Seattle Public Utilities

Taylor Creek Sediment Study

Seattle, Washington

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Perkins Geosciences

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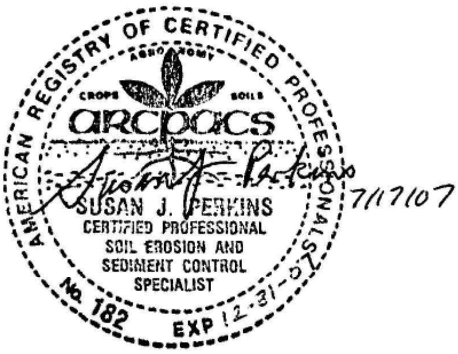

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1. Introduction

1.1 Background

The Taylor Creek delta has grown in recent years to a point where it restricts fish access to the creek and landowner use of docks. Sediment has also reportedly filled in the channel in the first several hundred feet above the mouth, aggravating overland flooding. Removal of the delta by dredging is being considered. This study estimates the time interval for which dredging would remain effective by quantifying the rate of sediment supply from the watershed to the delta, with an emphasis on the coarse sediment fraction that forms most of the delta. A sediment budget provides guidance on effectiveness of any upstream erosion control or sediment storage measures.

1.2 Project Scope

The project scope included the following tasks.

◊ **Gathering and Reviewing Existing Information** -- This task included interviewing city staff and landowners; and obtaining engineering plans, survey data, hydraulic model files, rainfall and stream flow records, and a time series of aerial photographs of the Taylor Creek delta.

◊ **Field Work** -- This task included identifying and measuring sediment sources in the canyon and its forks, resurveying cross-sections in the creek to determine changes in sediment storage, and measuring sediment size.

◊ **Sediment Budget Analysis**-- This task consisted of source and deposition components. It included estimating erosion rates in the canyon, changes in sediment storage in the alluvial fan, deposition rates in lower Taylor Creek, and delta growth rates in Lake Washington.

◊ **Sediment Management Strategies** -- This task evaluated effectiveness of potential strategies for reducing or managing Taylor Creek's sediment load. These include delta dredging, adding large woody debris (LWD), sediment trapping, erosion control, and peak flow reduction.

◊ **Report** -- An initial draft report was reviewed by two geomorphologists: Derek Booth, Ph.D. of Stillwater Sciences and Nicholas Allmendinger, Ph.D. of Otak, Inc. Their suggestions were incorporated into the final report.

1.3 Watershed Geomorphology and Geology

Taylor Creek is located in the very southeast corner of Seattle and flows north to Lake Washington (Figure 1). The two forks of Taylor Creek originate on a gently-rolling plateau about 300 to 400 feet above sea level. The plateau is the source of most of the water discharge but little sediment, because the soil is covered with impervious surfaces or vegetation. Headwater streams on the East Fork plateau are mostly culverted. The West Fork plateau has mostly open channels through a power line right-of-way and a large wetland above Renton Avenue S.

The two forks flow down the side of the plateau in small, steep ravines, then join and flow down a steep-sided ravine known as Deadhorse Canyon which is the site of Lakeridge Park. The ravine is forested and has no current development other than walking trails. A sewage treatment plant was briefly located at the base of the East Fork in the 1950s, and a former sewer line went down the mainstem creek valley. Landslides and streambank erosion in these ravines are the main sources of sediment to the creek.

Below Deadhorse Canyon, Taylor Creek has a small alluvial fan where some of the creek's coarse sediment load is deposited (Figure 2). A road crosses the creek at two locations within the canyon mouth/alluvial fan area. Below the alluvial fan, Taylor Creek then enters a rock-lined channel which conveys it a short distance through a low-gradient valley. The creek crosses under Rainier Avenue S in a long culvert, then crosses the former lakebed of Lake Washington in a rock-lined channel and terminates at a small delta at the edge of the modern lake.

Taylor Creek and its forks flow through sediment deposited primarily by glaciers. The plateau is underlain by Vashon till. Some Vashon advance outwash is exposed in places in the upper canyon walls. Only a short reach of the upper East Fork flows through sand and gravel of the Vashon advance outwash. The canyon mostly is made up of older, consolidated pre-Vashon glacial and nonglacial sediments. The canyon walls are mostly clay and silt but also contain a fair amount of sandy glacial till, which is a dense mixture of sand and silt/clay with minor amounts of gravel (Golder 1995; Troost et al. 2007). At the bottom of the canyon, the creek and its forks primarily flow through landslide colluvium and stiff to dense glaciolacustrine silt/clay.

Refer to the Taylor Creek watershed assessment maps (SPU 2003) and channel conditions report (Perkins 2002) for more information.

1.4 Taylor Creek watershed urbanization, flow increases, and timing of major storms and landslides

Taylor Creek drains a densely developed, 1 square mile area within the City of Seattle and unincorporated Skyway. Over 90 percent of the development in the East Fork of Taylor Creek occurred in the 1940s. Development in the West Fork occurred mainly from the 1940s through the 1960s with a peak in the 1950s, and final build-out lasted through the 1980s. The mainstem below the forks has a small drainage area and is mostly parkland.

Urbanization caused a large increase in storm water runoff with essentially no detention. The channel of Taylor Creek now receives what was formerly a 100-year flood nearly every year (Hartley and Greve 2005). These large flow increases have accelerated erosion rates in the ravines of Taylor Creek and its two forks.

The recent history of large rainfall and flood events was collected to compare with the history of sediment deposition and erosion in the alluvial fan and delta. Taylor Creek has had a stream gage operated by the City of Seattle for only three years. The City has a nearby rain gage that has recorded precipitation since 1998. Precipitation recurrence-intervals for 24-hour, 48-hour, and 72-hour durations were determined from Schaefer (2003).

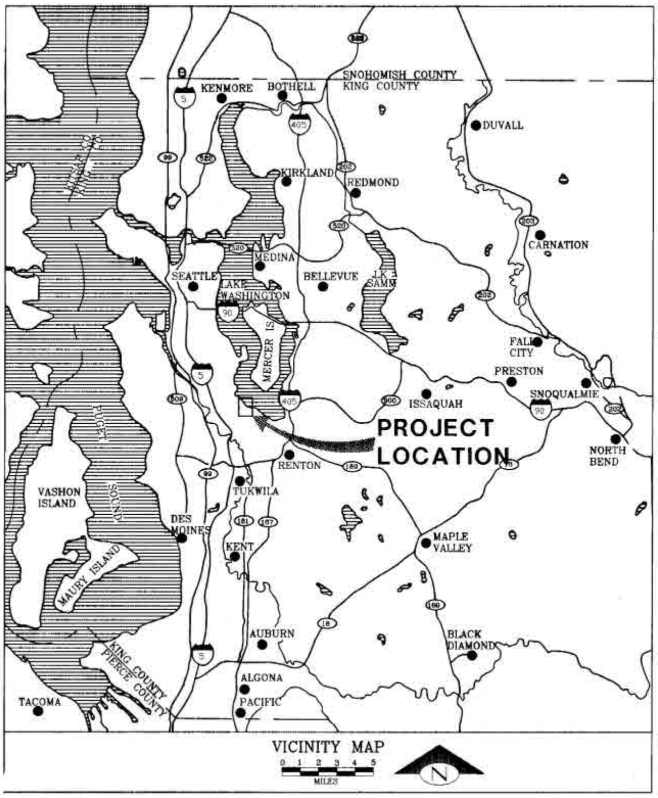


Figure 1. Vicinity map and aerial photograph of Taylor Creek watershed (figures provided by Seattle Public Utilities).

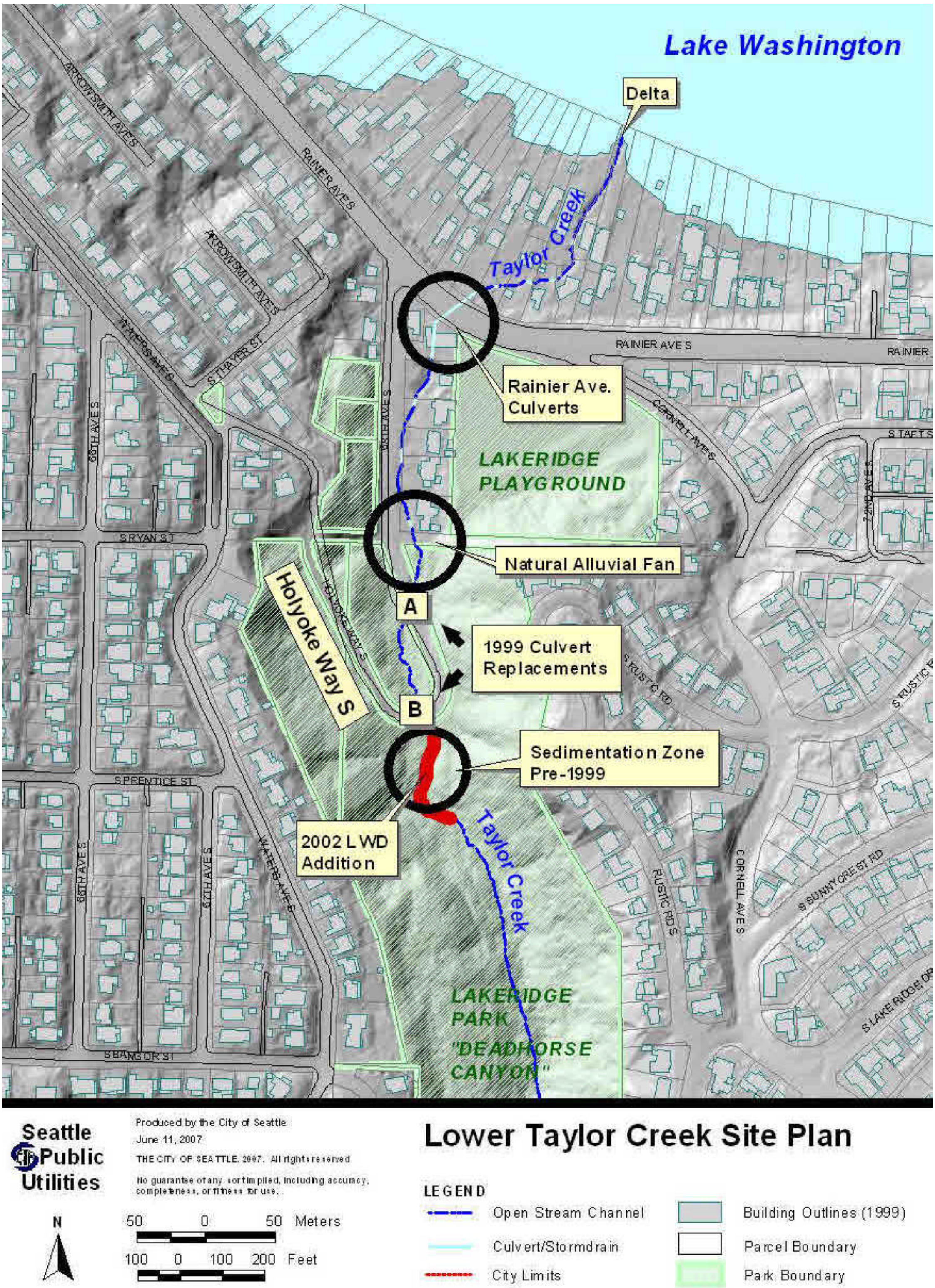


Figure 2. Site map of lower Taylor Creek showing delta and culverts replaced in 1999.

Table 1 shows the largest stream discharges and rainfall events for the gaged periods of record. Precipitation data show a 25-year event occurred in early November 2006, a 10-year event in November 2001, and possibly a 100-year event in October 2003 that was gaged elsewhere in Seattle although not reported by the local rain gage. Reported rainfall at the local gage was likely in error, since Taylor Creek had a high flow in October 2003 that caused additional sediment deposition in the delta, according to property owner Joann Ruffini. The 2006 25-year storm produced a discharge of 51 cfs. Other high flows in the last three years occurred in January 2006 and June 2005 according to the stream gage. Anecdotal reports indicate high flows prior to installation of the local gages occurred at the delta in 1981, 1985 and 1990.

Landslides in Seattle most commonly occur during intense rainstorms that follow high antecedent precipitation in the previous two weeks. Cumulative precipitation thresholds for landslides were obtained from Chleborad et al. (2006). Precipitation at rain gage 10 was sufficient to trigger landslides in November 1998, November 2001, and November 2006 (Table 1). Fresh-looking landslides were observed during field work in December 2006.

The Seattle landslide inventory was also used to assess landslide timing. Only two landslides in the Taylor Creek watershed are recorded in the landslide inventory. Both occurred at 11221 Crestwood Drive in Vashon advance outwash on the upper canyon wall of the East Fork of Taylor Creek. A debris flow in 1984 was followed by a small landslide in 1986. Since most landslides in Taylor Creek occur in Lakeridge Park, they would probably not be reported by landowners or compiled in the City's landslide inventory. Based on the timing of inventoried landslides elsewhere in south Seattle, additional landslides are most likely to have occurred in 1997, 1991, and 1980-1981 (Figure 3). In addition, landslides along the creek can be caused by bank erosion during high flows.

Table 1. Significant precipitation or stream discharge events for Taylor Creek during period of gaged record.

Date	Precipitation Events at Gage 10 (recurrence interval and duration)	Taylor Creek Stream Discharge (cfs)	Sufficient Cumulative Precipitation to Trigger Landslides
11/26/1998	8 yr-24 hr; 5 yr-72 hr	ungaged	YES
11/15/2001	10 yr-48 hr; 10 yr-72 hr; >5 yr-24 hr	ungaged	YES
10/20/2003	100 yr-24 hr elsewhere in Seattle	ungaged	?
1/18/2005	5 yr-48 hr	44	
6/2/2005	no data	52	
1/12/2006	2 yr-72 hr	45	
1/31/2006	no data	50	
11/6-9/06	25 yr-72 hr; 15 yr-24 hr; >10 yr-48 hr	51	YES
Period of Record	**1998-2007**	**2004-2007**	

<u>NOTES</u>

1. This table does not show rainfall events with recurrence intervals below 5 years unless there was a large stream discharge.
2. The cumulative precipitation thresholds for landslides in Seattle are 3.5 inches in the past 3 days and 5.2 inches in the past 18 days.
3. Rain gage 10 is located near Taylor Creek.
4. On 10/20/03 rain gage 10 showed little rain, but this storm elsewhere in Seattle was a 100-year, 24 hour event. The resulting flood reportedly resulted in sediment deposition on the Taylor Creek delta.

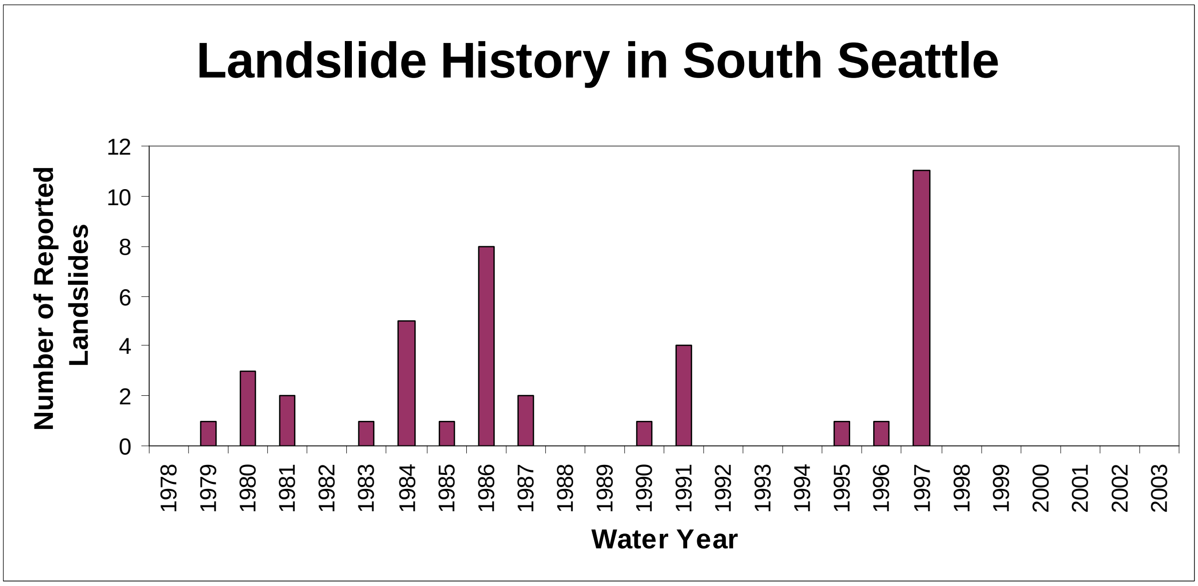


Figure 3. Number of landslides in south Seattle by year from 1978 through 2003, from City of Seattle landslide inventory. Includes 2 reported landslides in the Taylor Creek basin in 1984 and 1986.

2. Methods

2.1 Delta Growth and Deposition Rates

2.1.1 Field work

A field survey with laser level and tape was performed on February 2, 2007 while the lake was at its lowest winter level. A delta profile and three cross sections were surveyed to a depth reachable using hip waders. A lake bottom elevation was obtained from the dock on the west side of cross section L2. Cross sections L1 and L2 were situated with endpoints at docks recognizable on the air photos (Figure 4). Cross-section L3 was 15 feet landward from the delta tip. The survey recorded distances, elevations, lake water surface and the boundaries between sand and gravel deposits along the survey lines. The delta length above water was remeasured on March 22, 2007 at a higher lake level.

A surface pebble count and paired bulk sample of the subsurface gravel were taken in the same location on the apex of the delta, where gravel was coarsest. The bulk sample was sent to a geotechnical lab for sieve analysis. Appendix A contains sediment size data.

2.1.2 Delta length and width

Delta growth was examined on a time series of 14 aerial photographs from 1939 to 2005. Most of the photos were enlarged to a nominal scale of 1 inch to 100 feet. Four air photos were obtained from SPU's GIS coverage and were printed at a scale of 1 inch to 50 feet due to their lower resolution. The exact scale of each aerial photograph in the vicinity of the delta was determined as follows. The length of a dock was taped in the field and then measured on an air

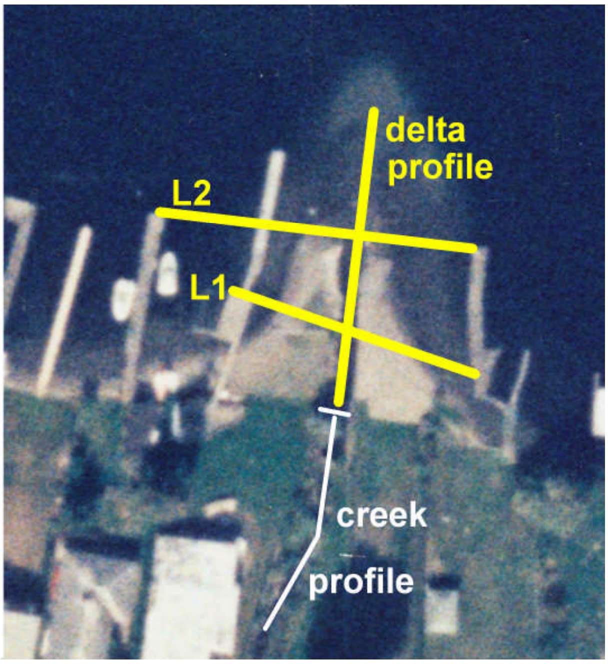


Figure 4. Site plan of Taylor Creek delta on 1997 aerial photograph, showing location of delta profile and cross-section lines L1 and L2. Taylor Creek enters the delta at the edge of the lawn. The long dock on the west (left) side of the delta floated away in 1999 or 2000, except for the portion south of L1.

photo. The dock length was used to determine the length of a house that was common to all but the earliest two air photos. The scale of each air photo was then calculated by measuring the house. A similar procedure was used to scale the earlier photos to a different house. The estimated error in this scaling procedure was 2 percent.

