage 4. After some period of time, quasi-equilibrium is reached in Stage 5 within the enlarged channel cross-section and restabilization occurs with an inset floodplain and channel cross-section in the enlarged channel section.

The aforementioned, geomorphic process is most prevalent in the canal reaches in the non-urbanized agricultural portions of the canal that are free to adjust (river stations 226+00 to 671+21). A photo sequence in this vicinity (Figure 5) illustrates the ramifications of these geomorphic processes on bank stability and canal conveyance capacity loss. Over time degradation is continuing to move upstream and resulting bank erosion problems will progress upstream from the reaches that presently have the greatest stability problems in the rural reaches of Linn County. This migration is partially halted by a large grade control structure located at station 275+00, approximately 700 feet upstream of the Fry Road crossing (Figure 6), and coarse gravel bed material present in reaches upstream from this structure. Areas with the highest potential for future incision include the portion of the canal extending from Goltra Road upstream to Tallman Rd. These future incision problems could be halted by installing grade control structures or check dams at key locations to restrain further canal incision and associated instability problems.



Degrading Channel Station 420+00

Actively widening Channel Station 290+00

Depositional Channel Station 250+00

Figure 5: Channel Evolution Sequence (adapted from Fischenich and Morrow 2000)

Figure 6: Grade Control Structure Upstream of Fry Road.

CEM stage and the depth of historical canal entrenchment were utilized to differentiate reaches within the rural sections of Linn county and portions of the canal within the City of Albany (Otak February 26, 2008). Canal segments with the highest historical rate of entrenchment are highly correlated to areas with frequent bank failures (Figure 7). Reaches that are currently in CEM Stages 2 or 3 are susceptible to future bank failure problems.

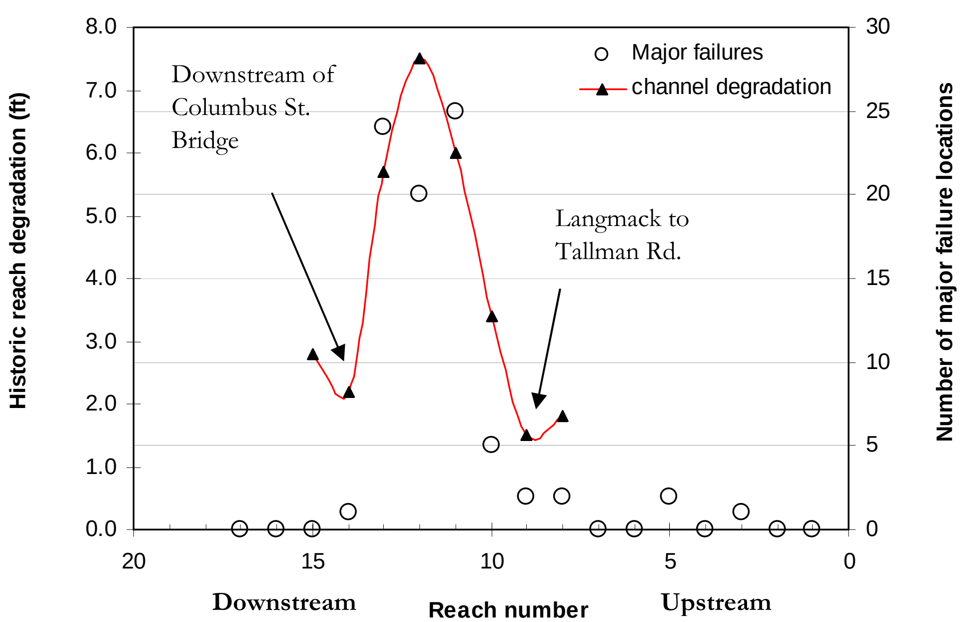


Figure 7: Major Bank Failure Frequency and Channel Degradation Along the Longitudinal Profile of the Albany Canal

Canal CEM Stage and Implications for Current Canal Hydraulics

A commonly used parameter in estimating channel sediment transport capacity is specific stream power (Bagnold 1966). Specific stream power is defined as the product of the boundary shear stress and mean channel velocity (Equation 1).

$$specific\ stream\ power = \tau V\ (lb/ft-s) \qquad \textbf{Equation 1}$$

Where:

$\tau = boundary\ shear\ stress\ (lb/ft^2)$

$V = main\ channel\ velocity\ (ft/s)$

Historical reach degradation rates and specific stream power (for the current average flow rate of 85 ft^3/s) plotted on Figure 8 reveal that the maximum stream power rates are proceeding upstream of the observed bank failures as predicted by the CEM theory. Maximum historical degradation rates, and subsequent bank failure prone areas noted in the field reconnaissance, fall downstream of this zone of maximum stream power (Figure 8) as the incision progresses upstream. This process can be complicated by local grade control features and outcrops of more resistant geologic bed material, which slow down the migration of the incision zone.

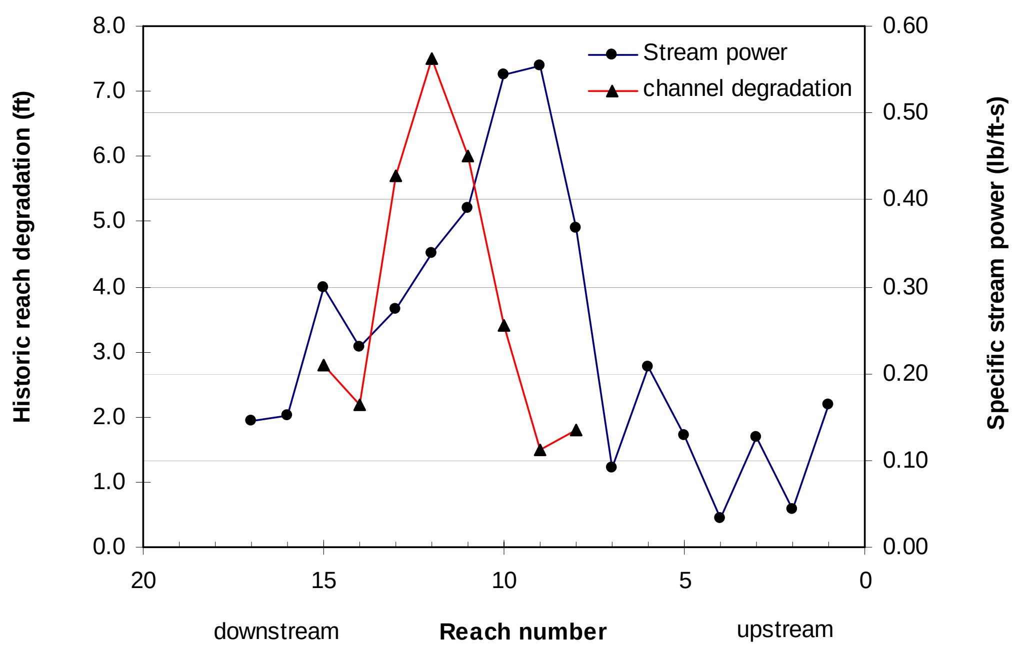


Figure 8: Historical Canal Degradation and Current Specific Stream Power Plotted for Each Hydraulic Reach (reach numbers increase sequentially from upstream to downstream)

This geomorphic assessment is only valid in the rural areas of the canal that are free from the hydraulic controls present in many of the urbanized regions of the canal. This geomorphic model represents a continuum of channel form adjustment, and reaches are characterized as discrete evaluations of the best representative model stage, however a reach may be transitioning from Stage 2 in the upstream portion of the reach to a Stage 3 in the downstream portion. Areas where the canal channel evolution stage is 3 or 4 will be most susceptible to bank failure problems at the present time. In the future, reaches which are presently classified as evolutionary Stage 2 should be closely monitored. When these reaches degrade to a depth that is greater than the critical bank height determined by local soil and vegetation characteristics, future bank failure is imminent. A significant impact of these failure prone reaches is that large quantities of sediment will be supplied to the canal from the failing stream banks, which will ultimately be transported down to the urban Albany reaches. This presents a possibility of future downstream canal aggradation and potential flooding problems, which can only be alleviated by costly dredging in those reaches.

One potential method of mitigating future incision problems, and assisting bed and bank stability is the use of grade control structures. By constructing small cost effective check dams in strategic locations erosive velocities and high stream powers can be mitigated and future canal incision can be halted. This will prevent future cases of bank over-heightening, but will do little for presently over heightened banks.

Data analysis of bank over-heightening/over-steepening of current major failure locations

A threshold for differentiating Stage 2 and Stage 3 channels is the critical bank height for incipient failure. Bank angle is also an important factor for stability. Measured bank angle and bank height are plotted for the major failures field database in Figure 9. This data indicates a bank angle threshold of 40 degrees and a bank height threshold of seven feet for incipient geotechnical failure for the soils in this area. Some soils and vegetation characteristics will withstand steeper angles and higher banks, but this lower envelope should be considered the threshold for failure. Outliers in the lower left corner of the figure indicate cases where hydraulic erosion generates bank failure. In these cases of excess velocity and or shear stress is capable of mobilizing sediment at the bank toe, thus creating scour and bank instability. This is a different failure mechanism than the majority of failures observed along the canal, which are primarily geotechnical failures. Any bank failures occurring below bank heights of seven feet could possibly be attributed to hydraulic erosion processes.

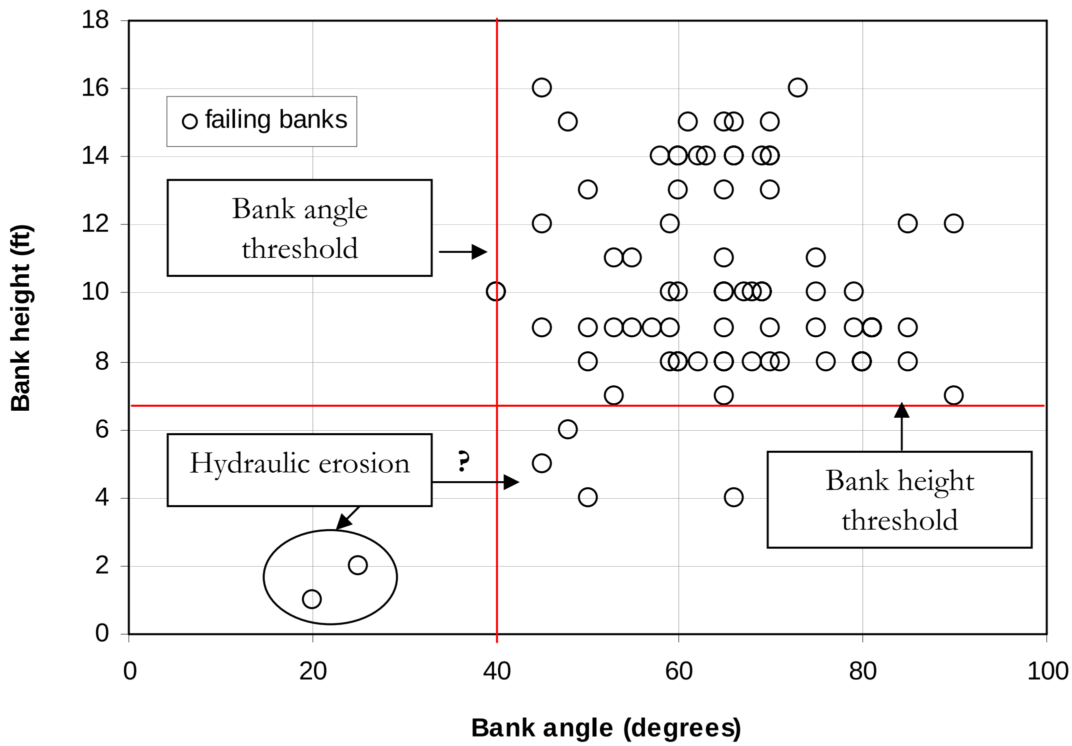


Figure 9 Bank Height and Angle for Major Failure Locations

Measurements of the bank angle and height of nearby stable or reference banks were collected at each major failure site. Probability distributions of these measurements are shown in Figures 10 and 11. These data indicate that banks can be stable at similar heights to the failed banks, but the reference median bank angle (~50 degrees) is significantly less steep than the median bank angle for the failure locations (~70 degrees). This trend indicates two possible conclusions: 1) Bank angle is stronger driver of instability than bank height, or 2) Bank angles are steeper because the failure plane of the bank angle was measured, which would indicate that the data show effects of bank failure on bank geometry rather than bank angle being a cause of bank failure. Analysis of this field data also indicates that local soils can support bank angles up 40 degrees, nearly a 1:1 slope. Beyond this threshold bank failure is common. Given this data, layback slopes for non-reinforced canal banks should be greater than 1:1 (Horizontal to Vertical), particularly if the stabilized slope has a bank height greater than seven feet. Layback slopes in the range of 1:1 to 1.5:1 can be utilized if revegetation measures and turf reinforcements mating are incorporated into the design. Slopes approaching 1:1 could be utilized if the consequences of slope adjustment and minor sluffing are acceptable at the bank stabilization location otherwise larger factors of safety would be advisable.

