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Technical Report No. SRH-2010-08

Yakima River Geomorphology and Sediment Transport Study:
Gap to Gap Reach, Yakima, WA

U.S. Department of the Interior
Bureau of Reclamation
Technical Services Center
Denver, CO

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Yakima River Geomorphology and Sediment Transport Study:

Gap to Gap Reach, Yakima, WA

Prepared for the County of Yakima, Washington

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Executive Summary

The following report investigates future conditions of the Yakima River with regard to a proposed levee setback and levee removal in the Gap to Gap reach. This reach of the Yakima River is significantly impacted by infrastructure on the floodplain, and by numerous floodplain gravel mining pits in the vicinity of Yakima and Union Gap. According to the Reaches Report (Snyder and Stanford, 2001), the Gap to Gap reach was identified as having some of the highest potential for habitat rehabilitation along the Yakima River, in spite of the disruption to natural channel processes by anthropogenic activities.

In this study, hydraulic engineering and geomorphic analyses are combined to provide insight into future channel conditions over a timeframe of 25 years. The report first details the geomorphology of the reach, followed by details related to numerical modeling. The discussion section develops conclusions using both geomorphology and hydraulic modeling to predict future channel condition. The major focus of this study was to examine the effects of changes to two levee configurations. The Boise-Cascade levee is located on the west side of the Yakima River a short distance downstream of the mouth of the Naches River and is proposed for removal. DID #1 levee (Diking Improvement District), located in the vicinity and downstream of State Route (SR) 24 along the east side of Yakima River, is proposed to be setback to reduce flooding impacts. Channel changes near the City of Yakima's wastewater treatment plant are also a concern following levee setback and have been specifically documented to provide guidance for planning. The results of this study and other studies will help guide Yakima County in planning efforts regarding flood protection, future changes to infrastructure within the riparian corridor, and improvement to aquatic and riparian habitat.

In order to examine the effects of levee setback and removal, supporting information was developed and includes:

- average annual sediment load;
- estimates of sediment input to the reach from the mainstem Yakima River and the Naches River;
- estimates of the relative significance of large and small floods, considering the effects of various flood magnitudes and duration;
- estimates of the impact to channel and floodplain morphology from large floods
- areas of high and low energy throughout the reach;
- physical observations of dynamic and stable river segments;
- fluvial response to human modifications and gravel pit capture;
- historical changes in vertical and lateral channel position; and
- mapping of floodplain areas and stream terraces

The geomorphic investigation utilized surficial geologic mapping, historical channel analysis and field observations to document fluvial processes in the Gap to Gap reach and the response to human impacts and floods along the Yakima River. Field observations of channel dynamics revealed that the study reach could be divided into segments that had been laterally dynamic within the last five years and those that had relative lateral stability. Dynamic reaches were noted to have recent channel avulsions, lateral erosion, an abundance of large woody debris either on bars or in the channel itself, prograding bars and channel splays, and smaller secondary or side channels that have developed or reactivated. Stable reaches showed a similar main channel position with relatively few lateral channel changes in the past five years. Bank erosion, in the form of vertical unconsolidated banks or banks with failing riprap, was documented in the stable reaches as well as some gravel bar deposition. However, the erosion was not significant enough to cause major lateral channel change.

Nodal analysis and total channel length calculations indicate that channel complexity is continuing to increase in segment 5a from low values in the 1960's. Channel complexity is expected to continue to increase following the levee setback in segment 5a, but is not anticipated to reach the levels that were present during the 1930's and 1940's. Other channel segments have mostly decreased in channel complexity throughout the historical period (1927 to 2008), reflecting the impact of levee confinement, channel simplification, vertical accretion of floodplain sediments and vegetation encroachment. Unvegetated gravel bars, mapped from 1939 to 2009, reflect channel response to the hydrologic record, in which unvegetated bar areas increase following floods and recover their vegetation between large floods. This is in contrast to a progressive trend in unvegetated bar area through the historical period, which could signal channel aggradation or degradation. Changes in main channel sinuosity vary by segment and do not show any consistent increase or decrease for all segments in the study reach. Channel avulsions may either cause increases or decreases in sinuosity while levee construction that restricts channel movement is typically associated with decreasing channel sinuosity.

Comparisons between 1969 and 2005 channel survey data revealed significant aggradation between the railroad bridge and Terrace Heights bridge, reflecting channel avulsions and channel modifications near instream gravel mining at the Terrace Heights pit. Significant aggradation has also occurred between the downstream end of the DID #1 levee and Union Gap. Some of the changes to cross sectional area that indicate significant aggradation are a response to the river avulsing into and aggrading gravel pits. The comparison also reveals a decrease in mean cross sectional elevations, downstream of the Naches River confluence, downstream of the Terrace Heights Bridge, adjacent to the Beech Street pit, and in Union Gap at and just downstream of the I-82 bridge. The same comparison reveals an average aggradation rate of the channel and floodplain between 0.05 and 0.15 feet per year throughout most of the Gap to Gap reach, with notable exceptions near the Naches River mouth, between Terrace Heights Bridge and the Beech Street pit, and in Union Gap

Numerical hydraulic and sediment modeling was used to provide information regarding future sediment transport conditions, such as locations of aggradation and degradation, and to evaluate overall channel stability. An investigation into climate change over the analysis period indicates that sediment transport will not be greatly affected. Hydraulic modeling identifies differences in water surface elevation and channel velocities contrasting the initial (t=0) existing, initial proposed, and final (t=25 yr) proposed conditions. Future predictions were based on the previous 25 years of hydrology (water years 1985 – 2009) in the reach using historical gage data. Most notable differences between existing and proposed conditions when examining projected sedimentation are; degradation along the Beech Street pit, and aggradation downstream of the SR 24 Bridge under the proposed conditions. Under both scenarios, aggradation between the downstream end of the DID #1 levee and Union Gap is expected to be no greater than 1 foot. Aggradation in this portion of the study reach will likely be localized, possibly creating conditions for lateral channel change.

Much of the data analysis uses results from the modeling and geomorphic investigation that are broken into five segments within the study reach. No segment is predicted to change vertically, on average, by more than 1.5 feet considering mean bed elevations, although some localized aggradation/degradation is anticipated. Implications of removing the Boise-Cascade levee are minimal, showing a slight decrease in sediment transport capacity and a negligible amount of additional aggradation in the vicinity. Removal of this levee does not result in additional flooding, however the removal may exacerbate lateral channel change. The setback of the DID #1 levee downstream of SR 24 will significantly reduce water surface elevations (as much as 5 feet at 44,000 ft^3/s) and velocity (as much as 6 ft/s at 44,000 ft^3/s) considering the initial proposed conditions. Following a 25-year simulation some aggradation is anticipated here (approximately 2 feet) however an overall decrease in water surface elevation following the simulation period is realized. The setback of the DID #1 levee will decrease erosive forces on the right bank levee in the vicinity of the wastewater treatment plant and provide a wider floodplain over which lateral channel change will likely occur. Degradation at and upstream of the SR 24 Bridge past the Beech Street pit is expected, as velocities upstream of the SR 24 Bridge increase due to the removal of the constriction causing a backwater condition and an ensuing adjustment of the channel slope. The river has historically aggraded approximately 1,500 feet upstream of the SR 24 Bridge. The most downstream segment in the study reach (downstream of the DID #1 levee) indicates some aggradation under existing or proposed conditions, as the setback of the DID #1 levee does not affect aggradation in this segment.

An analysis of 241 suspended sediment measurements taken within the study reach between 1975 and 1993 shows that the average annual total sediment load of the Yakima River in the Gap to Gap reach was 80,000 tons/year over the measurement period. The forecasted annual average total load in the Gap to Gap reach over the next 25 years is 96,000 tons/year.

Observations in the geomorphic study are combined with the historical analysis, energy regime, and predictions of sediment transport to arrive at anticipated future channel conditions. A detailed analysis is provided from upstream to downstream in all five segments of the river, discussing historical and predicted aggradation/degradation, locations of eroding banks and levees, unstable areas, high and low energy, and locations of anticipated bank erosion and channel avulsion. This analysis also includes discussions on the various gravel pits throughout the study reach.

The predicted future channel conditions that form some of the conclusions in this report could be negated if the river avulses into a deep or voluminous gravel pit, creating a sink for sediment which will starve downstream reaches and possibly causing an upstream migrating nickpoint that could threaten or damage infrastructure. An overall benefit for the removal of the Boise-Cascade levee and the setback of the DID #1 levee is shown, with no indication of disruption to fluvial processes. However there are risks associated with the setback of the DID #1 levee that include potential avulsion into the Newland ponds and further degradation of the channel along the Beech Street pit. These risks can be managed with proper planning, maintenance, and engineering. The proposed changes are expected to improve flooding conditions in the vicinity of SR 24 and the wastewater treatment plant and are also expected to improve habitat by connecting more of the river to the floodplain. This study and others have concluded that the Yakima River is capable of considerable recovery due to its readily mobile bed. Some recovery of channel complexity has been observed since the 1960’s and the proposed conditions are expected to hasten the recovery in the segment where the levee setback is proposed.

1 Introduction

The Yakima River provides valuable resources for the citizens of the Yakima Valley, including water for municipal and agricultural uses as well as recreation. The river and its floodplain also provide habitat for a multitude of aquatic and wildlife species. Considering the importance of this resource to the residents of Yakima County, it is of great interest to plan for its use and protection into the future (Yakima County, 2007). Responsible stewardship of the Yakima River will include the provision of reasonable protection from flood damage but also includes the responsibility of maintaining a vibrant ecological community. Human and ecological needs are not always mutually exclusive with proper planning; therefore, it is possible for the citizens of the valley to benefit from both types of action. An opportunity exists to provide Yakima Valley residents with an increased measure of flood protection while also improving the overall ecology of the Yakima Valley by considering changes to current levee configurations. This study is part of a greater effort by the Yakima County Flood Control Zone District (YCFCZD) to reduce flooding impacts to the cities of Yakima and Union Gap while also improving aquatic and riparian habitat along the Yakima River in the Gap to Gap reach. The Bureau of Reclamation (Reclamation) was requested to conduct a geomorphic and sediment transport study to assess future channel conditions with regard to a levee setback along the left bank in the vicinity and downstream of Highway 24 (DID #1 levee). The study also examines the effects of removing the Boise-Cascade levee along the right bank just downstream of the mouth of the Naches River. A site map and locations of proposed levee modifications are shown in Figure 1 and Figure 2.

1.1 Geologic Setting

In the Gap to Gap reach, the Yakima River flows through constrictions at Yakima and Ahtanum ridges, which are two ridges in a series of periodically spaced anticlinal basalt ridges separated by broad synclinal valleys within the Yakima Fold Belt subprovince (Watters, 1989). In this subprovince, ridges typically have relief of less than 600 m with some of the greatest relief occurring along the Frenchman Hills, Saddle Mountains, Umtanum Ridge and Yakima Ridge. The synclinal valleys are formed in between the uplifted ridges and are filled with clastic sediments that may be as thick as 1,500 ft, creating a relatively flat-bottomed topographic expression in the valleys (Kinnison and Sceva, 1963). The ridges were deformed beginning in the late Tertiary and had developed their present structural relief by the end of the Pleistocene. Young faults described along Toppenish Ridge and Ahtanum Ridge provide evidence for the continued growth of the Yakima Fold Belt in the vicinity of the study area (Reidel et al 1993). Surface ruptures along the north flank of Toppenish Ridge have displacements of up to 4m; radiocarbon ages from organics within the ruptures yield ages of 505 ± 160 ^{14}C yr BP and 620 ± 135 ^{14}C yr BP (Campbell and Bentley, 1981). Trench excavations along Toppenish Ridge show evidence of

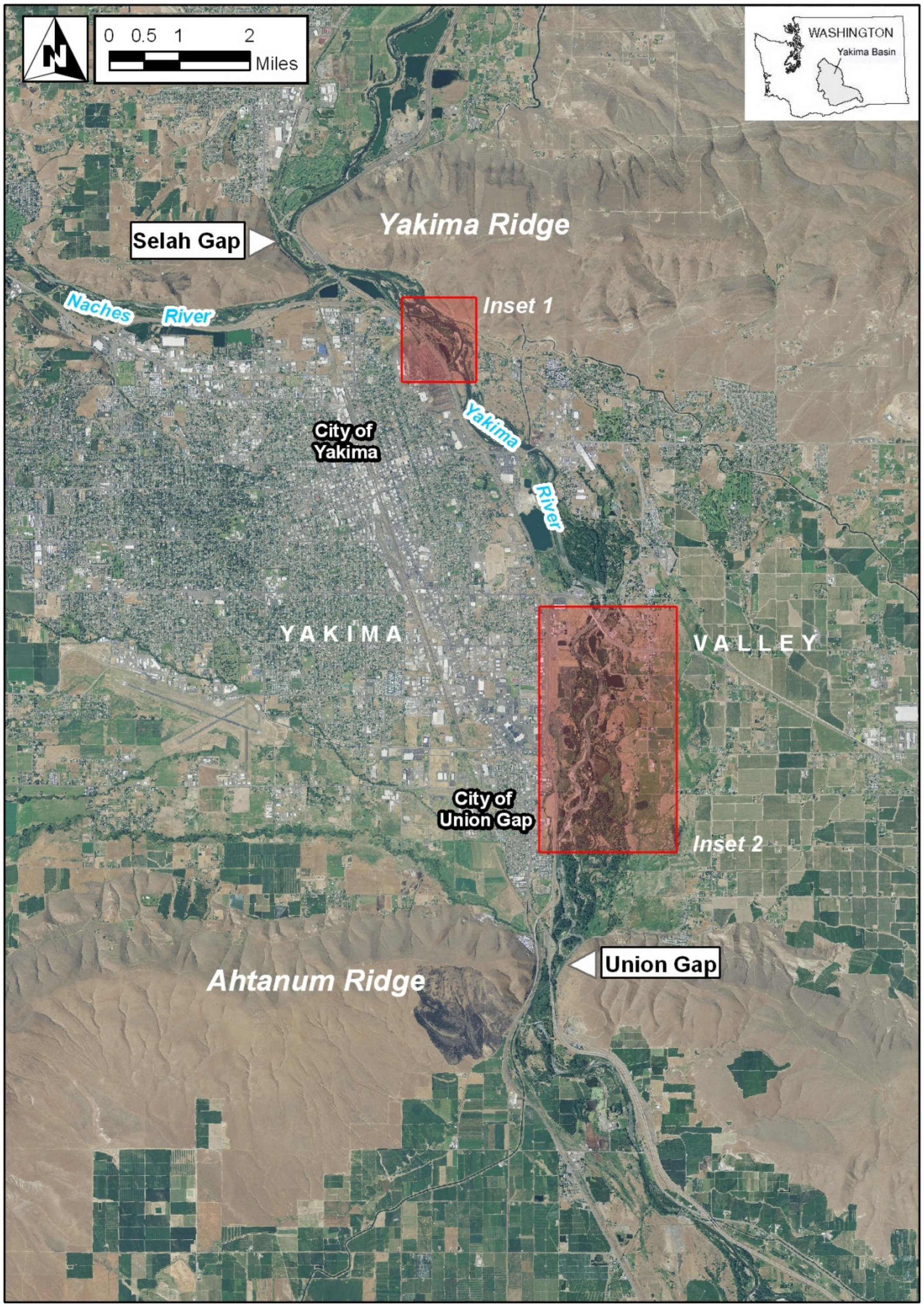

Figure 1: Location map of the Gap to Gap reach. Flow is from north to south. Insets for the highlighted areas are shown in Figure 2

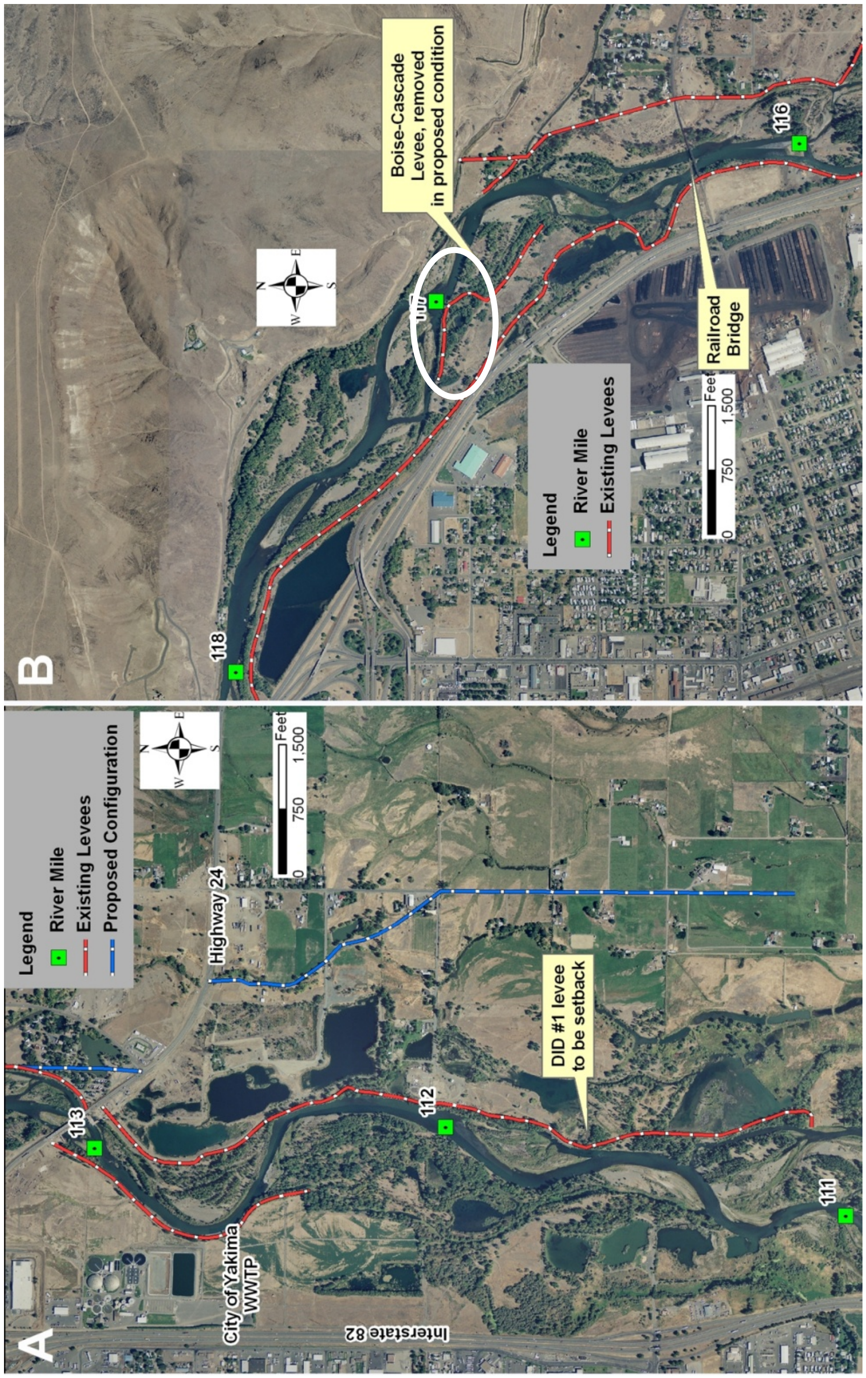

Figure 2: A –DID #1 levee to be setback. Proposed levee setback location is shown in blue. B –Boise-Cascade levee to be removed. Locations are shown in Figure 1.

displacement of the Ellensburg Formation over Pleistocene soils and gravels (Geomatrix Consultants, Inc., 1988). Along Ahtanum Ridge, Pliestocene gravels are displaced by at least 7m near Union Gap and are covered by slackwater sediments that do not appear to be offset and are estimated to be 13,000 years old. However, other exposures to the east reveal offset slackwater deposits, which suggest the age of faulting to be younger than 13,000 years (Reidel et al 1993). Based on research performed in the area, Geomatrix Consultants , Inc, classifies the Toppenish ridge and Ahtanum ridge as an active and potentially active seismogenic structure, respectively (Geomatrix Consultants, Inc., 1988).