Delta length was measured from a common match point on each photo. The distance to the farthest-visible underwater tip of the delta was measured. The distance from the same match point to the farthest above-water point of the delta was also measured. The second measurement could not be made on any of the air photographs taken in summer when the entire delta was submerged by a higher lake level. Above-water delta width was measured along the two cross-section lines for each non-summer photo date. Estimated error on any given photo is up to 5 feet, which is less than 5% of typical delta length and 5-10% of typical delta width.

Lake Washington's elevation is controlled by locks that are operated by the Army Corps of Engineers. The lake level fluctuates about 2 feet from a winter base elevation of 20.0 (Army Corps locks datum) to about 22 feet in summer (Figure 5). To compare delta length and width between years, it was necessary to correct the measured lengths to a common lake level. The 20.73 ft. elevation of the March 2005 air photo was chosen. Lake levels for each photo date were obtained from the Army Corps of Engineers.

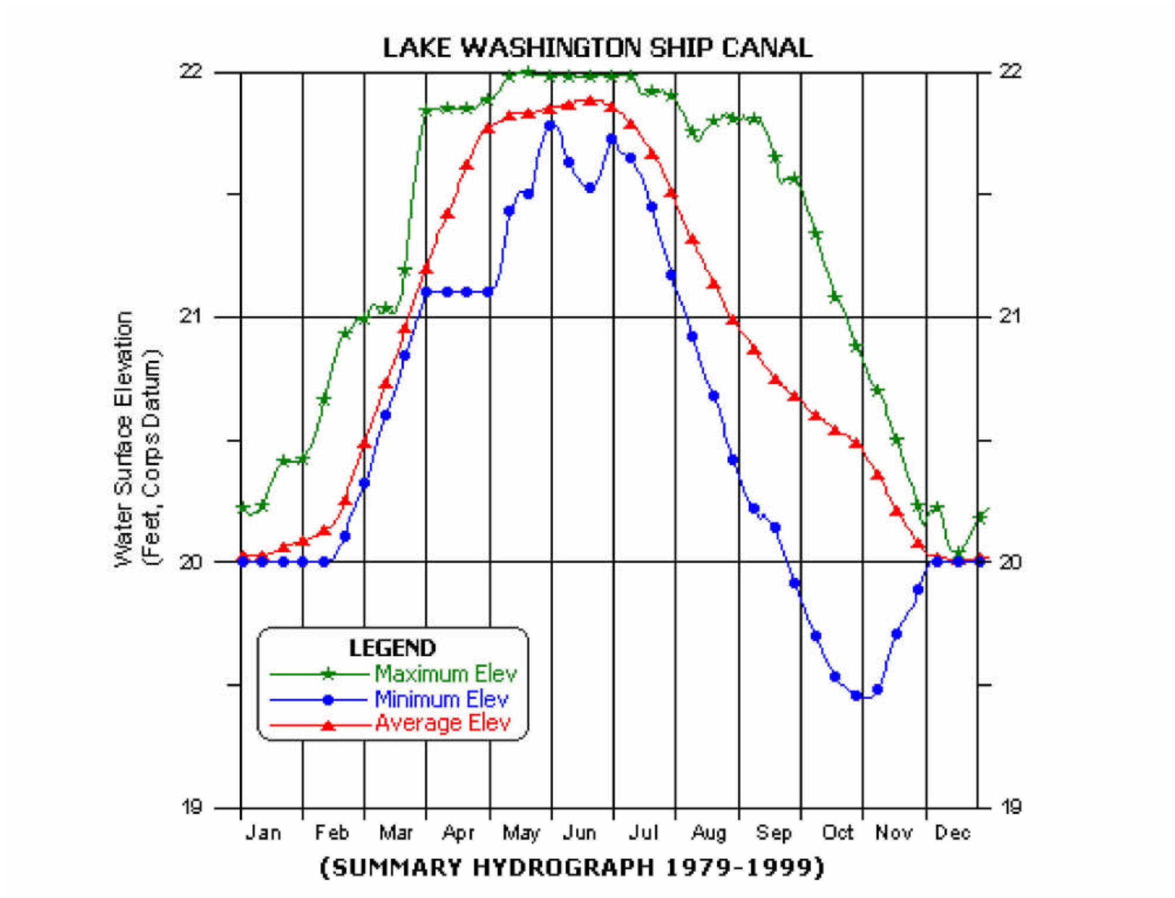


Figure 5. Lake Washington summary hydrograph showing seasonal changes in lake elevation due to regulation at locks. Source: U.S. Army Corps of Engineers. From http://www.nwd-wc.usace.army.mil/nws/hh/basins/lwscsh.html

Measured above-water delta lengths were adjusted upward or downward based on the difference in lake level using a measured 2007 slope of 2.1 percent for the foreset beds on top of the delta. This resulted in correction factors of up to 22 feet. Above-water delta widths were adjusted in a similar manner, using measured 2007 slopes along each cross section. These corrections assume that delta slope was the same in all years, an untested assumption. Storm timing could affect the local slope because sediment is deposited at different points on the delta depending on lake elevation.

Lake elevation should have a much smaller effect on the length of delta visible under water. The water looks clear in the air photos, and Secchi disk measurements at King County's nearby Lake Water Quality Monitoring Site # 831 recorded visibilities of 2.3 m to over 6 m during the 2001-2006 period (King County, 2007). This means the delta tip should become invisible to the camera at a depth well below the winter lake elevation. Below that depth, the delta consists of foreset beds with a steeper slope. The measured slope of 12.1 percent from the sloping lower end of the surveyed 2007 profile was used to correct the measurements to the desired lake elevation. This resulted in correction factors of 9 feet or less. The foreset beds below the depth of the profile probably have a much steeper slope in the range of 20 to 30 degrees (about 35 to

60%), in which case the correction would become negligible. For all photo dates, a lower-bound estimate of delta length was made assuming infinite below-water visibility and no correction factor for lake level. Since the visible delta tip is much farther from shore than the winter water's edge, the delta slope should not be affected by storm timing. For all these reasons, visible delta length under water is a more reliable indicator of delta growth rates than the above-water measurements.

After these calculations were made, a bathymetric map became available that was surveyed in late December 2004 (Downing, 2005). It provided a check on the location of the delta tip visible in the March 2005 air photo, which was taken at the 20.73 foot water elevation to which all the other air photos were adjusted. The lawn edge is shown on the map which allowed a fairly precise match with the air photo. The delta tip visible on the air photo is about 6 feet beyond the tip of the gently-sloping delta surface on the map, on a steep (33-50 %) drop-off. For the longer deltas from 1997 or 1999 onward, the correction for lake level is therefore negligible due to the steep delta slope.

Prior to sewage diversion in the late 1960s, Lake Washington was quite murky in summer due to algal blooms (King County, 2007). The submerged end of the delta visible on air photos would have been much shallower, possibly above the winter lake level. For the 1968 and earlier air photos, an upper-bound estimate of delta length was made using the flatter 2007 topset slope of 2.1 percent. Even with this maximum correction, the early delta measurements were significantly shorter than delta measurements in the 1990s and later.

2.1.3 Delta sediment volume and deposition rates

Delta volume was estimated for 1985, 1993, 1997and 2007 because these years bracketed different phases of delta growth and also had data on above-water length and width. Volumes were calculated using the end-area method which multiplies the average cross-sectional area by the length between cross sections.

The profile of the delta surveyed in 2007 was assumed be representative of previous years, but it was shifted up or down the delta to account for delta progradation and changes in width. To do so, the above-water delta length was subtracted from total visible length to obtain underwater length. Next, the above-water delta length was apportioned between the three surveyed cross sections using the distances measured in 2007 as a starting point. In years with a narrow upper delta, a greater proportion of the above-water distance went between cross sections L2 and L3, and less between L2 and L1, which was the widest, highest cross section. 1985 and 1993 had short, narrow deltas so all above-water delta length was assigned to L2 and L3. Volume calculation started at cross-section L1, which was judged to be the landward edge of past or future dredging.

There was considerable uncertainty about the depth from which to measure sediment accumulation. Landward from the tip of the 1993 delta, it was assumed that the delta prograded across a nearly flat slope left behind by previous dredging. The base elevation used was 7 to 8 ft. below summer lake level, which is consistent with the 1980s dredging depth reported by property owner Ruffini. The estimated 1100 yd^3 delta volume for 1993 agreed well with the reported 1986 permitted dredge volume of 1000 yd^3. Not accounting for past dredging and assuming the delta prograded across a deeper, sloping lakebed from 1985 on resulted in sediment-deposition rates that were unreasonably high even for an urban stream.

Beyond the tip of the 1993 delta it was assumed that no dredging has been done, so the delta prograded over a much deeper lakebed. The average delta cross-section area above Elevation +4 (NAVD 88) was used from the 2004 Downing survey.

Delta deposition rates were calculated for the time periods between each volume estimate, based on 1) delta volume changes alone, and 2) delta volume changes plus dredging. Changes in delta volume between dates have a potential error of about 30%, less than the potential error in the volume estimates themselves because the same method was used consistently for each date.

Volume estimates of past dredging were based on reported volumes from dredging permits and and the calculated 1993 delta volume. Potential dredged volumes were estimated for the 2007 delta using the same method described above for a range of possible dredging depths. Potential dredged volumes were also estimated using a December 2004 bathymetric map that became available prior to final revision of this report. Depending on dredged elevation, the December 2004 delta volumes were 10 to 30% lower than calculated for 2007. However, in 2007 the delta was considerably wider at the cross-section lines than 2005 and substantial deposition on the upper delta may have occurred in the December 2006 flood. The upper-delta length and width measurements indicate the 2005 delta was similar to the 1997 delta in size. Correcting for the previously-calculated difference in delta volumes between 1997 and 2007 led to reasonable agreement with the 2004 volumes.

2.2 Sediment Deposition in Lower Taylor Creek: Methods

The rate of sediment deposition in lower Taylor Creek from the upper edge of the delta (Figure 4) to Rainier Avenue was calculated by comparing repeated cross-section surveys. This section of creek was surveyed in November-December 1999 to construct a HEC-RAS model for flood analysis (Thomas/Wright 2000). The cross sections from that earlier survey were resurveyed on February 2, 2007. Elevation shots were taken at all former cross sections without a hydraulic control that would prevent sediment deposition. This part of Taylor Creek has armored banks and many boulders and culverts that form recognizable steps in the profile. This enabled reliable relocation of the previous surveyed points. Three shots were taken on the bed at each cross section, as done for the previous survey. Since no benchmark was referenced in the Thomas/Wright report, elevations were tied to the previous survey (which used the City of Seattle datum) by use of common points such as the low chords of bridges and culverts.

2.3 Alluvial Fan at the Mouth of Deadhorse Canyon: Methods

Figure 13 shows a site plan of the alluvial fan area and the culverts that were replaced in 1999.

2.3.1 Field work

The 1999 replacement of two undersized culverts with larger culverts triggered a series of channel adjustments. Most of these adjustments were documented by a series of monitoring and design surveys by Seattle Public Utilities (Table 2). The previous cross sections and profiles were relocated and resurveyed between December 2006 and February 2007 by Perkins Geosciences or SPU staff.

Pebble counts of sediment deposits were made. Summary statistics for the samples taken in this study, as well as some earlier pebble counts made by SPU, are given in Appendix A. The SPU pebble counts were not repeated at the same locations as they were located in pools or sites where sediment texture was influenced by rootwads. Previous ground photo sites were relocated and new photos taken for comparison. Bank stability and erosion areas were recorded using the same methods as upstream in the canyon, as described in section 2.4.

Table 2. Data sources used to calculate changes in sediment storage in the culvert replacement area

Year	Source	Type	Description	Reliability
Pre-Construction				
1997	Thomas/ Wright Inc.(TWI) design plans	profile	pre-construction profile of channel centerline	good -- engineering-level survey
1999	SPU	profile	pre-construction thalweg profile showing pool detail	fair -- surveyed with peashooter and hip chain, but appears to match fairly well
Construction				
1999	Thomas/ Wright Inc.(TWI) design plans	profile and plans	design profile and plans for culvert replacement project showing elevations of placed gravel, log weirs, and culverts	fair -- no as-built survey was done to show how constructed elevations may have differed from design
Post-Construction				
2000-2003, 2007	Perkins Geosciences and SPU	cross sections	10 monumented cross sections between culverts and downstream of lower culvert	mostly good -- used level and taped distances, monumented endpoints, benchmarks
2001-2007	SPU	cross sections	6 monumented cross-sections upstream from upper culvert	mostly good -- used level and taped distances, benchmarks; some missing end monuments
2000-2007	SPU	profiles	thalweg profiles showing pool detail	poor-benchmarks not recorded clearly, used peashooter and hip chain. Most were not usable. Distances differed between surveys.
2002	Natural Design, Inc. & Otak, Inc.	profile	thalweg profile above upper culvert, did not include pools	good -- tied to benchmarks, shot with level
2007	Perkins Geosciences	profile	thalweg profile below lower culvert and above upper culvert	good -- tied to benchmarks, shot with level, lower distances taped
2002, 2004, 2007	SPU	culvert clearance measure ments	distances from top of culvert to streambed were measured for nine volts each at inlet and outlet of each culvert	good -- well documented, repeatable measurements. Was tied to known benchmark in 2007.

2.3.2 Data analysis methods

The survey data listed in Table 2 were used to calculate changes in sediment storage and assess how the channel evolved in response to the new culverts.

Cross-section elevations were adjusted to reference a common benchmark (SPU BM #1) on the right bank downstream from the lower culvert. Endpoints were matched to common monuments, typically rebar-with-cap or nail-and-disk in a tree. The cross sections surveyed in 2000 were not tied to a known benchmark, but a good fit was obtained when the elevations were adjusted to match monumented ends of the 2001 cross sections. In a few rare cases, cross sections from other years had a similar problem and were adjusted in the same way. For the cross sections that were not tied to a benchmark, there is a potential error of 0.3-0.4 feet as the survey notes did not record whether the top or base of the rebar was surveyed. A few cross sections were discarded as they could not be adjusted reliably. In general, confidence is high for the cross-section data. Changes in channel form were of far greater magnitude than potential errors, and the changes agreed with photographic and field observations made by this author between 2000 and 2007. See Appendix C for cross-section plots.

The cross sections were used to calculate changes in sediment storage. The years 2001 and 2007 were chosen because they had reliable cross sections that were surveyed throughout the entire culvert zone. Upstream from Culvert B, most cross sections were repeated in 2002 which enabled calculation of sediment volumes before and after LWD was added.

The channel length represented by each cross section was determined based on grade breaks and channel width changes observed in the field. The change in area between successive measurements at each cross section was multiplied by the representative distance for that cross section to obtain change in sediment volume, then converted to rate by dividing by elapsed time.

Channel adjustments started soon after culvert replacement in 1999, yet cross sections were not surveyed upstream of Culvert B until summer 2001. A rough estimate of initial erosion and deposition was made by measuring elevation changes from channel profiles and multiplying by estimated channel width to obtain volume. The error in this procedure could be as great as +/- 50%. Based on field evidence, it was assumed that this sediment deposited a short distance downstream of Culvert B prior to summer 2001.

The profiles were adjusted to a common benchmark and common starting points, then plotted together and compared by eye. Most of the SPU profile surveys were discarded as the elevations fluctuated from year-to-year in an unbelievable manner that suggested the errors had occurred at turning points or benchmarks. The remaining, credible profiles were plotted on a common scale to illustrate changes in channel morphology. In addition, profiles were constructed using thalweg elevation changes at each of the surveyed cross sections and culvert openings, all of which were fixed, repeatable points (Appendix C).

Numerous LWD pieces were added to Taylor Creek upstream from the upper culvert (Culvert B) in 2002 to trap sediment and reduce bank erosion directly by protecting the bank, and indirectly by dissipating energy. The volume of sediment stored as a result of these logs was estimated in two ways. First, sediment-deposit dimensions were estimated in the field in December, 2006 using a hip chain to measure length and a survey rod to estimate width and height. Second, the length and height of sediment wedges upstream from log steps was calculated from elevation differences between 2002 and 2007 profile surveys and field measurements of channel width.

2.4 Taylor Creek Canyon Sediment Sources: Methods

Field work was conducted from December 2006 through February 2007. A hip chain was used to record distances. Sediment sources were inventoried along the mainstem canyon, the entire East Fork to the end of open channel at S.115th St., the entire West Fork below Renton Avenue, and the lower 300 feet of the south branch of the West Fork above Renton Avenue. The south branch West Fork survey was discontinued when it became obvious that the creek was not large enough to be a significant sediment source. The west branch of the West Fork was not surveyed because it is a low gradient wetland that does not export gravel and sand.

Size, freshness, erosion type, geology and sediment size-class were recorded for streamside landslides and major areas of bank erosion. Overall levels of bank erosion were ranked using the Channel Stability Index (Henshaw 1999; Appendix B) and compared to 2001 rankings. More than 20 landslide scars higher on the valley walls were evaluated for age of vegetation, sediment size, and delivery to the creek. Paired surface and subsurface samples were taken from a gravel deposit above the plugged sewage-treatment site culvert on the East Fork of Taylor Creek (Appendix A).

3. Results

3.1 Taylor Creek Delta

This section examines growth of the delta over time. Sediment deposition rates are estimated for the period from 1985 to 1997. See Figure 4 for a site plan of the delta.

A delta is a depositional feature that forms where a stream enters a body of water such as Lake Washington. Coarse sediment carried by the stream is deposited as soon as it hits the lake water, but finer particles such as silt and clay are carried further out into the lake. As sediment fills one channel, the creek switches course to one or more other channels. Over time this builds up the characteristic, fan-shaped form of a delta. As sediment builds up above lake level the creek is able to transport sediment farther downstream, so the delta grows out into the lake in a process called progradation.

The surface of the Taylor Creek delta is predominantly coarse gravel, with scattered cobbles up to 120 mm (5 inches) in diameter at the delta apex. Subsurface sediment at the delta apex has a median diameter of 13 mm (1/2 inch) and is a mixture of gravel and sand (Appendix A).

3.1.1 Delta Growth Rate and the Influence of Dredging

Table 3 is a timeline that describes delta appearance on each air photo along with other relevant events in the watershed such as dredging, major floods, and fish entry to the creek.

3.1.1.1 Delta length

Figure 6 shows changes in delta length over the period of photographic record. Three bars are shown for each date. The middle bar shows the best estimate of delta length corrected for lake level as described in Section 2.1.2. The other bars show the upper and lower bounds of the error estimates. Four phases of delta behavior were identified:

1. original delta formation
2. delta growth mostly offset by dredging
3. rapid delta growth in the absence of dredging
4. long delta with relatively steady length.

Original delta formation
The Taylor Creek delta is a relatively new geologic feature, having formed in its current location sometime after the lowering of Lake Washington in 1916. It may even have started growing sometime after 1939, at which time the entire lakeshore was still covered by a large mill platform (Table 3). Taylor Creek was in roughly its present location by 1946. The creek was channelized in the 1960s, with riprapped banks, driveway culverts and driveway bridges (Tanaka, 1991).

A very faint delta shape was visible below water in 1946 but was gone in the 1960 air photo. Possible explanations include murky water due to algal blooms (this was before sewage treatment) or dredging. Flood size and sediment load had already been increased by urban development in the 1940s, and continued to increase through the end of the 1960s by which time development was nearly complete.