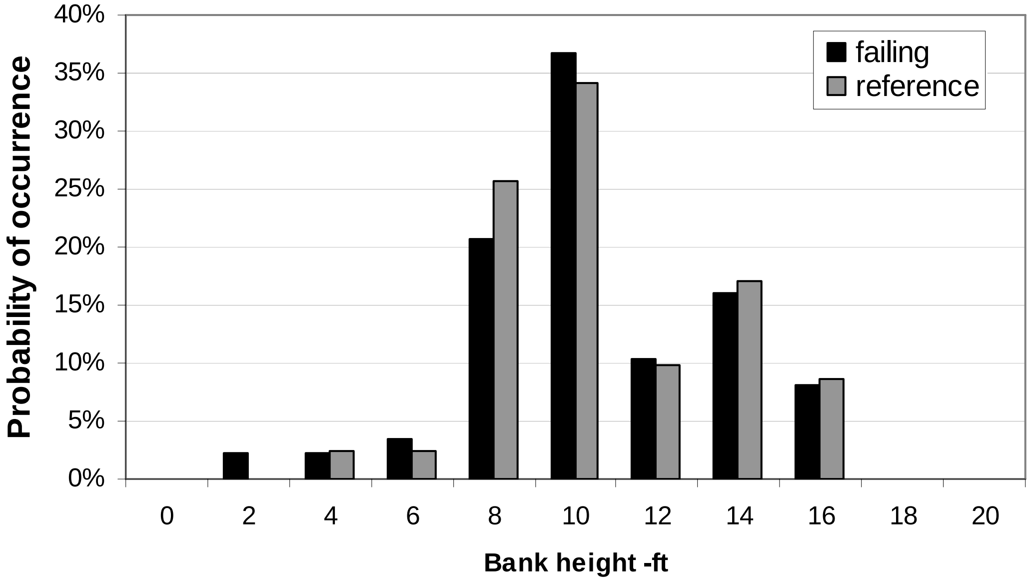


Figure 10: Probability Distribution of Bank Heights for Santiam-Albany Canal Failure and Reference Banks at Major Failure Locations

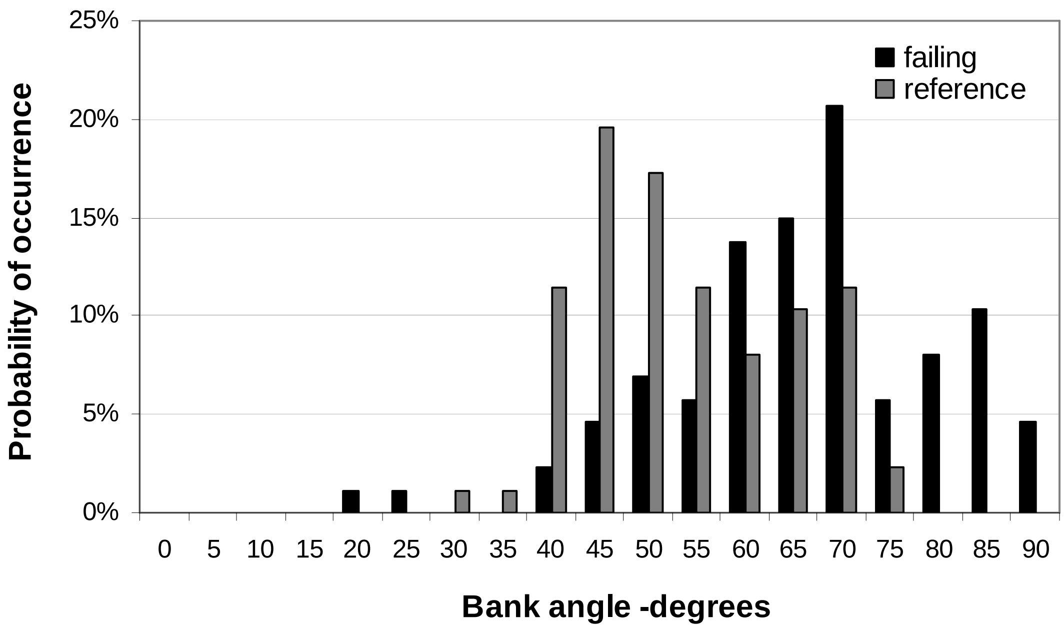


Figure 11: Probability Distribution of Bank Angles for Santiam-Albany Canal Failure and Reference Banks at Major Failure Locations

Analysis of Bank Failure Type and Process for Field Observations at Major Failure Locations

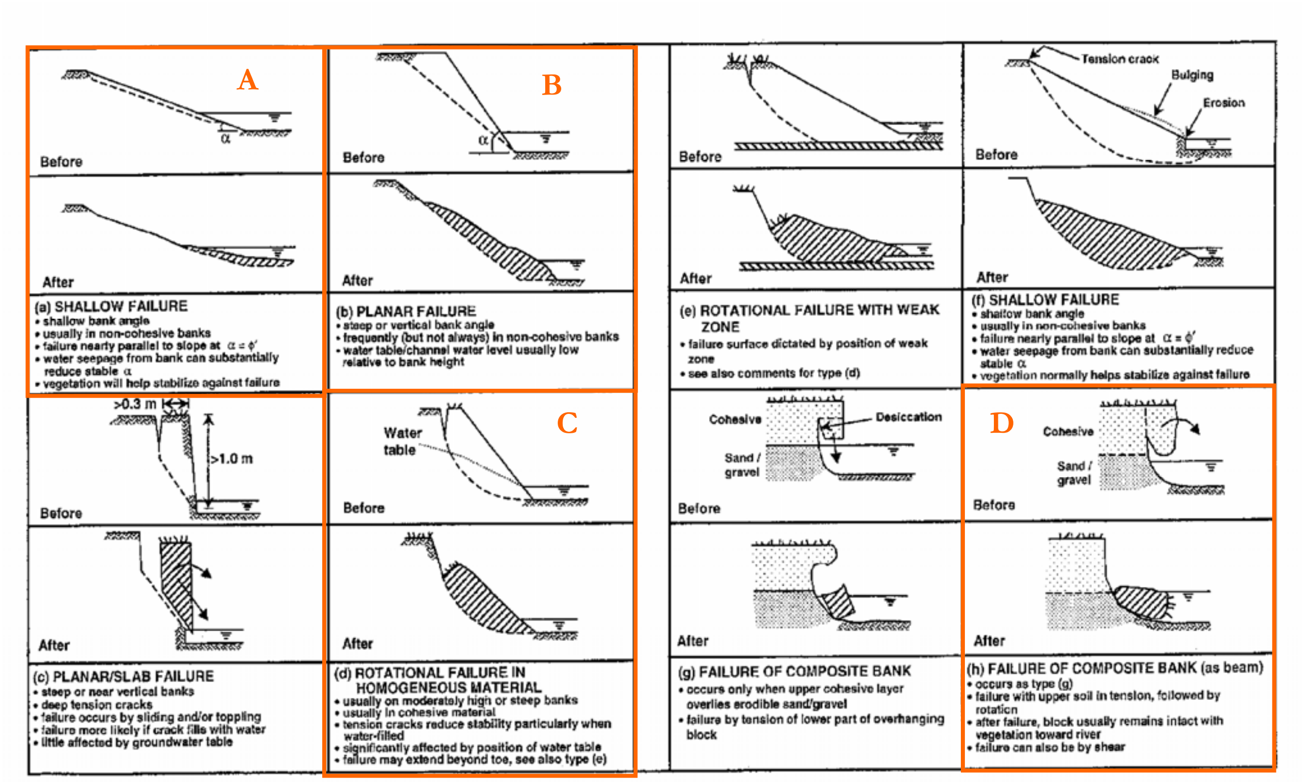
A qualitative estimate of bank failure type was also noted during the winter 2007 field reconnaissance of the bank failures in the canal. The results of these observations are reported in Tables 5 and 6. Four typical scenarios were delineated in the field, as shown in Figure 12. The presence of tension cracks and undercutting were also documented. Plane slip and rotational slip failures are geotechnical failures that result from exceeding a critical bank height threshold. Results of the data analysis of field observations indicate that 89 percent of the bank failures observed in the canal is geotechnical in nature. Only 2 percent of the failures are the result of scour, and 5 percent are related to cantilever type failures which can also be a result of hydraulic erosion of stratified soil layers that exhibit varying erosion resistance properties. In these failures a more easily eroded soil type may underlie a more resistant layer. Tension cracks are observed in 33 percent of the failures, these are another indicator of geotechnical failure. Only 9 percent of the plane slip failures exhibited undercutting. Undercutting could be attributed to fluvial erosion. Results of these analyses indicate that geotechnical type bank failures are the dominant failure mechanism for the canal. These geotechnical failures are primarily due to over heightened and over steepened banks resulting from long-term channel incision. However, failure in these banks can be triggered by other contributing factors such as bank saturation, tree surcharge, animal burrowing, etc., that will be discussed in the following sections.

Table 5: Qualitative Bank Failure Mechanisms Observed at Major Failure Locations

Failure Type	Count	%
Plane slip	69	84%
Cantilever	4	5%
Rotational slip	4	5%
Scour	2	2%
Shallow slide	2	2%
unknown	1	1%

Table 6: Frequency Of Tension Cracks And Undercutting Observed At Plane Slip Failure Sites

Plane Slip Failure Mechanisms	Count	%
Plane slip with tension crack	23	33%
Plane slip no tension crack	46	67%
Plane slip and undercut	6	9%
Plane slip and not undercut	63	91%



A – Equivalent of the *Shallow Slide*
B – Equivalent of the *Plane Slip*
C – Equivalent of the *Rotational Slip*
D – Equivalent of the *Cantilever Failure*

Figure 12: Qualitative Bank Failure Mechanisms Noted in Field Measurements of the Santiam-Albany Canal (Adapted from Lagasse et al. 2001)

Bank Saturation Due to Overland Runoff

The dominant drainage pattern along the canal is from southwest to the northeast (Figure 13). This generally results in significant overland flow drainage effecting the left bank (facing downstream) of the canal. Data from the field survey indicates that 63 percent of the failures occurred on the left bank side of the canal