The Missoula Floods, a phase of catastrophic flooding in the Columbia River system, are recorded in the Yakima Valley in the Toppenish Basin and Gap to Gap reach. The floods originated from failures of the ice-dammed glacial Lake Missoula and probably from other ice-dammed lakes within the Columbia River system during the late Pleistocene, or between 12,000-20,000 years ago (Benito and O'Connor; 2003). While the details of the hydraulics, flood routes and number of floods are topics of ongoing debate and research, the floods are known to have coursed through the area known as the channeled scablands, eventually making their way through the Columbia River Gorge to the Pacific Ocean, where they carved channels into the abyssal sea floor (Baker and Bunker, 1985). Documented landscape features related to the floods include mega ripples, rhythmically bedded slackwater sequences (rhythmites or touchet beds), scabland channelways, and boulder bars. In the Toppenish Basin, at least three sites, the Buena, Mabton and Zillah stratigraphic sites, are described in the literature and consist of flood rhythmites deposited from floods that backwatered up the Yakima Valley from the constriction at Wallula Gap (i.e., Waitt, 1985). The deposits are typically composed of massive to rhythmic laminations and are upward fining. They may also have overlying loess deposits, post-dating the Missoula Floods, and may include the Mt. St. Helens set S tephra (13,000 ^{14}C yr BP) within the flood deposits. In the Gap to Gap reach, the Missoula flood deposits are mapped in published literature on the east side of the study area (i.e., Harris and Schuster, 2000). The deposits may also exist in other areas in combination with loess deposits.

1.2 Hydrology

The Naches River, a significant tributary to the Yakima River, enters from the west at the northern end of the reach just downstream of Selah Gap (Figure 1) and has a drainage area of 1,106 mi^2. Upstream of the Naches River, the Yakima River has a drainage area of 2,138 mi^2 (USGS, 2008). At its mouth, the Yakima River drains an area of approximately 6,200 mi^2, with a mean annual unregulated runoff of 5,600 ft^3/s and a mean annual regulated runoff of 3,600 ft^3/s (Mastin and Vaccaro, 2002). The sediment supplied to the Gap to Gap reach comes primarily from the Naches River, as transport capacity and supply in the Yakima upstream of Selah Gap is limited by lower slopes and the presence of the Yakima Canyon. In the recent past, incoming sediment from the Yakima River upstream of Selah Gap has been impacted due to extensive gravel mining near Selah and Roza Dam limiting the sediment supply (Stanford et al., 2002). Sediment transport measurements collected for this study indicate that the Naches provides approximately an order of magnitude greater sediment volume to the Gap to Gap reach than does the mainstem Yakima River. The relatively large amount of sediment brought to the Yakima River by the Naches River led Stanford et al. (2002) to conclude that the Gap to Gap reach is one of the more fluvially active reaches in the Yakima Basin. Stanford et al., (2002) also concluded that the restoration potential is highest in the Gap to Gap reach, compared to four other reaches studied.

Streamflow for the Yakima River is controlled by three headwater dams on the Yakima River, constructed between 1912 and 1933 and three dams on the Naches River constructed between 1908 and 1925 (Project Data, 1981). To deliver irrigation water to approximately 500,000 acres, 14 diversion dams and 2,000 miles of canal have been constructed as part of the Yakima Project (Yakima County, 2007). About 60 percent of total water use in the basin is attributed to agriculture. Return flows from agricultural land account for as much as 80 percent of the Yakima mainstem flow in the Lower Valley during irrigation season (USGS 1993). The storage reservoirs are primarily operated for irrigation, although Reclamation also operates the dams using a set of flood rule curves implemented following significant flooding in 1933 (Yakima County, 2007). Flooding is common in Yakima County and since 1894 the flow in the Yakima River has exceeded flood stage 48 times (Yakima County, 2007). Most of the precipitation in the basin falls as snow in the winter months with accumulation beginning in late October or early November and ends by April (Mastin, 2008). Flooding in the Yakima Basin generally occurs during spring runoff or the winter months when temperatures rise and induce snow melt. These periods are often accompanied by heavy rainfall. Water operations have affected the timing and magnitude of discharge in all reaches of the Yakima River, which has multiple impacts on the natural system. Future hydrologic scenarios assume water operations in the near future are similar to what has occurred in the recent past. Detailed information regarding changes to in-stream flows due to water operations can be found in the available literature (e.g. Vaccaro, 1986; Ring and Watson, 1999, Mastin and Vaccaro, 2002; Reclamation, 2002, Yakima County, 2007; Braatne et al.; 2007).

This report provides projections of sediment transport and channel conditions for the next 25 years, and includes an event-based evaluation of four floods in the historical record that represent the spectrum of flood types that have affected the Yakima Valley, including a high magnitude, long duration flood; a high magnitude, short duration flood; a long duration, low magnitude flood; and a flood on the Naches River without a significant concurrent flood on the Yakima River. These floods were evaluated for sediment transport characteristics and their results are compared.

1.3 Anthropogenic impacts

The Yakima River in the vicinity of Yakima, WA has been heavily impacted by historical in-channel and floodplain gravel mining and is one of the most heavily impacted river systems in the state of Washington (Norman et al 1998). In the Gap to Gap reach, the earliest gravel mining in the Yakima River floodplain can be observed in 1949 aerial photography and was most active from about 1945 to 1973, reaching its peak during the construction of Interstate 82 during the 1960's and early 1970's (Clark, 2003). The number of gravel pits in the active floodplain as defined by Clark (2003) waned in the 1970's following gravel pit captures near Terrace Heights Bridge and along Interstate 82. This was followed by an increase in gravel pits in the active floodplain from 1979 to 2000, mostly driven by the development of additional pits in the Newland Ponds area and at Edler Ponds. As of 2000, 42% of the geomorphic floodplain (defined by Clark, 2003) and 18% of the active floodplain was occupied by gravel pits. The presence of gravel pits adjacent to the river presents a significant risk to infrastructure and natural channel processes (Norman et al., 1998). Major levee construction began in 1947 in response to the 1933 flood flood and continued with the construction of Interstate 82 in the mid to late 1960's. Along much of the river length, levee construction has reduced floodplain area and connectivity and limited channel migration in some areas (e.g., Eitemiller et al., 2002). These modifications have acted to simplify the channel, thereby reducing the capacity for the Yakima River to convey flood waters, variability in channel environments, and habitat for threatened or endangered species. Construction of Wapato Dam in 1917 changed the base level at the downstream end of the Gap to Gap reach, so that the effects of the dam extend approximately 5,000 ft upstream (see section 4.3 for further discussion). Flooding near the major highways along the Yakima River in the Gap to Gap reach became a concern following channel avulsions during the 1970's into floodplain gravel pits, which shifted the channel to the west against Interstate 82. Erosion of highway embankments and other revetments along the Yakima River is also a concern for this critical infrastructure. Lorang et al. (2005) evaluated the lateral stability of the Yakima River in the Gap to Gap reach using stream power to identify potential erosion or avulsion points. A similar, but more detailed approach is used in this study, where hydraulic and sediment transport properties are combined with a geomorphic investigation to predict future channel condition.

In spite of the impacts to the Yakima River between Selah and Union Gaps, this reach has been identified by Stanford et al. (2002) as the most promising reach of river in the Yakima Basin with respect to a successful rehabilitation.

1.4 Study Goals

The primary focus of the study is to predict future channel condition with respect to locations of aggradation and degradation and anticipated channel change over a period of 25 years. The context under which future channel condition is being evaluated is the proposed setback of DID levee #1 and the removal of the Boise-Cascade levee (Figure 1 and Figure 2). Other areas of focus are: average annual sediment load; estimates of sediment input to the reach from the mainstem Yakima River and the Naches River; estimates of the relative significance of large and small floods, considering the effects of various flood magnitudes and duration; and areas of very high energy throughout the reach. These topics have been investigated with a combination of hydraulic and sediment transport modeling and a geomorphic study.

1.5 Previous Work

Several previous studies have taken place over the past 40 years that are referenced throughout this report. Because the primary audience for which this report is written (Yakima County) is familiar with the hydrology and flooding history of the Yakima River, these details will not be discussed at length in this report. The geology, hydrology, and flood history are presented in detail in several publications (e.g., Kinnison and Sceva, 1963; USACE, 1970; USACE, 1973; Dunne et al., 1976; Vaccaro, 1986; Ring and Watson, 1999; Harris and Schuster, 2000; Snyder and Stanford, 2001; Mastin and Vaccaro, 2002; Yakima County, 2007). The following is a brief review of the most relevant of these reports.

> In 1970 the U.S. Army Corps of Engineers performed a floodplain study summarizing previous significant floods, damage from these floods, potential for future floods, and an inundation map of the Intermediate Regional Flood (0.01 probability) and the Standard Project Flood (probable maximum flood) (USACE, 1970).
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> In 1976 Dunne et al performed a study for the Greenway Foundation titled "The Yakima River Regional Greenway Master Plan". The study area is coincident with that of the current study and details the geologic structure and hydrology of the valley, the sediment transport, and geomorphology of the Yakima River (Dunne et al., 1976). Dunne documents a transition in the gradient of fluvial terraces and the floodplain in the vicinity of Moxee (Hwy 24) Bridge from a higher gradient terrace and floodplain upstream to lower gradient surfaces downstream. He attributes this change in gradient to differential uplift of the bounding ridges of Yakima Valley, in which Yakima ridge is uplifting at a faster rate than Ahtanum Ridge. Dunne also documents areas that in the future may experience lateral migration or channel avulsion in the Gap to Gap reach. The estimates are made for a 25-year period, or from 1979 to 2004.
>
> In 2001 the Flathead Lake Biological Station produced a report titled "Review and Synthesis of River Ecological Studies in the Yakima River, Washington, With an Emphasis on Flow and Salmon Habitat Interactions". This report culminated a broad study of the Yakima River that resulted in a few reports, most commonly referred to as the 'Reaches Study". This report focused on the ecology of the Yakima River from headwaters to the mouth with emphasis on recovery of endangered salmonid species through improvements to habitat. The Gap to Gap reach was identified as having the highest potential for successful rehabilitation, realizing the significance of the river interacting with its floodplain (Snyder and Stanford, 2001). The results detailed in the Reaches Study were the primary justification for the Yakima River Basin Water Enhancement Project (YRBWEP) purchasing floodplain property in the Gap to Gap reach to allow for rehabilitation of salmonid habitat.

Eitemiller et al. (2002) examined the impact of anthropogenic features to seven floodplains in the Yakima River Basin and developed ecological baseline information to aid river managers in making decisions concerning the ecological health of the river system. In the Gap to Gap reach, Eitemiller mapped anthropogenic features (i.e., levees and revetments), channel types from an ecological perspective, and the active floodplain, which includes channels and floodplain areas absent of anthropogenic features including levees, agriculture or residential and commercial structures. Eitemiller et al. found that human features such as levees and revetments had reduced the active floodplain area, and hence the lateral connectivity of the river, by 28% between 1927 and 2002; overall channel length had also decreased by 43%, thus reducing habitat availability for aquatic species.

Clark (2003) discusses the impact of in-channel gravel mining and anthropogenic features on the Yakima River channel in the Gap to Gap reach. Her objective pertinent to this study was to quantify changes in channel complexity resulting from gravel extraction and pit capture in the Gap to Gap reach. As part of her thesis, Clark mapped channel centerlines and polygons, vegetated and unvegetated portions of the floodplain, gravel pits, and revetments on seven sets of rectified aerial photography from 1927 to 2002. Results from her analysis showed that channel complexity decreased as a result of in-channel gravel mining and levee building during the 1960's and has been recovering through the latest year in her study, 2002. Clark concludes that although in-stream gravel mining has had a measureable impact on channel complexity, the floods on the Yakima River have the potential to reclaim mined areas in the floodplain through pit capture and subsequent reworking of sediments and has done so during the historical period.

In 2005 Lorang et al. published a paper that resulted from the 2001 Reaches Study. This paper describes methodologies for determining depth and channel velocities from multi-spectral aerial photography and determining stream power throughout the reach. Lorang et al. used the aerial photography to obtain such parameters as depth and velocity and slope was provided by a 30m DEM. The energy regime is described for a portion of the Gap to Gap reach.

In 2007 Yakima County produced an update to the "Upper Yakima River Comprehensive Flood Hazard Management Plan" (CFHMP, Yakima County, 2007). The reach of interest in this study extends from the head of the Yakima Canyon at the upstream end to just downstream of Union Gap (including the Gap to Gap reach). This document fulfills one of the main requirements for Yakima County to be eligible for funding from the State of Washington. The report covers the flooding history and impacts, management of and planning for flood hazards, and reviews previous studies. Also included is an analysis of flood mitigation alternatives. The

CFHMP serves as the guiding document for future actions to mitigate flooding impacts along this reach of the Yakima River.

1.6 Report Organization

This report first discusses the results of geomorphic and hydraulic analyses separately and then combines results from both analyses in order to understand fluvial processes along the Yakima River in the Gap to Gap reach and from this to predict the effects of levee removal and setbacks. Chapter 2 describes the geomorphic analysis, which combines historical measurements and more recent physical observations. Historical measurements include channel complexity measures, 1969-2005 cross section and thalweg comparisons, main channel sinuosity calculations, and gravel bar area computations. Observations during 2008-2009 field work which spanned the winter 2009 flood describe the character of recent fluvial modifications during the 2009 flood as well as between 2005 and 2008. Observations aid in the division of the study reach into segments that have experienced recent channel change and segments that have been relatively stable during the past 5 years. Chapter 3, 4, 5 and 6 discuss the details of the hydraulic modeling. The modeling section covers data collection, construction, calibration, and verification of the hydraulic and sediment models, followed by the results. Chapter 7 combines both the geomorphology and sediment modeling analyses to discuss the overarching goal of predicting future channel condition following the levee setback and removal.

2 Geomorphic Analysis

The geomorphic analysis refines surficial geologic mapping in the vicinity of the study area, describes gravel pit capture dynamics and the effects of extreme floods along the Yakima River, provides field observations of river processes in support of the hydraulic modeling and documents historical trends in channel aggradation and degradation on a reach-wide scale. Predictions of future channel conditions following levee setback and removals are derived from results of the geomorphic analysis and are combined with hydraulic modeling results in Chapter 7.

2.1 Surficial Geologic Mapping

The surficial geologic map differentiates landforms along the Yakima River and provides a spatial and temporal context for the present Yakima River morphology. Previous geologic mapping exists at a scale of 1:24,000 (Campbell, 1976), 1:100,000 (Schuster, 1994; Walsh, 1986; Harris and Schuster, 2000) and 1:250,000 (Campbell, 1979; Waitt, 1979). The present map refines this mapping, focusing on further differentiating Holocene deposits related to the Yakima River. Previous mapping of the Holocene floodplain and active floodplain by Clark (2003) and Eitemiller et al. (2002) was also reviewed and compared to the present mapping.

2.1.1 Methods

The primary sources of information used to develop the surficial geologic map include historical photos, soils, LiDAR and 1:40,000-scale NAPP stereo images. 2008 NAIP photos were utilized as a base for mapping; units were field checked to the extent possible given that the Yakima floodplain and valley are developed and owned privately in many areas. Map units are defined by grouping landforms with similar characteristics such as position on the landscape, surface morphology, soil and sedimentological characteristics, process of formation, and surface dissection. Eleven soil/stratigraphic descriptions for the fluvial deposits most relevant to this study were performed to understand the formation of each deposit and to develop estimates of the timing of deposition along the Yakima River (Appendix A and B). Charcoal samples from the soil pits were collected to develop quantitative age information for the floodplain units; samples were floated for macrobotanical identification; four samples were selected for AMS radiocarbon analysis. Charcoal was very sparse in the deposits that were described and only a limited number of radiocarbon ages were thus developed (Appendix B). Further work and bulk sampling of deposits could potentially add more information to the timing of deposition along the Yakima River.

2.1.2 Map Unit Descriptions

Map unit descriptions provide detailed information for each fluvial landform along the Yakima River and are illustrated in Figure 5 and Table 1 of this report.

Qa4 Wetted channels

Wetted channels include all channels that contained water in 2008 photography and that had a surficial connection with the main Yakima River channel. Some channels that contained mostly ponded water were also included in this unit because the mapping of this unit is partially discharge dependent and the photos were flown at a relatively low flow from what could be deciphered on the aerial photography. Channel centerlines were also mapped and categorized according to the Eitemiller et al (2002) biological definition of channels and include (Figure 4):

- Eupotamon—wetted main stem and side channels
- Parapotamon—wetted channel connected to the eupotamon only at the downstream end
- Springbrook—groundwater (or spring) fed channel (from Stanford and Ward, 1993)
- Outflow channel—channel that drains an anthropogenic feature, such as a gravel pit or waste water treatment plant

Other channel types included in Eitemiller's mapping are mapped as paleochannels (Qpc) and are not utilized. These included:

- Pleisopotomon—channel slough completely disconnected from the eupotamon, but occurring within the hydrologically active floodplain

- Paleopotamon—abandoned meanders and oxbow lakes, occurring far from the hydrologically active floodplain

Qa3 Unvegetated gravel bars

This unit includes bars along the Yakima River that were predominantly free of vegetation in the 2008 aerial photography. These bars are inferred to have been recently mobilized by flows along the Yakima River in order to remain free of vegetation. There may be a few areas that are mapped in this unit that may have been cleared, but it is difficult to determine in some areas whether the bars were initially reworked by fluvial processes and subsequently modified by human activities. Materials that comprise this unit are mostly unconsolidated sand and gravel.