Delta growth mostly offset by dredging
By 1968, the delta was visible again and slightly larger. Delta length was stable in the 1968 through 1985 air photos, most likely because of dredging. Neighbor Dennis Kelly recalls being told that Mr. Litchfield dredged the delta a few years before Kelly arrived in 1979 (Kelly statement to Susan Perkins, 2/2/07 site visit). There were no records in the WDFW archives to support this, though at that time dredging was often done without obtaining a permit (Larry Fisher, WDFW). Joanne Ruffini, Mr. Litchfield's daughter, reported that flooding had become an annual occurrence by 1985 with damage requiring thousands of dollars of repairs in 1981 and the mid-1980s. The location of 1981 flood damage was not specified. The dock area was dredged for the first time in the 1980s according to Ms. Ruffini. The dock went from "being in 18 feet of water to 1.5 feet overnight due to a slide" and the area was dredged 6 feet. This agrees with timing of landslides in the Taylor Creek watershed (Section 4.1). Dredging 1000 cubic yards from the dock/beach area was permitted and completed in summer 1986. Dredging at the mouth of Taylor Creek and placement of a rock wall extension for Taylor Creek outflow was permitted and completed in 1987.

The floods of November 1990 caused problematic sediment deposits in the delta area, as described in King County's response to a complaint by Mrs. Wallace Litchfield (Tanaka, 1991): *"A considerable volume of sediment has formed a delta alongside the pier on the Litchfield's lakefront, changing the course of the stream and impacting the use of their pier. The stream capacity on the Litchfield property has been significantly reduced by storms occurring within the last year. Mr. and Mrs. Litchfield reported the previous stream depth at one point alongside their house to be about five feet. The current depth is less than one-foot deep."* In November, 1991 a permit exemption was granted for "as necessary" maintenance-hand-dredging at the mouth of Taylor Creek of less than 10 yd^3, according to Ruffini.

Rapid delta growth in the absence of dredging

By 1993 the delta was 34 feet longer than 1985 despite the 1991 dredging. The delta continued to grow through 1999. Visible delta length grew 41 feet between 1993 to 1999, a rate of 6.8 feet per year. During this period of growth, delta length remained steady or fell slightly during short periods without floods, but grew 24 feet from1995 to 1997, a time of region-wide flooding.

Table 3. Timeline of aerial photographs, delta changes, and major events affecting the Taylor Creek delta and its sediment load

Date	Photo Type	Delta Area Description	Events
1939 Month Unknown	B+W	Creek area and lakeshore covered by a huge wood platform and railroad: Seattle Mill & Log Co.	Holyoke St. and culverts were built upstream between 1926 and 1936.
1946 Month Unknown	B+W	Mill platform removed.Very faint delta shape at creek mouth. Tree foliage indicates photo may have been taken in the summer at high lake level.	Most E. Fork Taylor Cr. urban development occurred by end of 1940's, with essentially no stormwater detention.
6/27/1960	B+W	No delta visible at all. Docks built (recognizable in all successive photos).	Lack of delta due to murky water due to algal blooms from untreated sewage, or dredging?
4/9/1968	B+W	Submerged delta visible.	Most W. Fork Taylor Cr. urban development occurred by the end of 1960's. Wetlands on W. Fk. provide sediment detention and some stormwater detention.
3/20/1974	B+W	Delta visible, a small part unsubmerged. Creek outlet flows north.	Delta reportedly dredged prior to 1979 arrival of property owner Dennis Kelley.
3/8/1985	B+W	Delta visible, part unsubmerged. Creek outlet shifted to west.	Severe flooding and delta deposition began 1981. Landslide upstream. Dredged in 1986 and 1987.
3/13/1993	B+W from SPU GIS layer	Delta visible and longer, part unsubmerged. Creek outlet flows north.	1991 drainage complaint to King County re sediment deposition "impacts use of pier" and fills creek 4 ft. (probably Nov. 1990 floods). Dredged 1991.
9/22/1995	Color	Large delta visible, part unsubmerged. Creek outlet flows north.	
3/9/1997	Color	Large delta visible, part unsubmerged. Creek outlet flows north.	Good run of salmon up creek in about 1997 or 1998.
07/1999	Color from SPU GIS layer	Large submerged delta visible.	Holyoke culverts replaced in summer 1999. Project went out to bid July 15, 1999 so construction started after this air photo.

continued on next page

Table 3, continued

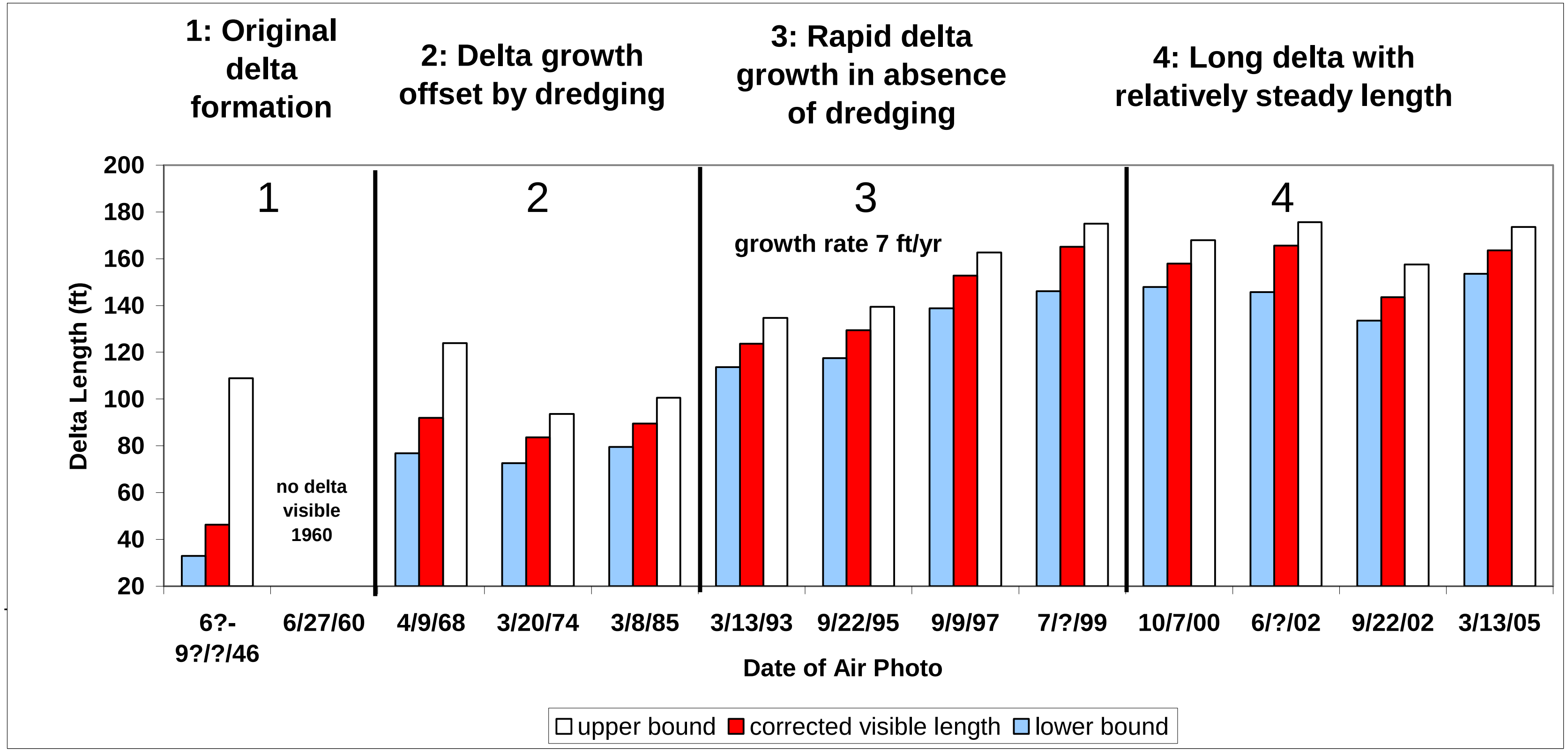
Date	Photo Type	Delta Area Description	Events
10/7/2000	Color	Large delta visible, part unsubmerged. Creek outlet flows north.	Wooden portion of Ruffini dock dislodged and stranded on delta. First spawning surveys this year, good fish access to the creek.
06/2002	Color from SPU GIS layer	Large submerged delta. Dislodged dock still present.	10-year rainfall event in Nov. 2001 delivered "substantial" amount of sediment to delta. No spawning fish passage thereafter.
9/22/2002	Color	Large delta visible but shorter. Unsubmerged parts of the delta divided by channels. Creek outlets to west and east.	Shallow outlet channels still prevent fish access across delta. Dislodged dock still present.
3/13/2005	Color from SPU GIS layer	Large delta visible, part unsubmerged with no gaps. Dislodged dock is no longer present.Creek outlet flows north.	October 2003 storm reportedly made delta sediment deposition worse. Some fish access to creek after storm.
2/2/2007	field survey	Creek outlet shifted to west.	Dec. 2006 flood opens deeper channel to west side of delta. Best salmon runs in creek in about 9 years.

Long delta with relatively steady length

From 1999 through the latest available aerial photograph in 2005, visible delta length fluctuated but was fairly steady. The changes between air photos were less than or equal to the potential error of +/- 20 to 30 feet. Delta length in 1999 and 2005 was nearly identical.

It is clear that sediment supply to the delta did not stop. A 10-year rainfall event in November 14-15, 2001 delivered at least 100 yd^3 of sediment to the delta (Macmillan, 2007) and the October 2003 storm made sedimentation at the delta worse according to property owner Ruffini. There reportedly has been no dredging since 1991.

The relatively steady length of the delta since 1999 is better explained by morphologic or hydrodynamic controls on delta length although the exact mechanism is unknown. The delta tip visible in the March, 2005 air photo corresponds to a 50% (27°) slope on the December, 2004 bathymetric map (Figure 7). Any sediment reaching a slope that steep would probably cascade down the slope and out of view in the air photo. The bathymetric contours show a broad ridge extending west-northwest with top elevations 6 to 10 feet below winter lake level. Sediment that drops off the tip of the delta may be transported in that direction by currents or waves. Another hypothesis is that wave action may play a role in truncating the tip of the delta. As the delta lengthened, it grew out over a progressively deeper lakeshore and presumably became more exposed to waves and currents. When the wind blows from the north, the delta is subjected to high waves due to the orientation of Lake Washington according to a local resident (Deszo, 2007).



Notes:
1) The center bar in each cluster shows best estimate of delta length. Other bars show effects of potential errors.
2) Measurement errors on any given photo sum to +/- 10 feet. Other errors are associated with correcting to uniform lake level.
3) Measurements at different lake levels were corrected to a typical March elevation of 20.73' (Army Corps datum).
4) 1946 photo date unknown, but likely June or later judging by leaves on trees. Error bars reflect the range of possible lake elevations.
5) Length is measured from profile station 42 ft., even with edge of lawn on northwest side of creek.

Figure 6. Delta length visible on aerial photographs between 1946 and 2005 showing four phases in the development of the delta

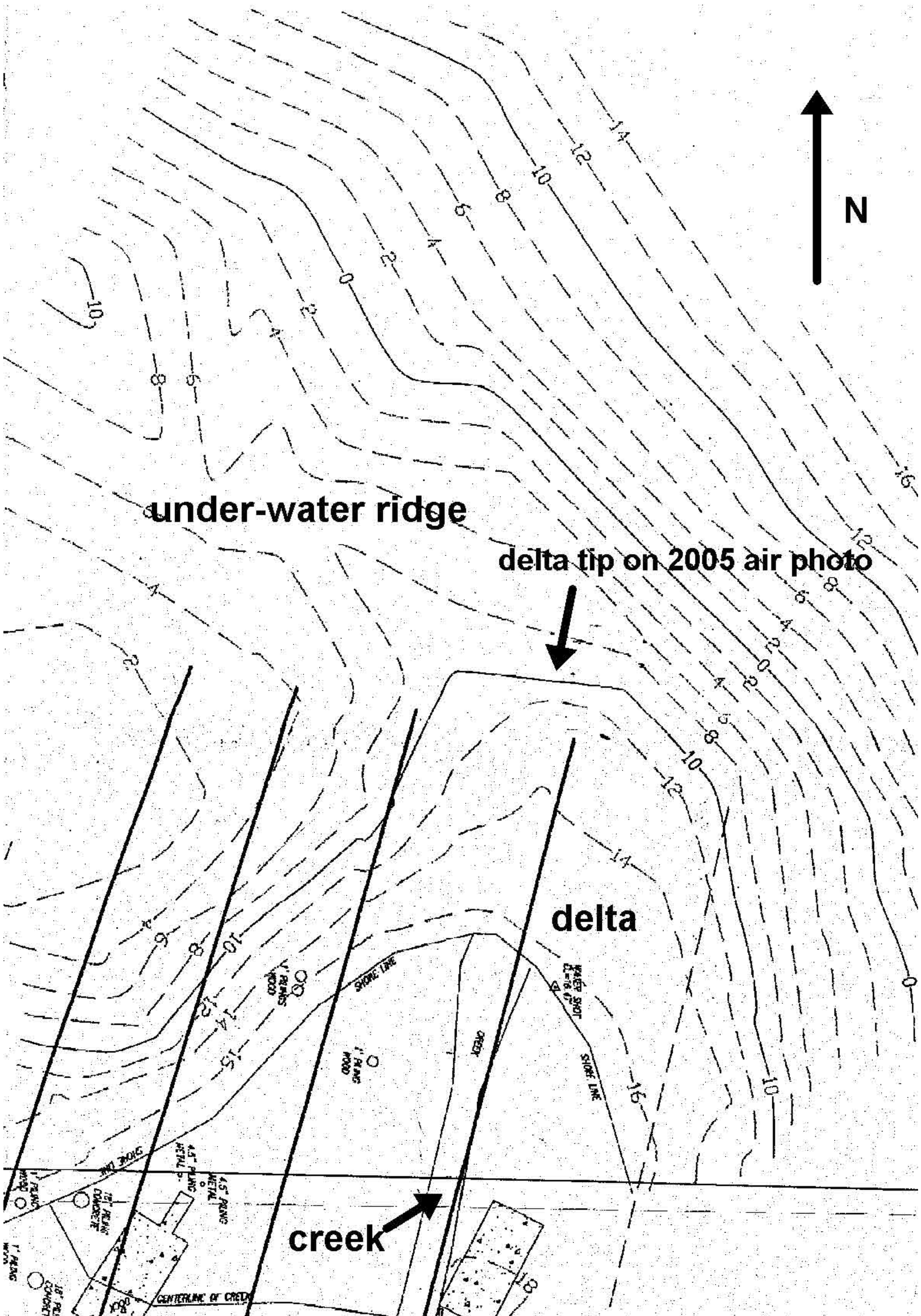


Figure 7. Survey of the Taylor Creek delta December 28, 2004 by Downing & Assoc. Arrow points to location of the delta tip on March 2005 aerial photograph.

3.1.1.2 Growth of the Upper Delta

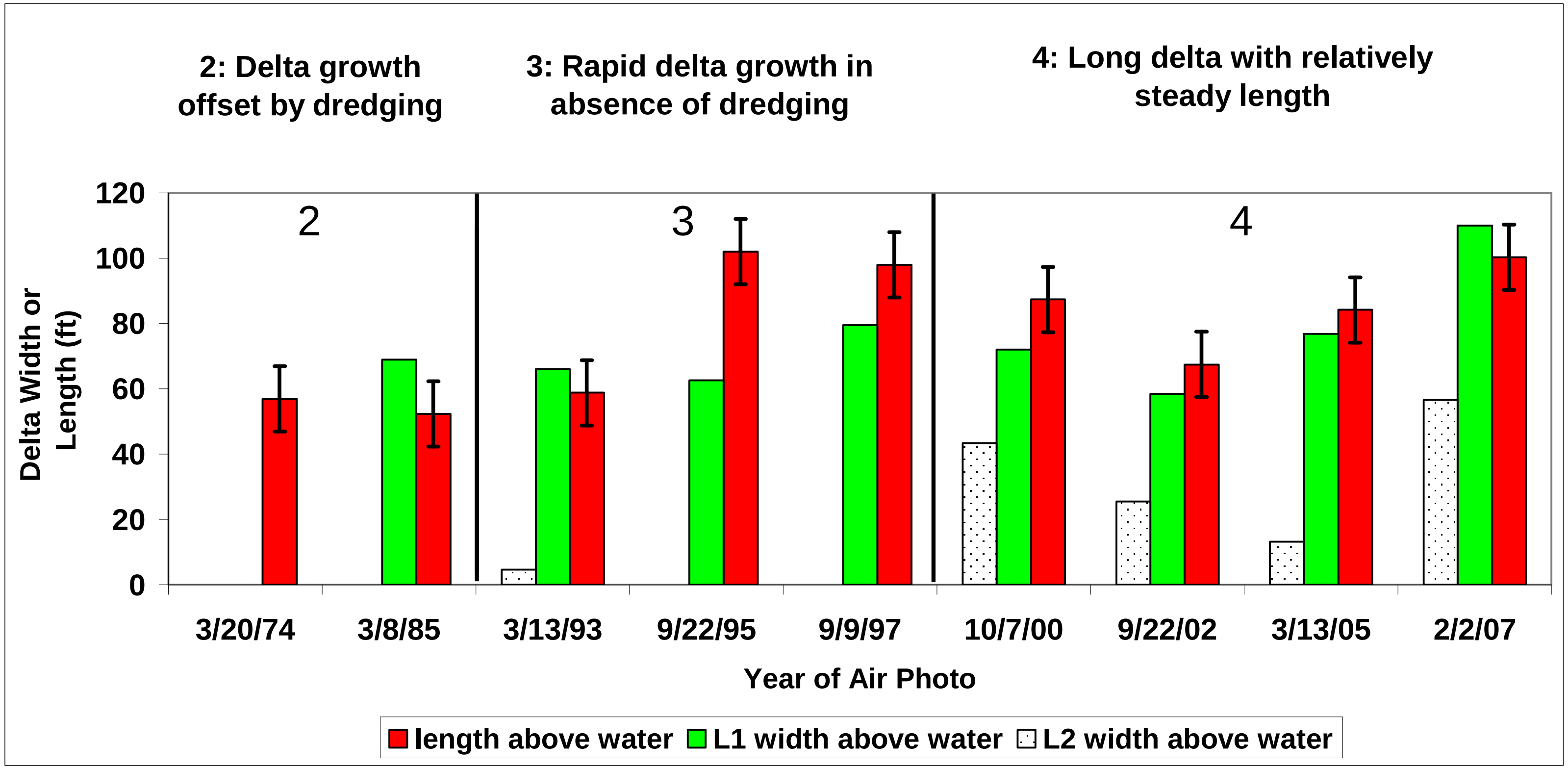
Delta length above lake elevation 20.73 ft. (Army Corps locks datum) is referred to here as "above-water delta length". Figure 8 shows above-water delta length plotted along with above-water delta width on the two cross-sections shown on Figure 4. Error bars show the confidence level of the measurements. There were fewer data points because the entire delta is usually submerged in summer air photos. In addition, no above-water delta was visible in 1968, the date of the first spring low-water photo. The upper portion of the delta had apparently not grown high enough to be exposed yet in 1968.

The upper delta showed slightly different growth trends than the delta length visible under water. The delta was first visible above water in 1974, and its length remained fairly steady at about 50 to 60 feet from 1974 through 1993. Above-water delta length then grew to about 100 feet from 1993 to 1995, a rate of 21.5 feet per year. It was also about 100 feet in 1997 and 2007, but dropped in the intervening years. The 20-foot drop between 2000 and September 2002 is puzzling as there are anecdotal reports of delta growth in the November 2001 flood. Possible explanations for the apparent reduction in length include air photo distortion (visible underwater length also dropped in that photo), or overcorrection for lake level if sediment deposition made the slope steeper than the assumed slope. A less likely possibility is that a few hundred cubic yards of dredging were done to reestablish the creek outlet since there were submerged channels visible in the upper delta.