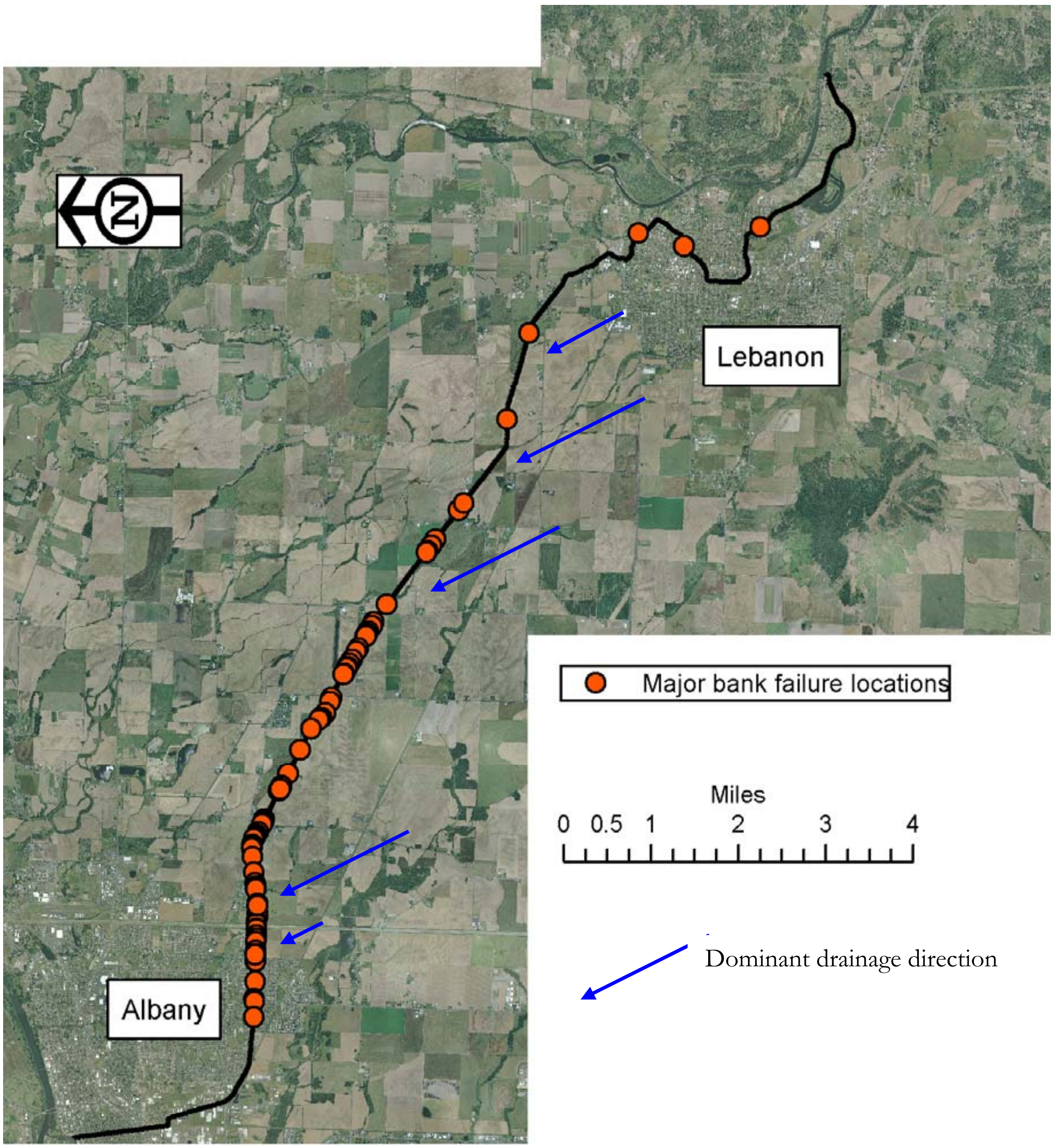


Figure 13: Aerial view of dominant overland drainage paths and bank failure locations along the Santiam-Albany canal

Soil geotechnical shear strength can be represented by Equation 2.

$$\tau = c' + \sigma' \tan\phi$$

where

$c' = cohesion$ **Equation 2**

$\sigma' = normal\ stress\ on\ the\ failure\ plane$

$\phi = friction\ angle$

The assumption can be made that the friction angle is zero under fully saturated conditions for cohesive soils, like those found along the canal. Therefore, full saturation is the most likely scenario for geotechnical failure. Overland drainage conditions that promote continuous reaches of bank saturation are prone to failure. Saturated soils exist at approximately 50 percent of the field observed bank failure sites, and significant groundwater seepage exists at 17 percent of those sites. Bank saturation coupled with steep high banks is a primary mechanism of failure along the canal, an example is shown in Figure 14.

Figure 14: Saturated Soils Leading to Bank Failure Near Station 340+00

Gully formation from concentrated overland flow

Along the length of the canal overland drainage paths frequently cross the canal. Some of the larger drainages; Cox Creek, Burkhart Creek, and Periwinkle Creek cross under the canal. In other cases overland flow is routed across the canal in above ground pipes. In some instances along the canal overland drainage is allowed to flow directly into the canal (Figure 15). This creates a hazard of creating an overland gully that introduces significant amounts of sediment into the channel and creates localized bank stability problems. Field drainage should be intercepted and routed into the canal at approximately the operational water surface elevations to mitigate the instability at these locations.

Figure 15: Overland Flow Gullying Downstream of Cox Creek Crossing 426+00

Wetting/Drying Freeze/Thaw cycles

Wetting and drying and freeze/thaw cycles greatly increase potential of failure in cohesive soil banks. Fortunately, the climate of the Willamette Valley is fairly mild, which limits freezing of soils in the area. Freeze/thaw and frost action widens pre-existing cracks and disaggregates surface material (Knighton 1998), acting as a pre-conditioning process for bank failure (Figure 16). Vegetative cover which serves to insulate canal banks from freeze thaw cycles offers the best potential for mitigating this problem.

Bank wetting and drying is another driver of bank instability. Failure in cohesive streambanks will often occur during rapid drawdown of the water surface. This occurs because the banks are saturated resulting in decreased soil strength and confining water pressure from the canal is no longer present to buttress the bank. Bank wetting and drying also causes swelling and shrinking leading to the development of fissures and tension cracks in the soil, thus creating a potential failure plane (Thorne 1982). Canal operations should be conducted to avoid canal bank wetting and drying. These operations should address both flow rate and hydraulic control structures.

Figure 16: Disaggregation of Cohesive Bank Material from Freeze/Thaw Action

Role of vegetation in canal bank stability

Vegetation characteristics play an important role in canal bank stability. Vegetation can be both beneficial and detrimental for canal bank stability depending on the scenario. This section will briefly describe failure mechanisms caused by the present vegetation regime in the canal as well as benefits for bank stability provided by vegetation.

Benefits of bank vegetation for stability

The role of vegetation in providing increased stability of stream banks is well documented. Bank roots generally reinforce stream banks and provide tensile strength to the stream bank soils. Studies have shown up to 20,000 fold increases in erosion resistance for vegetated banks compared to unvegetated banks (Smith 1976). Field data from the major failure locations on the canal indicates the potential benefits of vegetation for bank stability (Table 7). Nearly 70 percent of the bank failure locations had slope faces that were nearly devoid of significant vegetation needed to reinforce soil structure. Percentages are greater than 100 percent because the bank may have been classified with multiple types of vegetation for one site. This highlights the importance of having some form of vegetation present to stabilize the canal banks. The width of the vegetated corridor also plays a vital role in bank stability (Table 8). This data indicates that cases with vegetation corridors of less than 10 feet contribute 88 percent of the bank failure locations. The riparian area provides bank reinforcement and intercepts overland runoff that leads to bank saturation. The riparian corridor can also provide pollutant removal benefits improving water quality in the canal.

Table 7: Major Failure Vegetation Characteristics

Slope Face Vegetation Characteristics	Count	%
bare slope face	58	71%
grass slope face	10	12%
shrub slope face	9	11%
treed slope face	8	10%
Top of Bank Vegetation Characteristics		
bare top of bank	21	26%
grass top of bank	58	71%
shrub top of bank	22	27%
treed top of bank	10	12%

Table 8: Vegetated Corridor Width at Major Failure Locations

Vegetated width	Count	%
Zero	3	4%
<= 5 feet	26	32%
5-10 feet	43	52%
11-20 feet	9	11%
> 20 feet	1	1%

Detriment of Bank Vegetation on Bank Stability (tree mortality and surcharge)

Bank vegetation can also be a detriment to canal stability. One problem in particular is the abundance of large trees that are reaching the end of their lifespan along the canal. These trees add excess surcharge (weight) to the bank. There are two different failure mechanisms that result from these trees:

1. The excess surcharge from the tree leads to a rotational slip failure leaving the tree rootball at the toe of the slope (Figure 17)
2. The tree leaning into the canal creates a moment arm for bank failure toppling the tree into the canal (Figure 17).

Figure 17: a. Rotational Slip and b. Leaning Moment Arm Tree Failure Mechanisms

Both of these mechanisms lead to bank failure that introduces both sediment and woody debris into the system. This has severe ramifications for both downstream capacity and flooding issues (Figure 18). These failures can also lead to flow impingement and hydraulic erosion of the opposing stream bank after the wood is introduced into the system.

Figure 18: Debris Introduced Into Canal From Tree Failure Mechanisms

Rodent Burrowing

Nutria (Myocastor coypus) (Figure 19) are invasive and prolific rodents that are prevalent along the entire length of the canal. Nutria are semi-aquatic rodents that feed on riparian vegetation and roots. Nutria burrowing (Figure 19) is common along the entire length of the canal. Burrowing has three negative consequences for bank stability:

1. Burrows create preferential conduits (piping) for overland flow to enter the bank and saturate soils.
2. Burrows disturb the soil structural integrity of the bank, thereby weakening the bank.
3. Burrows disturb root soil contact leading to increased tree mortality and increasing the incidence of tree failures.

Although nutria damage is prevalent along much of the canal, analysis of the major failures database indicates that burrowing damage was noted at only 6 percent of the major failure locations. This indicates that the nutria damage is certainly a nuisance and one of the causative factors of bank failure, but it is not a major driver of bank stability. Another negative influence of the nutria populations is the negative consequences on water quality from nutria excrement and nematodes that are shed by nutria that lead to skin infections in humans.

A major problem posed by nutria burrows for future canal operating flows is that they will be conduits for seepage flow out of the canal increasing the likelihood of property damage adjacent to the canal when the canal operating flows are augmented.

Figure 19: Nutria and Burrowing Damage Along Bank at Station 22+869

Impinging Flow and Hydraulic Eddying from Obstructions and Debris

When trees and debris from failing banks and tree mortality failures enter the canal they can initiate further bank failure by changing the channel hydraulics. This mechanism can also be set up in the urban environment with flow obstructions and infrastructure. Typically flow is constricted or redirected into the opposing bank creating increased velocity and hydraulic erosion of the canal bank (Figure 20). This is referred to as impinging flow. Secondary currents both behind the obstruction and at the impinging flow failure site are also set up with this mechanism leading to further scour. This is referred to as hydraulic eddying.

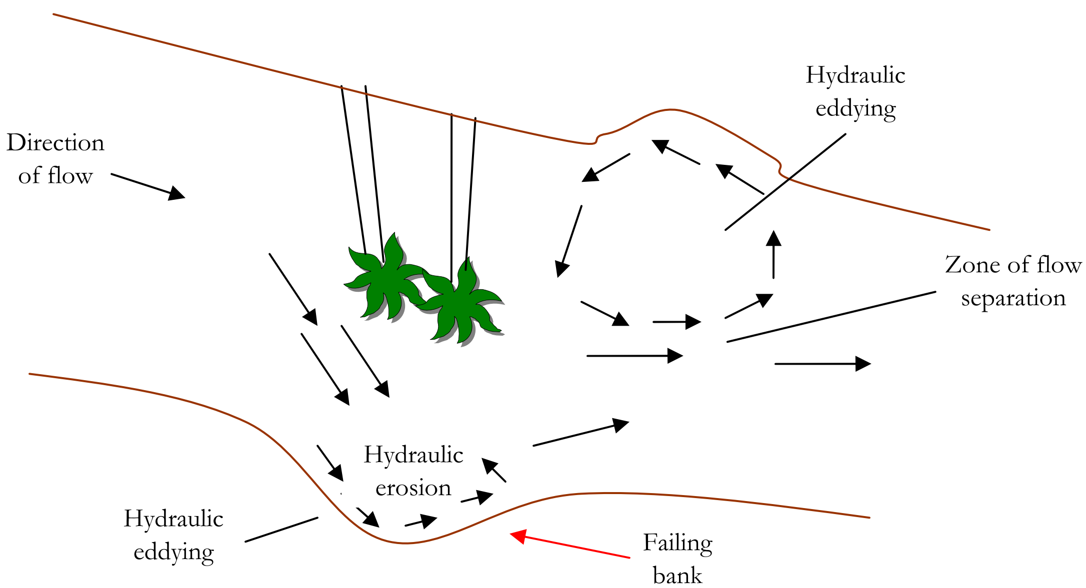


Figure 20 Impinging Flow and Schematic

This failure process is common along both the rural and urban portions of the canal (Figure 21). Among the major failure sites, 16 percent of all failure sites introduced debris into the canal that resulted in impinging flow and flow constriction at the failure site. Any debris introduced into the canal should be removed on an annual basis.