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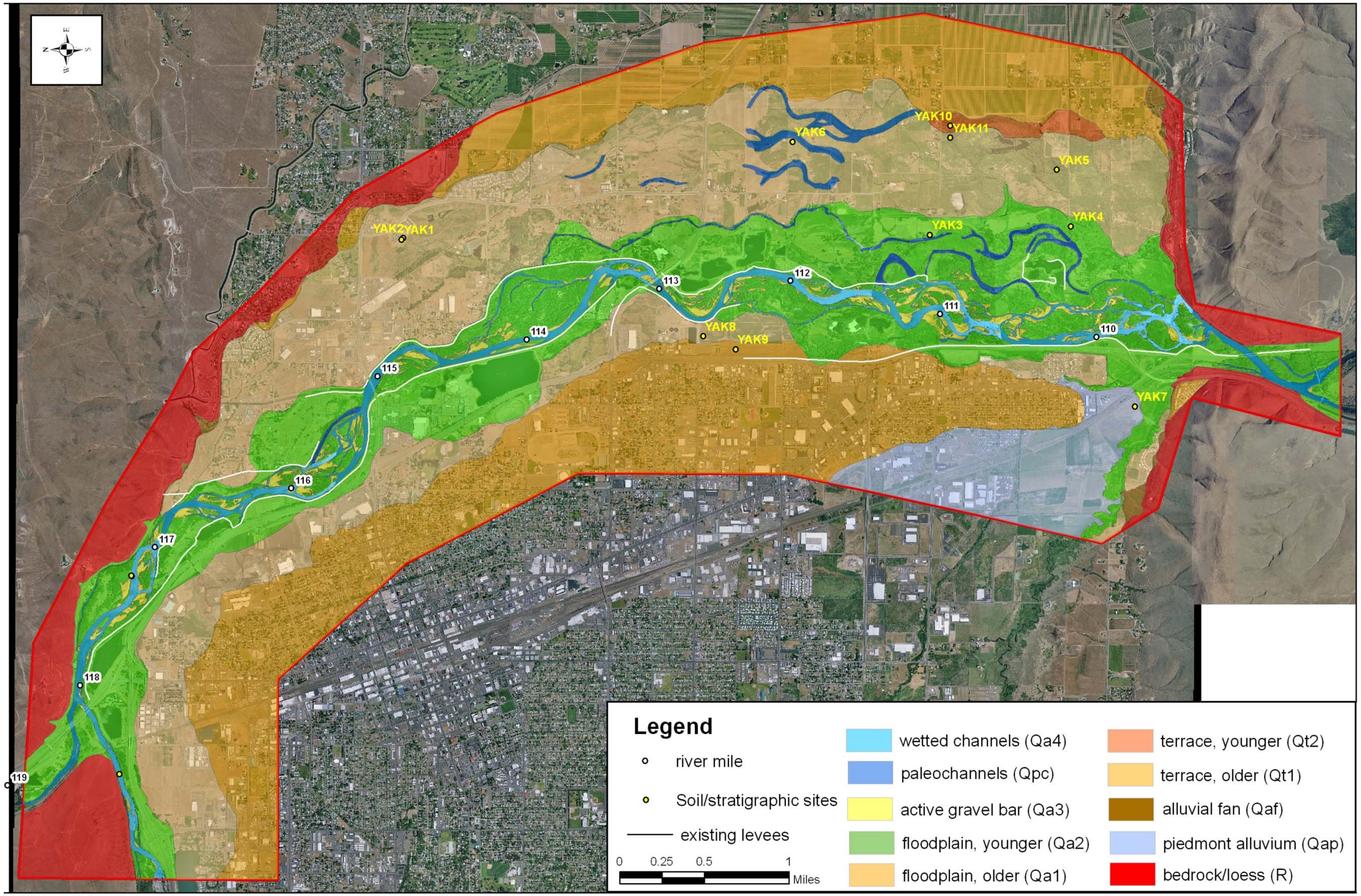

Figure 3: Surficial Geologic Map of the Gap to Gap study area.

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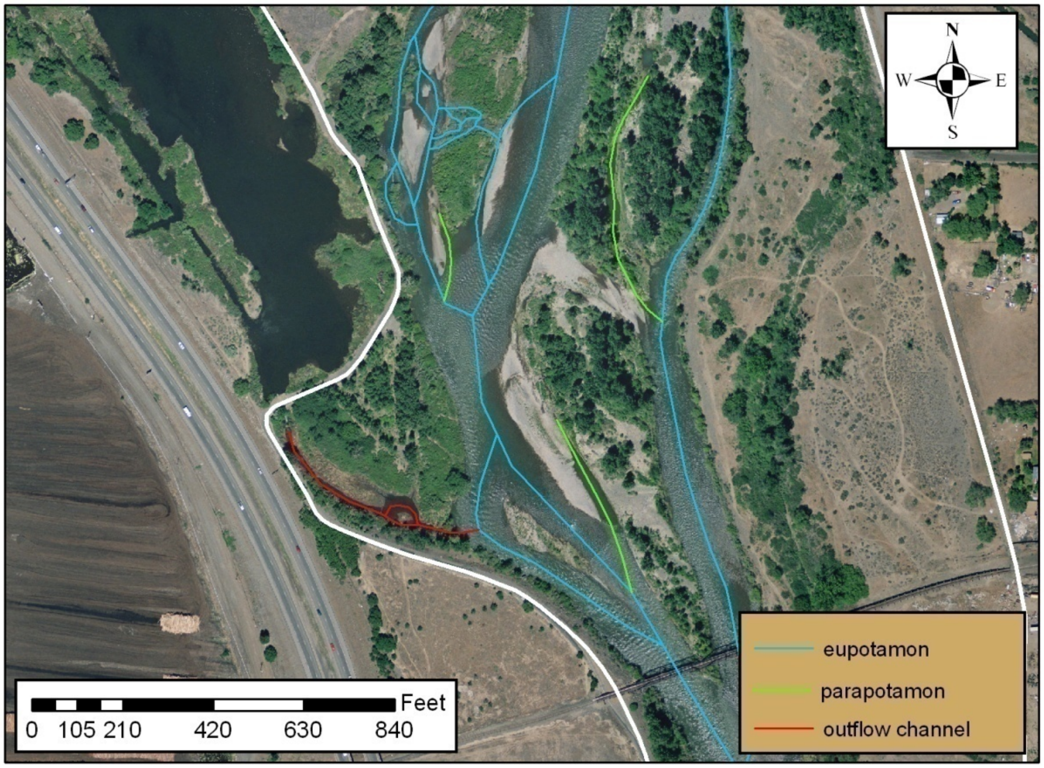

Figure 4. Example of 2008 channel mapping in segment 2 upstream of the railroad bridge. Existing levees are shown in white. Flow is from top to bottom in the photograph.

Qa2 Floodplain alluvium, younger (Holocene)

The Qa2 unit is described as floodplain alluvium deposited by the Yakima River or its tributaries within about the last 300 years. Surface morphology is generally irregular with relict channels visible in many areas. Deposits are composed of unconsolidated sand and gravel and generally have a fine-grained (sandy) cap of overbank deposits over gravelly channel deposits. The Qa2 alluvium corresponds to the Weirman soil series (Lenfester and Reedy, 1985; Table 1), which is described as soils formed in mixed alluvium on floodplains and low terraces. Based on the pedon description and soil descriptions during this study, the soil profile generally consists of a sandy loam A horizon with loam to loamy sand C horizons, which are gravelly at depth. In some places, such as at YAK4, the unit may have layers of silt-rich or clay-rich sediments, which represent intermittent near-channel backwater environments. Radiocarbon ages developed for this unit from soil pit YAK3 at a depth of 40 cm and soil pit YAK4 at a depth of 40-42 cm indicate that the deposits are less than 300 years old near the surface (Appendix A and B). Sample YAK 4-1 is from a charcoal bed at a depth of 14-17cm below the surface and indicates that the deposits at this depth and higher are historical in age, or within about the last 50 years. The Qa2 unit includes both vegetated components of mid-channel bars along the Yakima River and floodplain areas adjacent to the Yakima River, Naches River and Ahtanum Creek. The extent of this unit was determined from the locations of historical channels dating from 1927 to the present, soils mapping by Lenfester and Reedy (1985), surface morphology, elevations based on 2005 LiDAR, and field checking of the study area. This unit also includes historical paleochannels, which are described separately under the Qpc unit.

Qa1 Floodplain alluvium, older (Holocene)

The Qa1 unit can be described as floodplain alluvium deposited by the Yakima River or its tributaries within about the last 1,000 years. Surface morphology is relatively smooth and gently sloping downvalley. Some low-relief bar and swale topography is still visible in some areas, and reveals past channel positions of the Yakima River. Some of the relict channels (or pre-historical paleochannels) can be distinctly mapped on this surface and are discussed separately as the Qpc unit. Deposits are composed of unconsolidated sandy and gravelly alluvium and may be entirely fine-grained (sandy) in the upper meter or may have gravelly channel components. Several soil series are mapped with the Qa1 map unit and include the Logy, Toppenish, Track, Weirman, Wenas, Yakima and Zillah soil series (Table 1). Soils formed in the older floodplain alluvium are generally weakly to moderately developed and may have gleyed or mottled horizons, indicating that they are wet for at least part of the year and are influenced by groundwater interactions. Radiocarbon analysis of charcoal from site YAK2, a trench excavated behind the Pacific Northwest University of Health Sciences facility indicates that the deposits in this area are about 700 years old (Appendix A and B). The charcoal was sampled from a paleochannel inset against older river alluvium; therefore, it is apparent that this unit has components that are older than 700 years. Further radiocarbon analysis would be needed to refine the age estimate; this study estimates an age of up to 1,000 years for the near-surface deposits that are associated with this unit.

Qt2 Terrace, younger (Holocene)

The Qt2 unit, or Holocene terrace, is limited in extent and is mapped only along the eastern side of the study area adjacent to Qa1. In this area, a terrace scarp was observed during field work as well as on 2005 LiDAR. The terrace is a narrow strip of alluvium that is about 5ft above the Qa1 surface. Surface morphology is relatively planar and slopes downvalley and appears to merge with the Qa1 surface. The soil profile was described at the northeast corner of Reclamation property along Bell road and is composed of fine-grained alluvium (Appendix A). Soil map units that correspond to the Qt2 surface include the Outlook, Toppenish and Wenas soil series (Table 1). Based on the pedon descriptions for the soil series and well as soil profile YAK10, the soils are weakly to moderately developed with a silt loam to loam texture. Although not described at YAK10, the soils in the soil series typically display mottling or gleying, a sign of groundwater influence. The soils may also contain gravelly material below a depth of 50 cm. Although bulk samples were collected and processed for charcoal identification, the charcoal samples were too small to be dated using AMS radiocarbon analysis.

Qt1 Terrace, older (Late Pleistocene-Early Holocene)

The Qt1 map unit occurs along the east and west sides of the Yakima valley as a prominent and extensive terrace, about 15 ft above the Qa1 surface. Surface morphology is relatively planar and most of the surface is covered by either agriculture or residential and commercial establishments. Soils on this surface correspond to the Ashue, Esquatzel, Naches, Umapine, and Warden soil series (Table 1). Except for the Esquatzel soil series, these soils typically either have an argillic (Bt) or carbonate (Bk) horizon that is moderately developed in the soil profile. While radiocarbon ages were not able to be developed for this unit due to the lack of charcoal recovered from the soil profiles, the Qt1 unit is estimated to have a maximum age of Late Pleistocene to early Holocene. This is based on its inset relationship to Lake Missoula outburst flood deposits on the east side of the valley outside of the mapped area. The outburst floods occurred during the Late Pleistocene (Baker and Bunker, 1985). Although not explored in this study, it is possible that the Qt1 units on the east and west side of the valley were not formed at the same time and represent different time periods in the formation of the Yakima Valley. This idea is put forward because of the varying soil development and parent materials from one side of the valley to the other in the Qt1 alluvium, reflecting different sediment sources which may correspond to a difference in the timing of deposition. On the west side of the valley, the Ashue soil series predominates on the Qt1 surface and is composed of gravelly alluvium with an argillic horizon; on the east side of the valley, the Umapine soil predominates and is composed of fine-grained silty alluvium with a carbonate horizon. This surface could also be a terrace that has been cut on Missoula flood deposits, which are mapped to the east of the Qt1 terrace in the Moxee Valley. The Umapine soil also appears to be inset into the Ashue soil on the west side of the valley and is developed on the Qap unit, or the piedmont alluvium. This would suggest that surfaces where the Umapine soil is located are younger than those with the Ashue soil. This is similar to relationships in the Wapato Valley, where the Umapine surfaces are mapped as younger alluvium along present axial drainages as part of the Toppenish-Umapine series and older terraces or alluvium are mapped as the Ashue-Naches series (Rasmussen, 1976).

Qpc Paleochannels

Map unit Qpc includes relict channels that are historical (post-1927) and pre-historical (pre-1927) in age. The historical paleochannels are located within the Qa2 map unit and were occupied during the period of historical aerial photography (1927 to present). It is thus possible to assign an age to the paleochannels based on the time in which they are observed to be occupied by the Yakima River and when they are abandoned. Most of the paleochannels mapped within the Qa2 alluvium formed between 1948 and 1966 and were abandoned by 1979 as a result of levee construction.

Paleochannels that are mapped on the Qa1 alluvium pre-date the period of historical aerial photography and are presumably greater than 300 years old based on radiocarbon ages for the Qa2 alluvium. Using the age estimates from both the Qa1 and Qa2 units, it is likely that most of the channels on the Qa1 unit were abandoned no later than 300 years ago by the Yakima River as the younger floodplain alluvium was deposited and reworked. It is also possible that some of the paleochannels were utilized by tributaries that entered from the eastern peidmont along the reach and flowed parallel to the Yakima River before joining the main stem.

Qap Holocene piedmont alluvium

The Qap unit, Holocene piedmont alluvium, is located in the southwest portion of the study area along Ahtanum Creek and other small creeks that drain the western piedmont of the Yakima Valley. Soils are included in the Umapine soil series, and are predominantly formed on silty and sandy sediments with a moderately developed Bk horizon. Surface morphology of this unit is gently sloping toward the Yakima River with tributary drainages incised into the surface. This unit is interpreted to be either reworked material from Missoula flood deposits or loess deposits or material transported a longer distance by drainages from the surrounding mountain front. The unit is mapped separately from Qt1 because it is not deposited or modified by the Yakima River but rather by tributaries along the western piedmont. Site YAK7 was described in this unit and is composed of a loamy A horizon with an underlying carbonate horizon with weakly developed clay films in pores. Charcoal or other datable materials were not recovered from this site, but it is likely that this unit is similar in age to the Qt1 terrace, as the same soil series is developed on both.

Qaf Alluvial fan deposits

The Qaf unit is composed of alluvial fans shed from the mountain fronts along the margins of Yakima Valley. Mostly small fans are mapped and can be observed as cone-shaped landforms along the anticlinal ridges near Union Gap. No age estimates are made for this unit.

R Bedrock/colluvium/loess

Hillslope deposits are mapped as a composite unit and may include bedrock, colluvium, landslides and loess in varying areas. The extent and description of these features are derived from previous mapping in the Yakima Valley (i.e., Harris and Schuster, 2000). Bedrock in the study area is predominantly Middle Miocene basalt flows, middle to upper Miocene continental sedimentary rocks (Ellensburg Formation), and Pliocene conglomerates (Thorp gravel) (Harris and Schuster, 2000). Loess is Holocene to Pliestocene in age and included the Palouse Formation (Bentley et al 1993). Missoula flood deposits may also be present within the area mapped as this unit, but are not delineated in any of the published mapping that was utilized for this study.

2.1.2.1 Comparison to previous geologic mapping

Previous geologic mapping (i.e., Harris and Schuster, 2000) delineates the Yakima River floodplain as Quaternary alluvium (Qal); in this study, this Qal unit is separated into two floodplain units (Qa1 and Qa2) as well as piedmont alluvium (Qap) sloping from the western mountain front. The Qt terrace in previous mapping corresponds to the Qt1 unit mapped in this study. This study also delineates the Qt2 unit, which was not previously separated from the floodplain (Qal unit in previous mapping). Contacts for the units differ from previous mapping, particularly in the northeast corner of the study area, where the older floodplain unit (Qa1) is mapped in place of the older terrace (Qt1 unit).

Mapping in the floodplain area is very similar to previous mapping of the floodplain by Eitemiller et al (2002) and Clark (2003). A few small differences occur where soils mapping is used in this study to expand the extent of the younger floodplain unit based on soil development in areas that were obscured by either agriculture or commercial development in 1927 aerial photography. In the Toppenish Basin, Reichmuth et al (2007) hypothesized that following deposition of the Missoula Flood deposits in the Late Pleistocene, the Yakima River began to shift eastward across the basin to its present position, reworking or removing Missoula flood deposits and depositing alluvium associated with the Yakima River. The authors identified 7 major shifts since the Late Pleistocene based on relict channels that are now occupied by smaller tributary streams. The Toppenish Basin is presently composed of Yakima River deposits in the central part of the valley with Missoula flood deposits mostly along the valley margins. The Yakima Valley is similar in that deposits of the Yakima River also comprise the central part of the valley. Following the Missoula Floods, the Yakima River reworked and exported much of the Missoula Flood sediment, leaving only remnants along the eastern side of Yakima Valley and Moxee Valley. Other remnants of the flood deposits exist along valley margins, but are mostly capped by loess formed during the Holocene and late Pleistocene and are thus mapped as loess deposits (Simon and Schuster, 2000). In contrast to the Toppenish Basin, the Yakima River has shifted from east to west in Yakima Valley rather than from west to east during the Late Holocene. The geomorphic map shows older floodplain deposits and paleochannels that are at least 700 years old along the eastern side of the Yakima Valley floodplain; progressively younger deposits are mapped toward the western side of the floodplain where the Yakima River currently exists. This conclusion is also supported by topography across the floodplain, which show that the floodplain is highest along its eastern edge and slopes toward the present location of the Yakima River (Figure 5; see also Entrix, 2010).

Table 1: Correlation of surficial geologic map units and soil map units (Soils data derived from Lenfesty and Reedy, 1985)

Surficial Map unit	Description	Corresponding soil map units	Soil profile
Qa4	wetted channels	Water	no soil development
Qa3	unvegetated gravel bars	*included in soils formed in mixed alluvium on floodplains and low terraces*	
		Weirman SL, channeled	(A/AC/C/2C)
Qa2	floodplain alluvium, younger	*soils formed in mixed alluvium on floodplains and low terraces*	
		Weirman SL, channeled; fSL; grfSL	A/AC/C/2C
		Zillah SiL, channeled	A/C
Qa1	floodplain alluvium, older	*soils formed in floodplain alluvium*	
		Logy SiL	A/B/2C
		Toppenish SiL	A/B/Bg/2C
		Track L	A/Bg/B/C
		Weirman fSL; grfSL; fsL,wet	A/AC/C/2C
		Wenas SiL	A/B/Bg/Cg/2Cg
		Yakima SiL	A/B/2C
		Zillah SiL	A/C
Qt2	Holocene terrace, younger	*soils formed in floodplain alluvium*	
		Outlook SiL	A/Ag/Bg/Cg
		Toppenish SiL	A/B/Bg/2C
		Wenas SiL	A/B/Bg/Cg/2Cg
Qt1	Holocene terrace, older	*soils formed on low terraces*	
		Ashue L	A/Bt/C
		Esquatzel SiL	A/B/C
		Naches L	A/Bt/C
		Umapine SiL	A/Bk/C
		Warden SiL	A/B/Bk
Qpc (Qa1; Qa2)	Paleochannels	*soils formed in floodplain alluvium*	
		Wenas SiL	A/B/C
Qap	Piedmont alluvium	*soils formed on low terraces*	
		Umapine SiL	A/Bk/C
Qaf	Alluvial fan deposits	*soils formed on slopes*	
		Willis SiL (2-5%, 5-8% and 8-15% slopes)	A/B/Bkqm/R
		Warden SiL (5-8%, 8-15% slopes)	A/B/Bk
R	Bedrock/loess	*soils formed on slopes*	
		Starbuck-Rock Outcrop Complex (0-45%, 45-60% slopes)	A/B/R
		Kiona Stone SiL (15-45% slopes)	A/B/R

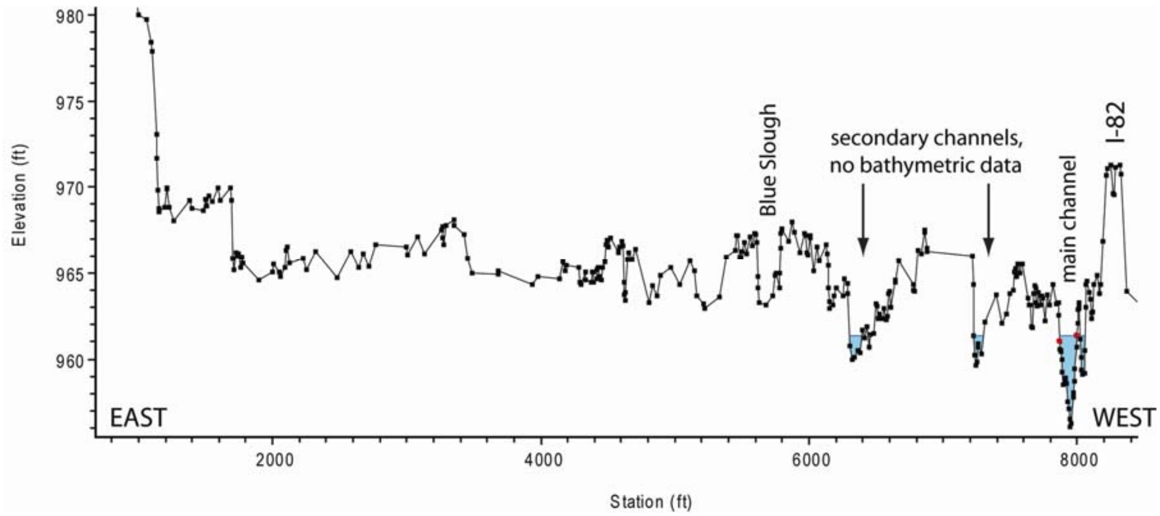

Figure 5. Example cross section in the Gap to Gap reach near Union Gap.