Flood timing relative to lake level is a potential cause of size fluctuations in the upper delta. Floods that occurred while lake levels were up in fall or spring would deposit sediment higher on the delta than floods that occurred at lower, winter lake levels. This could affect the slope of the upper delta and thus corrections for lake level could be in error. Sediment deposited high on the delta may subsequently be eroded by Taylor Creek or waves, then redeposited lower on the delta (especially so with line L2, which is farther out in the lake). For all these reasons, growth rate of the delta tip under water (section 3.1.1.1) is a more robust indicator of delta growth than the above-water measurements of the upper delta.

Above-water width of cross section L1 was generally wider from 1997 on. Cross-section L2, farther out in the lake, was submerged in more photos but in general was wider from 2000 on. Widths fluctuated from photo to photo and had no consistent ratio relative to above-water length, probably due to shifting locations of sediment deposition. The creek flowed down the west side of the delta in 1985 and 2007 (Table 3 and Figure 9), causing the upper delta to widen and grow higher. Delta width at L1 exceeded above-water length in those two years. However, the creek also flowed down the sides of the delta in 2002 but above-water width was relatively low. This anomalous photo also had seemingly inconsistent above-water length results as described above.

Underwater delta width appeared similar in most years, extending from dock to dock. Between 1999 and 2002 (both photos shot at similar high summer lake levels), the delta appeared to expand 10 to 15 feet west into the space vacated by the Ruffini's dock, which floated away sometime between July 1999 and October 2000. In general, the presence of docks seems to have forced the delta into an elongated shape.



1) Delta dimensions above water could only be measured for the photos taken when lake level was low enough
2) Measurement errors on any given photo sum to +/- 10 feet, shown in error bars.
3) Lake levels were corrected to a typical March lake level of 20.73 feet (Army Corps of Engineers Lake Washington datum).
4) Above-water delta measurements were adjusted for lake level using surveyed delta slope measured in 2007.
5) Length is measured from profile station 42 ft., even with edge of lawn on northwest side of creek.
6) Cross section L1 crosses the creek at profile station + 7ft. (35 ft. from beginning of delta).
7) Cross Section L2 crosses the creek at profile station - 39ft. (81ft. from beginning of delta).
8) 2007 data are from field measurements.
9) A missing bar for L2 width means that part of the delta was submerged on the date of the photo.

Figure 8. Above-water delta dimensions from 1974 through 2007, corrected to a typical March lake level of 20.73 feet (Army Corps locks datum).

Figure 9. Photograph showing Taylor Creek outlet on the left (west) side of the delta in February, 2007. The creek reportedly switched to this location during the storm of November 5-7, 2006. The low dock on the right side of the photo prevents the creek from flowing down the east side of the upper delta.

3.1.2 Fish Passage over the Delta

Wild Fish Conservancy assessed spawning use and barrier status of lower Taylor Creek and its delta in nearly-weekly surveys for the 2000 through 2006 spawning seasons (November, December, and parts of October and January). Based on their data, the delta is probably a barrier to spawning coho and sockeye salmon except during high stream flows or early in the season while lake level is still high enough to flood the delta. The delta appeared to be a fish barrier on 62% of the surveyed days in the 2000-2005 spawning seasons (Figure 10).

Table 4 shows the number of fish that entered Taylor Creek during the seven years of surveys, compiled from Wild Fish Conservancy's final report (McMillan, 2007). These are minimum numbers, since additional fish may have entered the creek only to have the evidence was removed prior to the next survey by the frequent floods of an urban creek. Small numbers of coho were able to enter the creek in 4 out of 6 years, with 2006 the best return. In October, 2002, a creek-side resident stated there had been a large run 4 to 5 years earlier (1997 or 1998 if memory was correct). Sockeye were able to enter the creek in 5 out of 7 years but most sockeye spawning occurred on the delta. The large number of sockeye that went upstream in 2006 was uncharacteristically high, the best in well over a decade according to a local resident.

Information in this paragraph comes from weekly reports provided to Seattle Public Utilities by Wild Fish Conservancy during the course of their study. Fish access was generally good in fall 2000. The November 14-15, 2001 flood (a 10-year rainfall event) deposited a substantial amount of mud and gravel on the delta, raising it an estimated 2 feet at the mouth of the creek. The deposit was 50-60 feet wide and extended toward the lake 30 feet or more. Even at high flows, the creek was disbursed into several channels over the fan. This split-flow condition persisted until the 10/14/03 survey, at which point the stream had finally cut a channel down through the delta that improved fish passage. This was short-lived, as a large October 21-22 storm split flow into two channels, reducing passability during low flows. High water in 11/19/03 resulted in more sediment deposition and channel splitting, although passage improved somewhat in December 2003. Finally, in December 2004, a high flow down cut through the delta and consolidated flow into one main channel. As of 12/20/05, flow was (again? still?) consolidated into "one good main channel".

A creek-side resident said the 11/7-8/06 storm (a 25-year rainfall event) cut a deep channel through the side of the delta that improved fish passage to the best in about 9 years, and attributed the large 2006 return of salmon to the new channel (Deszo, 2007). However, Wild Fish Conservancy found that a significant rise in stream flow was still needed to get fish across the delta due to the small size of the creek. There were only three brief periods of entry in 2006, all during periods of high flows (November 8 and December 12 for coho, and November 13-14 for sockeye). Stream discharges on those days of entry were 18, 17, and 25-30 CFS, respectively.

There is no information on fish entry prior to 2000 other than the anecdotal reports of a good run in the creek in 1997 or 1998. Local resident Deszo remembers the creek plugging up with sediment when the delta "went out 50 feet overnight", but it wasn't clear whether that memory was in the 1990s or later (it matches Wild Fish Conservancy's description of the November 2001 flood). It is unknown whether there was good fish access throughout the 1990s as a result of 1991 dredging, or if blockage problems resumed much earlier than 2001.

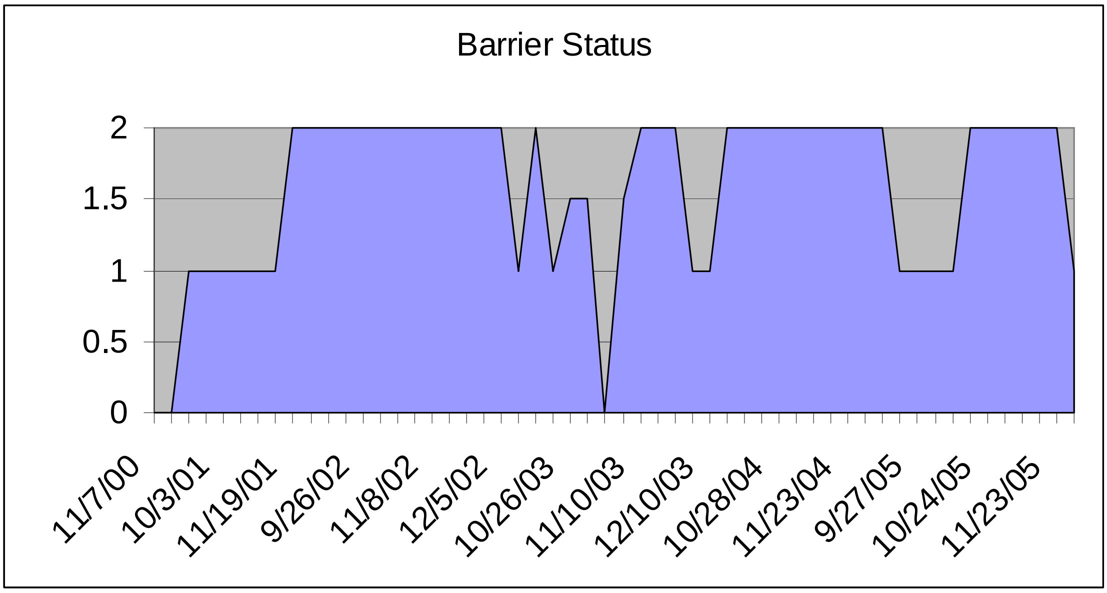


Figure 10. Barrier status of the Taylor Creek delta on surveyed dates between 11/7/00 and 12/20/05. 0 = passable at low flows, 1 = partial barrier passable at moderate flows, 2 = barrier passable only during high flow events. Figure created by Katherine Lynch, SPU, from weekly stream survey reports by Bill McMillan, Wild Fish Conservancy.

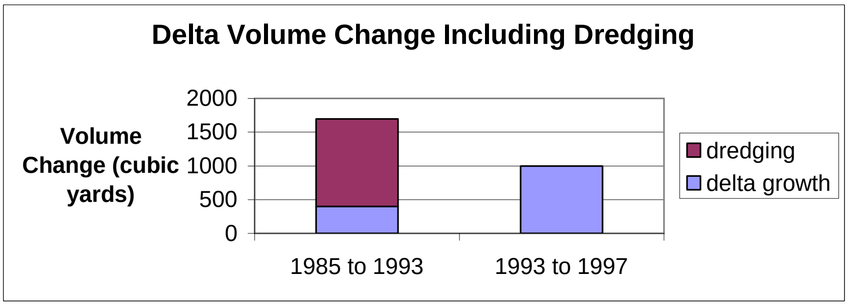
Table 4. Minimum numbers of salmon that entered Taylor Creek, compiled from data in McMillan (2007).

Year	Number of Coho	Number of Sockeye
2000	--	~4-8
2001	2 (pre-flood only)	4? (timing unclear)
2002	4-5	4?
2003	4 (post-10/23 storm)	unknown
2004	0	2?
2005	0	0?
2006	>= 5	31

3.1.3 Delta Volume Change and Deposition Rates

The delta grew about 400 yd^3 from 1985 through 1993, but several times that volume was removed by dredging (Figure 11). From 1993 through 1997, the delta grew about 1000 yd^3 with no reported dredging. The estimated delta growth rates including dredging were 210 yd^3/yr (range160-310) for 1985-1993 and 250 +/-80 yd^3/yr for 1993-1997 (Table 5). The average rate for the two time periods combined was about 220 yd^3/yr.

Delta length after 1999 remained steady. The calculated delta growth rate from 1997 to 2007 was 110 yd^3 per year due to increased width and height of the upper delta. This time period was not included in the table of results because an unknown but large amount of sediment was transported deeper into the lake and not accounted for as described in Section 3.1.1.



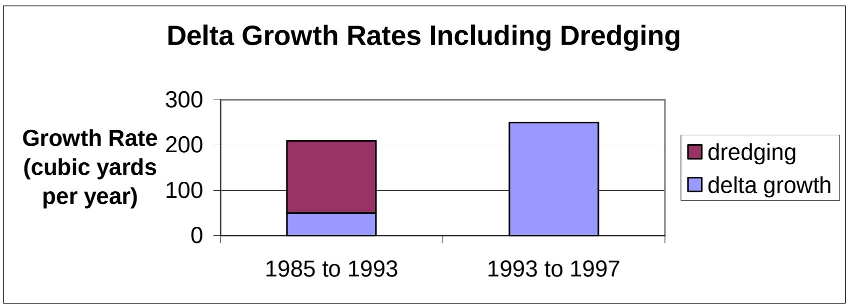


Figure 11. Delta volume changes and growth rates including sediment removed by dredging.

Table 5. Estimated delta deposition rates

Time Period	1985 to 1993 delta growth mostly offset by dredging	1993 to 1997 rapid delta growth in absence of dredging	1985 to 1997
Delta Volume Change (cy)	400 +/-120	1000 +/-300	1400 +/-420
Deposition Rate Based on Volume Change Only (cy/yr)	**50 +/-20**	**250 +/-80**	**120 +/-40**
Dredging Volume (cy)	1300 (1020-2000)	0	1300 (1020-2000)
Total Volume including Dredging (cy)	1700 (1300-2500)	1000 (700-1300)	2700 (2000-3800)
Total Deposition Rate Including Sediment Removal by Dredging (cy/yr)	**210 (160-310)**	**250 +/-80**	**220 (170-320)**

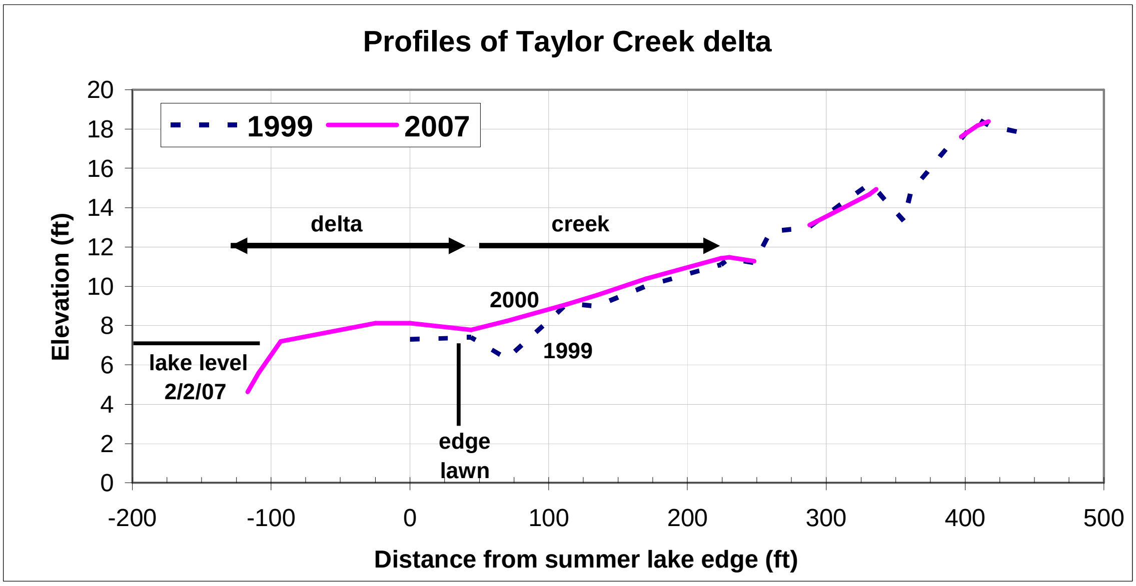
Notes

1. Low end of dredging estimate assumed only the permitted volumes were dredged: 1000 cy delta in 1986 and 10 cy channel in both 1987 and 1991.
2. High end of dredging estimate assumed 1000 cy were dredged in both 1986 and 1991.
3. Rates were rounded to the nearest 10 cubic yards.

3.2 Sediment Deposition in Lower Taylor Creek

Figure 12 shows 1999 and 2007 profiles of Taylor Creek from the upper edge of the delta to Rainier Avenue S. Sediment deposition was thickest in the lowest 135 feet of channel next to the delta. A former pool near the mouth of the creek filled in 1.9 feet. The streambed rose 1.0 feet at station 0, a point on the upper delta that is just upstream from an old concrete dock on the east bank and about 42 feet downstream of the lawn edge (Figure 7). The upstream part of the surveyed reach had only slight deposition ranging from 0 to 0.3 feet. About 40 yd^3 of gravel and sand were deposited in Taylor Creek from Station 0 upstream to Rainier Avenue S in 6-1/2 years, an average rate of 6 yd^3 per year. Because the channelized creek is so narrow both below and above Rainier Avenue, sediment deposition rates in lower Taylor Creek are very small compared to the delta.

No estimates were made prior to 1999 due to lack of data, but up to 4 feet of sediment reportedly was deposited in the lower creek near the delta in 1990 and dredged the next year (Section 3.1.1.1). Deposition followed by dredging probably also occurred in the early 1980s.



Note : this uses the same City of Seattle datum as the 2000 survey by Thomas/Wright, Inc.
Winter water surface (line 2/2/07) is 20.0 Corps locks datum.
Delta profile is probably accurate to +/-0.1 ft. in regard to these datums.
The rod may not have been exactly on water surface due to soft, irregular substrate.

Figure 12. Profiles of Taylor Creek below Rainier Avenue showing about 1 foot of sediment deposition in the creek just upstream from the delta between 1999 and 2007. See Figure 4 for location of delta and creek profiles. The 1999 profile is from Thomas/Wright, Inc. (2000).

3.3 Sediment Changes at the Canyon Mouth/Alluvial Fan

3.3.1 1999 culvert replacements

Holyoke Way S. was constructed sometime between 1926 and 1936 based on Metzger Atlases made in those years. The new road crossed Taylor Creek twice near the base of Deadhorse Canyon (Figure 13). The lower culvert under 68th Ave S., hereinafter referred to as Culvert A, is about 800 feet upstream of Rainier Avenue S. Culvert B is located about 300 feet farther Upstream, where Holyoke Way S makes a sharp hairpin turn and has a high road embankment that crosses the valley.

In 1999, the City of Seattle replaced undersized 3-foot culverts at the two road crossings with much larger, 14-foot wide culverts. The old culverts were too small to convey storm runoff from the urbanized basin, which was mostly built out by the end of the 1940s. By 1999, Culvert B could only pass the 2-year flood and the road embankment served as a dam for an unintended storm water detention basin (TWI and Taylor, 1999). Over the years, about 500 yd^3 of gravel deposited in the backwater zone upstream from Culvert B, raising the valley floor and creating a broad depositional zone that extended about 160 feet upstream. The channel downstream from Culvert B was starved for sediment and eroded about 200 yd^3 from its bed, cutting down to form a 7-foot high hanging culvert as shown in Figure 14. There was a drop of over 4 feet from the culvert to the surface of the plunge pool below, preventing fish passage. Culvert A also had a plunge pool but was not hanging.

Along with the culvert replacements, the streambed between the two culverts was raised with about 200 yd^3 of imported gravel to remove the plunge pools and facilitate fish passage (TWI 1999). About 130 yd^3 of gravel were placed in the new culverts to create a gravel bed. About 8 log weirs were anchored about 2 feet into the streambed. Each weir either had, or was expected to form, a small plunge pool below and a small backwater pool above it. The new channel between the culverts was wider, straighter and steeper. It was also had more hydraulic roughness due to the addition of log weirs and rootwads that were cabled in place.

The culvert replacement project went out to bid on July 15, 1999 and construction started later that summer. No as-built survey was performed to document whether finished stream bed elevations matched the profile shown in the design, but there is no evidence to the contrary. Photographs, profiles, and the stream adjustments documented in subsequent years all appear to be in agreement with the design as shown on the plans.

According to Dennis Hess, SPU's on-site construction inspector, Taylor Creek was diverted into a PVC bypass pipe during construction. The culvert replacements and construction of the gravel bed and log weirs were done in dry conditions. Once the in-stream work was completed, the creek was turned back into the new channel. The first storm occurred after that while the construction crew was still on-site finishing work on the upland portion of the project, so prior to mid-September. Mr. Hess observed that the creek washed some of the placed gravel on the streambed into the pools above the log weirs, and buried the first one or two weirs below Culvert B (phone conversation with Dennis Hess, based on his memory without referring to inspection records, 3/13/07).

3.3.2 Summary of channel response to culvert replacements

Figure 13 and Table 6 summarize changes in sediment volume in the culvert-replacement area. About 200 yd^3 of the pre-1999 sediment deposits above the upper culvert (B) were eroded after culvert replacement. The erosion rate above Culvert B was highest between summer 2001 and summer 2002. Sediment eroded from upstream of Culvert B mostly deposited downstream between the culverts. In most areas between the two culverts, the streambed has risen 0.5 to 1.5 feet for a net gain of about 110 yd^3. Most of the gravel that was added to Taylor Creek between the two culverts is still in place, buried by sediment from upstream. The initial slug of sediment made its way farther downstream over several years and reached Culvert A by 2003 or earlier. About 60 yd^3 were deposited below Culvert A, mostly within Lakeridge Park.