Figure 21: Examples of Impinging Flow and Back Eddy Failure Mechanisms

Bend Scour

In cases where the canal planform geometry makes sharp bends, erosion will often occur on the outside of the bend. This is due to both accelerated velocities on the outside of the bend and secondary currents that are set up by helical flow patterns typically present in bends. Sharp bends are not common on the canal and thus bend scour is a minor mechanism for bank failure along the canal. One example of bend scour failure is shown in Figure 22.

Figure 22: Bend scour present near station 702+60

Undercutting and Soil Slump Due to Changes In Bank Vegetation and Soil Stratigraphy

There are many instances along the canal particularly in the urban Lebanon area where bank slump has occurred on banks with fairly low bank height (~4 ft). One potential cause of this failure mechanism is the layered bank stratigraphy associated with residential lawns that result in differing resistance to erosion and wetting/drying cycles. The vegetation provides reinforcement and resistance to erosion. Whereas the underlying layer is subject to wetting/drying and freeze/thaw cycles that weaken the soil structure below the grassy vegetation. The non-vegetated portion of the bank sloughs into the channel and that material is carried away by hydraulic forces, leaving an over-hanging grassy bank that fails by cantilever mechanism. Examples of this mechanism are shown in Figures 23 and 24.

Figure 23: Bank slough failure near station 797+13

Figure 24: Bank slough failure near station 724+62

Failing Infrastructure

In some cases canal bank failures occur in areas that have been protected previously. These areas are usually retaining walls or revetments that have reached the end of their design life spans. This type of failure typically occurs in the urban portions of the canal in Lebanon and Albany. In some instances rooting from mature trees causes the bank instability; whereas, in other areas, the present infrastructure quality does not meet design criteria for functionality, aesthetics or safety. Examples are shown in Figures 25 and 26.

Figure 25: Failed retaining wall in Lebanon near station 771+45

Figure 26: Inadequate Retaining Wall in Albany Station 3+38

Spatial Distribution of Bank Failure Mechanisms in the Santiam-Albany Canal

This section addresses the spatial distribution of bank failure mechanisms on a reach-by-reach basis for the canal. The reaches utilized in this analysis are those offered by Otak, 2008. The river stationing for the analysis reaches is indicated in the heading for each reach. The reach analysis also describes the spatial location, geologic and soil properties of the reach. A basin-wide map of the analysis reaches is presented in Appendix B. Summary **Table 9** is provided to indicate failure mechanisms present on a reach by reach basis.

Reach 1 (963+79 – 928+20)

This reach extends from the head gates at the South Santiam River to the bridge crossing near Halcyon Mobile Park., a distance of approximately 3,559 feet. The upper portion of the reach is underlain by unconsolidated silt, sand, and gravel that are floodplain deposits of the South Santiam River. These materials are locally exposed in the canal bed. Soils developed on the floodplain deposits consist of the Newberg series, which are primarily sandy loams (U.S.D.A., 1987).

The stream banks are generally stable in this reach. The coarse cobble and gravel bed material has prevented channel incision. There are some locations with moderate bank instability. These locations are primarily associated with landscape and housing encroachment, as well as tree mortality.

Reach 2 (928+20 – 866+47)

This reach is 6,173 feet long and extends from Halcyon Mobile Park to the River Road Bridge located downstream of Cheadle Lake. Gravels to cobbles, locally overlain by a mantle of silt, were observed in the canal bed. This reach of the canal is underlain by South Santiam River floodplain deposits (O'Connor and others, 2001). Soils of the Newberg series have developed on the floodplain deposits. The soils consist primarily of sandy loams (U.S.D.A., 1987).

The banks are generally stable and there are no major failure locations within this reach. Soil saturation and piping are a concern on the left bank side of the canal in the vicinity of Cheadle Lake. These banks separating the canal from the lake are presently stable but ground water flow was observed during field reconnaissance and should be addressed in the long term canal repair plan. Some tree mortality failures were observed that resulted in flow impingement on the opposite bank.

Table 9: Summary of Bank Failure Mechanisms Present on a Reach Basis for the Santiam-Albany Canal															
Reach number	**River Stationing**	**Reach description**	**Dominant Soil Type**	**Channel incision leading to over-heightened banks**	**Bank saturation**	**Gullying from overland runoff**	**Impinging/eddying flow patterns**	**Bend Scour**	**Soil slump due to vegetation/stratigraphy changes**	**Failing infrastructure/Urban encroachment**	**Wetting/ Drying**	**Freeze/Thaw**	**Rodent burrowing**	**Tree mortality**	**Weak soils**
1	963+79 - 928+20	South Santiam Inlet to Halcyon mobile park	Newberg fine sandy			x			x	x		x	x	x	
2	928+20 - 866+47	Halcyon mobile park to River Rd. bridge	Newberg fine sandy		x		x					x	x	x	x
3	866+47 - 829+68	River Rd. bridge to Franklin St.	Malabon silty clay loam				x		x	x	x	x	x		x
4	829+68 - 773+21	Franklin St. to Lebanon WTP	Clackamas gravelly silt				x		x	x	x	x	x		
5	773+21 - 694+63	Lebanon WTP to Crown Zellerbach (CZ) gates	Newberg fine sandy				x	x	x	x		x		x	x
6	694+63 - 679+03	CZ gates to Albany gates	Newberg fine sandy									x		x	
7	679+03 - 649+58	Albany gates to Highway 20 bridge	Malabon silty clay loam				x					x		x	
8	649+58 - 524+60	Highway 20 to Langmack Rd.	Clay loams/silty		x	x	x		x	x		x		x	
9	524+60 - 486+70	Langmack Rd. to Tallman Rd.	Salem gravelly silt		x	x	x					x			
10	486+70 - 417+08	Tallman Rd. to Red Bridge Rd.	Coburg silty clay loam	x	x	x	x				x	x	x	x	x
11	417+08 - 276+65	Red Bridge Rd. to grade/irrigation control	Amity/Dayt onSilt loam	x	x	x	x				x	x	x	x	x
12	276+65 - 226+36	Grade control to Periwinkle Cr. Crossing	Woodburn/ Dayton silt	x	x		x					x	x	x	x
13	226+36 - 162+18	Periwinkle Creek crossing to Columbus St.	Concord/ Dayton silt	x	x					x		x			
14	162+18 - 99+84	Columbus St. to cohesive clay bed reach	Concord silt loam							x		x	x		x
15	99+84 - 61+66	Cohesive clay reach to Albany headcut	Concord silt loam									x			
16	61+66 - 38+60	Headcut to sluice gate backwater reach	Dayton silt loam									x			
17	38+60 - 1+43	Low gradient reach upstream of Albany WTP	Holcomb silt loam							x	x	x			

Reach 3 (866+47- 829+68)

Reach 3 is approximately 3,679 feet long, extending from River Road Bridge to the Franklin Street Bridge in the City of Lebanon. It is underlain by Pleistocene sand and gravel deposits that post-date the Missoula Floods (O'Connor and others, 2001). These deposits consist of unconsolidated sand and gravel laid down by the ancestral South Santiam River. Observations of the materials underlying the canal bed indicated a transition from the coarser upstream deposits to sand and silt. Soils developed on the Pleistocene sand and gravel deposits are soils of the Malabon series. In general, the Malabon series consists of silty clay loam (U.S.D.A., 1987).

Canal banks in this reach are typically stable, with some localized areas of bank erosion. There is one major failure location in this reach. The dominant mechanism for failure is soil slumping due to changes in vegetation and bank material stratigraphy associated with lawns that abut the canal. Wetting and drying mechanisms exacerbated by backwater conditions also contribute to failure locations within the reach. Hydraulic eddying is another contributing factor for bank failure as back eddies formed by flow obstructions set up secondary currents that contribute to bank erosion.

Reach 4 (829+68 – 773+21)

Reach 4 is 5,647 feet long, extending through urban Lebanon from the Franklin Street Bridge to the Lebanon WTP. The reach is underlain by Pleistocene sand and gravel deposits that post-date the Missoula Floods (O'Connor and others, 2001). These consist of unconsolidated sand and gravel deposited by the ancestral South Santiam River. Silt deposits were the predominant bed material observed in the canal. Malabon silty clay loam and Clackamas gravelly silty loam represent the soils that have developed on the sand and gravel deposits (U.S.D.A., 1987).

Failure mechanisms within this reach are very similar to Reach 3. The dominant bank failure processes are bank slump due to urban lawns, wetting and drying, and hydraulic eddying from secondary currents. Banks are generally stable and not over-heightened. The silting of the bed material indicates aggradation within the reach.

Reach 5 (773+21- 694+63)

This reach is 7,858 feet long, extending from the Lebanon WTP to the Crown Zellerbach (CZ) gates. This portion of the canal is underlain by Pleistocene sand and gravel deposits that post-date the Missoula Floods (O'Connor and others, 2001). These are unconsolidated deposits of sand and gravel laid down by the ancestral South Santiam River. Malabon silty clay loam and the Newberg fine sandy loam are the soils developed on the Pleistocene sand and gravel deposits (U.S.D.A., 1987).

Bank failures in this reach are typically associated with urban encroachment on the canal banks. In places, infrastructure is threatened or failing. The Newberg fine sandy loam soils are more susceptible to soil slump and localized sloughing, due to low plasticity. Some locations indicate tree mortality may potentially lead to future bank failure problems. Bend scour is present in the vicinity of river station 702+00 on the left bank side of the canal.

Reach 6 (694+63 – 679+03)

Reach 6 is 1,560 feet long, extending from the CZ gates downstream to the Albany gates. Pleistocene sand and gravel deposits that post-date the Missoula Floods underlie this reach (O'Connor and others, 2001). These deposits were laid down by the ancestral South Santiam River. Bed materials transition from cobble and gravel at the upstream end to silt at the downstream end in the zone of influence of the Albany gates. The Newberg fine sandy loam and Malabon silty clay loam are the soils developed on the Pleistocene sand and gravel deposits (U.S.D.A., 1987).

Banks are stable in this reach. Urban encroachment is minimal and the stream banks are well vegetated and stable. Channel incision is minimal, likely prevented by the underlying gravels in the reach. There are some isolated areas of tree mortality problems, however these locations are infrequent and of little consequence for bank stability

Reach 7 (679+03 – 649+58)

Reach 7 is 2,945 feet long, extending from the Albany gates to the Highway 20 crossing. The reach is underlain by Pleistocene flood deposits that post-date the Missoula Floods. These deposits consist primarily of unconsolidated sand and gravel deposited by the ancestral South Santiam River. Outcrops of gravel were observed near the downstream end of the reach. Malabon silty clay loam is the soil underlying most of the reach. Clackamas gravelly silty loam occurs at and upstream of the Highway 20 crossing (U.S.D.A., 1987).

Banks are generally stable within this reach; however, there are areas where urban encroachment results in over-steepened channel banks with minimal bank vegetation that are susceptible to freeze/thaw processes and subsequent bank instability. Tree mortality is prevalent in some areas resulting in tree failure and subsequent flow impingement and hydraulic eddying exacerbating bank erosion in these locations. Channel incision is mitigated by the geologic outcrops of gravel in the canal bed. There are no major failure locations within this reach.

Reach 8 (649+58 - 524+60)

This rural reach extends 12,498 feet from the Highway 20 Bridge crossing to Langmack Road. It is underlain primarily by Pleistocene flood deposits (post-dating the Missoula Flood) of the ancestral South Santiam River. These deposits consist primarily of unconsolidated deposits of sand and gravel. The lower end of the reach is underlain by the primary fine-grained facies of the Missoula Flood deposits (O'Connor and others, 2001). These deposits consist of interbedded clay and silt, with minor amounts of sand. Several different soils have developed on the Pleistocene flood deposits and Missoula Flood deposits. These include the Bashaw silt, Chapman loam, Coburg silty loam, Conser silty loam, Courtney gravelly silty loam, and Malabon silty clay loam.