2.2 Field observations of channel dynamics (2008-2009)

Two float trips were made during Fall 2008 and Fall 2009 to document channel morphology and characteristics and to describe the processes by which the Yakima River changes its course and manages its sediment load in the Gap to Gap reach. During this time, observations were made concerning physical processes and features including bank erosion, channel splays, recent (post-2005) channel avulsions, bar progradation and deposition, sediment pulses, large woody debris in the channel and on bars, and other various notations. These observations were made not only to understand the processes acting in each segment to effect change, but also to differentiate the relative magnitude of fluvial modification that the channel has been recently undergoing along the length of the study reach. Based on field observations, the active channel and younger floodplain (Qa2, Qa3, Qa4) in the study area were divided into 5 segments that were either undergoing recent and extensive fluvial modifications during the last 5 years (2005-2009) or that remained relatively similar over the last 5 years (Table 2; Figure 6). Segments that were defined as having major fluvial modification have experienced recent channel avulsions, lateral erosion, had an abundance of large woody debris either on bars or in the channel itself, were noted to have prograding bars and channel splays and the development or reactivation of smaller secondary or side channels. Segments that had experienced minor fluvial modifications within the last five years showed a similar main channel position with few new side channels formed. Bank erosion in the form of vertical unconsolidated banks or banks with failing riprap was documented in some cases as well as some gravel bar deposition; however, the erosion was not significant enough to cause major lateral channel change.

The segment boundaries in this study are comparable to previous boundaries, but differ in some areas. Clark defined five zones in the Gap to Gap reach that were largely based on infrastructure. These generally correspond to the segments in this study with two exceptions: (1) segment 2 straddles the boundary between Clark's zones 1 and 2; and (2) segment 3b straddles the boundary between Clark's zones 3 and 4. Segments are shown in Figure 6 with the extent of the active channel and younger floodplain (Qa2, Qa3, Qa4 units). Clark's zones are shown using her delineation of the active floodplain. Segments are described in the paragraphs below with particular emphasis on recent observations.

Table 2: Segment boundaries and characteristics in the Gap to Gap reach

Segment	Cross section numbers	Landmarks	Observations of Lateral channel movement and processes (2005-2009)	Morphology	Average thalweg elevation (ft)	Channel gradient (ft/ft)	Main channel Sinuosity (ft/ft)	Main channel length (mi)	Channel complexity (Total channel length, mi)
					Difference (2005-1969)	Difference (2005-1969)	Difference (2009-1927)	Difference (2009-1927)	Difference (2009-1927)
1	53884 to 47911	Naches confluence to triangular gravel pit	STABLE Minor bank erosion and gravel splays on mid-channel bars	anabranching	1064.7	0.0023	1.15	1.5	3.2
					0.9	0.0013	0.03	0.04	-0.8
2	47317 to 36618	Triangular gravel pit to Oxford Hotel	DYNAMIC Channel avulsion, side channel filling, bar progradation, LWD deposition	anabranching	1039.5	0.0031	1.23	2.2	8.9
					2.9	-0.0003	0.08	0.14	-6.3
3a	35718 to 27156	Oxford Hotel to Old SR 24	STABLE Minor bank erosion	single thread to split flow	1006.9	0.0025	1.13	1.8	4.3
					-1.7	0.0005	-0.08	-0.12	-10.4
3b	25985 to 25130	Old SR 24 to new SR 24 Bridge	DYNAMIC Channel avulsion	anabranching	990.2	0.0046	1.21	0.5	1.9
					3.4	-0.0002	0.06	0.02	-2.5
4	24821 to 16807	SR 24 Bridge to Edler Ponds no. 2	STABLE Minor bank erosion and gravel deposition	split flow to anabranching	979.1	0.0019	1.25	1.5	5.0
					-0.2	-0.0012	-0.04	-0.05	-7.8
5a	15643 to 3926	Edler Ponds no. 2 to Union Gap	DYNAMIC Lateral erosion, point bar progradation, gravel splays, channel avulsion, filling and widening of channel entrances, LWD jams	anabranching	952.2	0.0026	1.20	2.5	21.8
					1.5	-0.0008	-0.18	-0.37	-4.8
5b	3926 to 20	Union Gap to Wapato Dam	STABLE Changes in Ahtanum Creek confluence location	single thread to split flow	929.8	0.0009	1.13	0.9	--
					-0.5	-0.0090	--	--	--

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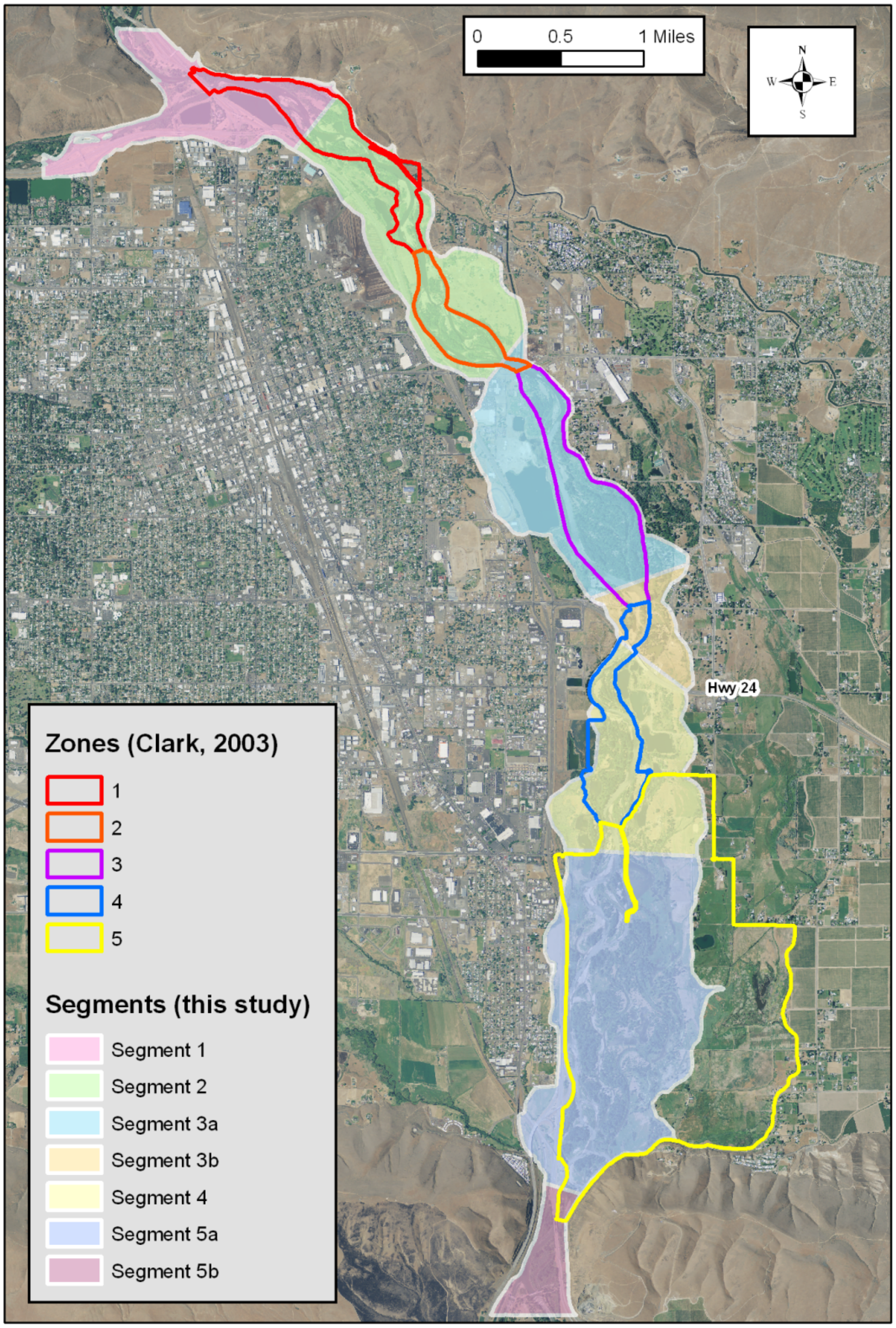

Figure 6: Comparison of zones from Clark (2003) and segments defined in this study

2.2.1 Segment 1

Segment 1 extends from Selah Gap to the triangular gravel pit and can be described as a braided to anabranching system with semi-stable islands and a vegetated floodplain (Figure 7). The majority of levees in this segment were built between 1927 and 1949 and exist along the right bank; the river is naturally confined along its left bank by bedrock and colluvial deposits. Much of the highway and gravel pits were in place by 1966 photography and some of the vegetation was also cleared to mine the underlying gravel. Only the triangular pit has been partially reclaimed by the river; the other larger and deeper gravel pits along the right bank remain behind levees and revetments. Although these areas were flooded during the 1996 flood, the berms surrounding the gravel pits were not breached. Gravel splays on mid-channel bars and lateral bars are apparent and show that bars are remaining active in the current flow regime. Major channel changes however have not been observed recently and thus this segment is described as one with minor changes during the last 5 years.

Figure 7: Segment 1 location map, 2009 aerial photography. White lines indicate levees. Flow is from left to right.

2.2.2 Segment 2

Segment 2 extends from the triangular gravel pit to the Oxford Hotel (Figure 8). The segment has an anabranching channel planform and is leveed on both sides of its floodplain. Canals existed in the 1927 photography; the upstream-most canal was abandoned between 1927 and 1949, during which time a new takeout was established along the left bank just downstream from the old takeout. Levees built between 1927 and 1949 cut off a large portion of the eastern floodplain that was active in 1927; levees built between 1949 and 1966 along the eastern and western floodplain protect the highway along the right bank and provided a lateral boundary to the Terrace Heights gravel pit and bypass channel that existed during the 1960's on river left. This segment was relatively devoid of vegetation in the 1960's within the levees and has since redistributed sediment throughout the Terrace Heights gravel pit and has a dense growth of vegetation. Several bank exposures are apparent along segment 2 and include those near the river access along the right bank levee and downstream of the triangular gravel pit along the left bank, which is composed of fine, sandy sediments over unconsolidated gravelly deposits. Channel change in this segment has been significant since 2005; many observations were made of fresh gravel splays, fill and abandonment of secondary channels, channel avulsion, bar progradation and deposition of large woody debris. Upstream of the railroad bridge, many of the side channels had filled with gravel between 2005 and 2008 aerial photography. Changes downstream of the railroad bridge included greater volumes of water flowing into the left channel upstream of the Terrace Heights gravel pit and gravel deposition and bar building at the heads of mid-channel islands or lateral bars. From field observations, it is apparent that this segment has been very dynamic during the past 5 years and is one of the most heavily modified segments historically due to the large gravel pit that occupied the majority of the channel during the 1960s.

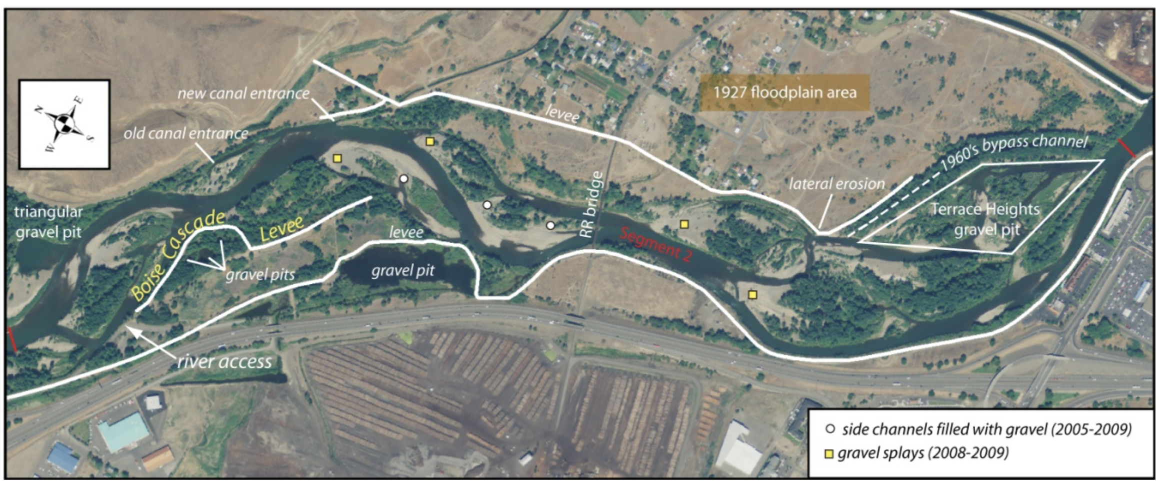

Figure 8: Segment 2 location map, 2009 aerial photography. Flow is from left to right.

2.2.3 Segment 3a

Segment 3a extends from the Oxford Hotel to just upstream of the old State Route 24 crossing (Figure 9). Channel morphology in this segment is mostly single thread with a few small side channels on the east and west sides of the main channel. Levees built between 1927 and 1949 continue from segment 2 on both sides of the floodplain, and cut off the western channel that existed in 1927. The levees presently protect the highway and the Beech Street gravel pit on the west side and residential and commercial development on the east side of the river. In the 1927 aerial photography, the channel in this segment existed as a split flow to anabranching channel with abundant unvegetated gravel bars; since that time, vegetation has encroached onto the large mid-channel island and the split flow channel has become a single main channel with a narrow side channel that appears to have been dug at some point in the recent past to maintain the surface connection with the main channel. Contributing to this channel simplification are channel modifications apparent in the 1949 photography, in which the channel was directed into its single thread path, abandoning the 1927 right branch and creating a new channel against the levee. This segment appears to have experienced relatively little change during the past 5 to 10 years; bank erosion along the densely vegetated left streambank was observed in the form of vertical bank exposures and trees toppled into the channel, but lateral movement has not been significant. Caps of fine sediment over gravelly substrate in bank exposures along this reach indicate that this area experiences overbank sedimentation during floods, contributing to an increasing stage of the floodplain surface.

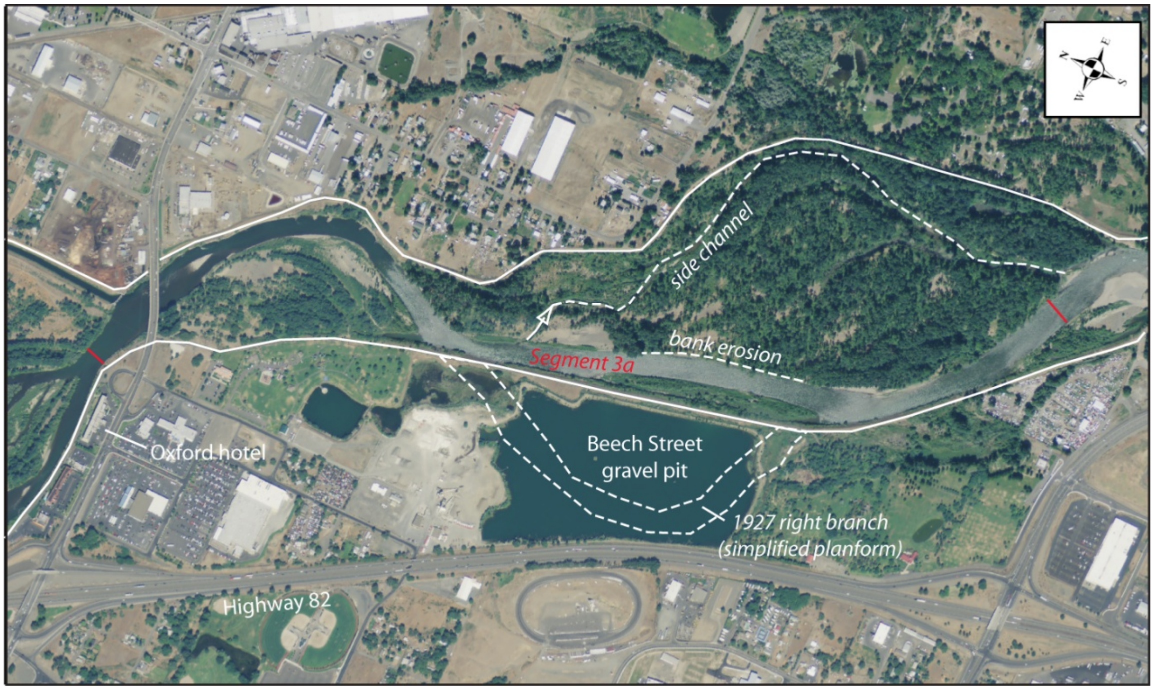

Figure 9: Segment 3a location map, 2009 aerial photography. White lines indicate levees. Flow is from left to right.

2.2.4 Segment 3b

Segment 3b is a short segment upstream of the new SR 24 Bridge and has a braided to anabranching channel morphology (Figure 10). This segment is the most tightly constrained of any segments in the study area and has levees upstream and downstream of the bridge that were constructed by 1949 along the left bank, most likely in response to the 1948 flood by the appearance of unvegetated gravel splays behind the levees and by 1966 in other areas to protect the new SR 24 bridge and the sewage treatment plant in the western floodplain. The channel existed as a split flow to single thread channel through the 1960's and was rearranged during floods in the 1970's to a braided channel with multiple flow paths around unvegetated gravel bars. Channel avulsions between 1992 and 2000 (presumably during the 1996 flood) as well as during the winter 2009 flood make this short segment very dynamic and prone to channel change during high magnitude discharges.