There has been a net export of about 22 yd^3 from the culvert replacement zone over the eight years since the culverts were replaced. This is equivalent to one tenth of one average year of coarse sediment supply, based on the delta's average growth rate of 220 yd^3 per year (Section 3.1.3). The exported sediment came primarily from above Culvert B, either from erosion of the old deposits behind the former undersized culvert or directly from Deadhorse Canyon. The culvert replacements have changed the location of sediment deposition in the canyon mouth area. Instead of depositing sediment upstream from Culvert B, the creek now deposits sediment between the culverts and just downstream from Culvert A, which is the natural location for an alluvial fan.

The following sections provide more detail on Taylor Creek's response to the culvert replacements. Appendix C contains additional data tables, profiles and cross-section plots.

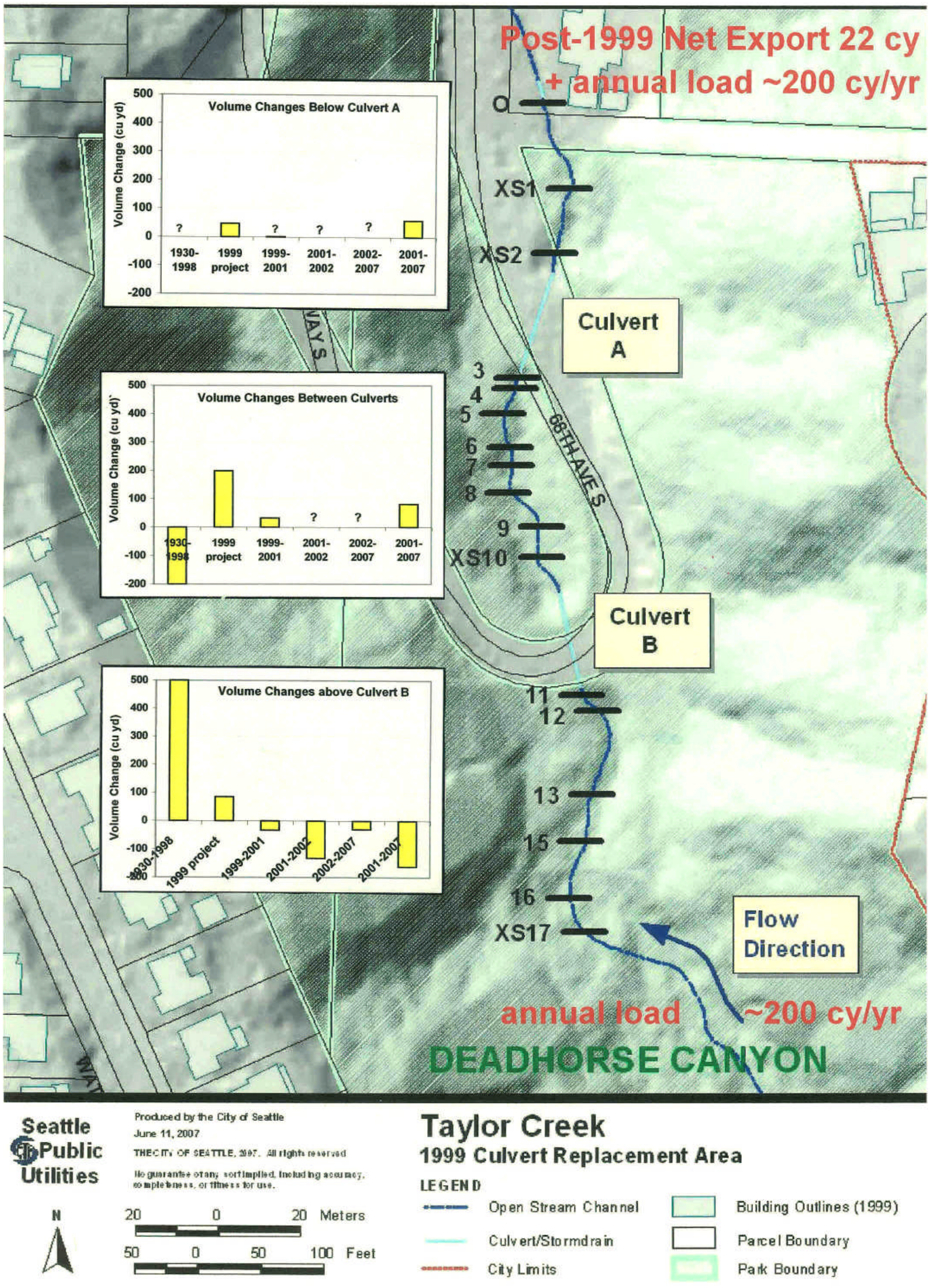


Figure 13. Site map of alluvial fan/canyon mouth area showing locations of replaced culverts and surveyed cross sections. Graphs show changes in sediment storage.

Figure 13. Site map of alluvial fan/canyon mouth area showing locations of replaced culverts and surveyed cross-sections. Graphs show changes in sediment storage.

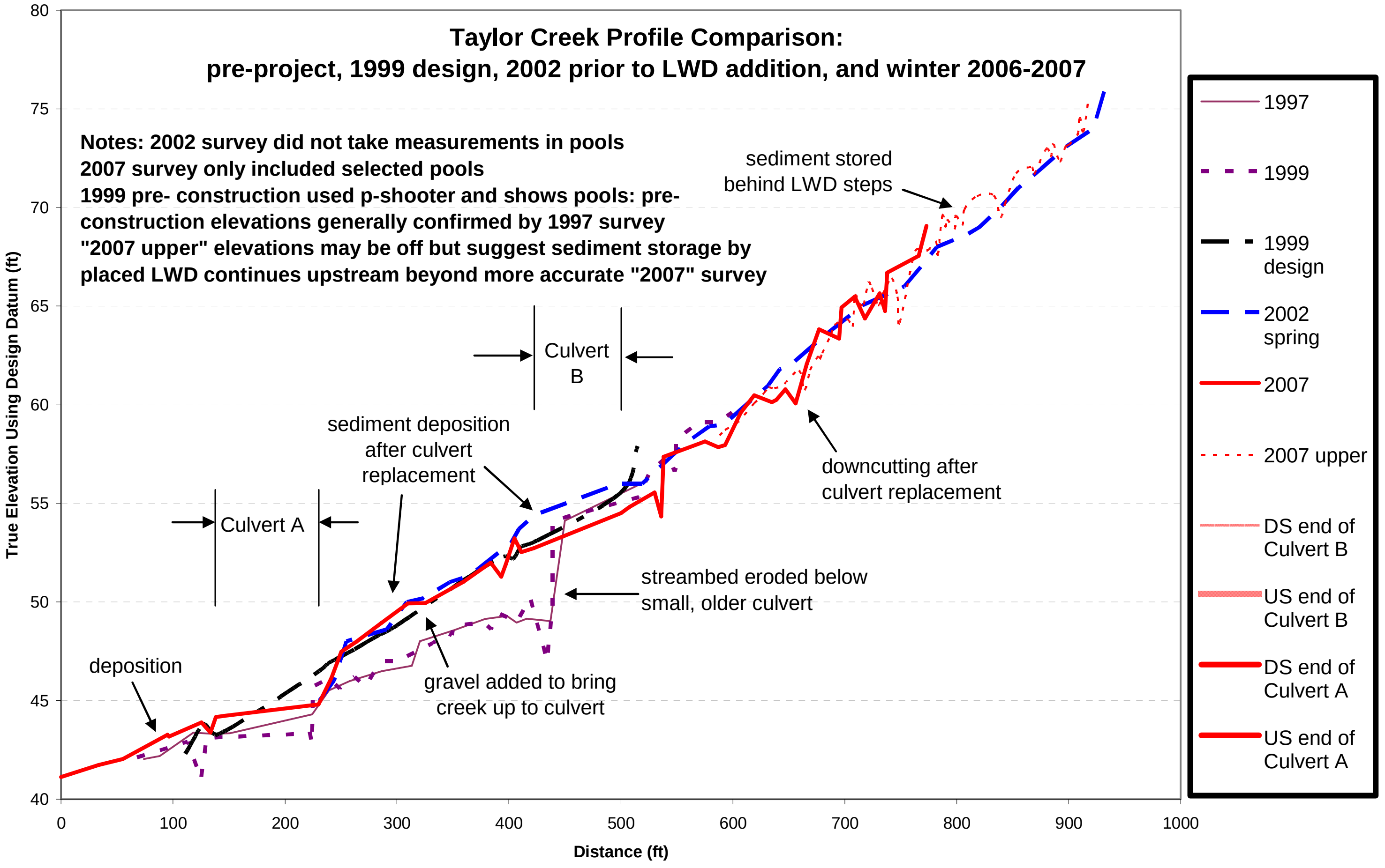


Figure 14. Profiles showing the streambed of Taylor Creek prior to construction (1997 and 1999), the designed new channel (1999 design), and post-construction (2002 and 2007). Although not shown on the profile, the design included eight log weirs with associated pools. No as-built survey was performed. Station 0 is shown on Figure 13. Cross-section 17 is located at about Station 640.

Table 6. 1999-2007 sediment volume changes and deposition rates in the alluvial fan area following culvert replacement. Results in unshaded cells have a high confidence level. Results in shaded cells are approximate or unknown. See Figure 13 for a graphical presentation of these results on a site map.

1999-2007 Sediment Volume Changes in Culvert Replacement Area

Area	***+ is up, - is down*** **Volume Change (cu yd)**				
	1999-summer 2001	**summer 2001-summer 2002**	**2002-2007**	**2001-2007**	**1999-2007**
Culvert B upstream to bend	-33	-132	-30	-162	-195
Between Culverts A and B	32	>=51	<=30	81	113
Culvert A to down-stream end of park	>=1	unknown	unknown	59	60
Entire Culvert Replacement Area	**~0**	**unknown**	**unknown**	**-22**	**-22**

Volumes in unshaded cells were estimated from repeated cross-section surveys. Shaded cells indicate the volume splits between pre- and post-2002 was approximate, based in part or all on profile changes due to lack of 1999 or 2002 cross-sections.

1999-2007 Rate of Sediment Volume Changes in Culvert Replacement Area

Area	***+ is up, - is down*** **Volume Change (cu yd)**				
	1999-2001	**2001-2002**	**2002-2007**	**2001-2007**	**1999-2007**
Culvert B upstream to bend	-17	-132	-6	-27	-24
Between Culverts A and B	16	>=51	<=6	13	14
Culvert A to down-stream end of park	<=1	unknown	unknown	10	8
Entire Culvert Replacement Area	**-1**	**unknown**	**unknown**	**-4**	**-2**

3.3.3 Channel Response Upstream of Culvert B

The streambed at the inlet to the new upstream culvert (Culvert B) was reportedly constructed about 9 inches lower than before. Of equal importance, the large new culvert allowed easy passage of water and sediment. During the first heavy rains in mid-November 1999, a knickpoint formed and moved upstream from Culvert B (Taylor, 1999). A knickpoint is a short, steep slope that separates a lower streambed downstream from a higher streambed upstream. Knickpoints travel upstream because the steep slope of the knickpoint erodes faster than the adjacent, flatter sections of streambed. As the knickpoint moved upstream, Taylor Creek cut down through sediment that had accumulated since about 1930 in the backwater zone of the former, undersized culvert (Figure 15). The knickpoint advanced about 60 feet upstream from the culvert in the first winter, 100 feet upstream from the culvert by summer 2001, and all the way to the bend at the entrance to Deadhorse Canyon in the November 15, 2001 flood (a 10-

year rainfall event). The channel downcut through up to two feet of sediment deposits (Figures 16 and 17), exposing boulder-cobble steps at the entrance to the canyon that apparently stopped upstream knickpoint migration. Downcutting steepened and destabilized the creek's banks, which led to more erosion through channel widening.

The first two rainy seasons after the culverts were replaced had relatively small floods, and only about 30 yd^3 of sediment were eroded. About 130 yd^3 eroded between summer 2001 and 2002 due to upstream passage of the knickpoint. An additional 30 yd^3 eroded after 2002, the net result of downcutting at each end of the reach that was partly offset by deposition of 47 yd^3 of sediment in the vicinity of cross sections 13 through 16. The LWD added in 2002 was responsible for at least 25 yd^3 of sediment storage, as described in more detail below.

The sandy gravel that had accumulated upstream of the old, undersized culvert was a smaller caliber sediment than the bedload from the canyon. By early 2002, the former backwater deposits had been eroded away and the streambed had coarsened. Downcutting reexposed some large boulders in the streambed at the upstream end of the former depositional zone. The new surface texture was about half gravel and half cobbles, with a median diameter of 58 mm (Appendix A, XS 15&16). Gravel-cobble bedload from the canyon upstream was now being transported all the way through the former depositional zone.

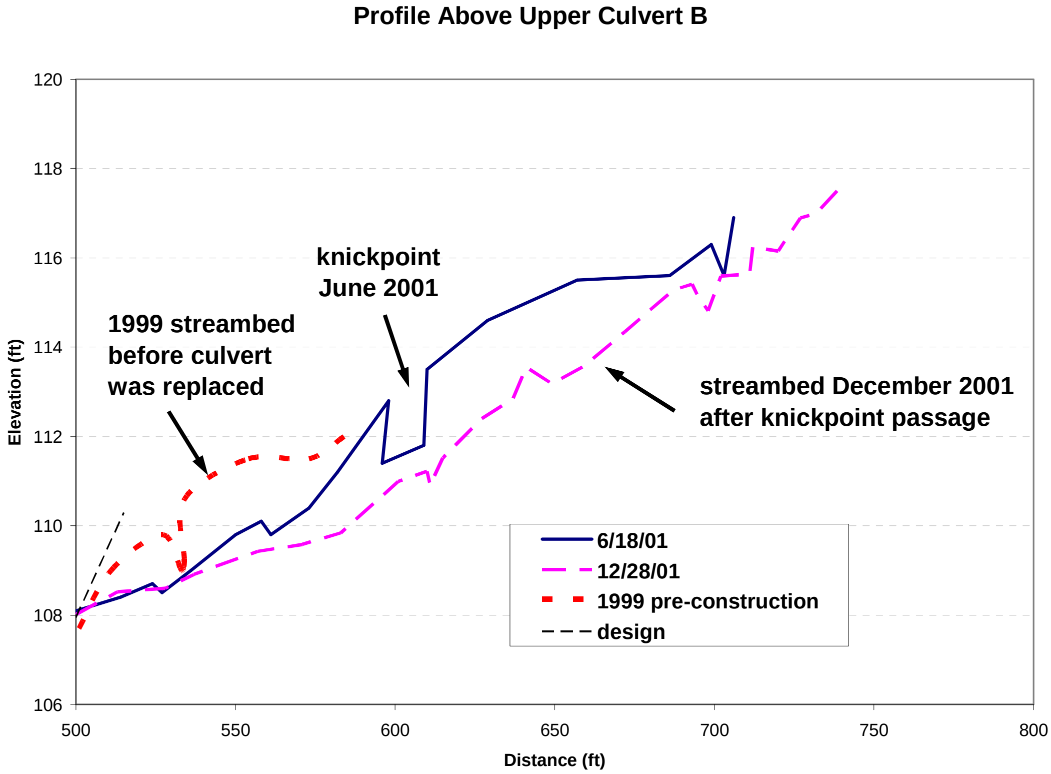
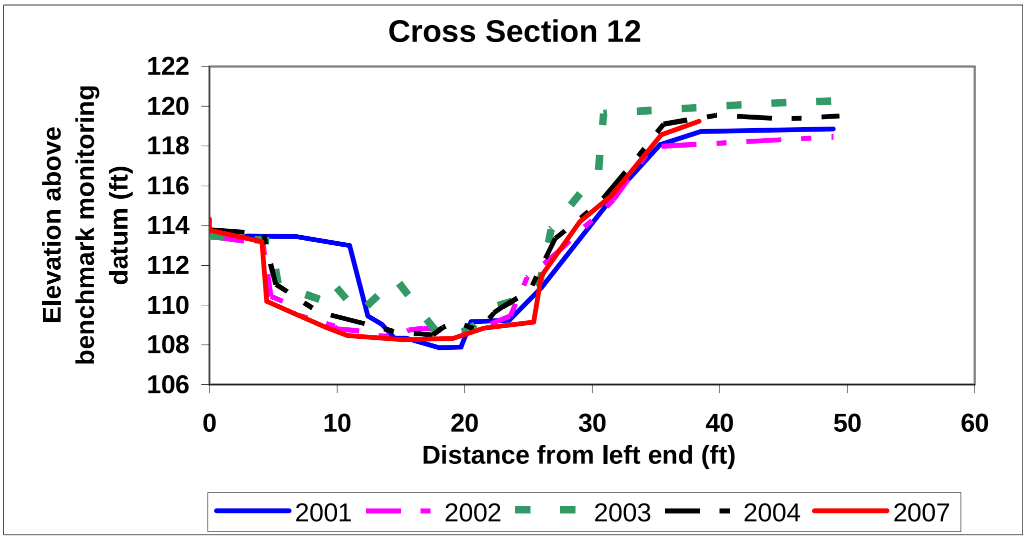


Figure 15. Stream monitoring profiles starting at the upstream of Culvert B (Station 500), showing upstream knickpoint migration after culvert replacement in 1999.

Figure 16. 2000 and 2007 photographs taken from the same location above Culvert B, looking upstream through cross sections 16 and 17. The broad gravel deposits have been eroded away, replaced by a deeper channel with cobbles and some boulders on the streambed.

3.3.3.1 Channel response to addition of large woody debris (LWD) in 2002

After the November 2001 flood, rapid bank erosion threatened a trail and was eroding a high, clayey bank near the culvert inlet. In summer 2002, SPU installed dozens of logs in the first 450 feet of channel upstream from Culvert B (see Figure 2 for location). In the narrower canyon upstream from XS 17, logs were placed to form steps in the stream profile that would



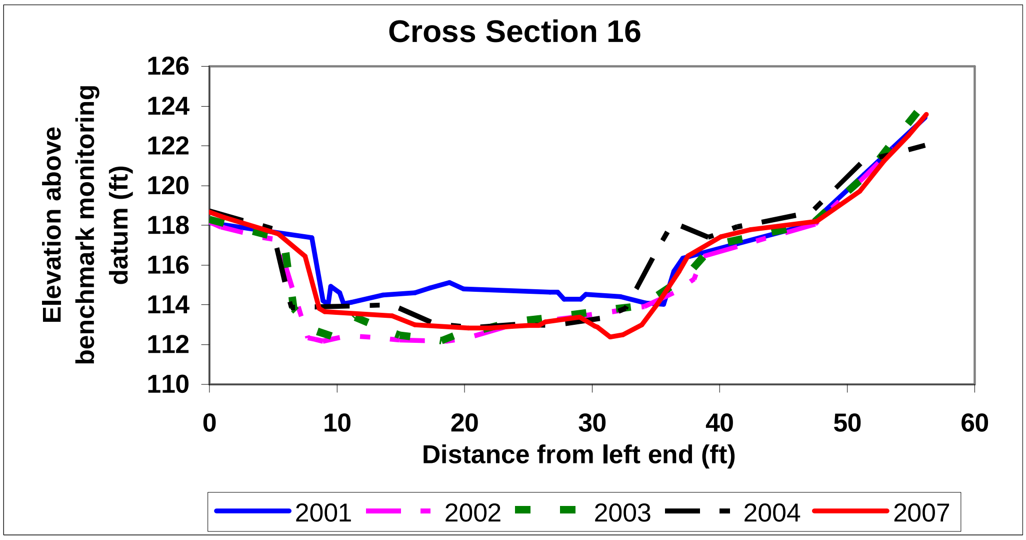


Figure 17. Cross-section surveys showing widening and channel incision after upstream passage of the knickpoint. Cross-sections 12 and 16 are 32 and 125 feet upstream of Culvert B, respectively (see Figure 13).

trap sediment upstream and reduce the effective gradient. The log ends were not anchored, but were instead jammed against boulders, bank protrusions and other logs for stability.