Historical longitudinal profile data indicates that this reach has incised approximately 1.8 feet since the canal was initially constructed. Several knick points were observed along the reach indicating that it is actively incising. Coarse gravels from the Pleistocene flood deposits underlie most of the reach and have prevented incision to some degree. Incision has been moderate and bank heights generally have not exceeded critical failure thresholds. There are areas where overland runoff has either gullied the canal banks or created zones of bank saturation resulting in stability problems. There are some areas of urban encroachment on the canal in the upstream portion of the reach resulting in infrastructure and soil slump type failures. Overall the banks in this reach are stable. There were only two major failure locations identified in the reach during the field reconnaissance.

Reach 9 (524+60 – 486+70)

This rural reach extends from the Langmack Road crossing to Tallman Road, a distance of 3,790 feet. It is underlain by the primary fine-grained facies of the Missoula Flood deposits; these deposits consist of interbedded clay and silt, with some minor sand (O'Connor and others, 2001). Soils that have developed on the flood deposits include the Awbrig silty clay loam, Coburg silty loam, Courtney gravelly silty loam, and Salem gravelly silt loam (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised approximately 1.5 feet since the canal was initially constructed. Active knick zones were not observed along the reach. However, hydraulic modeling results indicate that this is the steepest reach in the canal with reach average energy slope of 0.0026 (ft/ft); therefore, future incision is likely. The canal bed transitions from gravel to consolidated clay and silt in this reach. Incision has been moderate and bank heights generally have not exceeded critical failure thresholds. There are areas where overland runoff has either gullied the canal banks or created zones of bank saturation resulting in stability problems. Tree mortality failures along this reach are infrequent. Banks within this reach are generally stable. There were only two major failure locations identified in the reach during the field reconnaissance.

Reach 10 (486+70 – 417+08)

This rural reach extends 6,962 feet from the Langmack Bridge crossing downstream to the Red Bridge Road crossing. The reach is underlain by the primary fine-grained facies of the Missoula Flood deposits, a series of interlayered clay and silt, with minor sand (O'Connor and others, 2001). Soils developed on the flood deposits include the Coburg silty loam, Concord silt loam, and Waldo silty clay loam (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised approximately 3.4 feet since the canal was initially constructed. Active knick zones were not observed along the reach. However, hydraulic modeling results indicate that this reach is significantly steeper than downstream reaches that have had greater incision depth over time. The reach average energy slope in this reach is 0.0022 (ft/ft) compared to 0.0013 (ft/ft) in the more incised reaches downstream. The steeper slope indicates that future incision is likely within this reach. The canal bed is primarily consolidated clay and silt, with areas of gravel deposition on the hardpan bottom. Bank heights are approaching critical failure thresholds within the reach. Land use is rural in this reach and there are areas where agricultural overland runoff has either gullied the canal banks or created zones of bank saturation resulting in stability problems. Tree mortality failures along this reach are common and often induce canal blockages and impinging flow on the canal banks. There were five major failure locations identified in the reach during the field reconnaissance.

Reach 11 (417+08 – 276+65)

This rural reach extends 14,043 feet from Red Bridge Road downstream to a large grade control structure located at Station 276+65. The reach is underlain by the primary fine-grained facies of the Missoula Flood deposits, a series of interlayered clay and silt, with minor sand (O'Connor and others, 2001). Soils developed on the flood deposits include Amity silt loam, Concord silt loam, Dayton silt loam and Woodburn silt loam. Twenty-five major bank failures were observed along this reach (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised approximately six feet since the canal was initially constructed. Active knick zones were not observed along the reach. The reach average energy slope in this reach is 0.0014 (ft/ft) indicating that slope adjustment is near complete in this reach and now the dominant channel process is widening and bank failure. The canal bed is primarily consolidated clay and silt with areas of gravel deposition on the hardpan bottom. Banks heights typically exceed critical failure thresholds within the reach and bank failures are common along the reach, often inducing canal blockages and impinging flow on the canal banks. Land use is rural and there are areas where agricultural overland runoff has been directed through the canal banks, creating zones of bank saturation and gullying resulting in stability problems. There were 25 major failure locations identified in the reach during the field reconnaissance, the largest number of any reach along the canal. A large grade control structure is present at the downstream end of this reach that serves to prevent future degradation in the reach.

Reach 12 (276+65 – 226+36)

This reach is 5,029 feet long, extending from the grade control structure located at Station 276+65 to approximately the Periwinkle Creek crossing. Primary fine-grained Missoula Flood deposits, consisting of interbedded clay and silt (with minor sand), underlie the canal (O'Connor and others, 2001). Soils developed on the flood deposits include the Amity silt loam, Dayton silt loam, Waldo silt loam, and Woodburn silt loam (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised approximately 7.5 feet since the canal was initially constructed. This is the largest degradation rate along the canal. Active knick zones were observed along the reach indicating that some slope adjustment is occurring presently. However, reach average energy slope in this reach is 0.0013 (ft/ft) indicating that slope adjustment is near complete in this reach and now the dominant channel process is widening and bank failure. The canal bed is primarily consolidated clay and silt with areas of gravel deposition on the hardpan bottom. Banks heights exceed critical failure thresholds within the reach and bank failures are common along the reach, often inducing canal blockages and impinging flow on the canal banks. Land use is predominantly rural and there are areas where agricultural overland runoff saturates the canal banks resulting in stability problems. At the downstream extent of the reach the land use transitions to urban and some private property is threatened by failing canal banks. There were 20 major failure locations identified in the reach during the 2007 field reconnaissance. A gradient control is present at the downstream end of this reach where Periwinkle Creek passes under the canal. There are areas along the reach where historic bank failures and associated vegetation and trees serve to stabilize the bank toe, typical of a CEM Stage 4 channel (Schumm et al. 1984).

Reach 13 (226+36 – 162+18)

Reach 13 extends from the Periwinkle Creek crossing downstream to Columbus Street, a distance 6,418 feet. Interlayered clay and silt, with minor sand, of the Missoula Flood deposits underlie this reach (O'Connor and others, 2001). Soils developed on the flood deposits along this reach include Amity silt loam, Concord silt loam, Dayton silt loam, Waldo silt loam, and Woodburn silt loam (U.S.D.A., 1987). Major bank failures were observed in 24 locations along this reach of the canal.

Historical longitudinal profile data indicates that this reach has incised approximately 5.7 feet since the canal was initially constructed. The reach average energy slope in this reach is 0.0011 (ft/ft) indicating that slope adjustment is nearly complete. The canal bed is primarily consolidated clay and silt with areas of sand, silt and gravel deposition on the hardpan bottom, indicating some aggradational trends in the reach. Banks heights hover around critical failure thresholds within the reach and bank failures are not as frequent as they are in the more highly incised upstream reaches. Land use is predominantly suburban to urban, and some private property is threatened by over-heightened and over-steepened canal banks. There are also areas where agricultural overland runoff saturates the canal banks resulting in stability problems, particularly on the left bank side of the canal downstream of Interstate 5. There were 24 major failure locations identified in the reach during the field reconnaissance, indicating significant instability problems particularly within the urbanized portion of the reach.

Reach 14 (162+18 – 99+84)

This reach of the canal extends 6,234 feet from Columbus Street downstream to the in-channel debris rack located upstream of the Marion St. culvert. The reach is underlain by the primary fine-grained facies of the Missoula Flood deposits. These deposits consist of interlayered clay and silt, with minor sand (O'Connor and others, 2001). Soils that have developed on the flood deposits consist of the Amity silt loam, Concord silt loam, and Dayton silt loam (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised approximately 2.2 feet since the canal was initially constructed. The reach average energy slope in this reach is 0.001 (ft/ft) indicating future slope adjustment should be minimal. The canal bed is primarily consolidated clay and silt with areas of silt and sand deposition on the hardpan bottom, indicating some aggradational trends in the reach. Banks heights hover around critical failure thresholds within portions of the reach; however, bank failures are not frequent. Land use is predominantly suburban to urban and some private property is threatened by over-heightened and over-steepened canal banks. There was one major failure location identified in the reach during the field reconnaissance indicating that the banks are generally stable. Areas of instability are typically associated with urban encroachment on the canal banks.

Reach 15 (99+84 – 61+66)

This reach is 3,818 feet long extending from the Marion Street crossing to a head cut located approximately 330 feet upstream of the Railroad Bridge in Albany. Interlayered clay and silt of the Missoula Flood deposits underlie this reach (O'Connor and others, 2001). Soils developed on the flood deposits include the Amity silt loam, Concord silt loam, Dayton silt loam, and Woodburn silt loam (U.S.D.A., 1987).

Historical longitudinal profile data indicates that this reach has incised 2.8 feet since the canal was initially constructed. The reach average energy slope in this reach is 0.0014 (ft/ft). This is likely a result of the outcrop of marine shale from the Tertiary geologic epoch, creating a localized geologic control on the canal bed at the downstream extent of the reach. The canal bed is primarily consolidated clay and silt with areas of silt and sand deposition on the hardpan bottom, indicating some aggradational trends in the reach. Banks are stable throughout the reach and there were no major failure locations identified during the field reconnaissance.

Reach 16 (61+66 – 38+60)

Reach 16 is 2,306 feet long, extending from head cut to the sluice gate downstream of the Queen Avenue crossing. The reach is underlain by interlayered clay and silt (with minor sand) of the Missoula Flood deposits (O'Connor and others, 2001). Soils developed on the flood deposits along this reach of the canal include the Dayton silt loam and Woodburn silt loam (U.S.D.A., 1987).

This is an aggrading reach within the lower end of the canal in the urban Albany area. The reach average energy slope is (0.008 ft/ft). There were no major failure locations within the reach and the banks were stable throughout the reach.

Reach 17 (38+60 - 1+43)

This reach is 3,717 feet long, extending to the Albany WTP. It is underlain by inter-layered clay and silt (with some sand) of the Missoula Flood deposits (O'Connor and others, 2001). Soils developed on the flood deposits consist of the Clackamas gravelly silt loam, Dayton silt loam, Courtney gravelly silty loam, and Holcomb silt loam (U.S.D.A., 1987).

This is an aggrading reach within the lower end of the canal in the urban Albany area. The reach average energy slope is (0.004 ft/ft) and is highly depositional. There were no major failure locations within the reach and the banks were stable throughout the reach. Dredging is planned for the reach and there are many areas where the current infrastructure is outdated or inadequate to retain the canal banks if dredging impacts are significant. The stability of these areas should be addressed in the dredging analysis.

Dredging Considerations

Dredging has been proposed for portions of the canal. The reaches discussed in this section refer to the dredging reaches proposed by HDR 2008. These reaches are different from the hydraulic reaches proposed by Otak, 2008. This section discusses the geotechnical implications for the proposed dredging in the Lebanon and Albany locations. Aerial views of the dredging reaches and associated berms are presented in Appendix C. These were provided by HDR.

Reach 1 Dredging Considerations (844+67 – 773+11)

Dredge Reach 1 extends from approximately River Drive (located at Station 844+67) to the Lebanon Water Treatment Plant (WTP), located at Station 773+11). The proposed dredging segment is underlain by Pleistocene sand and gravel deposits that post-date the Missoula Flood (O'Connor and others, 2001). Malabon silty clay loam and Clackamas gravelly silty loam represent the soils that have developed on the sand and gravel deposits (U.S.D.A., 1987).

Based on the information reviewed and limited reconnaissance by Kleinfelder, most of the proposed dredging reach had canal banks that appeared relatively stable. However, local slope failures were reported by Otak (October 11, 2007). It is likely that wetting and drying of bank soils due to variations in flow rates and stages (i.e., water elevations) of canal water will continue to cause local slope failures.

HDR (February 28, 2008) reported that the preliminary results of their dredging analysis used an estimated dredging depth of approximately one foot and canal banks would be inclined no steeper than 1Horizontal: 1Vertical. The estimated volume of excavated soils was approximately 14,200 cubic yards. Using the information provided for review as the basis of this limited evaluation, it is likely that the dredging can be completed; however, local areas of slope failure and/or instability should be anticipated.

Recommendations

A geologic reconnaissance along the dredging reach several weeks prior to dredging is recommended. The reconnaissance objective is to verify field conditions, with particular emphasis on the condition of the canal banks at that time. The presence of new slope failures, as well as areas of potential slope instability, seepage, and areas of accelerated erosion, should be documented and discussed with the Project Geotechnical Engineer. Areas and structures (such as bridges, decks, walkways, and other appurtenances) that could be subject to potential adverse impact during dredging should be identified before dredging.