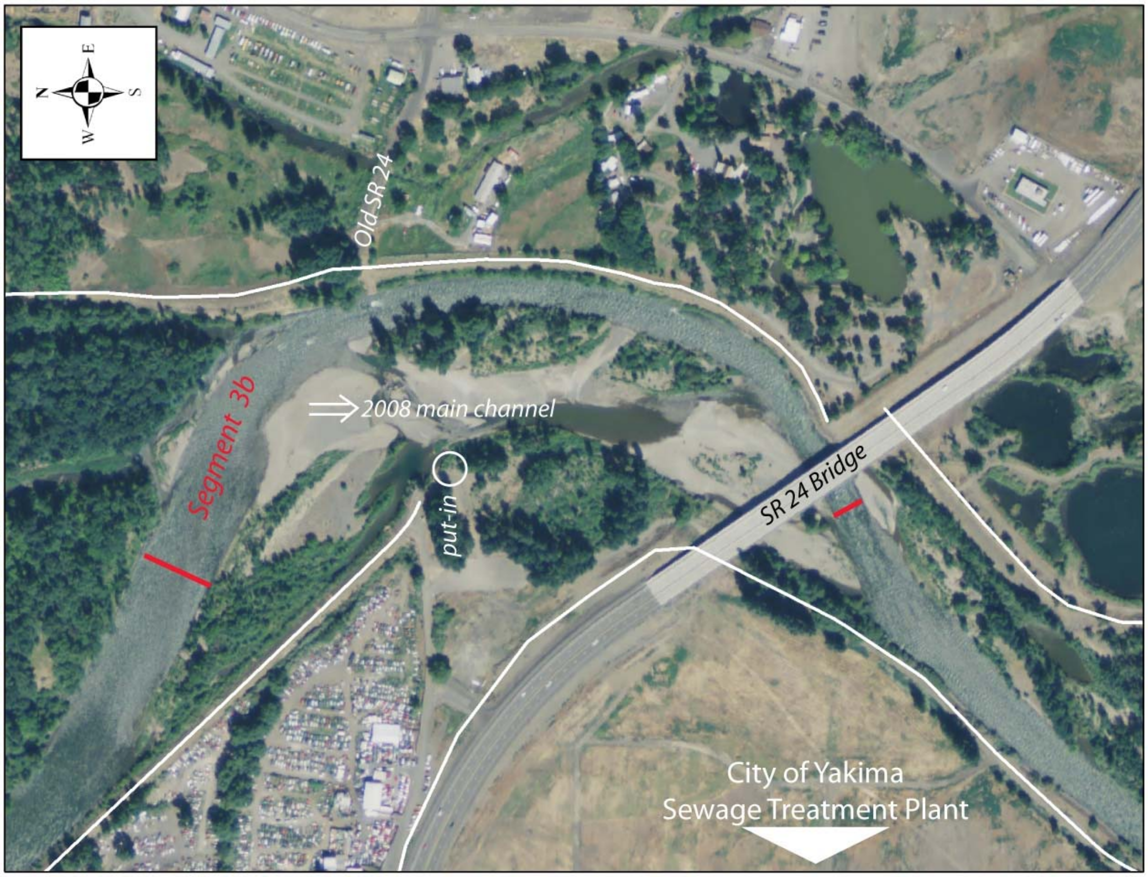

Figure 10: Segment 3b location map, 2009 aerial photography. White lines indicate levees. Flow is from left to right.

2.2.5 Segment 4

Segment 4 extends from just downstream of the State Route 24 Bridge to the Edler Ponds area and is a single thread channel with some small side channels on the left and right banks (Figure 11). In early photography, this segment has a split flow to anabranching morphology with a wide floodplain and many unvegetated bars. By 1966, some discontinuous levees had been constructed along the left bank, blocking some areas of potential avulsion, and a continuous levee had been built along the right bank to protect the sewage treatment plant. Based on the dramatic change in channel position and character between 1949 and 1966 aerial photography, it is likely that this segment was channelized sometime between 1949 and 1966. By 1979, a continuous levee had been constructed along the eastern side of the channel as a barrier between floodplain gravel pits and the main channel. Vegetation encroachment on the bars inside the levees has been substantial from the 1990s through 2009; enlargement of the gravel pits in the eastern floodplain and the addition of several pits in the Edler Ponds area can be observed between 1992 and 2000. Field observations in 2008 and 2009 indicate that the channel in this segment is “locked” into place by the levees and revetments that confine the floodplain and channel. Channel survey data as well as the greater height of the point bar above the channel compared to the heights of other point bars indicate that the channel has locally incised against the rip rap on the upstream bend near the sewage treatment plant. Failure of the rip rap and formation of lower elevation benches suggest that the channel is undercutting the right bank at depth, which is causing the rip rap to fail. Floods continue to access the high point bar on the opposite bank, depositing sediment along the margins of the surface. Floodplain surfaces downstream in the segment are inundated during larger flows; on this surface, flotsam is floated against the upstream sides of trees, fresh gravel is deposited on the bar surfaces and scour holes are formed on surfaces near the main channel. The Edler Ponds area is inundated only during high-magnitude floods, such as the 1996 flood. Bank erosion in areas without rip rap or levees is apparent in the form of vertical banks, which expose a thin cap of fine sediment over gravel.

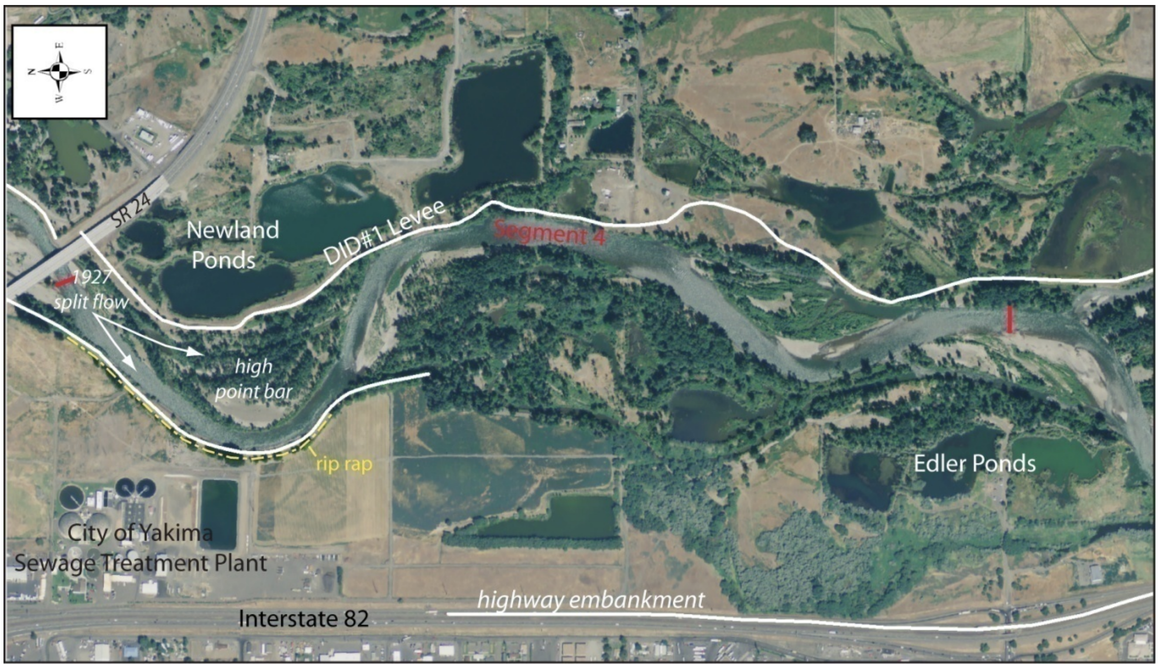

Figure 11: Segment 4 location map, 2009 aerial photography. White lines indicate levees. Flow is from left to right.

2.2.6 Segment 5a

Segment 5a extends from the Edler Ponds area to just upstream of the Interstate 82 bridge (Figure 12). This segment is the longest and most dynamic segment in the Gap to Gap study area and has maintained an anabranching channel morphology throughout the historical period (1927-2009). Levees and revetments are located at the upstream end of the study segment in the eastern floodplain and along Interstate 82 in the western floodplain; however, they do not constrain the floodplain as narrowly as in other segments. Channel changes have been significant historically and mainly occur through the process of channel avulsions. Lateral erosion is also apparent in some locations, which in some cases is a precursor to channel avulsions by either eroding into a pre-existing abandoned channel or by creating a highly sinuous meander geometry, which the river then cuts off. In 1927, the main channels were located in the eastern portion of the younger floodplain; by 1949, avulsion to a new channel on the western side of the floodplain created a split flow scenario, switching the majority of flow into the new western channel and decreasing flow in the eastern channels. Channel avulsions and gravel pit captures between 1966 and 1979 continued to shift the main channel location from the eastern floodplain to the extreme western floodplain along I-82. The main channel has remained in this location; however, many smaller avulsions and channel abandonments have occurred between 1966 and 2009 that have maintained numerous unvegetated gravel bars and limited vegetation encroachment. Recent changes in channel position between 2005 and 2008 make this a segment that is likely to continue to change in the future. These changes take the form of lateral erosion, point bar progradation, gravel splays, channel avulsion, filling and widening of channel entrances, and large woody debris jams. Channel surveys in this area show decreasing elevations in the floodplain toward the main channel against the freeway; for channel shifts to occur toward the east, sediment deposition in the channel would be required to create the conditions suitable for an eastward channel avulsion (see Figure 5).

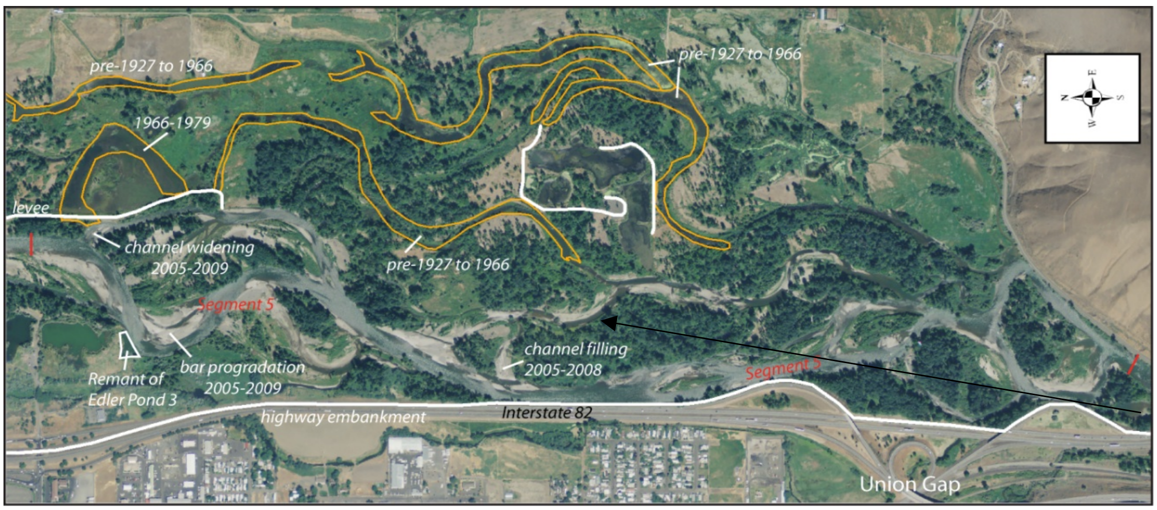

Figure 12: Segment 5a location map, 2009 aerial photography. White lines indicate embankments and levees. Flow is from left to right.

2.2.7 Segment 5b

Segment 5b extends from just upstream of the I-82 bridge to Wapato Dam (Figure 13). Channel morphology is single thread through this segment and split flow near Wapato Dam; channel position is restricted by bedrock ridges at Union Gap so that very little lateral movement is possible. Historical aerial photography available for this study does not extend to Wapato Dam; however channel positions for the upstream portion of the segment show that the main channel has been located along the left bank since 1927. This suggests that channel position is probably similar for the downstream portion of the segment as well for the historical period. Changes in Wapato Dam may have altered lateral channel position; however the dam took advantage of the mid-channel bar complex between the split flow channel as part of its construction and has essentially fixed the channel position in this area. Hydraulic modeling in this study indicates that Wapato Dam exerts a backwater effect on the Yakima River channel to approximately the USGS gage above Ahtanum Creek (#12500450) in Reach 5b (see Chapter 4 for further discussion). Although the photography is not complete for 1927, Ahtanum Creek appears to have flowed into a wetland environment along the Yakima River and was channelized at least partially by 1949, where it entered the Yakima River channel upstream and downstream of the bridge. The upstream confluence was abandoned by 1966, by which time the I-82 interchange was built in this area and the entirety of Ahtahnum Creek was directed downstream of the bridge to its present confluence.

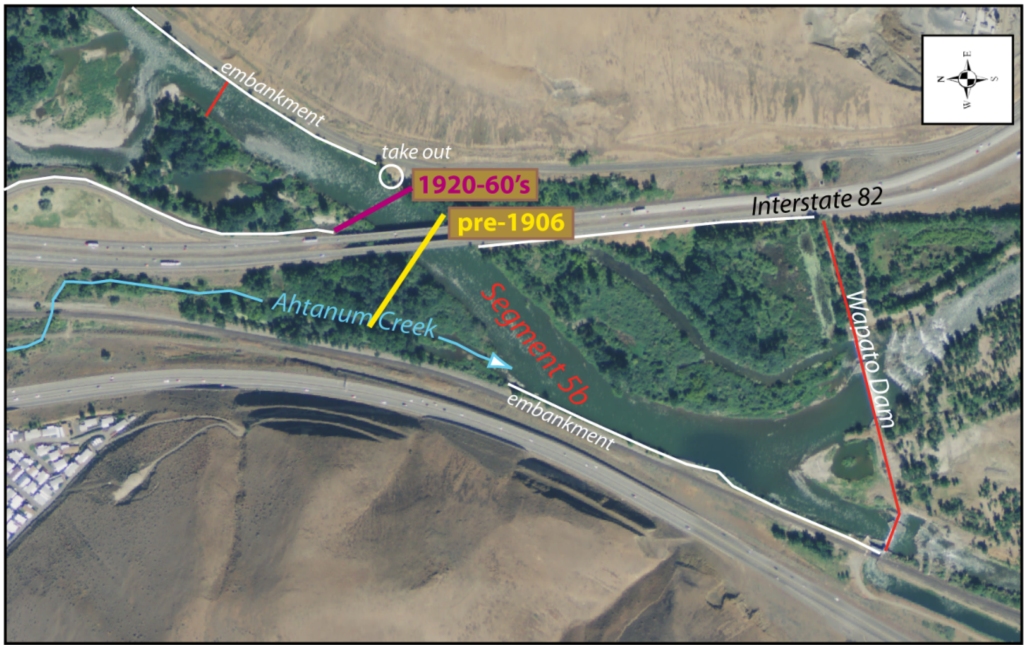

Figure 13: Segment 5b location map, 2009 aerial photography. Purple and yellow lines indicate approximate locations of previous bridges over the Yakima River. White lines indicate embankments. Flow is from left to right

2.2.8 Minor tributaries from the western piedmont

Tributaries from the western piedmont flow southeast into the lower portion of the Gap to Gap reach from the Ahtanum Valley and include Ahtanum Creek, Wide Hollow Creek, Spring Creek and Bachelor Creek (Figure 14). These tributaries have been used for irrigation since the early 1900's and are thus channelized into canals even in the earliest photography. Ahtanum Creek was partially straightened by the 1890's in its lower section and further channelized by 1949. Areas of abandoned meanders are still visible on aerial photography and are also reflected in soils mapping of the area. Wide Hollow Creek appears to have previously entered Ahtanum Creek in the vicinity of Fullbright Park but was already channelized in 1927, likely to power the grist mill located downstream on its current path. Its confluence with the Yakima River was blocked by the highway embankment by 1966 and was replaced with a culvert to allow creek flows to reach the Yakima River downstream of the area shown in Figure 14.

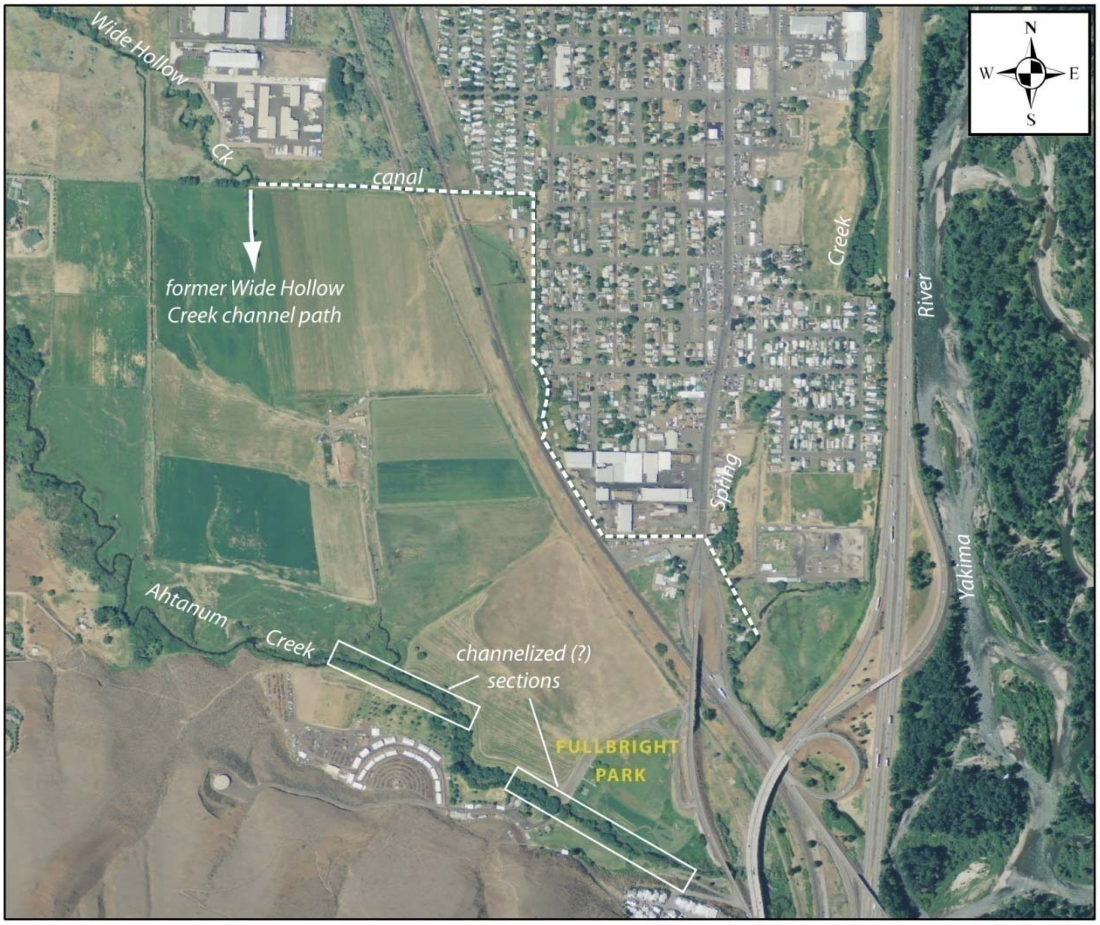

Figure 14: Tributaries from the western piedmont, 2009 aerial photography. Flow is from top to bottom.

2.3 Gravel pit captures in the Gap to Gap Reach

While many gravel pit captures can be documented along the Yakima River, the process by which these gravel pits are reincorporated into the river channel is difficult to determine due to the lack of available aerial photography during the critical period of pit capture. Physical models that simulate gravel pit capture in the floodplain document lateral erosion followed by failure of gravel pit berms and subsequent breaching by the river (Little River Research & Design, 2007). Following the breach, headcutting and incision occurs upstream of the pit in combination with rapid filling of the gravel pit as the river attempts to reestablish its grade and equilibrium. Incision downstream of the pit is also common as the flow is typically sediment starved when it exits the pit, which induces bed scour. The disruption of sediment continuity can also induce further lateral instability and lead to erosion of streambanks and other critical infrastructure along the river channel (Kondolf, 1998). Terraces may also form in response to channel incision and may be able to be observed in some cases. Abandonment of the previous channel may occur depending on the channel geometry at the specific location. Once the gravel pit fills, sediment transport can be restored to former rates and the system stabilizes.

Case studies of gravel pit captures on rivers illustrate the geomorphic response (i.e., Kondolf, 1998; Sear and Archer, 1998; Norman et al 1998; Scott, 1973). For example, on the Cowlitz River upstream of Toledo, WA, breach of a revetment during the November 1995 flood allowed the river to access a gravel pit in the floodplain behind the revetment. The pit was partially filled with flotsam and sediment during the flood. Knickpoint migration upstream of the pit could be observed in the form of a standing wave that moved upstream during the course of the flood from the pit to the breached revetment. The repaired revetment was breached a second time during the February 1996 flood, which continued to scour the new channel. The revetment was reinforced following this flood and the river forced to flow down the pre-1995 channel. It was apparent that the lower elevation of the new channel would have caused the complete abandonment of the pre-1995 channel had the revetment not been repaired (Norman et al 1998).