In the wide, former depositional zone from Culvert B upstream to the bend just beyond XS 17, the LWD very successfully stopped bank erosion in the two problem areas and caused bars to deposit in low-velocity zones next to the banks. None of the LWD had raised the elevation of the stream channel as of 2007, and the channel continued to downcut after 2002 in some locations. The creek went under or around the placed logs, many of which had shifted when floated by high flows. Five years after LWD placement, about 25 yd³ of sediment were stored in gravel bars sheltered by placed LWD. Sediment storage behind a log step at cross section 12 was not counted, as it predated the wood placement.

In the narrower canyon upstream of the cross section 17 and the bend, the placed LWD successfully raised the bed and trapped sediment upstream of each log step as shown on the profile (Figure 14). Placed LWD in the first 286 feet of the canyon stored 48 yd³ of sediment. Most sediment storage occurred in gently-sloping sediment wedges upstream from LWD steps. The canyon is narrower than the culvert zone and thus more conducive to stable steps because flow cannot go around to one side as easily. One LWD jam at the mouth of the canyon failed in a December 2006 flood and released about 21 yd³ of gravel downstream. The December 2006 flood also caused some further channel scour in the vicinity of cross section 17 downstream from the failed jam. Prior to that flood there were 69 yd³ stored in the first 286 feet of the canyon. The storage capacity of the LWD in the reach is full.

As of January 2007, the LWD stored about 17 yd³ per 100 linear feet of channel. The rate was the same in the lower canyon and in the wider zone between the canyon and Culvert B.

3.3.4 Channel response between the two culverts

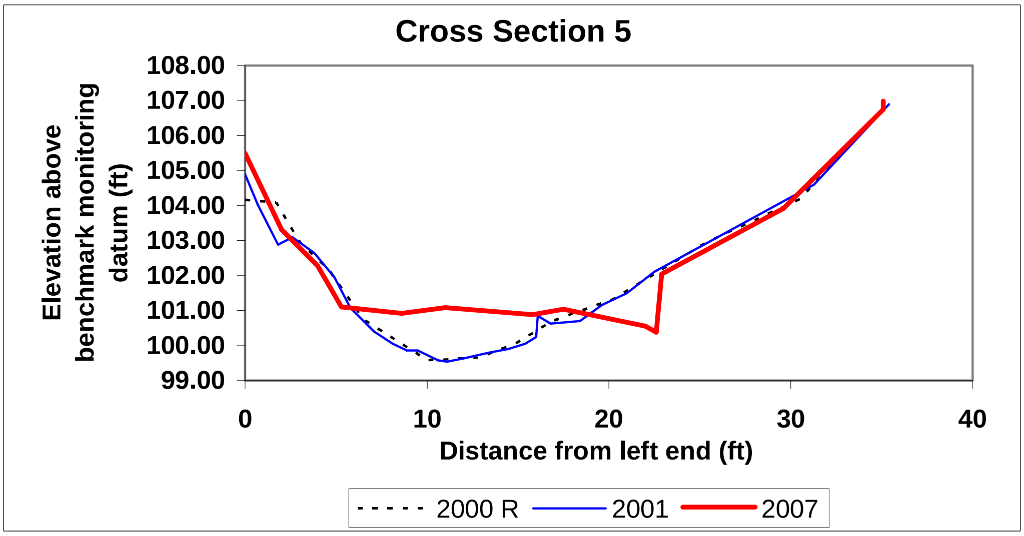
Gravel eroded by downcutting above Culvert B initially deposited within Culvert B and a short distance downstream. The broad, rootwad-roughened new channel between the culverts had a much lower sediment-transport capacity than upstream. It became the new depositional zone. The original gravel placed during construction was buried by sediment from upstream. Over the next few years, gravel from upstream continued to move downstream from Culvert B, burying more log weirs and pools as it went. The sediment wave moved 70 feet downstream of Culvert B by February 2001, and 140-150 feet downstream by summer 2002. All weirs except the final log weir, 180 feet downstream, were buried by 2003 and remained buried in 2007 (Figure 18). Sediment did not bury the final log weir because local hydraulics cause scour at the inlet to Culvert A.

About 80 yd³ of sediment were deposited between the two culverts between 2001 and 2007. Figure 19 shows sediment deposition at two of the cross sections. Only a few cross sections below Culvert B were surveyed in 2002, so there was insufficient survey data to determine whether some of the 130 yd³ pulse of sediment from above Culvert B in 2001-2002 moved beyond the culvert-replacement zone that same year. At least 50 yd³ of it was deposited a short distance downstream from Culvert B (Table 6).

The thalweg is the lowest spot in a channel cross-section. Thalweg elevations rose initially at the outlet of Culvert B. Once the more erodible, finer gravel deposits had been removed from above Culvert B, the sediment supply declined to the rate produced by the canyon upstream. In 2001, some rootwads that were promoting deposition at the outlet of Culvert B were repositioned to reduce blockage of the culvert. As a consequence of both these factors, the streambed in Culvert B had fallen by 2004 (Figure 14). Thalweg changes below Culvert B were small from 1999 through 2001 except for filling of pools with gravel prior to the establishment of cross sections. After 2001, average bed elevation between the culverts rose by 0.5 to 1 foot except at the downstream end. Although there has been recent, minor downcutting of the main channel through the original sediment deposits in cross sections 8 through 10, none of the buried weirs had been reexposed by 2007. The reach between culverts remains a net sink for sediment.

Taylor Creek between the culverts became very wide and braided when the initial sediment deposits buried the constructed channel. The creek had shallow, poorly-defined channel threads with a median sediment diameter (D_{50}) of 20 mm and a D_{84} of 55 mm (Appendix A, "below XS 10" sample). By 2007, the creek had developed a single, deeper channel with some mild bends and had coarsened with a D_{50} of 34 mm and D_{84} of 81 mm. Some of the former gravel bars had become vegetated floodplain. These changes are consistent with a declining coarse sediment load compared to earlier when the accumulated fill above Culvert B was eroding.

Figure 18. Paired photographs looking upstream from Culvert A towards Culvert B, showing the channel the first winter after construction (above), and the same location in 2007 after the log weirs were buried with sediment (below).



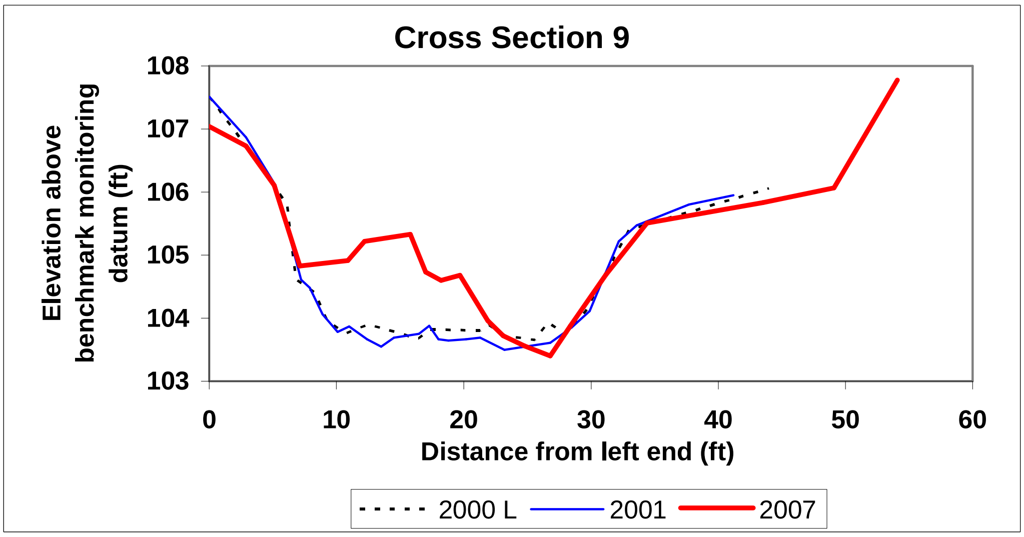


Figure 19. Cross-section surveys showing accumulation of sediment between the two culverts since the year 2000. Cross-sections 5 and 9 are 161 feet and 63 feet downstream of Culvert B, respectively (see Figure 13). The 2000 and 2001 surveys were done in summer. The "2007" surveys were done in Dec. 2006 (XS 5) and Jan. 2007 (XS 9).

3.3.5 Channel response from Culvert A downstream

Problematic local scour and bank erosion occurred in fall 2001 at the inlet of Culvert A and threatened to undercut the first weir upstream. Repairs were made in 2002 that included adjusting the weir and rootwads to reduce future scour. This erosion probably generated less than a couple of cubic yards of sediment.

Sediment deposited at the outlet of Culvert A from 2001-2007 due to partial blockage by a root wad. There was no change from 2000 to 2001, but possibly one foot of earlier aggradation occurred prior to 2000.

Below Culvert A, the thalweg rose about one foot prior to 2001 and continued to rise through 2007. Average bed elevation rose by a foot or more. About 60 yd^3 were deposited between Culvert A and the downstream end of Lakeridge Park, mostly after 2002 (Table 7).

According to the owner of the first house downstream from the park, in about 2003 there was a visible rise in stream bed elevation at the upstream end of his property (field interview with Mike Clemens, 2/2/07). The bed reportedly rose about 1 foot in 2002 at Clemens' driveway bridge (labeled "0" on Figure 13) but has since scoured about 6 inches. The bar below the driveway bridge reportedly formed after 2003. The bed elevation has remained fairly stable, perhaps because he removes the largest cobbles by hand which helps keep gravel moving. Once past the bar below the driveway bridge, the current moves faster and Clemens thought there has been no sediment buildup downstream.

3.3.6 Gradient Changes In The Alluvial Fan Area and Their Effect on Sediment Transport Rates

Holyoke Way S was built between 1926 and 1936. The total volume of sediment deposits above Culvert B was about 500 yd^3, much of which still remains on the vegetated terrace south of the creek. Assuming this accumulated in 70 years, the average deposition rate would be only 7 yd^3 per year which is far less than the sediment supply from the canyon upstream. This indicates that most sediment from Deadhorse Canyon was able to make its way through the undersized culvert and continue downstream.

Figure 20 shows how creek gradients in the alluvial fan area have changed in response to culvert replacements. See Figure 14 for profiles of the creek at different times.

In 1997, scour below the undersized upper culvert had reduced the gradient between culverts to 2.5 percent. Deposition above the small, upper culvert had increased the gradient there to 5.3%.

In 1999, the bed between culverts was raised back up to roughly its natural elevation, resulting in a 3.6% slope. The slope above the upper culvert was either 5.3%, the same as 1997, or a little steeper if indeed the bed at the culvert inlet was lowered about 9 inches. The new, larger culverts no longer impeded water and sediment transport. This has allowed the gradients above and below the culverts to equalize over time.

Headcutting rapidly eroded the sediment deposits above Culvert B and the gradient above the culvert dropped to 4.2 percent in 2002 and 3.7 percent in 2007. The channel also widened during that time and the bed coarsened. Consequently, sediment transport capacity has declined significantly since the culverts were replaced in 1999.

Although steeper than before, after construction the channel between the two culverts was flatter, wider and rougher than upstream. This caused sediment to drop out as soon as it exited culvert B. The length of channel between and including the two culverts steepened rapidly from 3.6% after construction to 5.1% in 2002. The initial steepening resulted from deposition at the upstream end and scour at the downstream end. The scour problem was repaired which brought the downstream bed up. Deposition at the upstream end was worsened by an

Gradient Changes in Culvert Replacement Zone

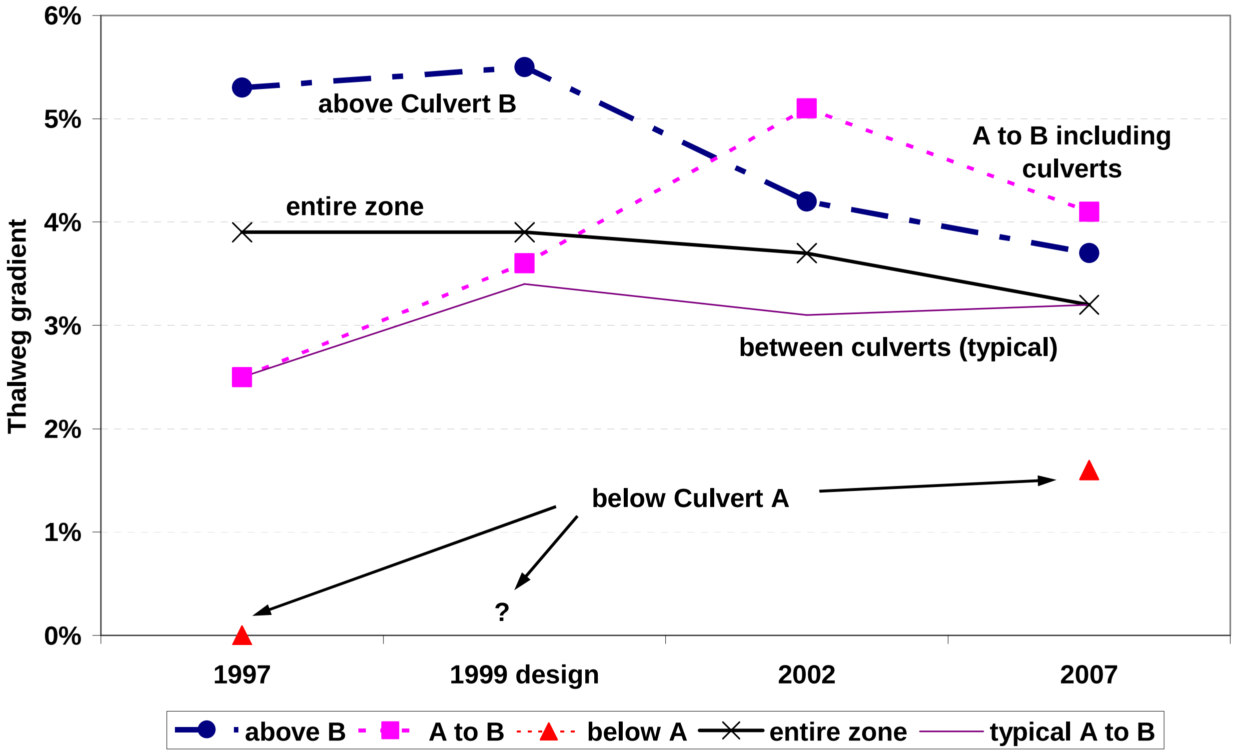


Figure 20. Gradient changes in the culvert replacement zone.

obstructing root wad which was repositioned. By 2007, the sediment wave from erosion of the accumulated fill upstream of Culvert B had passed the downstream culvert and the upstream bed lowered. Gradient between the two culverts dropped to 4.1% by 2007, still higher than the initial design due to some remaining inlet scour downstream.

The middle section of the reach between culverts has retained a gradient of about 3% throughout all the channel adjustments but changed channel pattern. However, the creek is now deeper and narrower compared to the earlier shallow, braided channel.

The channel below Culvert A was flat in 1997 because discharge from the undersized culvert had scoured a long pool. The undersized culverts attenuated pulses of sediment during floods which reduced sediment deposition at this location. The gradient after construction is unknown, but currently is 1.6%. This may be steeper than after construction if sediment deposition was faster at the upstream end.

To summarize, channel adjustments in the 8 years since the culverts were replaced have resulted in a more even stream profile whose gradient gradually declines downstream. Taylor Creek has redistributed the accumulated sediment from above the upper culvert to downstream. The locus of deposition first occurred between the culverts, where deposited sediment has now built banks high enough to deepen the channel and increase sediment transport capacity. The locus of deposition moved later to below Culvert A, where deposition is still occurring. The new culverts have allowed the creek to establish a more natural grade and deposit its sediment in a location favored by geomorphology. At Culvert A the valley floor flattens and widens, making it a natural location for an alluvial fan. Its gradient may steepen in the future as a result of sediment deposition near the culvert outlet. Future sediment deposition may reduce clearance of Culvert A and the first driveway bridge downstream.

3.4 Sediment Supply from Deadhorse Canyon and Its Forks

This chapter focuses on the gravel and sand fraction of Taylor Creek's sediment load, since the delta is composed of those sizes. Finer sediment (silt and clay) gets carried beyond the delta into Lake Washington and eventually settles onto the floor of the lake. Taylor Creek's geology gives it a relatively low supply of sand and gravel compared to many urbanized streams in the Puget Lowland. The canyon is primarily dense, pre-Vashon glacial and nonglacial sediments that contain very little gravel. Taylor Creek's streambed downstream from the forks has abundant boulders that reduce downcutting by forming stable steps.

The reach names referred to in this chapter come from SPU's urban streams watershed assessment (SPU 2003; Perkins 2002). Figure 21 shows stream reaches, topography and some of the landslides. Appendix B gives stability class ratings by reach. Bank erosion was likely worsened by a 25-year recurrence interval rainstorm in November, 2006 that preceded field work.

3.4.1 East Fork Taylor Creek

Vashon advance outwash, a very erodible source of sand and gravel, is rare in Taylor Creek but is a significant source of delta sediment. It is exposed along the stream only in the uppermost 420 feet of the East Fork Valley (Reach EF02) upstream from Lakeridge Park and the Seattle city limits (Figure 21). The valley walls are about 30 feet high which limits the size of landslides (Figure 22). Two large, valley-spanning debris jams have trapped some of the sediment and provide grade control, thereby reducing downcutting (Figure 23).

Vashon advance outwash also is exposed in the uppermost canyon walls farther downstream. A 1984 debris flow delivered Vashon outwash sediment to the East Fork downstream from the debris jams, at the top of the East Fork Canyon (EF01) reach. The debris-flow deposit forced the creek against a cliff composed of erodible, sandy, glacial till. This is an area of ongoing erosion that has worsened since my first field survey in 2001. The creek has moved laterally so that it no longer flows across a bed of concrete slabs as it did in 2001. The potential exists for severe downcutting of this steep, 22%-gradient channel, which could cause the upstream logjam to fail. This would release stored sediment and increase erosion rates by channel downcutting.

The third notable area of erosion on the East Fork is the bypass channel around the plugged culvert near the mouth of the East Fork. The bypass channel has enlarged dramatically since 2001, but since nearly all the eroded sediment was silt or clay it did not contribute to delta growth. Continued erosion at the inlet to the bypass channel could lead to failure of a concrete wall that steps up the channel 4 feet and stores gravel behind it. Should this occur, it would trigger downcutting further upstream. A small, groundwater-fed channel delivers a minor amount of sand to the bypass channel from a slowly-eroding, till landslide known as the Grotto.