In Dredge Reach 1, a major concern is seepage of canal water beneath and through the berms at several locations. In June 2007, the City of Albany performed a flow test in the canal with flow rates varying from approximately 175 to 180 cubic feet per second. Seepage occurred through (and likely beneath) the right bank berm between the railroad and Highway 20 crossing (approximately Station 810+00 to Station 825+00) onto residential properties, particularly the Bailey and Adams residences, during the flow test. No other seepage areas were reported within the reach. The condition of the berms along and near the Bailey and Adams residences needs to be upgraded to reduce seepage and improve bank stability.

If we are able to lower the water surface elevation (WSE) by redesign of the Lebanon WTP intake and control structure, the WSE will remain at current levels. Otherwise, at full hydropower operation the WSE will rise approximately 1.5- to 2-feet. These two scenarios may have different impacts on the long-term stability of the existing berms.

Several options for reducing berm seepage along this segment of the canal have been reported (Foundation Engineering, Incorporated, November 9, 2007; HDR, November 7, 2007; and Brown and Caldwell, February 15, 2008). Various liner options, including bentonite and/or geotextiles, are commonly used to reduce seepage through and beneath berms. Additional geotechnical investigation is recommended to support the design and construction of an appropriate liner system. Characterization of the soils underlying the canal bed and along the berms should be completed to develop an understanding of the soil type(s), consistency and/or density, and hydrogeologic characteristics. This information will assist in the identification and selection of the appropriate liner system and provide the basis for estimating installation costs.

Potential groundwater seepage from the canal banks (including berms) and/or groundwater within the proposed dredging reach must be considered since it could adversely effect dredging. Groundwater and/or bank seepage could impact dredging, reduce access for equipment, and require construction dewatering. If construction dewatering is necessary, the design of a dewatering system, water storage (and possible treatment), and ultimate disposal might be necessary to facilitate dredging in this reach.

Reach 6 Dredging Considerations (58+00 to 1+43)

Dredge Reach 6 extends from the railroad crossing in Albany (58+00) to the Albany Water Treatment Plant (1+43), a distance of approximately 4,690 feet. The proposed dredging segment is underlain by inter-layered clay and silt of the Missoula Flood deposits (O'Connor and others, 2001). Soils developed on the flood deposits include the Amity silt loam, Concord silt loam, Dayton silt loam, and Woodburn silt loam (U.S.D.A., 1987). City staff and observations by HDR, Herrera Environmental Consultants, and Otak reported the presence of consolidated geologic materials along portions of the canal bed downstream of the 7th

Avenue Bridge. The type, extent (including depth), and nature of this geologic unit has not been determined. It is recommended that characterization of the hardpan unit be performed to determine its potential impact on dredging.

No major slope failures were reported within the limits of the proposed dredging reach (Otak, October 11, 2007). HDR (February 28, 2008) reported that berms exist at three locations along the dredging reach. The stability and seepage characteristics of these berms are unknown.

HDR (February 28, 2008) reported their preliminary dredging analysis used estimated dredging depths ranging from approximately one to six feet and that canal banks would be inclined from vertical to 1Horizontal: 1Vertical. Estimated volumes of dredged soils ranged from approximately 1,000 to 8,000 cubic yards. Using the information provided for review as the basis of this limited evaluation, it is likely that the dredging can be completed using the preliminary alternatives prepared by HDR (February 28, 2008); however, local areas of slope failure and/or instability could occur and should be anticipated.

Recommendations

A geologic reconnaissance is recommended along the dredging reach several weeks prior to dredging. The objective of the reconnaissance is to verify field conditions, with particular emphasis on observing and documenting the condition of the canal banks at that time. The presence of new slope failures, as well as areas of potential slope instability and areas of accelerated erosion, should be documented and discussed with the Project Geotechnical Engineer. Potential adverse impacts to structures (such as bridges, decks, walkways, and other appurtenances) should also be identified prior to dredging.

The potential for groundwater seepage from the canal banks and/or groundwater occurring within the vertical extent of dredging should be considered since it could adversely impact proposed dredging. Shallow groundwater or bank seepage could impact dredging activities, reduce access for equipment, and require construction dewatering. Should construction de-watering be necessary, the design of a dewatering system, water storage (and possible treatment), and ultimate disposal might be necessary to facilitate dredging in this reach.

Recommendations for Stabilizing Current Canal Bank Failures and Mitigation of the Driving Mechanisms for Failure

This section provides suggestions for stabilizing current bank failures and mitigation of the driving mechanisms that are causing bank instability in the Albany-Santiam canal. Generally, the recommendation can fall into two categories corrective and preventative measures. Corrective measures would repair past failures before they are exacerbated, whereas preventative measures serve to remove or minimize the causes of future failures. Recommendations at this stage are generally qualitative in nature. Site specific hydraulics, soil properties and site constraints should guide design on a site-by-site basis.

Channel Incision Leading to Bank Over-heightening

There is nothing that can be done about the historic incision that has taken place in the canal; however efforts can be made to arrest future incision problems in areas that may be subject to future incision. Incision can be halted through the use of gradient control structures that will serve to stabilize the existing canal bed profile and provide hydraulic control that will reduce erosive velocities and potentially induce deposition. These grade control structures should be placed in reaches with steep hydraulic gradients, which are presently showing degradational tendencies. The primary emphasis should be on the rural Linn County portion of the canal, particularly reaches 7 through 12. The structures should be on the order of two to three feet in height and placed at an equilibrium slope determined through hydraulic and sediment transport analysis. There are a number of methodologies available to determine the equilibrium or stable slope for a reach, among these are regime theory, maximum erosive velocity or sediment continuity methods. Recommendations on grade control structure size and location will be provided in subsequent technical memoranda.

Bank Saturation and/or Gullying Due to Overland Drainage

Overland runoff from the agricultural lands generally flowing to the left bank of the canal should be controlled to minimize zones of bank saturation. This can be accomplished by collecting the overland runoff prior to reaching the edge of the canal bank and piping the water into the canal at the water surface elevation for a typical operational flow. Another alternative that is currently used is to route the overland runoff along the drainage path across the canal.

Maintaining a riparian vegetative corridor is important for bank stability. The vegetation roots provide conduits for better drainage and the plant water transpiration mitigates long term bank saturation. Additionally, vegetation roots help to reinforce the bank soil by providing tensile strength to the soil.

Impinging Flow and Hydraulic Eddying From Obstructions and Debris

Impinging flow and hydraulic eddying conditions can be mitigated by removing canal debris and maintaining smooth transitions at the canal bankline. Historic bank failures have resulted in trees and snags that are located within the canal's ordinary high water channel and direct velocity vectors into the stream banks. These debris jams should be removed to maintain streamlines that are predominantly in the downstream direction. This can be considered a corrective measure which is being implemented from 2007-2008. Future canal management plans should incorporate routine inspections along the entire canal length for recent bank failures that have introduced debris into the canal and subsequent removal of the debris. This can be considered a preventative measure. Future canal projects should also address inconsistent boundaries at the canal bankline to minimize areas of flow separation and eddying at the bank line that result in scour and bank failure.

Bend Scour

Active bend scour is minimal along the canal. There was only one location identified from the available data where bend scour was the primary mechanism of bank failure. Bank stabilization and revetment is recommended as the appropriate mitigation for this failure mechanism. It may be useful to incorporate flow redirection into the bank stabilization projects, but the design should ensure that erosional velocities are not directed toward the opposite bank.

Undercutting and Soil Slump Due to Changes in Bank Vegetation and Soil Stratigraphy

Most failure locations along the urban portions of the canal in Lebanon and Albany occur in areas where residential lawns extend up the edge of the canal. The lawn vegetation is not able to establish on the steep slope faces that are frequently inundated by canal waters. The resulting lack of riparian vegetation along the bank toe results in soil slump and bank failure. Relatively low cost bioengineering techniques that incorporate plant species tolerant of frequent inundation and rock toe protection could be utilized to stabilize these locations. A riparian buffer that consists of a variety of native grasses, forbs, and shrubs would improve bank stability as well as water quality in the canal.

A low height gravity retaining wall could also be used as another mitigation option if the riparian buffer is not preferred by the property owner. This would improve bank stability in these locations and reduce land loss and sedimentation problems. This would be a higher cost solution with minimal water quality benefits; however, there may be a higher degree of design certainty associated with this alternative.

It is also advisable for the canal management plan to incorporate a citizen outreach program to illustrate preferred easement vegetation management alternatives that will promote canal bank stability and limit sediment and debris sources introduced into the canal from bank failures.

Failing Infrastructure

Areas where current infrastructure elements are failing should be addressed in the long-term canal maintenance plan. This will include significant lengths of retaining wall construction in the urban reaches. Some retaining wall areas could be fixed with alternative bank stabilization measures including bioengineering, toe protection, and slope laybacks.

Bank Wetting and Drying

The canal operating procedure should be implemented in a manner that limits large fluctuations in the water surface along the canal. A continuous steady flow should be drawn into the head gates and the hydraulic control structures within the canal should be operated to minimize water surface fluctuations along the canal. Frequent wetting and drying associated with water surface fluctuations will exacerbate bank failures rates along all portions of the canal. Establishing riparian vegetation along the canal banks will mitigate some of the bank stability problems associated with wetting and drying.

Bank Freeze/Thaw

Establishment of a riparian corridor along the canal banks is the only mitigation technique available for freeze/thaw problems. The riparian vegetation will cover and insulate bank soils, thus mitigating some of these freeze/thaw cycles.

Rodent Burrowing

Nutria eradication and trapping programs have presently been implemented in the area and should be a permanent element of canal berm maintenance. Trapping and extermination can help to reduce, but not eliminate the detrimental effects of Nutria populations on canal bank stability in the long-term.

Tree Mortality

Tree mortality is a significant source of bank stability problems along the canal. Trees that are approaching the end of their life-span, and are leaning at unstable angles, should be removed from the canal banks to eliminate the excess surcharge they exert on the canal banks. If the canal banks are at heights greater than seven feet the potential of bank failure induced by excess surcharge from trees is greater. Tree removal should be conducted carefully because not all trees along the canal banks pose stability problems. In fact, many trees along the canal add to bank stability. This is due primarily to root reinforcement provided to the canal banks from the trees which add tensile strength to the canal bank soils.

Soil Characteristics

Nothing can be done to mitigate the type of soil associated with various reaches along the canal; however, efforts should be made to identify the soil type associated with reaches where bank stabilization projects are proposed along the canal. This preliminary data will indicate whether the project is located in a soil type that is inherently resilient or prone to bank erosion. If the site is located within a soil type that is inherently prone to bank erosion and bank instability, more conservative bank stabilization design should be utilized at the site. Site specific geotechnical investigations may be necessary as well. The decision to collect site specific geotechnical data will depend on the scale of the bank stability problem, project budget constraints and the consequences associated with project failure.

Conclusions

A systematic methodology to investigate key issues regarding bank stability along the Santiam-Albany Canal has been presented in this document. Included in the contents are; 1) The geologic and pedologic setting for the project, 2) A discussion of the mechanisms and processes leading to canal bank failure, 3) The spatial distribution of bank failures and failure mechanisms in the reach context (Otak, 2008), 4) Implications of future canal dredging and operations on bank stability, and 5) Recommendations for stabilizing current canal bank failures and mitigation of the driving mechanisms for failure that will lead to long-term canal stability and self maintenance.

A variety of data sources have been analyzed and interpreted to determine the key processes resulting in bank instability issues along the Santiam-Albany Canal. The primary mechanisms of failure are:

- Channel incision leading to bank over-heightening
- Bank saturation due to overland drainage
- Gullying from overland runoff
- Impinging flow and hydraulic eddying from obstructions and debris
- Bend scour
- Undercutting and soil slump due to changes in bank vegetation and soil stratigraphy
- Failing infrastructure
- Bank wetting and drying
- Bank freeze/thaw
- Rodent burrowing

- Tree mortality
- Soil characteristics

Mechanisms and processes associated with the bank failures have been discussed and quantified where data was available. The spatial distribution of failure processes and mechanisms has been presented on a reach basis. Mitigation techniques available to alleviate the bank failure mechanisms are provided. If these mitigation techniques are implemented systematically and along the failure prone reaches of the canal, long-term bank stability is feasible.