Based on historical observations of pit capture on the Yakima River (i.e, Dunne et al 1976; Norman et al 1998), recent observations of channel change in the Gap to Gap reach (i.e., Clark, 2003), and features documented on aerial photography, it is apparent that the gravel pits along the Yakima River are captured by channel avulsions during larger magnitude flows.

Historical photo sequences of pit captures on the Yakima River illustrate two common scenarios for how a gravel pit in the floodplain is reincorporated into the active channel:

1. Continued lateral migration of main channel into gravel pit area, which includes rapid filling of the gravel pit with sediment combined with lateral erosion of the pit area.

2. Channel avulsion into the pit area, followed by abandonment of the original channel or development of a split flow channel and mid-channel island.

Both of these scenarios can be observed along the Yakima River. In the first case, the gravel pit is typically located close to the outer bend of the main channel and is laterally eroded as the main channel migrates into the pit area. In the second case, the gravel pit is located in a low-lying floodplain area and captures overbank flow during a large flood, inducing knickpoint migration upstream from the pit and incision downstream, then eventually capturing main channel flow. Pit captures in the Gap to Gap Reach are described in the following paragraphs using historical aerial photography and other literature that documents any firsthand observations.

2.3.1 Triangular pit

The triangular pit is located in Segment 1 along the left bank and was excavated between 1949 and 1966 in the floodplain (Figure 15). Between 1979 and 1992, the pit was captured during an avulsion that created a split flow channel in the vicinity of the pit and a large secondary flow area in the gravel pit itself. 2000 photography shows that the pit had filled in partially with sediment at its upstream end; this situation continues to exist in 2009, in which channel splays happen frequently enough at the upstream end of the pit to maintain an unvegetated bar; the downstream end of the pit has a surface water connection to the channel and is a backwater area.

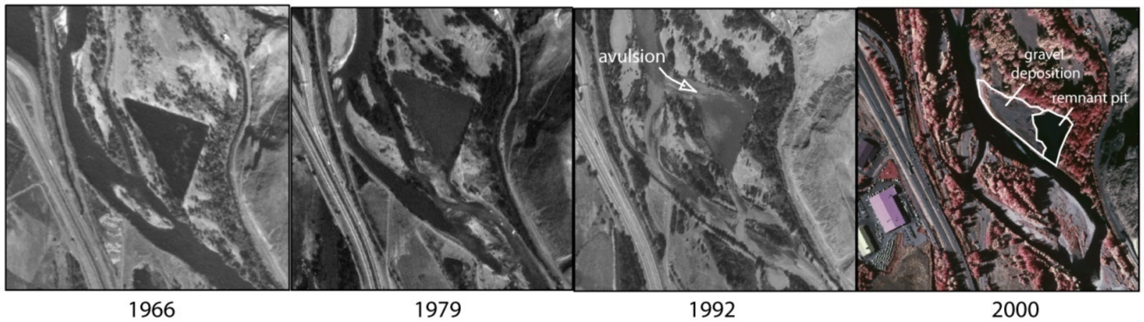

Figure 15: Historical photo sequence near the triangular pit in Segment 1.

2.3.2 Terrace Heights pit

The Terrace Heights pit is located in Segment 2 just upstream of the Terrace Heights Bridge over the Yakima River (Figure 16). The Terrace Heights pit was a diamond shaped pit excavated during the 1960's with excavation of in-channel sediments and diversion of the Yakima River through a bypass channel located along the left bank. This pit was captured at the downstream end in the late 1960's and at the upstream end during the 1971 flood (Clark, 2003). Since that time, the pit area has been infilling with sediment and vegetation, creating numerous small channels and backwater areas in the old gravel pit.

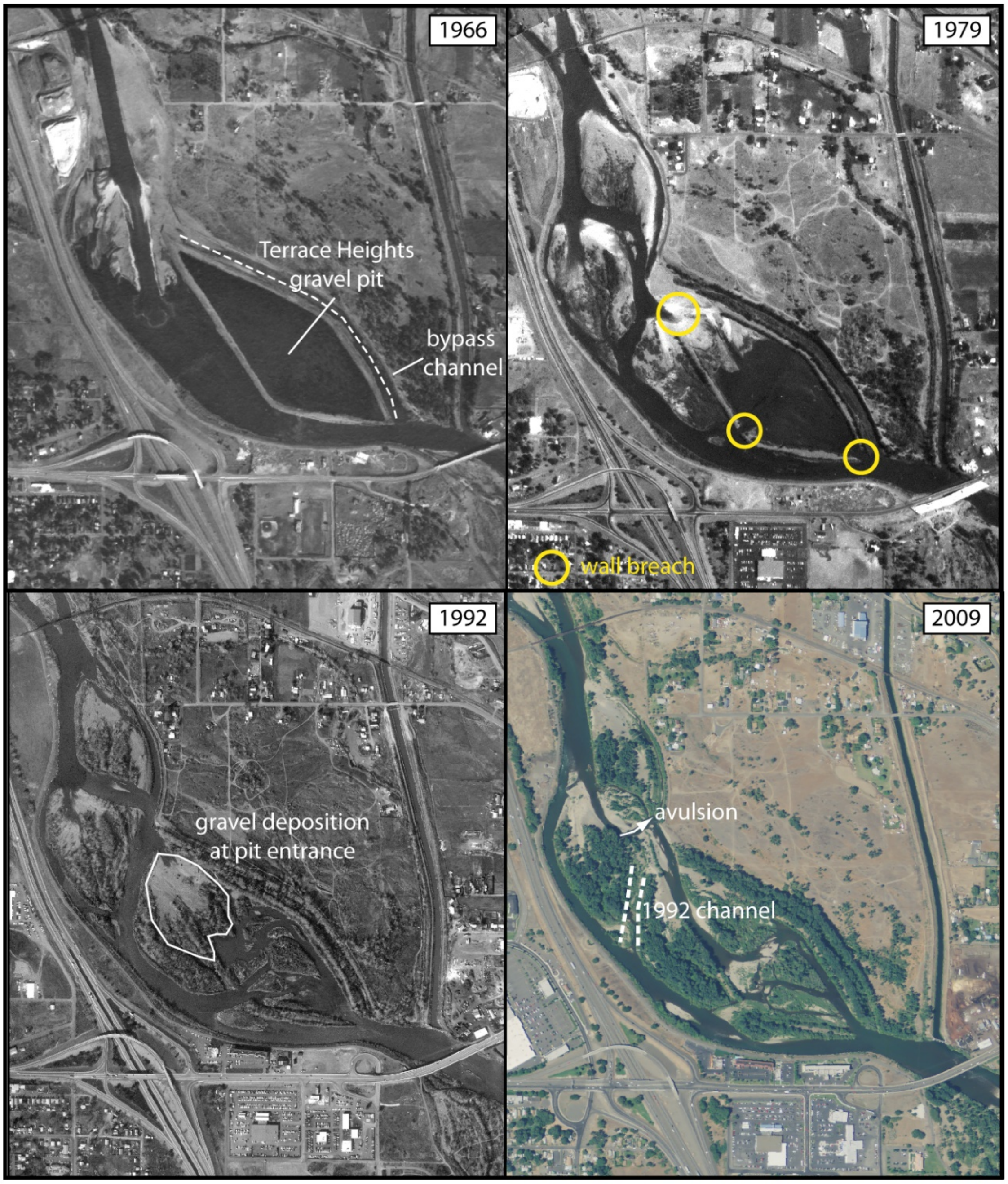

Figure 16: Historical photos near the Terrace Heights gravel pit.

2.3.3 SR24 pit

The SR24 pit was located along the western floodplain near the greenway access point just upstream of the SR 24 bridge in segment 3b (Figure 17). The gravel pit was excavated between 1949 and 1966; dikes surrounding the gravel pit were breached between 1966 and 1979 possibly during the 1971 flood that is documented to have breached other dikes in the study reach (i.e., Dunne et al 1976). It appears that following the breach, the pit was filled with sediment so that by 1979 photography, its appearance is only vaguely discernable. Deposition in this area could occur rapidly, as it has been located on the inside of the meander bend since at least 1927.

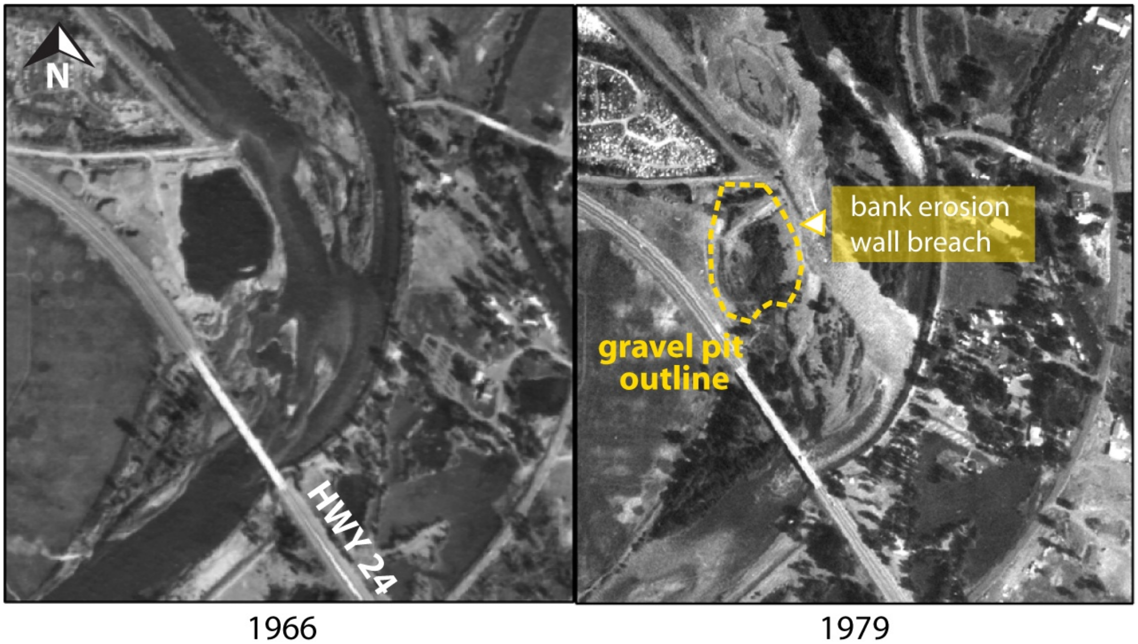

Figure 17: Historical photo sequence showing pit capture near SR24 Bridge

2.3.4 Edler Ponds pit no. 3

The Edler Ponds in segments 5a and 5b were excavated between 1992 and 2000, with the exception of the uppermost pit, which was initially excavated between 1966 and 1979 with continued expansion of the pit into the 1990's (Figure 18). The capture of the lowermost Edler Ponds pit (Pond 3) has been discussed previously by Clark (2003). The gravel pit dike was breached during April 2002, in which Clark documented fine-grained sediments being deposited in the northern portion of the pit where an eddy had developed and a coarser grained delta was forming at the junction of the gravel pit and Yakima River. The last observation in her thesis was from 2002, in which the dike had been breached. Since this time, continued filling of the remains of the pit and lateral channel movement and bar progradation toward the west has reduced the remaining pit area. A portion of the levee and the northwest corner of the pit are still visible in 2009 photography, but are greatly reduced as lateral erosion continues.

2.3.5 Segment 5a pits

Gravel pits in Segment 5a consisted of several large pits in the western floodplain along I-82, a group of smaller pits in the central part of the floodplain and some small pits scattered throughout the segment (Figure 19). Most of the pits were excavated between 1949 and 1966 although a few in the central portion of the floodplain were excavated between 1927 and 1949. In 1966, the main channel was located just to the north and east of the pits along the interstate. The time gap between 1966 and 1979 photos is large

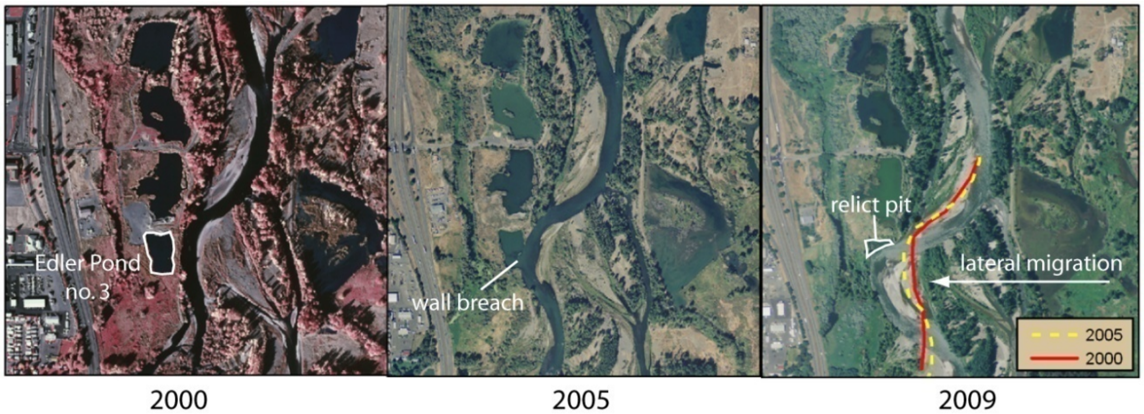

Figure 18: Historical photo sequence showing pit capture of Edler Pond no. 3.

enough for multiple channel changes to have occurred between the two sets of photos; Dunne et al (1976) documents that these avulsions were initiated by breaches in the dikes surrounding the gravel pits during the 1971 flood. These pits were mostly filled in with sediment by 1979 photography. The 1978 flood may have been a major cause of the rapid infilling of the pits. By 1992, the river had eroded into the remainder of the upper gravel pit and abandoned its channel for one further to the east close to a small gravel pit in the floodplain. This small gravel pit appears to have filled in with sediment by 2000.

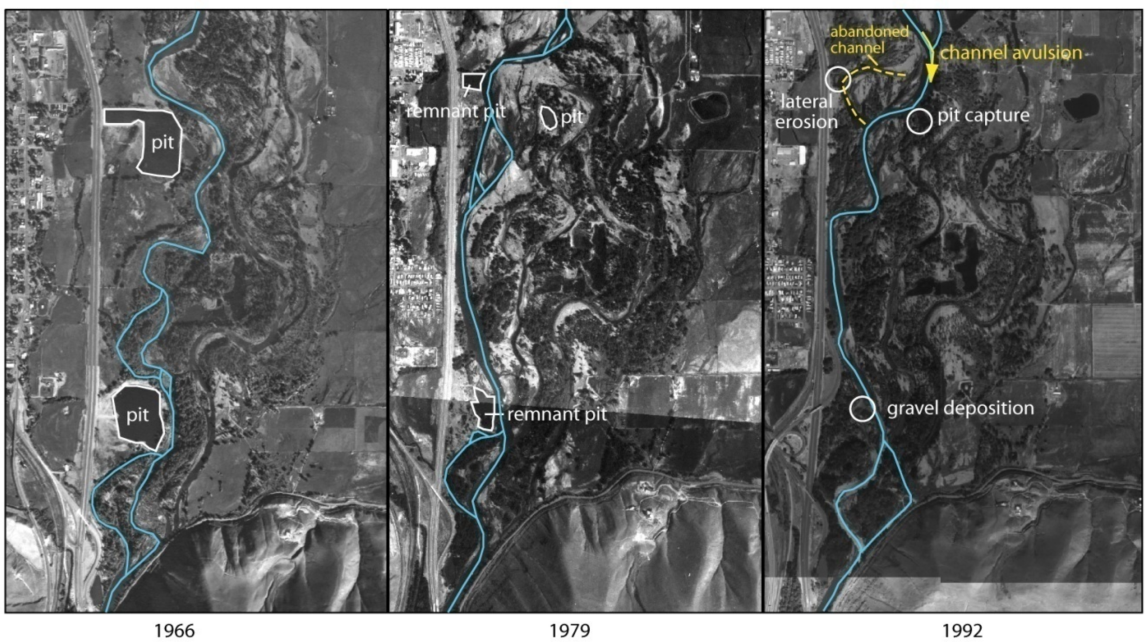

Figure 19: Historical photos of Segment 5a pits.

2.4 Historical Trends

In this section, historical trends in geomorphic data along the Yakima River provide information concerning changes in the geomorphic character of the river from 1927 to 2009. The objective of these analyses was to examine geomorphic changes to the channel during the historical period, including channel aggradation, degradation, and morphology. Trends analyzed in this section include channel complexity (1927-2008), bed elevation (1969 vs. 2005), laterally active areas (1927-2009) and channel sinuosity (1927-2009). Data from Clark (2003) were used extensively in these analyses and updated whenever possible to include the most recent data available. Sets of rectified aerial photographs include those from 1927, 1949, 1954, 1966, 1979, 1992, 2000, 2005, 2008 and 2009.

2.4.1 Channel Complexity

Channel complexity can be used as a measure of physical habitat quality and variety in river systems. By mapping the channel network, the number of bifurcations can be measured as an indicator of channel complexity. The assumption is that the greater the number of bifurcations, the greater the variety of habitat and channel complexity. Nodal analysis is one method that can be used to measure channel complexity (Whited et al 2002). With this method, a node is inserted at each channel's junction with another channel; the number of nodes in the study reach is then counted to derive a relative number to compare to other historical data sets (Figure 20). Clark (2003) demonstrated that nodal analysis can be used independent of discharge in aerial photography provided that discharges fall within a given range that does not dramatically impact the number of channels formed.

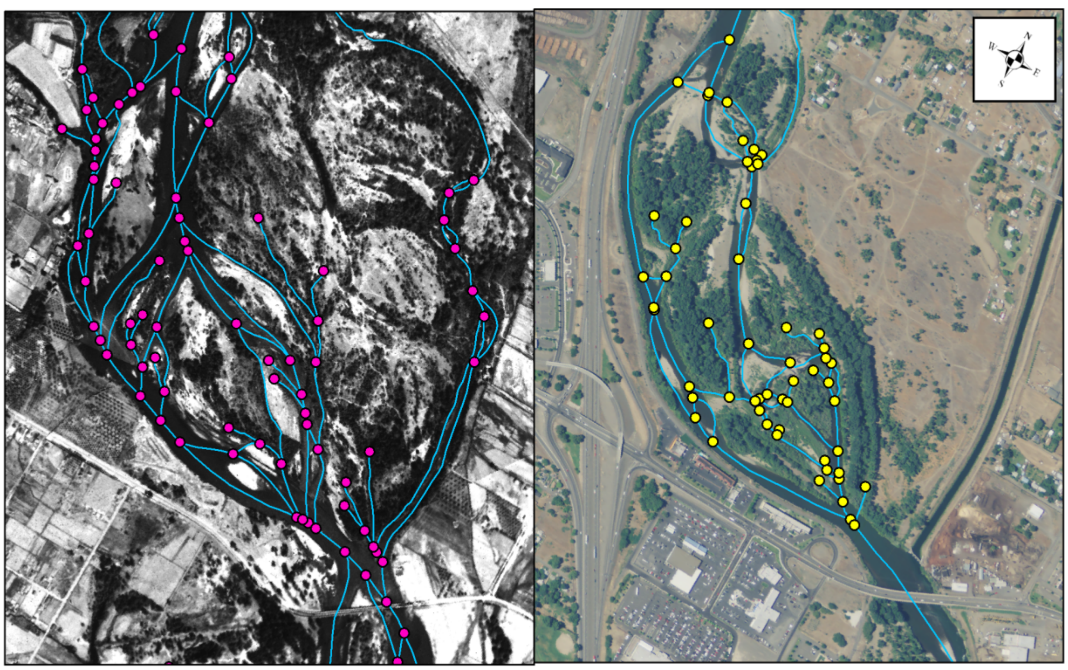

Figure 20: Example of nodal analysis in segment 2, upstream of Terrace Heights Bridge. Photo on left is from 1927; photo on right is from 2008.