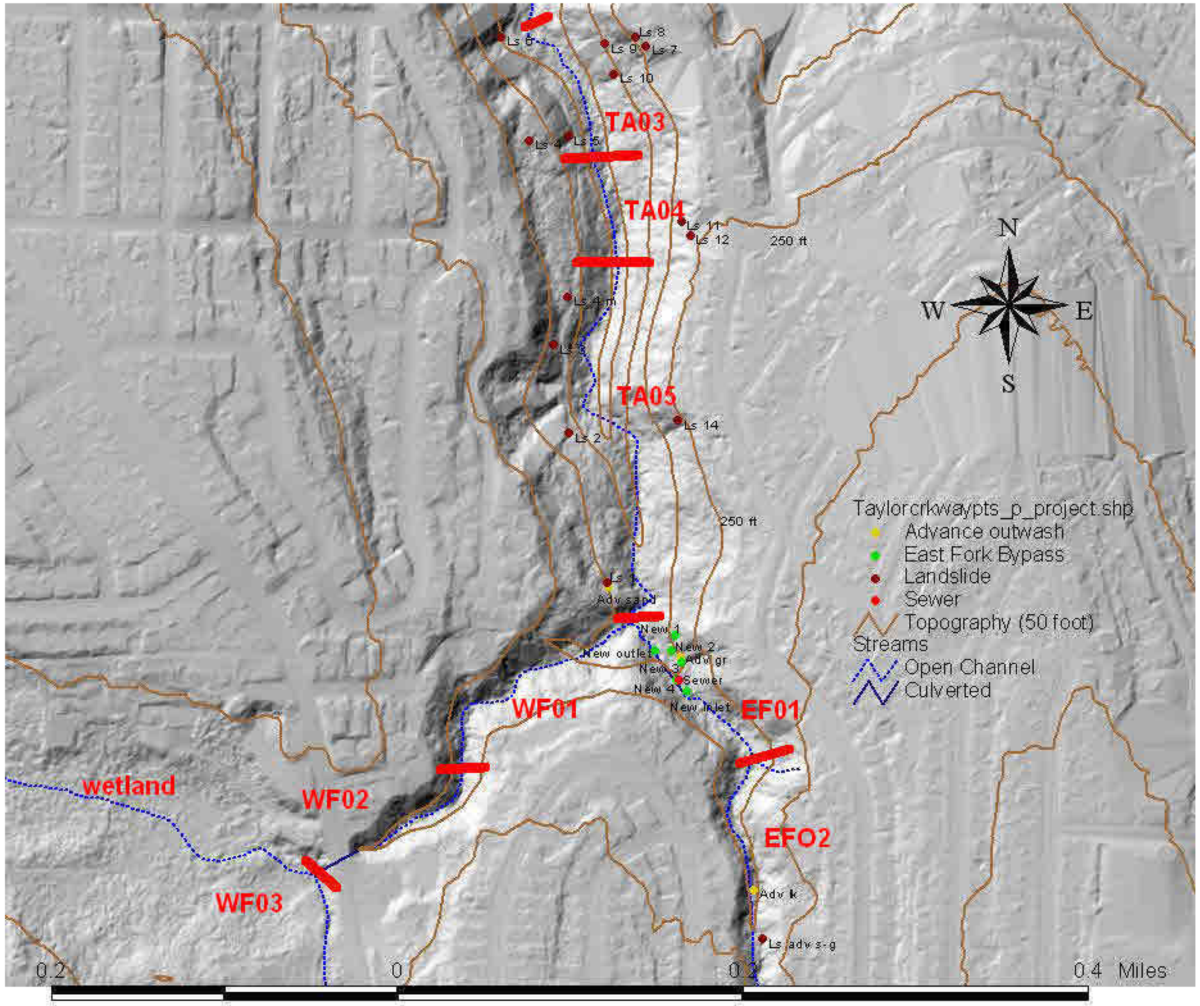


Figure 21. Lidar relief map showing stream reaches and some of the landslide scars inspected during field work. (Additional landslides were visited but no GPS waypoints were taken.) The yellow point in reach EF02 labeled "advance outwash" marks the contact between glaciolacustrine silt to the north and Vashon advance outwash sand and gravel to the south.

Figure 22. Photograph of a 30-foot-high landslide in Vashon advance outwash gravel, East Fork Valley reach.

Figure 23. Photograph of gravel deposits on East Fork Taylor Creek upstream of a valley-spanning LWD jam that raises the creek 4 feet.

A rough estimate of sediment supply was made from field estimates of landslide and streambank-erosion scar dimensions along the East Fork of Taylor Creek (Table 7). The advance outwash section of the East Fork Valley has about 300 yd^3 of recent and 1100 yd^3 of older erosion scars that delivered sand and gravel to the creek. Approximately 400 yd^3 of sandy gravel are stored behind two large debris jams that span the 25 to 30-foot wide valley floor. About 400 yd^3 of sand and gravel have been eroded from the debris-flow deposit area. Altogether, about 1800 yd^3 of coarse sediment have been exported to the bottom of the East Fork Canyon. The timeframe represented by the erosion volumes is difficult to determine from vegetation, since sandy erosion scars can stay bare for years before revegetating, especially if the creek remains at the toe of the eroding bank. The long-term sediment-supply rate would be about 50 yd^3 per year if erosion occurred over 30 years, or 25 yd^3 per year or less if a longer period of time is represented by the erosion scars. Short-term maximum sediment-supply rates from the East Fork could be 100 to 200 yd^3 per year if the fresh erosion scars all eroded in the last 3 to 6 years, however that timeframe is extremely speculative.

A minimum estimate of sediment-transport rate from the East Fork was obtained from the plugged culvert at the downstream end (Figure 24). The East Fork was routed through the 3-foot diameter culvert by a sewage treatment plant that operated briefly in the 1950s. The culvert reportedly plugged with coarse sediment rather frequently (perhaps during every flood event), and then would remain plugged until someone from the Parks Department came to unplug it (Chris Woefel, SPU, phone call 2007). It was unplugged during spring 2001, and appeared to have been plugged for quite some time by late 2006 because the bypass channel had enlarged dramatically. Based on 2001 field notes, about 35 yd^3 of gravel was released downstream each time the culvert was unplugged. While unplugged, additional amounts of gravel would have been transported through the culvert zone. If we assume the culvert was formerly plugged and then flushed at least once a year, at least 35 yd^3 per year of gravel would have moved downstream. If it became plugged less frequently, perhaps during larger floods that occurred three times per decade, the minimum bedload transport rate past the culvert would be about 10 yd^3 per year.

Each time the culvert plugged, bedload transport from the East Fork would have been interrupted until the channel upstream from the culvert refilled with 35 yd^3 of sediment. After that, some bedload sediment would have been conveyed downstream through the bypass channel. The bypass channel is now quite large and steep, capable of transporting the supply from upstream.

The sediment deposit upstream of the culvert serves to slow the transport rate due to its gentle 2% gradient and lack of banks (Figure 24). Gravel deposited upstream from the culvert has a surface median diameter (D50) of 28 mm and subsurface median diameter of 14 mm. The maximum particle size is 125 mm (5 inches). This size distribution is nearly identical to the sediment in the apex of Taylor Creek's delta in Lake Washington (Appendix A).

The only mapped culvert outfall on the East Fork did not produce noticeable erosion along the creek, but its effect on erosion of the upper valley wall was not investigated.

Table 7. Estimated rate of sand and gravel supply to the East Fork of Taylor Creek.

Source	Fresh Erosion Scar Volume (cy)	Older Erosion Scar Volume (cy)
Vashon outwash reach in upper valley (EF02)	300	1100
debris flow deposit & till cliff	300*	100
East Fork below debris flow (mostly fine sediment)	10	5
Total Coarse Sediment Volume	600	1200
Sediment storage behind LWD jams		300 to 500
Net Sediment Export	600	700 to 900
Net Export Fresh Plus Older		1300 to 1500
Time Frame (yr)	3 to 6?	30 to 50?
Speculative Short-Term Rate (cy/yr)	**100-200**	
Speculative Long-Term Rate (cy/yr)		**25-50**

*** an additional 300 yd.³ of debris flow deposit remain on the East Fork valley floor.**

Figure 24. Photograph of gravel deposit upstream from plugged culvert near the mouth of the East Fork. The plugged culvert is to the left of the person. The creek currently drops off a 4-foot-high concrete wall into the bypass channel to the right.

3.4.2 West Fork Taylor Creek

The West Fork supplies very little sand and gravel to Taylor Creek. Numerous fresh, small landslides and eroding stream banks were observed on December 15, 2006, the day after an intense wind and rainstorm (Figure 25). The West Fork Lower Canyon (WF01) has glaciolacustrine silt along the channel. Recent erosion in the lower 640 feet of channel produced less than 5 yd^3 of sand and gravel and even less was produced in the stabler, upstream portion of the West Fork Canyon. Two culvert outfalls with very small drainage areas have small gullies below them that have eroded into the dense glacial substrate. The gullies appeared stable and did not enlarge noticeably between 2001 and 2007.

The West Fork Plateau reach (TA03) has two small channels. The northwest fork of the West Fork is a wetland that does not transport coarse sediment. The south fork of the West Fork is a very small channel entrenched into very dense glacial till. The till contains very little gravel and is eroding slowly. So little gravel is being transported that till is exposed intermittently in the stream bed. Much of the coarse sediment from the south fork of the West Fork comes to rest in a wetland upstream from the Renton Avenue culvert, currently impounded by a beaver dam. In 2001, no beaver dam was present and a gravel bar had formed in the backwater zone near the culvert inlet. It seems likely that gravel delivery from the plateau to downstream is intermittent and a significant fraction of the already-small amount bedload sediment remains permanently stored in the wetland upstream of Renton Avenue.

The estimated sand-and-gravel supply rate from the West Fork to the mainstem of Taylor Creek is less than 10 yd^3 per year.

3.4.3 Mainstem Taylor Creek In Deadhorse Canyon

The high walls of Deadhorse Canyon are composed primarily of fine sediment, including glacial till, glaciolacustrine silt/clay and some interglacial deposits. The canyon contains numerous landslides (Figures 21 and 26). Many of the landslides are deep-seated and slow-moving, evidenced by tilted trees and vegetated benches formed by slide blocks. Other landslides are shallower features that failed rapidly. Field work for this study was done in winter when leaves were off the trees, which revealed the full extent of landsliding. Previous field work in 2001 was done in late spring with full leaf cover and as a consequence, the slopes appeared stabler.

The canyon walls are about 120 feet high, but most landslide scars are only 20 to 50 feet high. At any given location, a canyon wall might consist of 2 to 3 steep landslide scars each separated by a gently-sloping, colluvial bench made of landslide debris. The colluvium moves slowly downhill across the benches by soil creep, eventually sliding down the next steep segment to the bench below. At the bottom, Taylor Creek eats away at the colluvium through bank erosion, triggering small landslides as it does so. Only a handful of landslide scars had direct chutes from the top of the canyon down to the creek or valley floor. The soil in most slide scars was predominantly fine sediment. The colluvium typically had a small amount of sand and gravel (5-20%), likely derived from till layers. Some landslide scars have enough groundwater seepage to form gullies, which in at least one case delivered a small amount of coarse sediment all the way to Taylor Creek. Most landslide scars at the top of the west canyon wall are more than a century old based on the size of trees and stumps, whereas some of the mid-slope to lower-slope slide scars are younger or recent. The west side of the canyon has fairly long reaches of stable hillslope in between the slide areas.

Figure 25. Photograph of fresh bank erosion in glaciolacustrine silt in the lower West Fork Canyon reach.

The east canyon wall appears to be more unstable. Many of the upper slide bowls have young vegetation. The east side of the entire 400-foot long Middle Deadhorse Canyon reach (TA04) consists of landslides, both streamside and mid-slope. Vegetation on the east side of the channel was brushy or lacking, with no trees able to grow due to the frequent, slow soil movement. This reach has a very narrow channel with no floodplain, apparently because the east hillside slides down into the creek as fast as it is eroded. The west side of the reach has mostly stable slopes with mature trees.

Upper Deadhorse Canyon (TA05) has a wider valley floor, fewer landslides and less bank erosion. Lower Deadhorse Canyon (TA03) is intermediate in width and stability compared to the other canyon reaches. It has terraces composed of clay-rich landslide colluvium. The only mapped culvert outfall on the mainstem is on the east canyon wall in this reach. It did not produce noticeable erosion along the creek, but its effect on erosion of the upper valley wall was not investigated.

Landslide sediment enters Taylor Creek in 20- to 400-yd^3 increments, although the larger slides tend to divert the creek around them and are not completely eroded by the creek. The creek also eats away at the steep valley walls through bank erosion (Figure 27). At most half of the walls are sand or gravel based on nearby geotechnical borings by Golder (1995). A sediment-supply rate was not directly estimated for Deadhorse Canyon because the age of bank erosion scars and rates of landslide movement could not be reliably determined. Since there has been little net deposition at the canyon mouth, most sediment from the canyon has arrived at the delta. Subtracting sediment supply from the East Fork and West Fork of Taylor Creek from the delta deposition gives an estimated supply rate from the mainstem canyon of about 150 to 200 yd^3 per year (see Table 8 in the next chapter).

Figure 26. Photographs of streamside landslide (above) and mid-slope landslide (below) in Deadhorse Canyon, mainstem Taylor Creek.

Figure 27. Photograph of bank erosion in Deadhorse Canyon, showing clay-rich soil overlain by colluvium that contains some gravel.

4. Watershed Sediment Budget

Table 8 summarizes the results of the previous chapters in terms of three sediment-budget components -- delta deposition, transport rates and storage changes along lower Taylor Creek, and watershed supply. The estimates have a considerable margin of error due to incomplete evidence. This sediment budget only includes sand and gravel, which are the sediment sizes that make up most of the delta. The delta presumably includes fine sand that traveled through the creek as suspended load, but not the silt-clay fraction that is washed out farther into the lake.

4.1 Delta deposition

The delta deposition rate was estimated at 220 yd^3 per year (range 170 to 320 yd^3). This estimate was based on delta growth from 1985 through 1997 and should remain valid in the future unless significant flow detention is installed in the watershed. Urban development was essentially complete by the end of the 1960s, and initial channel enlargement in response to flow increases had already occurred prior to the starting point of this estimate in 1985.

4.2 Transport rates and changes in storage along the creek

The 2001-2002 transport rate above Culvert B of 130 yd^3 per year is based on repeated cross-section surveys with a high degree of confidence. That is a minimum transport rate for the year since additional sediment from the canyon passed through the reach. Water Year 2002 had a 10-year rainfall event. This transport rate is broadly in agreement with the estimated magnitude

Table 8. Watershed sand-and-gravel sediment budget

Sediment Budget Component	Confidence Level	Time Period	Average Rate (cy/yr)	Sediment Yield (tn/sq km/yr)
SUPPLY	low			
East fork short-term high rate		3-6 yr?	100-200?	58-116?
East Fork long-term average rate		30-50 yr?	25-50	15-29?
West Fork short-term high rate		<5 yr	<10	
Mainstem Taylor Creek			150-200	
Watershed Total			~220	
TRANSPORT AND CHANGES IN STORAGE	high			
Taylor Creek volume change above Culvert B		WY 2002	-130	75
East Fork minimum transport rate from culvert deposition			7-35 minimum	
Taylor Creek canyon mouth		~1920-1999	7	
Taylor Creek canyon mouth		1999-2007	-2	
Taylor Creek above Culvert B stored sediment due to LWD		2002-2007	10	
DELTA DEPOSITION	moderate			
Delta		1985-1993	210 (160-310)	
Delta		1993-1997	250 (170-330)	
Delta		1985-1997	220 (170-320)	130 (100-190)
Taylor Creek near delta		1999-2007	6	

NOTES:

1. Used sediment unit density of 1.65 tons/cubic yard and drainage area of 1.0 mi^2
2. These rates do not include the silt-clay size fractions, which are a large component of the total sediment supply.
3. Numbers in the average rate column are rounded.
4. Rates in any given year or decade could differ significantly from the average rates shown.
5. Mainstem Taylor Creek supply rate was inferred by subtracting East Fork supply rate from delta deposition.

of delta deposition. There was insufficient survey data to determine whether some of this pulse of sediment moved beyond the culvert-replacement zone that same year, but at least 50 yd^3 of it was deposited a short distance downstream from Culvert B.

When considered over a number of years, changes in sediment storage at the mouth of the canyon have been small relative to the growth rate of the delta downstream. The 500 yd^3 that accumulated upstream of Culvert B did so over about 70 years at an average rate of only 7 yd^3 per year. The average change in sediment storage at the canyon mouth in the nine years following culvert replacement was minus 2 yd^3 per year.

4.3 Sediment supply from watershed

Sediment supply could not be reliably estimated due to uncertainty about the rate of landsliding. Rough estimates for the East Fork and West Fork are 25-50 yd^3 per year and less than 10 yd^3 per year, respectively. Subtracting these rates from the delta deposition rate gives a sediment supply rate of about 150 to 200 yd^3 per year for the mainstem canyon.

4.4 Comparison with other watersheds

Rates were divided by drainage area and converted to metric units in the final column of Table 9 to enable comparison with sediment yields in other watersheds. Taylor Creek's estimated delta deposition rate of 220 yd^3 per year is equivalent to a sediment yield of 130 tonnes/sq km/yr of sand and gravel. Taylor Creek's sediment load also includes a nearly equal amount of silt-clay based on geotechnical borings by Golder (1995) and field evidence from this study. The estimated total watershed sediment yield may therefore be closer to 260 tonnes/sq km/yr.

For comparison, the Pipers Creek watershed in north Seattle has an estimated sediment yield of 120+/-20 tonnes/sq km/yr currently and 250 tonnes/sq km/yr prior to erosion control measures (Barton 2002). Only 54 tonnes/sq km/yr (6%) of the current sediment yield was gravel coarser than 8 mm. Pipers Creek's sediment supply includes a lot of Vashon advance outwash sand which is mostly finer than 8 mm. Results from other sediment budgets with at least partially urban land-use ranged from 55 to 520 tonnes/sq km/yr (Barton 2002). Taylor Creek's estimated sediment yield is similar to Pipers Creek. The high end of the Taylor Creek error estimate, when doubled to account for the silt-clay fraction, would imply a sediment yield of almost 400 tonnes/sq km/yr. A rate that high seems unlikely given the greater prevalence of erodible Vashon advance outwash in Pipers Creek. Reverting back to units of cubic yards per year, Taylor Creek's sand-and-gravel deposition rate is therefore more likely to err on the low side of the 220 yd^3/yr estimate's uncertainty range of 170 to 320 yd^3/yr than on the high side. A rounded rate of 200 yd^3/yr is recommended for planning purposes.

4.5 Expected Variation in Sediment-Transport Rates

The long-term average rate of sediment supply to the Taylor Creek delta is approximately 200 yd^3 per year. Sediment-transport rates can vary from year to year by a factor of ten, and can even vary greatly from decade to decade depending on factors such as landslides and the magnitude and frequency of storms. Therefore, sediment supply to the delta in any particular year or decade could vary considerably from the estimated average long-term rate.

The undersized culverts that were replaced in 1999 passed most sediment downstream. Their replacement did not affect the long-term average rate of sediment delivery to the delta. However, the undersized culverts greatly reduced the size of flood peaks and instantaneous rate of bedload transport downstream. Consequently, sediment was previously delivered to downstream of the culverts at a more even rate than came from the canyon upstream.

The larger culverts installed in 1999 pass most floods without attenuation, and thus can transport bedload sediment downstream at a faster rate during floods. This should lead to greater short-term rates of sediment deposition during floods at locations where there is a marked downstream decline in sediment transport capacity: immediately below Culvert A, and the delta.

5. Sediment Management Strategies

This chapter identifies and discusses potential sediment management strategies based on the findings of this study. This is not a feasibility analysis. Any strategies identified herein should be evaluated for technical feasibility, cost, property ownership, access, and permitability.

5.1 Dredging and Dock Reconfiguration

Dredging the delta could be performed to meet one or more of the following objectives:

1. Fish habitat -- a deeper channel through the delta to provide spawning access to Taylor Creek
2. Fish habitat -- a delta surface about 18 inches below winter lake level, near the creek mouth, for juvenile chinook migrating out from the Cedar River.
3. Dock access -- sufficient clearance along the west side of the delta to reconstruct a dock and moor a yacht. Required water depth would depend on yacht size and type of dock.

The dredged volumes that follow are approximate and should be confirmed with an updated bathymetric survey. The 2007 delta is larger than shown on the most recent survey (Downing 2005).

5.1.1 Shallow Dredging

Dredging about 600 yd^3 of sediment from the existing delta would establish a delta surface 18 inches below winter lake level. This elevation is only 3 to 3.5 feet below summer lake level and probably would not provide adequate depth for yacht access. Although the dock area could be dredged deeper, that would produce a steeper slope and likely fill in with sediment fairly rapidly. With an average sediment influx of about 200 yd^3/year, it would take only three average years for the delta to return to its current size which is mostly above water in winter. The benefit to fish would end sooner than that.