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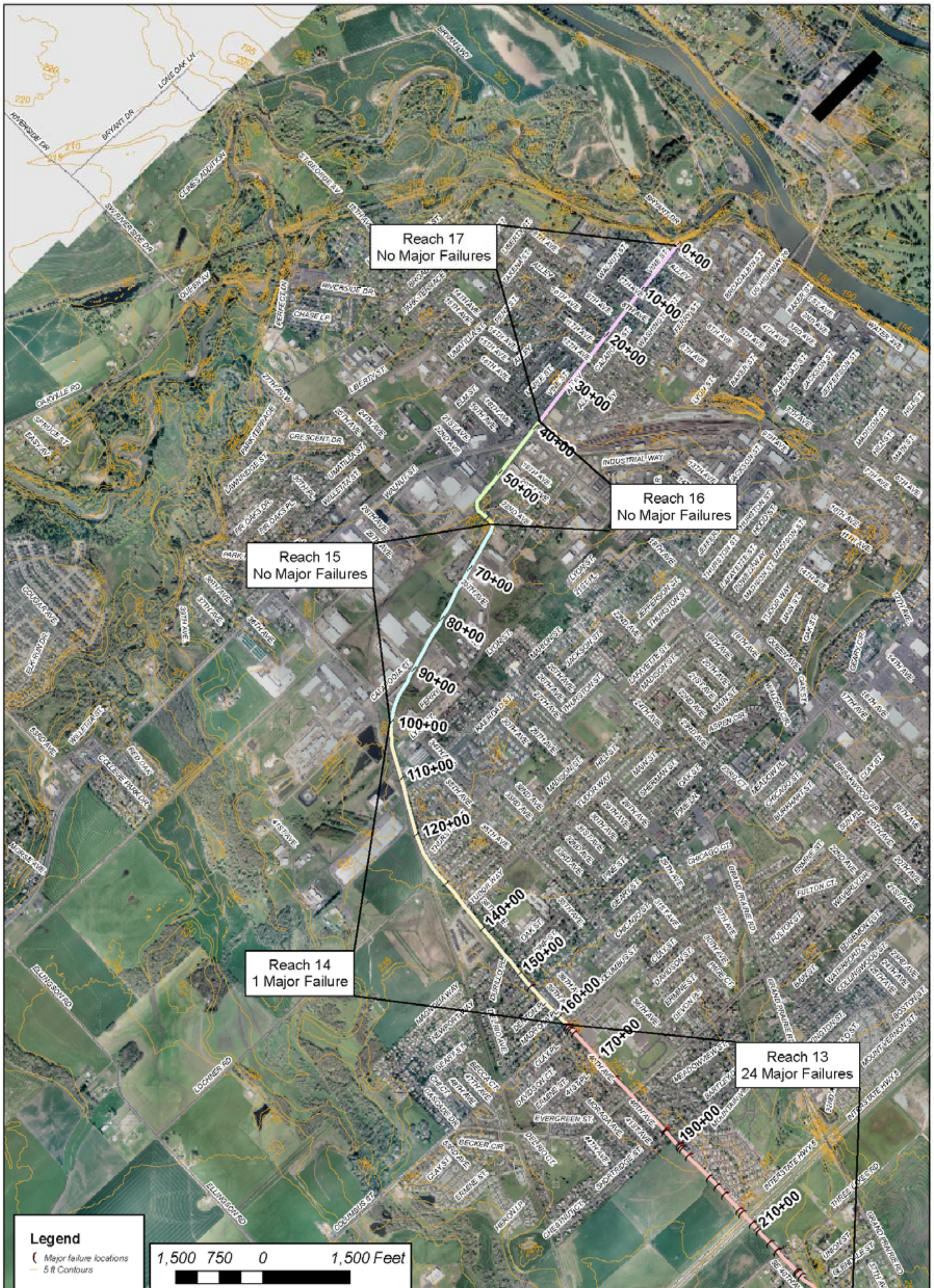
Appendix A —
NCRS Soil Types and Properties

Upstream river station (ft)	Downstream river station (ft)	Soil type	Soils key	Ksat (in/hr)	PI	Kf	Kw
96500	86700	Newburg fine sandy loam	73	9.06	1	0.24	0.17
86700	81300	Malabon silty clay loam	63	0.66	20	0.27	0.27
81300	80500	Coburg silty clay loam	26	0.03	49	0.18	0.18
80500	75700	Clackamas gravelly silt loam	23	0.03	49	0.18	0.18
75700	73000	Malabon silty clay loam	63	0.66	20	0.27	0.27
73000	68500	Newburg fine sandy loam	73	9.06	1	0.24	0.17
68500	65100	Malabon silty clay loam	63	0.66	20	0.27	0.27
65100	64700	Clackamas gravelly silt loam	23	0.03	49	0.18	0.18
64700	63700	Coburg silty clay loam	26	0.03	49	0.18	0.18
63700	63400	Conser silty clay loam	28	0.03	49	0.18	0.18
63400	62500	Coburg silty clay loam	26	0.03	49	0.18	0.18
62500	61900	Conser silty clay loam	28	0.03	49	0.18	0.18
61900	61300	Chapman loam	19	0.03	49	0.18	0.18
61300	60000	Conser silty clay loam	28	0.03	49	0.18	0.18
60000	58300	Bashaw silty clay	8	0.03	49	0.18	0.18
58300	57900	Coburg silty clay loam	26	0.03	49	0.18	0.18
57900	57400	Bashaw silty clay	8	0.03	49	0.18	0.18
57400	56700	Malabon silty clay loam	63	0.66	20	0.27	0.27
56700	56500	Bashaw silty clay	8	0.03	49	0.18	0.18
56500	56300	Coburg silty clay loam	26	0.03	49	0.18	0.18
56300	55000	Bashaw silty clay	8	0.03	49	0.18	0.18
55000	54700	Courtney gravelly silty clay loam	29	0.03	49	0.18	0.18
54700	54500	Coburg silty clay loam	26	0.03	49	0.18	0.18
54500	54100	Courtney gravelly silty clay loam	29	0.03	49	0.18	0.18
54100	53100	Coburg silty clay loam	26	0.03	49	0.18	0.18
53100	52700	Courtney gravelly silty clay loam	29	0.03	49	0.18	0.18
52700	51700	Salem gravelly silt loam	87	1.14	9	0.47	0.47
51700	51100	Courtney gravelly silty clay loam	29	0.03	49	0.18	0.18
51100	49400	Salem gravelly silt loam	87	1.14	9	0.47	0.47
49400	48900	Awbrig silty clay loam	7	0.44	29	0.34	0.34
48900	45300	Coburg silty clay loam	26	0.03	49	0.18	0.18
45300	45000	Concord silt loam	27	0.03	49	0.18	0.18
45000	44400	Coburg silty clay loam	26	0.03	49	0.18	0.18
44400	44000	Concord silt loam	27	0.03	49	0.18	0.18
44000	43700	Coburg silty clay loam	26	0.03	49	0.18	0.18
43700	43100	Concord silt loam	27	0.03	49	0.18	0.18
43100	42600	Waldo silty clay loam	98	1.14	9	0.47	0.47
42600	41700	Concord silt loam	27	0.03	49	0.18	0.18
41700	41000	Amity silt loam	3	1.14	9	0.43	0.47
41000	40600	Dayton silt loam	33	0.03	49	0.18	0.18
40600	40100	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
40100	39000	Dayton silt loam	33	0.03	49	0.18	0.18
39000	38700	Amity silt loam	3	1.14	9	0.43	0.47
38700	38300	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
38300	37600	Amity silt loam	3	1.14	9	0.43	0.47
37600	36900	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4

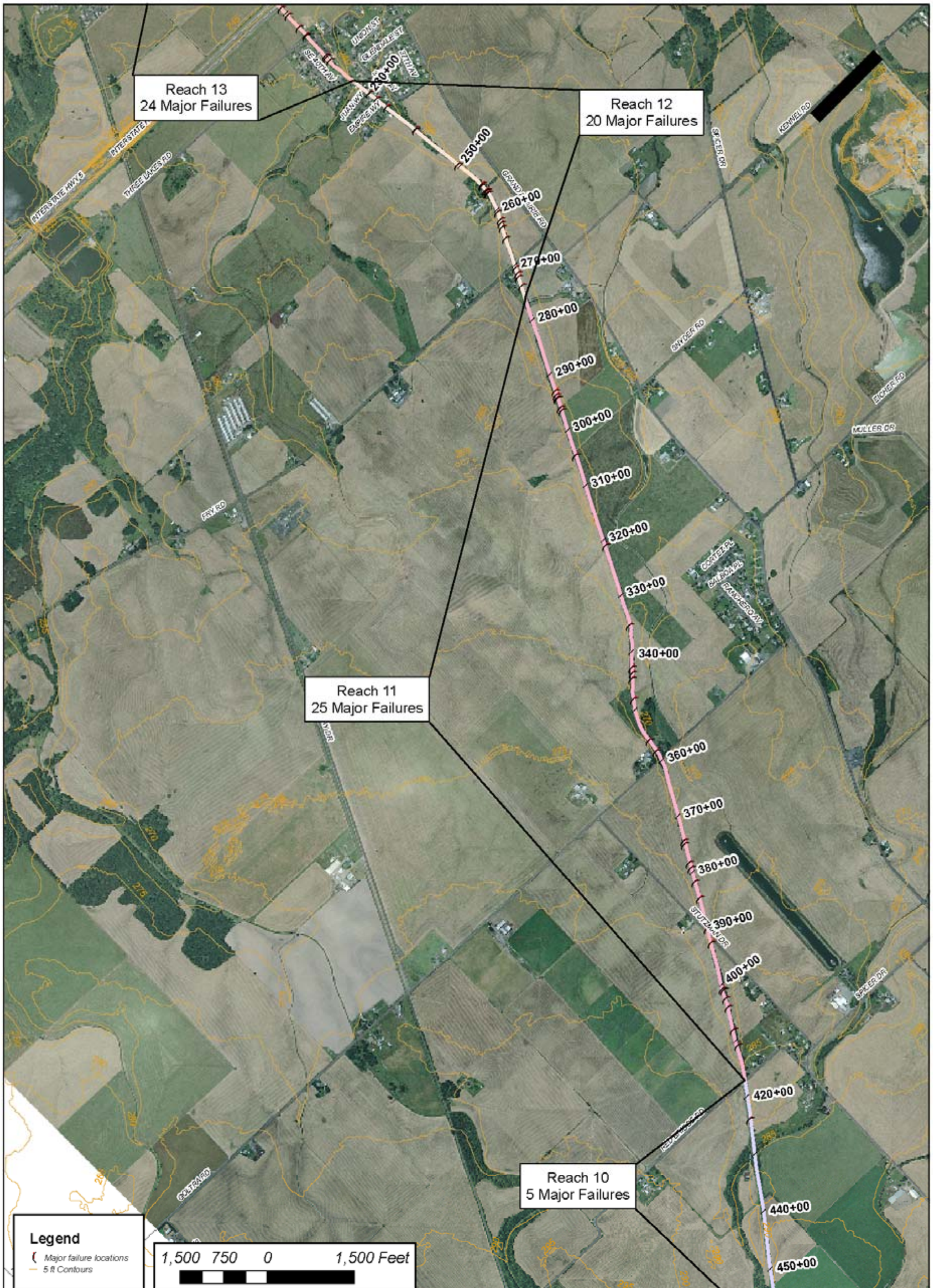
Upstream river station (ft)	Downstream river station (ft)	Soil type	Soils key	Ksat (in/hr)	PI	Kf	Kw
36900	36000	Dayton silt loam	33	0.03	49	0.18	0.18
36000	35500	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
35500	34600	Dayton silt loam	33	0.03	49	0.18	0.18
34600	33500	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
33500	33300	Concord silt loam	27	0.03	49	0.18	0.18
33300	32300	Amity silt loam	3	1.14	9	0.43	0.47
32300	32000	Dayton silt loam	33	0.03	49	0.18	0.18
32000	31400	Amity silt loam	3	1.14	9	0.43	0.47
31400	30900	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
30900	30700	Amity silt loam	3	1.14	9	0.43	0.47
30700	30000	Dayton silt loam	33	0.03	49	0.18	0.18
30000	29000	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
29000	28800	Dayton silt loam	33	0.03	49	0.18	0.18
28800	27400	Amity silt loam	3	1.14	9	0.43	0.47
27400	27200	Dayton silt loam	33	0.03	49	0.18	0.18
27200	25900	Amity silt loam	3	1.14	9	0.43	0.47
25900	25700	Dayton silt loam	33	0.03	49	0.18	0.18
25700	24500	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
24500	23300	Dayton silt loam	33	0.03	49	0.18	0.18
23300	22700	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
22700	22100	Waldo silty clay loam	98	1.14	9	0.47	0.47
22100	20800	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4
20800	20400	Dayton silt loam	33	0.03	49	0.18	0.18
20400	19300	Concord silt loam	27	0.03	49	0.18	0.18
19300	18800	Amity silt loam	3	1.14	9	0.43	0.47
18800	18200	Concord silt loam	27	0.03	49	0.18	0.18
18200	17700	Dayton silt loam	33	0.03	49	0.18	0.18
17700	16600	Concord silt loam	27	0.03	49	0.18	0.18
16600	16400	Dayton silt loam	33	0.03	49	0.18	0.18
16400	15800	Concord silt loam	27	0.03	49	0.18	0.18
15800	15500	Dayton silt loam	33	0.03	49	0.18	0.18
15500	15300	Amity silt loam	3	1.14	9	0.43	0.47
15300	15200	Dayton silt loam	33	0.03	49	0.18	0.18
15200	14900	Amity silt loam	3	1.14	9	0.43	0.47
14900	14400	Concord silt loam	27	0.03	49	0.18	0.18
14400	14000	Amity silt loam	3	1.14	9	0.43	0.47
14000	12300	Concord silt loam	27	0.03	49	0.18	0.18
12300	12100	Amity silt loam	3	1.14	9	0.43	0.47
12100	11400	Concord silt loam	27	0.03	49	0.18	0.18
11400	11200	Amity silt loam	3	1.14	9	0.43	0.47
11200	10300	Concord silt loam	27	0.03	49	0.18	0.18
10300	9900	Amity silt loam	3	1.14	9	0.43	0.47
9900	7400	Concord silt loam	27	0.03	49	0.18	0.18
7400	6800	Dayton silt loam	33	0.03	49	0.18	0.18
6800	6200	Amity silt loam	3	1.14	9	0.43	0.47
6200	5800	Woodburn silt loam, 0 to 3 percent slope	106a	1.18	10	0.4	0.4