For each photo year, Clark (2003) mapped channel centerlines for all wetted channels including the main channel, side channels, partially wetted overflow (or secondary) channels, dead arms (or sloughs), spring brooks and outflow channels. A single node represents each channel intersection; the number of nodes was then counted and compared between photo years. While channel mapping from Clark was available for all photo years, the nodal analysis was recalculated because the point files containing the nodes could not be located. Channel lines were also clipped to the boundary of the younger floodplain (Qa2 map unit) in order to only investigate the area of historical channel migration. 2008 channel centerline mapping was added to update the analysis.

Results from this analysis show the same trend as the analysis in Clark's (2003) thesis in that the largest number of nodes and inferred greatest channel complexity was present in 1927 and decreased through the 1960's, reflecting extensive levees and in-channel gravel mining that simplified the river channel (Figure 21). Some recovery of the channel has occurred following the 1960's, where channel complexity has increased from 1979 through 2008. In 1993, the number of nodes is greater than the surrounding years; this seems to be due to the reoccupation of some of the in-channel gravel pits between 1979 and 1993 and a greater number of channel bifurcations around in-channel gravel bars between 1993 and 2000. A similar upward trend in channel complexity continues through the 2008 data set and suggests that channel recovery is still continuing.

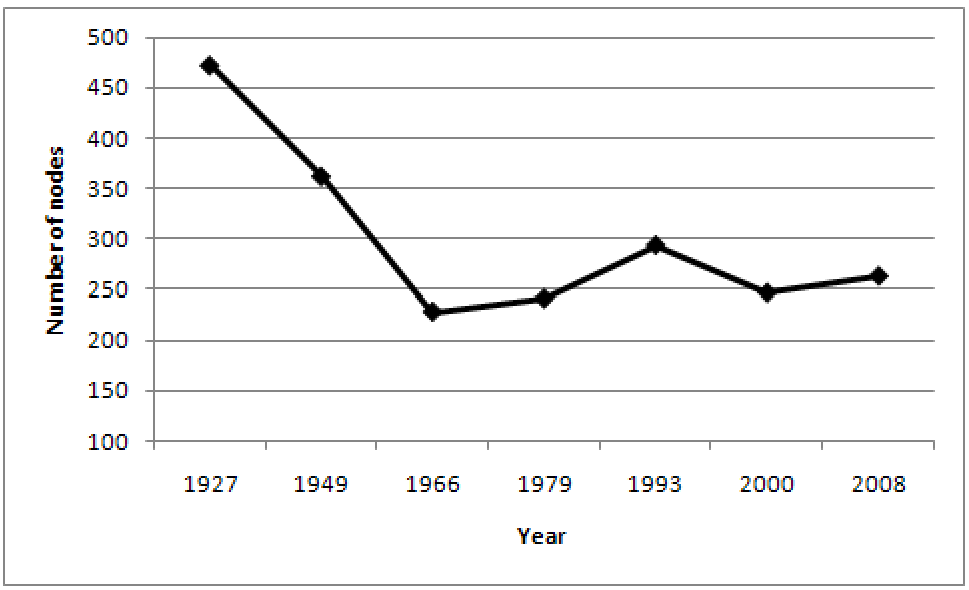

Figure 21: Nodal analysis modified from Clark (2003).

Separating the data by channel segment shows that segments 2 and 5a are the segments that appear to be increasing in channel complexity since 1966 and that direct the overall pattern in the number of nodes in Figure 21 (Figure 22). These are segments that have experienced major gravel pit captures and that historically have been dynamic reaches with abundant lateral channel change. In segment 2, the decrease in nodes from 1927 to 1966 is due to levee construction, which cut off a large portion of the eastern floodplain, and the development of the Terrace Heights gravel pit. In segment 5a, the large decrease in nodes from 1949 to 1966 is caused by the loss of some channels from levee construction in segment 4, but is also due to a smaller number of secondary channels visible on bars and floodplain areas in 1966 photography when compared to 1949 photography. Since the 1949 photography closely followed the 1948 flood, there were more channels that had been activated recently and that were visible on recently reworked bars and floodplain areas. Segments 3a and 4 have a general downward trend in the number of nodes. This is reflected in the channel simplification as a result of levee construction, bed degradation, and abandonment of secondary channels that has occurred historically in these reaches. Segments 1 and 3b have low fluctuations in the number of nodes throughout the historical period, which is reflective of their short reach lengths and consistency in the number of channel connections in each segment.

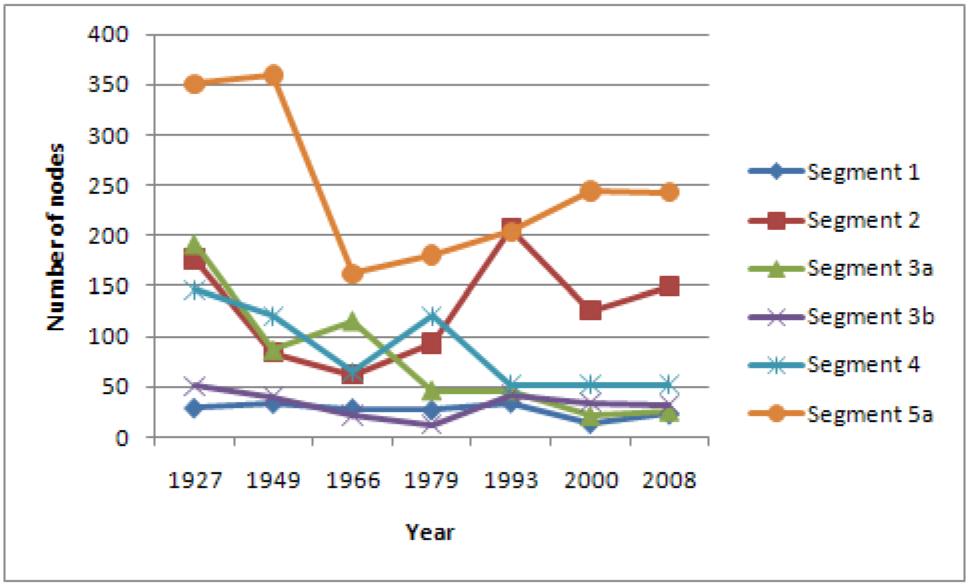

Figure 22: Nodal analysis separated by channel segment, 1927-2008.

Channel length of each study segment was also examined as a measure of channel complexity that would complement the nodal analysis. The calculation includes all channel types (i.e., eupotamon, parapotamon and springbrooks) within the younger floodplain boundary. In general, the segments show a decrease in channel length from 1927 to 2008, which is reflected in the disconnection of multiple channels by levees and revetments as well as vegetation encroachment into side channels. Most of the channel segments show a decrease in channel length from 1927 to 2008 and show the effects of historical modifications that include both levee construction and vegetation encroachment.

Segment 5a shows a decrease in channel length similar to the pattern in the nodal analysis. The increase from 1966 to 1979 is a result of the channel avulsion into the gravel pits, which created an additional channel in the western floodplain and thus, greater overall channel length. While channel length continues to increase in segment 5a, it still does not reach the same level as in 1927. In contrast to the nodal analysis, segment 2 shows an overall decrease in channel length, with only a minor increase in 1993. Therefore, while the capture of the Terrace Heights gravel pit created many more channel connections, the overall channel length only increased incrementally compared to other years of photography. Segments 1 and 3b show little variation in overall channel length. This is partially due to the short length of these segments but also may reflect that these segments are minimally affected by historical changes in the river channel with regard to channel complexity measures.

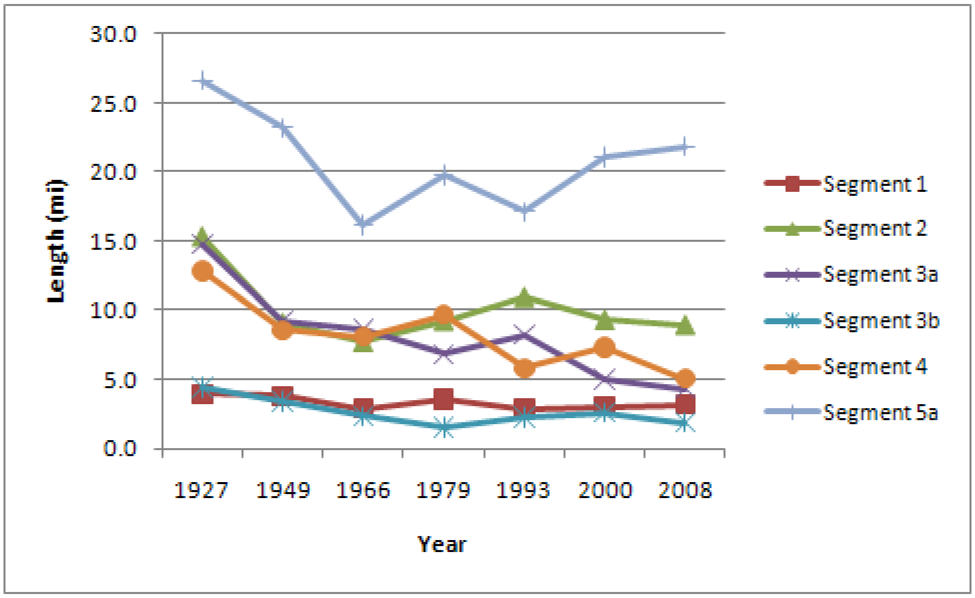

Figure 23: Channel length measurements by study segment.

2.4.2 Mapping of unvegetated bars

Unvegetated bars can be used as a measure of the area being actively modified by the Yakima River channel. While being reworked by the river, bars remain relatively vegetation free; as bars become isolated from flow or are not modified for a period of time, vegetation begins to encroach and unvegetated bars are incorporated into the floodplain. The bars may become reactivated during large floods that are capable of eroding the established vegetation and depositing or mobilizing sediment on the bar surfaces. Vegetation may also act to stabilize bars so that even large peak discharges may not be able to modify the bars, but instead will deposit fines in the floodplain due to higher surface roughness and slowed velocities in the vegetated areas. Increasing trends in bar area may indicate channel aggradation as a greater amount of sediment is deposited in the reach and stored in bars and in the channel bed. However, to conclude this, the increases should be unidirectional and should not correspond to modifications due to large floods. Decreasing trends in bar area may suggest either channel degradation or the encroachment of vegetation that is not able to be removed by large peak discharges.

Unvegetated bars were mapped by Clark (2003) as part of her thesis research, but were not used in any detail in her analysis. These bar features were re-attributed based on the dominant characteristic of each mapped polygon. For instance, if most of the polygon was covered by vegetation, the polygon was mapped as part of the floodplain; in contrast, if most of the polygon was unvegetated, it was mapped as an unvegetated bar. Bars were also mapped for 2008 and 2009 photography in order to update the analysis for the current study. Comparison of bar areas from 1927 to 2009 reveals that bar area does not increase or decrease consistently through time but rather is a function of sediment mobilization during floods and corresponding active areas (Figure 24). For example, increase in bar area between 1927 and 1949 is probably due to channel modifications during the 1933 and 1948 floods, which were both large floods in the gage record at Ahtanum. Increases from 1966 to 1979 and from 1993 to 2000 are also periods in which large floods occurred (1971, 1974, 1978, and 1996). Decreases in unvegetated bar area are related to vegetation encroachment during intervals in which the bars are not activated because of low flows. Bar area increases with the next flood that is large enough to rework the bars. Based on the pattern in bar areas, an aggradation signal is not apparent through time, but as stated previously, bar area appears to fluctuate based on the proximity of the date of aerial photography to sediment mobilizing discharges.

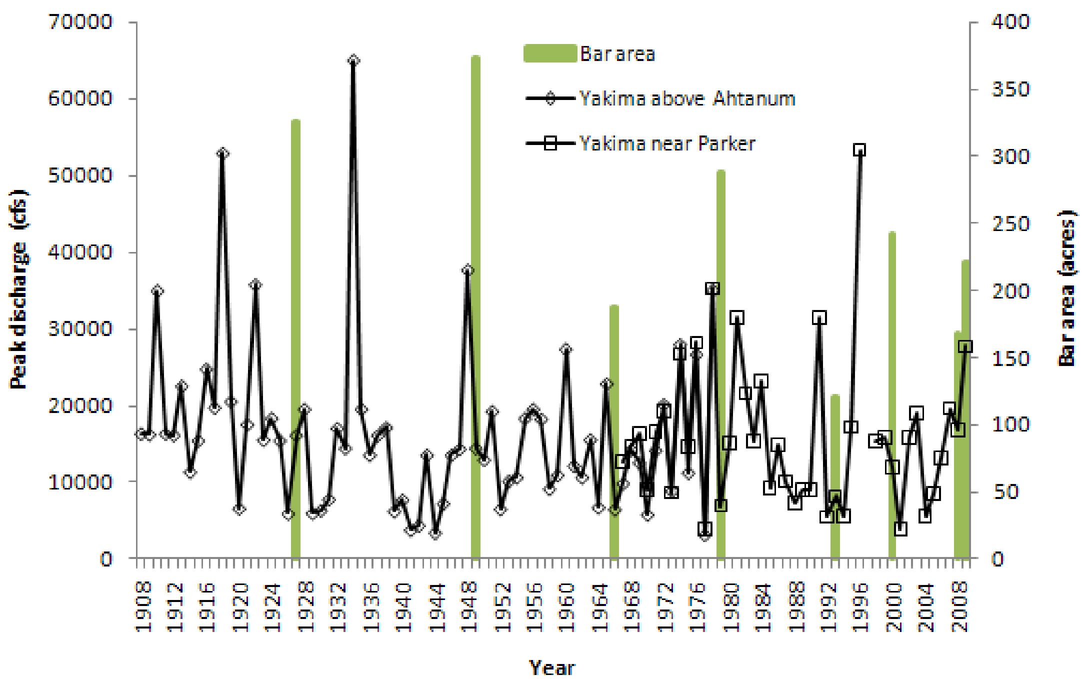

Figure 24: Unvegetated bar area and peak flow discharge plot.

When the bar area measurments are separated by study segment, the majority of the response can be observed in segment 5a, which is the most dynamic of all the study segments and also the longest segment (Figure 25). Segments 1 and 2 show similar trends to segment 5a, but at a smaller scale. Segment 4 shows a consistent decreasing trend in unvegetated bar area, which can be observed in historical vegetation encroachment and abandonment of the eastern side channel in this segment. Segments 2 and 3a also show an overall decrease in bar area from 1927 to 2009, suggesting that vegetation encroachment is also a major factor in these reaches.

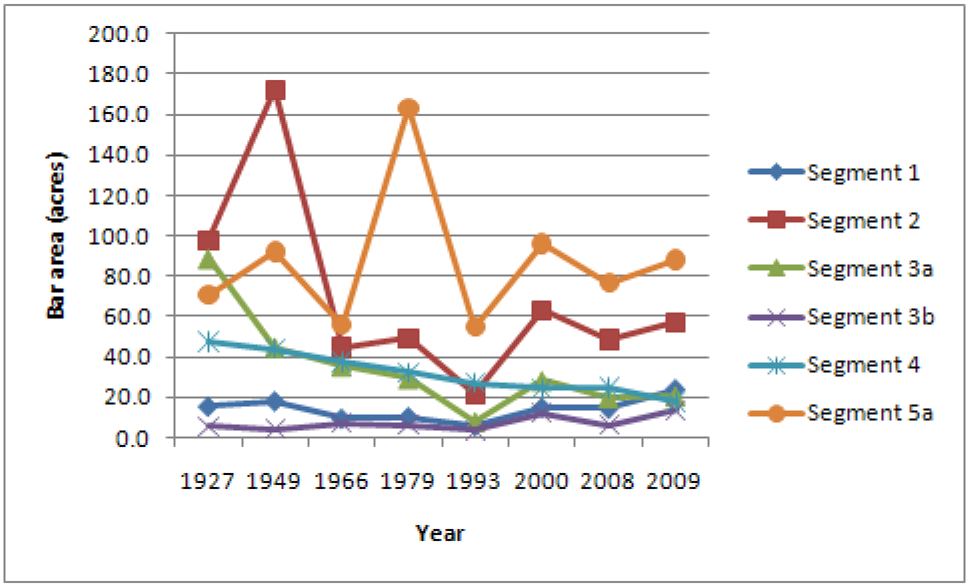

Figure 25: Unvegetated bar area measurements by study segment.

2.4.3 Sinuosity measurements

Sinuosity is a measure of meandering in a river system and is measured by the ratio of the channel length to the down-valley distance (Leopold and Wolman, 1957). While it is generally most useful in understanding changes in single thread channels, we have also calculated it for the main channel in the anabranching reaches. Changes in sinuosity vary by segment and do not show any consistent increase or decrease for all segments in the study reach (Figure 26). However, many of the changes in sinuosity can be related to channel changes during the historical period in each segment. For example, in segment 2, the increase in sinuosity from 1966 to 1979 may be reflected mostly in channel changes near the Terrace Heights pit, in which pit capture between 1966 and 1979 created a channel with greater sinuosity than the 1966 channel. In segment 3b, channel avulsions in 1996 and 2009 are reflected in significant decreases and increases in 2000 and 2009 sinuosity measurements. In segment 4, a decrease in sinuosity from 1949 to 1966 reflects the development of levees and channel changes associated with levee construction; similar sinuosity from 1979 to 2009 reflects stabilization of the channel, including vegetation encroachment along the channel banks. Segment 5a also shows a significant decrease in channel sinuosity from 1966 to 1979, which is most likely caused by the channel avulsion into gravel pits along I-82. Segments 1 and 3a show minimal change in channel sinuosity, with the exception of a decrease in segment 3a between 1927 and 1949. This apparent stability of channel form suggests that channel position is generally fixed in place, either by natural constraints or by human induced changes such as levee building and vegetation encroachment.

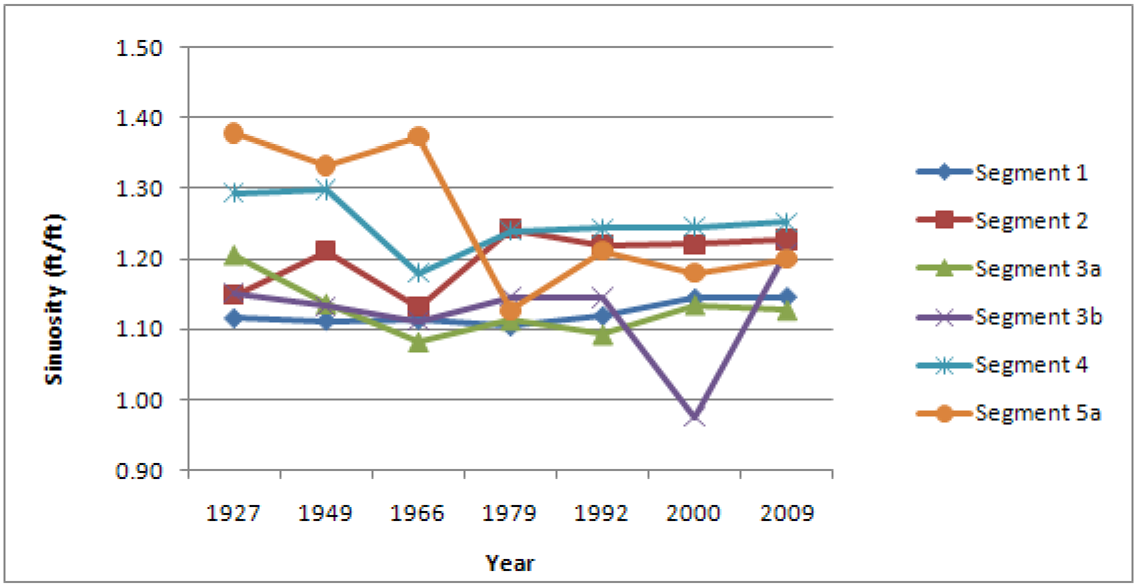

Figure 26: Channel sinuosity measurements by segment, 1927-2009.