As part of any dredging option, a deeper stream channel would be excavated to improve spawning access to Taylor Creek (see 5.1.3). For reasons described below, improved spawning access may not last as long after dredging as shallow-water habitat or dock capacity.

5.1.2 Deeper Dredging

Dredging to 6 feet below summer lake level would require removal of up to 1600 yd^3 of sediment and presumably improve dock access. The delta could be dredged with a sloping surface (for instance, the current slope of about 2%) to facilitate downstream movement of sediment. Most of the dredged surface would initially be deeper than the desired 18 inches, but would reach that elevation near the upstream end of the delta. The desired elevation zone would migrate outward over time as the delta grew. This option would provide a greater length of time before dredging was needed again. Dredging 1600 yd^3 would take about 8 average years to return to 2007 conditions, or fewer years should a large flood occur. The benefits to habitat would end sooner than that. There is insufficient information to determine when dock access would again become limiting.

Dredging to 6 feet below winter lake level would require removal of up to 2500 yd^3 of sediment and would take about 12 average years to return to 2007 conditions.

The required volume of dredging in the examples above could be about one-third lower if the delta tip below winter lake level was not included, but this risks increasing upper-delta deposition rates by blocking the outflow channel.

As part of any dredging option, a deeper stream channel would be excavated to improve spawning access to Taylor Creek (see 5.1.3). For reasons described below, improved spawning access may not last as long after dredging as shallow-water habitat or dock capacity.

5.1.3 Outlet Channel Excavation

The longevity of fish access across the delta following the last dredging in 1991 is unknown, but definitely was no more than 10 years and could have been much less (Section 3.1.2). Dredging deeper may not produce more years of unfettered spawning access to Taylor Creek. In any year, a fall flood that occurred while the lake was still relatively high could deposit sediment in the upper delta and plug the channel, which would then split into shallower channels precluding fish access.

Given the high sediment load and frequent floods of this urban creek, annual or biannual excavation of the outlet channel would provide the most reliable spawning access. Deepening the existing channel would require the smallest amount of excavation and could potentially be done with hand tools. Excavating a deeper channel to one side, into which the creek would then be diverted, would require small mechanized equipment. The ideal timing from the point of view of sediment control would be in the fall, once lake level has dropped but prior to spawning--the timing would need to be based on spawning surveys rather than a generic fish window. Alternatively, channel excavation could be done in late winter before the lake level rises, but there would be a higher risk of the channel filling back in prior to spawning.

Armoring the excavated channel with rootwads or riprap is not recommended because it would decrease the longevity of spawning access. As the dredged channel fills in with sediment, the creek must be able to shift laterally and cut a new, deeper channel elsewhere on the delta. If the creek is held in one place, all the sediment would be forced to deposit there and the channel would fill up more quickly. Rootwads also would increase sediment deposition by increasing roughness of the channel.

5.1.4 Dock Reconfiguration

Replacement of the former floating dock on the west side of the delta with a dock supported by piers would allow a higher dock closer to shore and reduce the impact of sedimentation.

Consideration should be given to removing the low concrete dock on the east side of Taylor Creek at the upstream edge of the delta, if doing so would not adversely impact the next dock to the east. The low dock is no longer functional because sediment has filled in beside it (Figure 9). Its presence has prevented the creek from sometimes flowing down the right (east) side of the delta, and thus has increased the rate of sedimentation on the left side of the delta.

5.2 Sediment Trapping

There is no room for a sediment pond with significant, multi-year storage on the mainstem of Taylor Creek. Even if there was room, a large sediment pond would be likely to block fish access. This section discusses options for storing smaller amounts of sediment along the creek.

5.2.1 Proposed Sediment Basin Upstream of Rainier Avenue

SPU has designed fish passage improvements under and upstream from Rainier Avenue S. (SPU 2005). The upstream end of the proposed project culminates in a small sediment basin. Due to size constraints the basin would trap about 30 to 50 yd^3 of sediment which is one-fourth or less of the estimated average annual sediment supply. The sediment basin is designed to facilitate easy clean-out by diverting the creek around it. However, the City will likely only be allowed to clean out the basin during the fish window in late summer. A single week of heavy rains could completely fill the sediment basin and a series of smaller pools downstream that are separated by weirs. Once these were full, sediment would be delivered to the delta for the remainder of the rainy season.

If combined with regular excavation of the outlet channel in the delta (5.1.3), this project would benefit fish passage in at least some years by delaying sediment delivery to the delta until after spawning. In years with early fall floods, though, the sediment basin would fill rapidly and substantial amounts of sediment could be delivered to the delta during spawning season.

The small resting pools below each weir are likely to fill with sediment each year. Provisions should be made to facilitate pool clean-out.

5.2.2 Sediment Pond on lower East Fork of Taylor Creek

There is probably sufficient room for a large sediment pond at the former sewage treatment plant site at the base of the East Fork. The site may still have an old access road that could be used for construction and maintenance, but this be should be confirmed because landslides could have damaged the road. Fish access to the East Fork is already blocked by a series of concrete walls from the former sewage treatment plant. The pond size should be at least 100 yd^3, and preferably double that in order to remain effective in moderate to large flood events.

Potential drawbacks include construction and maintenance costs, incompatibility with Lakeridge Park, and the fact that a greater amount of sediment enters Taylor Creek below the East Fork.

5.2.3 Sediment Storage by Large Woody Debris

LWD could be added to Taylor Creek and the lower East Fork of Taylor Creek to trap sediment. A section of Taylor Creek upstream of Culvert B was treated using logs without rootwads in 2002. Five years later, the LWD was responsible for storing 17 yd^3 of sediment per 100 linear feet of channel for a total of 73 yd^3 (section 3.3.3.1). If feasible, treating the remaining 1850 feet of channel could potentially store about 400 yd^3 of sediment. This would be a one-time benefit until the storage sites filled up, equivalent to about two average years of sediment supply. A longer-term benefit, though, would consist of reduced erosion and sediment-transport rates due to energy dissipation.

Possibilities for delivering LWD to the site include helicopter, using heavy equipment to transport logs up the trail and then winching them down to the creek, or using the old access road to the sewage treatment plant. Alternatively, dead or live trees could be harvested from the canyon near the treatment sites. LWD stability and effectiveness would be increased by using logs with rootwads. Rootwads greatly increase the weight of the logs and reduce floating and shifting during floods.

Additional sediment storage could be gained by adding more LWD to the reach between the Holyoke Way culverts and to the previous treatment zone. No logs should be placed below Culvert A because doing so might change the channel course and damage private property downstream.

The West Fork of Taylor Creek transports much less sand and gravel so adding LWD would produce no significant downstream benefit. Access would be difficult.

5.3 Erosion Control

Most landslides in Taylor Creek are caused by instability of the canyon walls which are still adjusting to hundreds of feet of downcutting by the creek since deglaciation. This type of erosion is essentially impossible to control.

Streambank erosion is difficult to control due to the high frequency and magnitude of floods caused by urbanization of the watershed. "Soft" bank protection methods such as coir logs or bank logs usually fail in high-energy streams such as Taylor Creek. Hard methods such as riprap have somewhat more success, but still require periodic maintenance. Armoring the banks of the entire creek is clearly incompatible with the park environment and the City's goal of improving fish access and habitat.

The following measures are recommended to reduce future erosion.

5.3.1 Addition of Large Woody Debris

Adding LWD for sediment storage as described in 5.2.3 may also reduce erosion by diverting flow away from stream banks, forming steps that prevent or reverse downcutting and reduce effective channel gradient, and reducing the amount of stream energy available for erosion. It might be problematic to add LWD in the narrowest canyon reach (TA04), since the channel is so narrow that reducing conveyance area might force flow into the unstable hillside.

The LWD added in 2002 successfully reduced stream bank erosion in the upper part of the alluvial fan reach (TA02), which is relatively wide with room for wood-forced gravel bars (Appendix B). It did not increase bank stability in the lower canyon reach (TA03) compared to

2001, although the recent occurrence of a 25-year storm event may have biased the results. This suggests that LWD might produce the best results in Upper Deadhorse Canyon (TA05) which is wider.

5.3.2 Preventive Measures in the East Fork

The following actions are recommended in the East Fork of Taylor Creek to prevent erosion rates from increasing:

1. Reinforce the concrete wall at the upstream end of the bypass channel around the plugged culvert (Figure 24). Scour has removed much of the soil that supported this wall. Continued scour could cause the 4-foot-high wall to collapse. This would trigger a one-time release of sediment stored upstream of the wall, and would also destabilize the creek upstream by headcutting.

2. Stabilize the upper 100 feet of reach EF01 to prevent downcutting of the steep channel, which could ultimately destabilize the lower part of reach EF02 (see section 3.4.1).

5.4 Stormwater Detention

5.4.1 Large-Scale Stormwater Detention Facility

Large-scale stormwater detention would be the best way to substantially reduce sediment-transport rates in Taylor Creek. King County's proposed East Hill detention facility on the West Fork of Taylor Creek was not authorized because it would have been sited in a headwater wetland. There are reportedly no other sites large enough for a major stormwater detention facility.

5.4.2 Small-Scale Stormwater Retention

City and County policies should encourage stormwater retention as future redevelopment of the watershed takes place, including Natural Drainage System projects. For example, King County's reconstructed wetlands could be extended around the ball fields in the East Fork. The East Fork of Taylor Creek should be targeted for the greatest sediment-reduction benefit, as it produces a large amount of sediment. The West Fork is not a significant source of delta-building sediment and already has some stormwater retention by wetlands.

5.5 Combined Sediment Management Strategies

There is no silver bullet that will solve the problematic sedimentation on the Taylor Creek delta. However, a combination of the strategies described above may improve the situation to some degree.

Taylor Creek's current sediment load is high enough that dredging would be required at least twice a decade to restore the desired delta conditions. Reducing the sediment supply from upstream would make dredging a more viable option by increasing the time between dredgings during which habitat and dock conditions were optimal.

6. Summary of Results

The Taylor Creek delta in Lake Washington has grown in recent years to a point where it restricts fish access to the creek and landowner use of docks. Removal of the delta by dredging is being considered. This study estimates the time interval for which dredging would remain effective by quantifying the rate of sediment supply from the watershed to the delta, with an emphasis on the coarse sediment fraction that forms most of the delta. The sediment budget also provides guidance on effectiveness of upstream erosion control and sediment storage measures.

Urban development in the watershed was nearly complete by the end of the 1960s and caused a large increase in storm water runoff with essentially no detention. The channel of Taylor Creek now receives what was formerly a 100-year flood nearly every year. These large flow increases have accelerated erosion rates in the ravines of Taylor Creek and its two forks since the 1930s, and hence increased the rate of sediment deposition in the delta.

Delta Growth Rate

Delta growth was evaluated using a time series of aerial photographs dating back to 1939. Four phases of delta behavior were identified:

1. **Original delta formation after lowering of Lake Washington in 1916.** During this phase the delta was very small.
2. **Delta growth mostly offset by dredging, approx. 1968 - 1991.** The delta was dredged in the 1980s, in 1991, and probably in the 1970s. Sediment deposited during floods affected use of the docks and filled in the lower part of Taylor Creek causing flooding, but was dredged to reverse the effects until the next major flood.
3. **Rapid delta growth in the absence of dredging, 1992-1999.** Despite the 1991 dredging, by 1993 the delta was 34 feet longer than 1985. In the absence of further dredging, the delta continued to grow through 1999. Visible delta length grew 41 feet between 1993 to 1999, a rate of 6.8 feet per year. During this period of growth, delta length remained steady or fell slightly during short periods without floods, but grew 24 feet from1995 to 1997, a time of region-wide flooding.
4. **Long delta with relatively steady length, 1999-2005.** Visible delta length fluctuated but was fairly steady despite large floods in 2001 and 2003 that reportedly deposited sediment on the delta. Delta length in 1999 and 2005 was nearly identical. There reportedly has been no dredging since 1991. The relatively steady delta length since 1999 is due to morphologic or hydrodynamic controls, not a reduction in sediment supply.

Delta growth rates were calculated for the latter part of phase 2 and for phase 3. The delta grew about 400 yd^3 from 1985 through 1993 but several times that volume was removed by dredging. From 1993 through 1997, the delta grew about 1000 yd^3 with no reported dredging. The estimated average delta growth rate including dredging was 220 yd^3/yr for both time periods combined.

Fish Passage over the Delta

Spawning use of lower Taylor Creek and barrier status of the delta were assessed by Wild Fish Conservancy for the 2000 through 2006 spawning seasons. The delta is probably a barrier to spawning coho and sockeye salmon except during high flows or early in the spawning season while lake level is still high enough to flood the delta. Small numbers of fish were able to access the creek at least once in most years. Sediment deposits in 2001 and 2003 floods caused the channel to split into shallower channels with reduced fish access until the creek was again able to cut a single, deeper channel. Fall 2006 had the largest spawning runs in years of both species, reportedly the best since a large run in about 1997 or 1998.

It is unknown whether there was good fish access throughout the 1990s as a result of 1991 dredging of the delta, or if blockage problems resumed much earlier than the documented episode in 2001.

Sediment Deposition in Lower Taylor Creek

Lower Taylor Creek has a narrow, artificial channel with armored banks. Comparison of profiles surveyed in 1999 and 2007 showed that 40 yd^3 of gravel were deposited in the 700-foot-long reach below Rainier Avenue after 1999. Most of the deposition occurred in the lower 135 feet of the creek where its gradient decreases next to the lake. In that location, the bed rose by 0.5 to 1.9 feet. Deposition further upstream was negligible, ranging from 0 to 0.3 feet. About 40 yd^3 of gravel and sand were deposited in Taylor Creek from Station 0 upstream to Rainier Avenue S in 6-1/2 years, an average rate of 6 yd^3 per year. Because the channelized creek is so narrow, sediment deposition rates in the lower creek were very small compared to the delta.

Deposition rates prior to 1999 were not estimated due to lack of data, but up to 4 feet of sediment reportedly deposited in the lower creek in 1990 followed by dredging in 1991. Deposition followed by dredging also occurred in the mid-1980s.

Sediment Changes Related to Culvert Replacement at the Mouth of Deadhorse Canyon

In summer 1999, undersized 3-foot culverts at two road crossings in the lower part of Lakeridge Park were replaced with 14-foot wide culverts. The old culverts blocked fish passage and were too small to convey storm runoff from the urbanized basin. About 500 yd^3 of gravel had accumulated upstream of the upper culvert. The channel downstream from the upper culvert was starved for sediment and had eroded its bed, making a 7-foot drop that prevented fish passage below the hanging upper culvert. When the culverts were replaced, the streambed between the two culverts was raised with imported gravel to remove the plunge pools and facilitate fish passage.

After culvert replacement, about 200 yd^3 of the pre-1999 sediment deposits above the upper culvert were eroded by the creek, mostly between summer 2001 and summer 2002. Sediment eroded from upstream of Culvert B mostly was deposited a short distance downstream. In most areas between the two culverts, the streambed rose 0.5 to 1.5 feet for a net gain of about 110 yd^3 by 2007. Most of the gravel that was added to Taylor Creek between the two culverts is still in place, buried by sediment from upstream. The initial slug of sediment made its way farther downstream over several years and reached the lower culvert by 2003 if not earlier. About 60 yd^3 were deposited below Culvert A, mostly within Lakeridge Park.

There has been a net export of about 22 yd^3 from the culvert replacement zone over the eight years since the culverts were replaced. This represents about one tenth of Taylor Creek's annual coarse sediment load of 200 yd^3 per year. The exported sediment came primarily from above the upper culvert, either from erosion of old deposits behind the former undersized culvert, or directly from Deadhorse Canyon.

The undersized culverts that were replaced in 1999 passed most sediment downstream, since only about 2 to 3 years-worth of coarse sediment had accumulated above them in about 70 years. Their replacement therefore did not affect the long-term average rate of sediment delivery to the delta. However, the undersized culverts reduced the size of flood peaks and the instantaneous rate of bedload transport during floods.

The larger culverts installed in 1999 can pass larger floods without attenuation, and thus should transport bedload sediment downstream at a faster rate during floods. This should lead to greater short-term rates of sediment deposition during floods at locations where there is a marked downstream decline in sediment transport capacity: below Culvert A (the natural location for an alluvial fan) and at the delta.

Sediment Supply from Deadhorse Canyon and Its Forks

The delta is composed primarily of sand and gravel. The primary sources of sand and gravel are the upper East Fork valley where Vashon advance outwash occurs, and the middle walls of the Deadhorse Canyon where glacial till occurs. The West Fork, lower East Fork, and most of Taylor Creek below the forks flow through fine-grained sediments that do not contribute to delta growth.

The canyon walls contain numerous, slowly-moving landslides that ultimately deliver sediment from high on the canyon walls down to the creek. Landslides are the largest source of sediment, followed by streambank erosion. Downcutting of the channel is fairly slow due to the dense glacial sediments and grade control provided by boulders and large woody debris.

Sediment-supply rates could not be reliably estimated due to uncertainty about the rate of landsliding. Rough estimates for the East Fork and West Fork are 25-50 yd^3 per year and less than 10 yd^3 per year, respectively. Since there has been little net deposition at the canyon mouth, most sediment from the canyon has arrived at the delta. Subtracting these rates from the 230 yd^3 per year delta deposition rate gives a sediment-supply rate of about 200 yd^3 per year for the mainstem canyon.

Taylor Creek Sediment Yield

The delta deposition rate was estimated at 220 yd^3 per year. Due to uncertainty about the amount of dredging and historic delta volumes, the actual rate could be as low as 170 or as high as 320 yd^3. This estimate was based on delta growth from 1985 through 1997 and should remain valid in the future unless significant flood detention/retention is installed in the watershed.

Taylor Creek's delta deposition rate of 220 yd^3 per year is equivalent to a sediment yield of 130 tonnes/sq km/yr for sand and gravel. Taylor Creek's sediment load also includes a nearly equal amount of silt-clay based on geotechnical borings by Golder (1995) and field evidence from this study. The estimated total watershed sediment yield may therefore be closer to 260 tonnes/sq km/yr.

For comparison, the Pipers Creek watershed in north Seattle has an estimated sediment yield of 120+/-20 tonnes/sq km/yr currently and 250 tonnes/sq km/yr prior to erosion control measures. Results from other sediment budgets with at least partially urban land-use ranged from 55 to 520 tonnes/sq km/yr. Taylor Creek's estimated sediment yield is similar to Pipers Creek. Taylor Creek's delta deposition rate is more likely to err on the low side of the estimated range than the high side. Reverting back to units of cubic yards per year, a delta deposition rate of 200 yd^3/yr is recommended for planning purposes.

Sediment-transport rates can vary from year to year by a factor of ten, and can even vary greatly from decade to decade depending on factors such as landslides and the magnitude and frequency of storms. Therefore, sediment supply to the delta in any particular year or decade could vary considerably from the estimated average long-term rate of approximately 200 yd^3 per year.

Sediment Management Strategies

Four types of potential sediment management strategies for Taylor Creek were evaluated. These are 1) delta dredging and dock reconfiguration, 2) sediment trapping, 3) erosion control, and 4) storm water detention and retention. Constraints imposed by geology and existing development limit the potential effectiveness of these strategies.

There is no single silver bullet that will solve the problematic sedimentation on the Taylor Creek delta. A combination of the strategies described above may improve the situation somewhat. Taylor Creek's current sediment load is high enough that dredging would be required at least twice a decade to restore the desired delta conditions. Reducing the sediment supply from upstream would make dredging a more viable option by increasing the time between dredgings during which habitat and dock conditions were optimal.

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