Upstream river station (ft)	Downstream river station (ft)	Soil type	Soils key	Ksat (in/hr)	PI	Kf	Kw
5800	3500	Dayton silt loam	33	0.03	49	0.18	0.18
3500	2500	Courtney gravelly silty clay loam	29	0.03	49	0.18	0.18
2500	0	Holcomb silt loam	46	0.03	49	0.18	0.18

Appendix B —
Reach Maps with Major Failure locations



otak	*Otak, Inc.* 17355 SW Boones Ferry Rd. Lake Oswego, OR 97035 Phone: 503.635.3618 Fax: 503.635.5395	Santiam-Albany Canal *Albany, Oregon* *Canal Reaches with Major Failure Locations*	Date: *June 4, 2008* Drawn: *TWS* Checked: Project No.: *140798* Sheet No.: *01*



Otak, Inc. 17355 SW Boones Ferry Rd. Lake Oswego, OR 97035 Phone: 503.635.3618 Fax: 503.635.5395	**Santiam-Albany Canal** *Albany, Oregon* *Canal Reaches and Major Failure Locations*	Date: June 4, 2008 Drawn: TWS Checked: Project No.: 14079B Sheet No.: 02	

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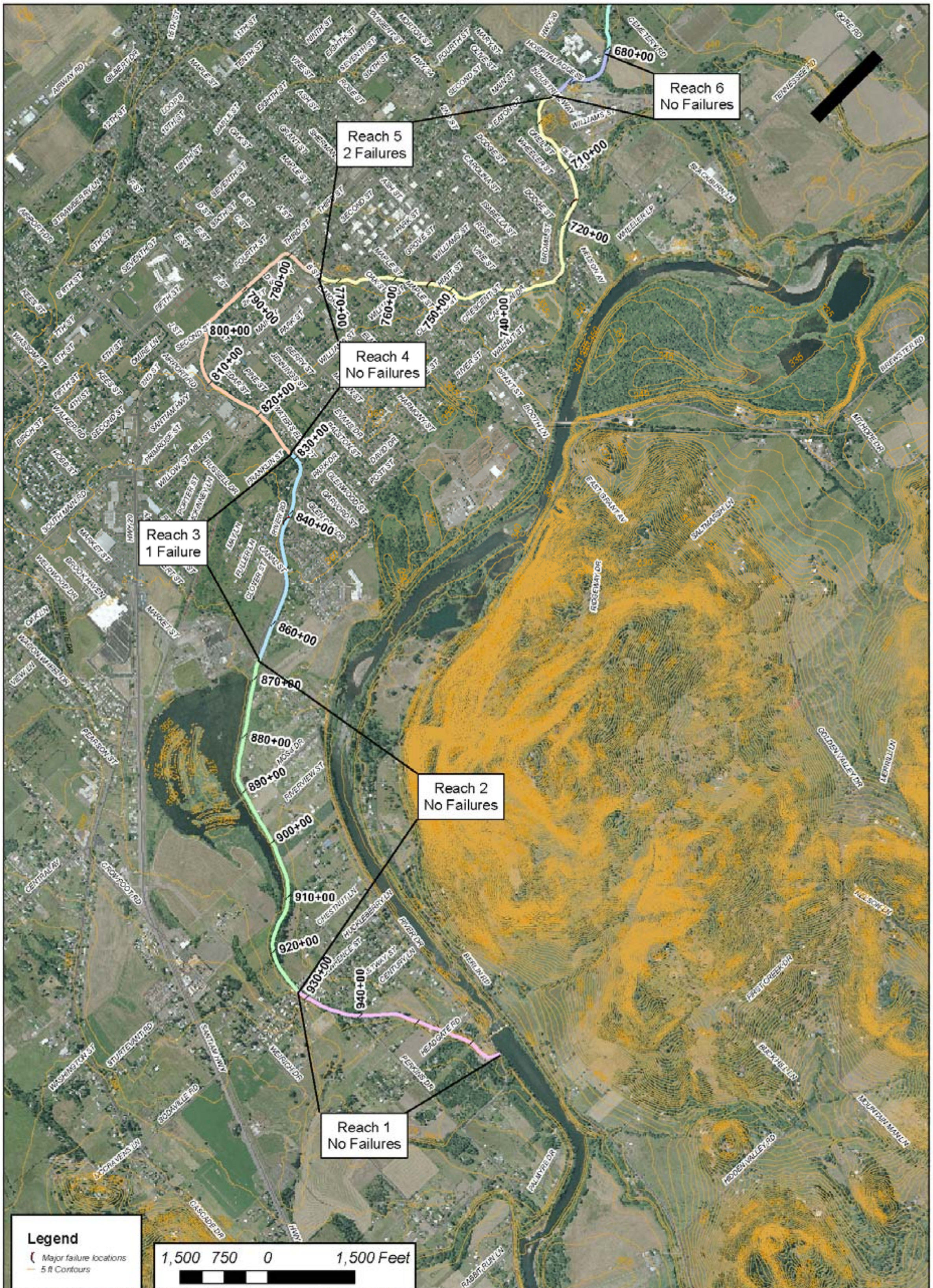
Santiam-Albany Canal

Albany, Oregon

Canal Reaches and Major Failure Locations

Date: June 4, 2008
Drawn: TWS Checked:
Project No.: 14079B
Sheet No.: 03



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Santiam-Albany Canal

Albany, Oregon

Canal Reaches and Major Failure Locations

Date:	June 4, 2008
Drawn: TWS	Checked:
Project No.:	14079B
Sheet No.:	04

Appendix C —
Proposed Dredging Maps

Albany Canal Improvements
Reach 1

- Canal
- Existing Berm
- Post-dredging Berm
- Flow Direction Arrows

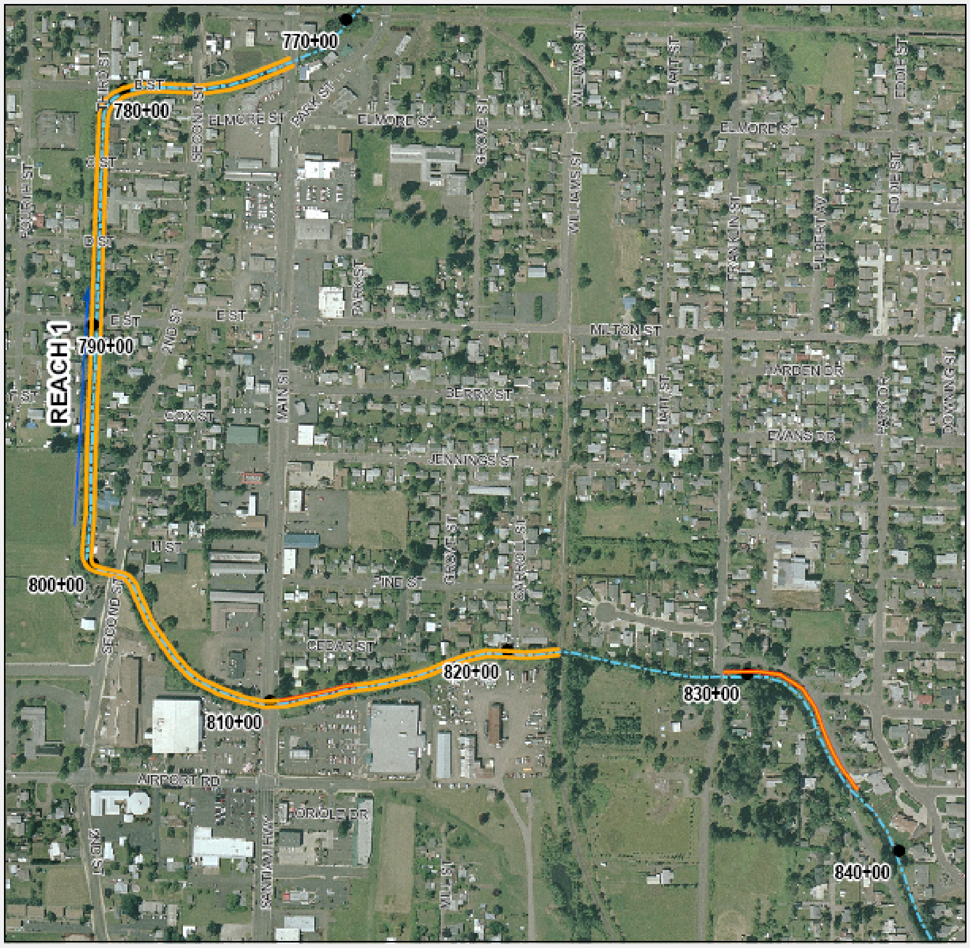
Notes:

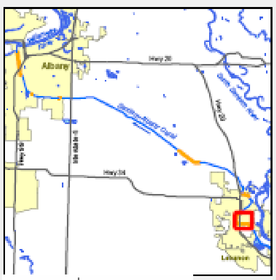
-Reach Length ~7,200 feet
-Existing berms were identified by the City of Albany
-Post-dredging berms still function as berms to meet freeboard criteria

0 250 500 Feet

1 inch equals 500 feet

N





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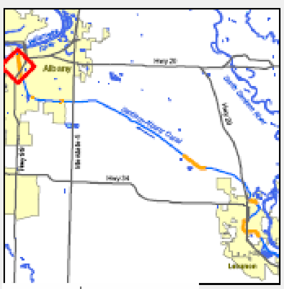
Albany Canal Improvements
Reach 6

- Canal
- Existing Berm
- Post-dredging Berm
- Flow Direction Arrows

Notes:
-Reach Length ~5,800 feet
-Existing berms were identified by the City of Albany
-Post-dredging berms still function as berms to meet freeboard criteria
-Details surveys are needed for berms upstream of Hwy. 99

0 500 1,000 Feet

1 inch equals 700 feet



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