2.4.4 Channel survey comparison (1969-2005)

In order to investigate vertical changes along the Yakima River in the study area, channel survey data were compared between 1969 and 2005. Survey data from 1969 were collected by the Army Corps of Engineers while 2005 cross section and thalweg data were derived from LiDAR and a bathymetric survey. 1969 cross sections were digitized from the scanned cross section plots. Cross section alignments and vertical corrections for the 1969 survey were provided by Yakima County (Appendix C). Alignments of the 1969 cross sections were used to extract data from the 2005 bathymetric survey and LiDAR data represented by a raster in a GIS. These alignments are shown in Figure 27. The cross section data were compared by vertically adjusting the 1969 data (using corrections provided by Yakima County and cross section data points generated by Reclamation) and horizontally matching known landmarks such as highways and levees between 1969 and 2005 survey data sets. Several of the cross section alignments were not able to be matched well and are noted in the results.

Changes in area and mean cross sectional elevation were calculated for channel sections within the floodplain. For segments with levees, only the floodplain area within the levees was included in the analysis. Supporting data for the comparisons included notes on the 1969 cross section plots and aerial photography from 1966, 1968, 1971 and 2005. Changes in cross sectional area were calculated by subtracting the 2005 cross sectional area from the 1969 cross sectional area. Changes in mean elevation were calculated by subtracting 1969 mean elevations from 2005 mean elevations, and making every attempt to remove levee points along the floodplain margins. Changes in cross sectional area and mean cross sectional elevations are discussed in the following paragraphs.

Using the uncertainty of the 1969 and 2005 cross section data, a level of detection is determined for the comparison. It is assumed that the vertical adjustments performed by

Yakima County removed all systematic error so that only random error remains in the two data sets. Following this assumption, the standard deviation of each data set is evaluated as $\vartheta_c = \left(\vartheta_1{}^2 + \vartheta_2{}^2\right)^{0.5}$ (where ϑ_c is the composite uncertainty and ϑ_1 and ϑ_2 are the data sets being compared) to obtain the uncertainty associated with the comparison. This is the limit of the ability to detect change between the data sets (Lane et al., 2003). The standard deviation of the 2005 data set is ± 0.5 feet and the standard deviation of the 1969 survey is ± 0.84 feet, resulting in a composite uncertainty, or level of detection, of 0.98, or 1 foot.

Figure 27: 1969 cross section alignments overlaid on aerial photography (2005). These alignments were provided by Yakima County and used to determine 2005 elevations for comparison.

2.4.4.1 Changes in cross sectional data

Changes in cross sectional area between 1969 and 2005 show reaches of aggradation and degradation that can be defined along the length of the study reach (Figure 28). Three main areas of aggradation can be defined:

1. Triangular gravel pit to Terrace Heights Bridge (Segment 2)

2. Beech Street Pit to Old SR24 (portion of Segment 3a)

3. Edler Ponds to Union Gap vicinity (Segment 5a)

Geomorphic observations during the course of field work for this study show segments 2 and 5a as recently dynamic, with multiple channel shifts and filling during floods and prominent gravel splays in many locations on unvegetated bars. Segment 5a shows one cross section (216) where degradation is noted from 1969 to 2005, which is in the vicinity of the Edler Pond no. 3 that was captured in 2002. The pit capture and scour along the right bank near the pit has created a deep pool along the outer bend, increasing the channel depth. From Beech Street Pit to Old SR24, channel simplification has been observed historically and includes the construction of the levee along Beech Street pit, which cut off a channel meander in the western floodplain, the abandonment of secondary channels in the eastern floodplain, and aggradation and vegetation encroachment in the eastern floodplain. Cross sections with the largest change in area correspond to the locations of captured gravel pits. For example, cross section 236 is located at the triangular gravel pit in segment 2, cross section 230 is located at the Terrace Heights pit in segment 2, and cross section 215 is located at one of the captured pits in segment 5a.

Four areas of degradation can also be defined and are less extensive than the areas of aggradation (Figure 28). They include:

1. Naches River mouth to triangular gravel pit (Segment 1)

2. Terrace Heights Bridge to Beech Street Pit (portion of Segment 3a)

3. Old SR24 to Edler Ponds (portion of Segment 3b; Segment 4)

4. Union Gap vicinity to I-82 Bridge (Segment 5b)

With the exception of Segment 3b, these segments were described as stable sections, experiencing few lateral changes during the period of recent observations (2005 to 2009). This is probably the result of main channel incision, which has locked the channel location into a relatively fixed lateral position. In many cases, the lateral position of the channel is against levees and revetments.

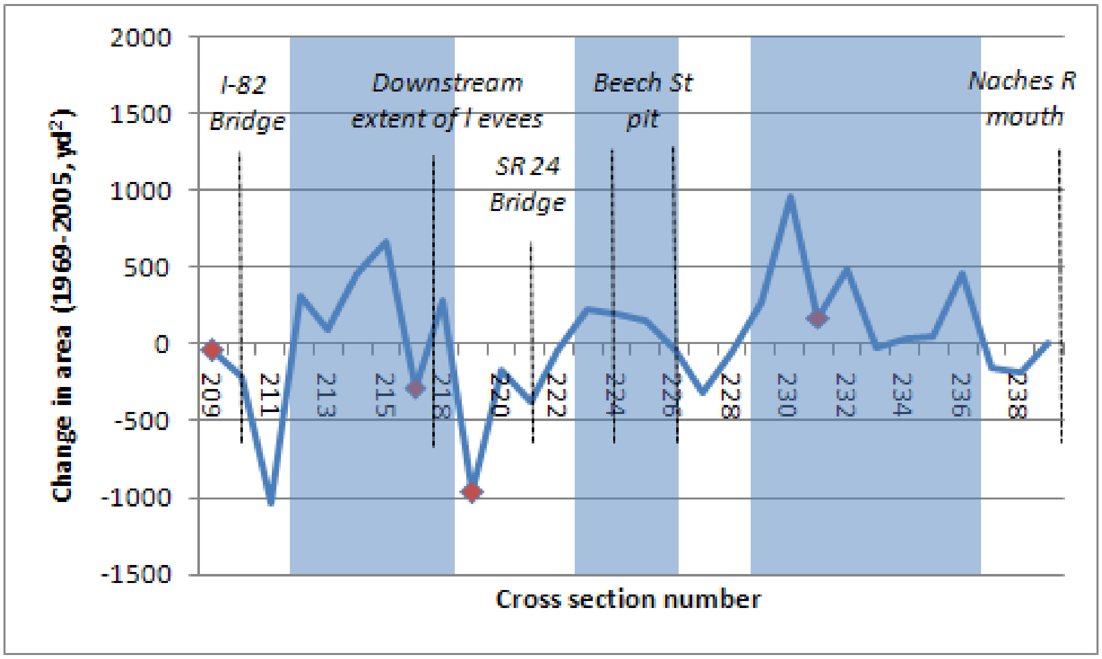

Figure 28: Changes in cross sectional area, 1969 to 2005. Refer to Figure 27 for cross section locations. Cross sections with red diamonds are those whose alignments did not match well between the two data sets.

Changes in mean cross sectional elevation from 1969 to 2005 follow trends in cross sectional area, such that in areas where the cross sectional area has decreased (indicating aggradation), bed elevations have increased (Figure 29). Several cross sections are listed specifically that show the greatest magnitude of aggradation or degradation (Table 3). These points are isolated to individual cross sections with the exception of cross sections 229 to 232, located between the railroad bridge and the Terrace Heights gravel pit. Net changes in Table 3 mostly vary between 2.4 and 3.9 ft, with greater changes at cross section 238 of 5.3 ft and 232 of 4.7 ft.

Table 3: Cross sections with greater than 2ft of mean cross sectional elevation change between 1969 and 2005 cross section surveys.

Cross section number	Location	Segment	Type of change	Net difference
238	Downstream of Naches River confluence	1	Degradation	-5.3
229-232	Railroad bridge to Terrace Heights pit	3a	Aggradation	2.4, 4.4, 2.6, 4.7
227	Upstream of Beech Street pit	3a	Degradation	-3.9
225	Beech Street pit	3a	Degradation	-3.2
214	Near City of Union Gap	5a	Aggradation	3.3
209	Union Gap	5b	Degradation	-3.0

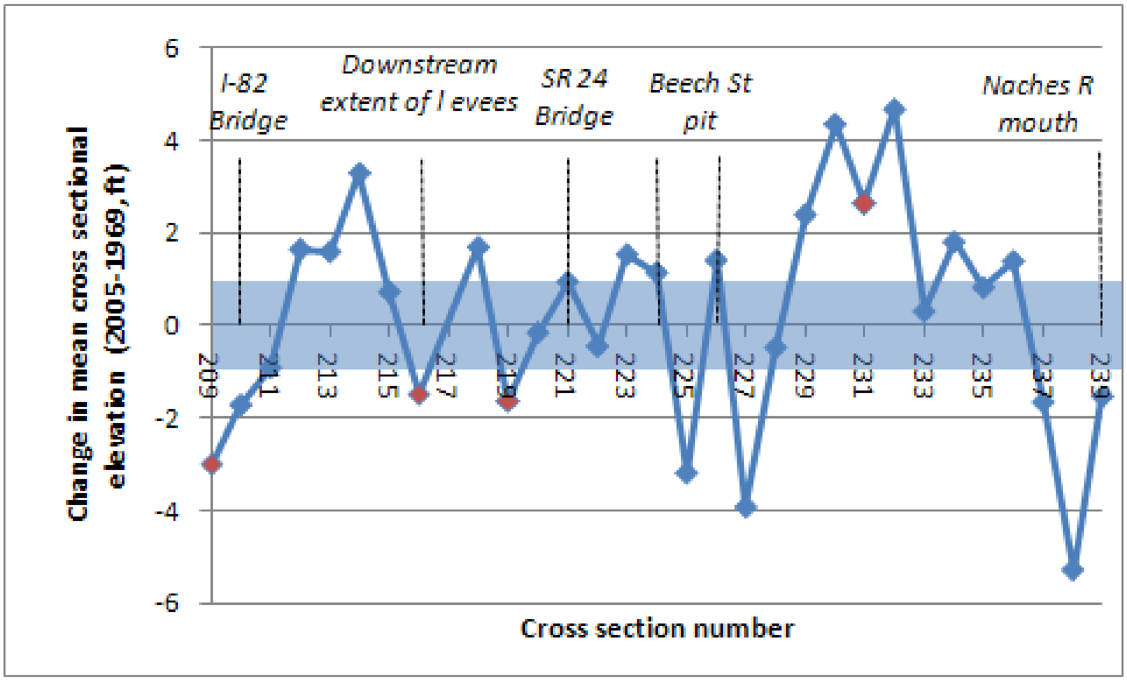

Figure 29: Changes in mean cross sectional elevation, 1969 to 2005. Positive values indicate aggradation, while negative values indicate degradation. The level of detection is shown as a blue shaded band; red colored data points indicate cross sections whose 1969 and 2005 horizontal alignments did not match well. Error associated with each data point is ± 1 foot. Refer to Figure 27 for cross section locations.

Two cross sections in the study show notable reversed trends from 1969 to 2005 when compared to the changes in area. At cross section 225 at Beech Street pit, changes in area indicate aggradation while changes in mean cross sectional elevations indicate degradation. While the cross section shows that the main channel along the right bank channel has deepened on average, floodplain accretion, the filling of secondary channels along the left bank and bar building along the right bank levee are great enough to show net aggradation for the cross section (Figure 30). At cross section 221, located at SR24 bridge, area calculations show a degraded channel from 1969 to 2005 while mean cross sectional elevations show an aggraded channel. Channel degradation is shown in area changes in the floodplain area along the right bank, which was eroded between 1969 and 2005. These floodplain changes in area are greater than the area associated with the aggradation in the main channel. Mean cross sectional elevations, however, reflect the aggradation of the main channel, which had transformed from a predominantly single thread channel in 1969 to a split flow channel in 2005.

Figure 30: Cross section 225, showing changes between 1969 and 2005 near the Beech Street pit. Red polygons indicate areas of aggradation while blue polygons indicate areas of degradation/erosion.

Using changes in mean cross sectional elevations, the rate of aggradation at cross sections that show increased bed elevations over the period of 1969 to 2005 (35 years) ranges from 0.01 to 0.16 ft/year with an average of 0.06 ft/yr. Averaging the aggradation rates for each segment and including cross sections with degradation as well indicate that segments 1, 3a, 4, and 5b have net degradational rates while segments 2, 3b and 5a have net aggradational rates. The aggradational and degradational rates correspond well with geomorphic observations from 2005 to 2009, which indicate that aggradading reaches are dynamic with significant lateral channel change and degrading reaches are stable with very little lateral channel change. Two soil pits were also excavated in the floodplain at sites YAK3 and YAK4 in segment 5a near Blue Slough as part of the geomorphic mapping (see Appendix A); calibrated radiocarbon ages of sediments at depths of 1.31 ft (40 cm) range from 290-0 Cal yr B.P. at YAK3 and 260-30 Cal yr B.P. at YAK4. Using the maximum radiocarbon age at each soil pit, this results in a floodplain aggradation rate of 0.0045-0.0050 ft/year. Using a minimum age of 30 years for both pits, the floodplain aggradation rate is 0.044 ft/yr. This rate is site specific, but provides some additional floodplain aggradation rates in the area of the levee setback.

Table 4: Rates of aggradation and degradation by segment. Negative values indicate degradation while positive values indicate aggradation.

Segment	Aggradation/degradation rate (ft/yr)
1	-0.094
2	0.077
3a	-0.018
3b	0.013
4	-0.001
5a	0.032
5b	-0.079

Thalweg elevations were plotted for the 1954, 1969 and 2005 survey data sets (Figure 31). Historical thalweg elevations were provided by Yakima County, as were the locations and alignments of the 1969 USACE cross sections. The vertical datum for the 1954 cross sections were adjusted from NGVD 29 datum to NAVD 88. Due to a questionable vertical datum used in the 1969 cross section survey, it was necessary to correct elevations of the 1969 cross section data individually to match known hard-points in the current survey of NAVD 88. An explanation of this adjustment was provided by Yakima County and is shown in Appendix C. Comparison of the 1954 and 1969 data sets with the 2005 data set do not show a consistent trend in aggradation or degradation throughout the entire study reach, nor do they show aggradation only at the downstream

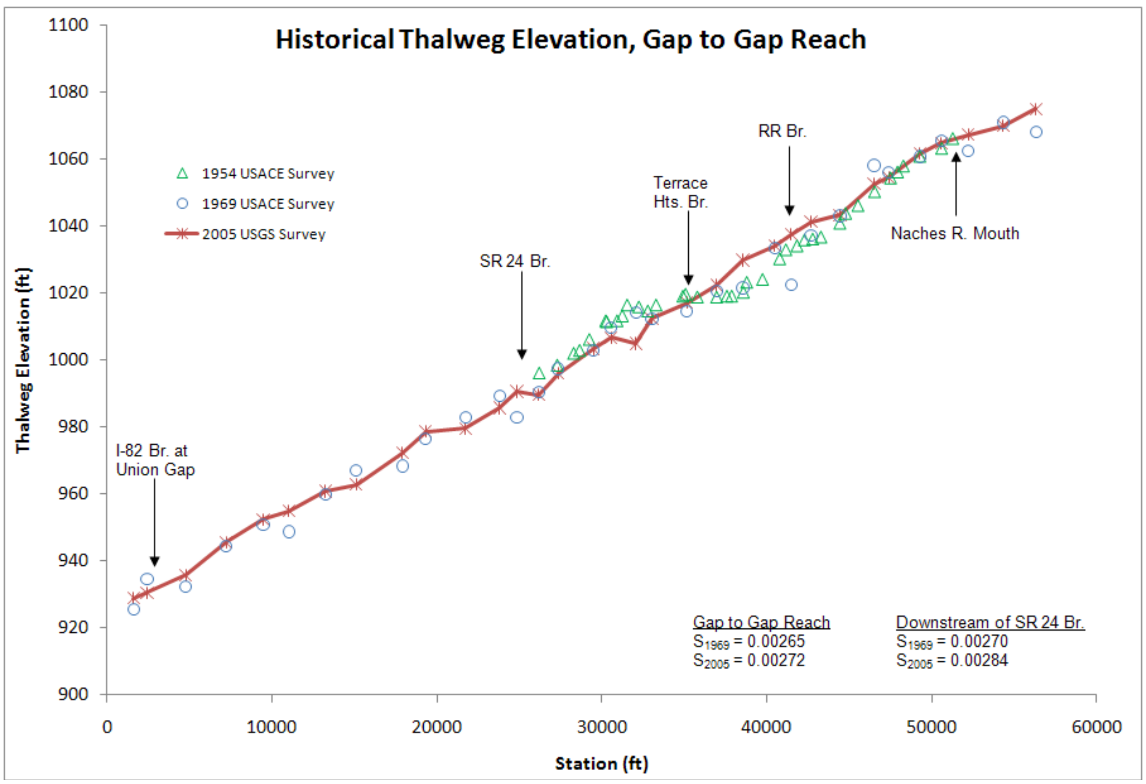

Figure 31: Comparison of thalweg elevations, 1954, 1969 and 2005 survey data.

end of the study reach, which could perhaps be attributed to Wapato Dam only. Rather, the data show flucutations in bed elevations through the reach that can be related to specific features and channel processes occurring in the Gap to Gap reach.

Patterns of aggradation and degradation can be observed using this plot and generally correspond with geomorphic observations of stable and dynamic reaches in Table 2. The geomorphic observations only involve observations of lateral change while the thalweg profile reflects vertical changes; however, these two types of channel change are linked in that reaches that have experienced degradation reveal less lateral channel migration and greater stability. Reaches that have experienced aggradation or a combination of aggradation and degradation are dynamic, exhibiting greater rates of lateral channel migration. An exception to this observation is Segment 4, in which observations between 2005 and 2009 show this reach to be laterally stable, while vertical changes show both aggradation and degradation from 1969 to 2005. Observations were not made in Reach 5b; however, it was considered laterally stable due to the constraints of Wapato Dam and Union Gap. Vertical measurements show this reach as vertically unstable, with incision at the I-82 bridge and aggradation downstream. Patterns in the thalweg elevations are also very similar to the patterns of aggradation and degradation using mean cross sectional elevations from the cross sections.

Greater fluctuations in channel bed differences are also noted for the leveed reach when compared to the reach downstream of the levees; variation in bed elevations within the leveed reach reaches a maximum of 24.4 ft while downstream of the leveed reach, the maximum variation is 10.5 ft. The locations of the greatest degradation are at points where the river encounters levees and revetments along the river, such as near the Beech Street pit and the city of Yakima sewage treatment plant. Areas of greatest aggradation also occur near infrastructure or breached gravel pits, such as the 15 ft difference in thalweg elevation near the Terrace Heights gravel pit.

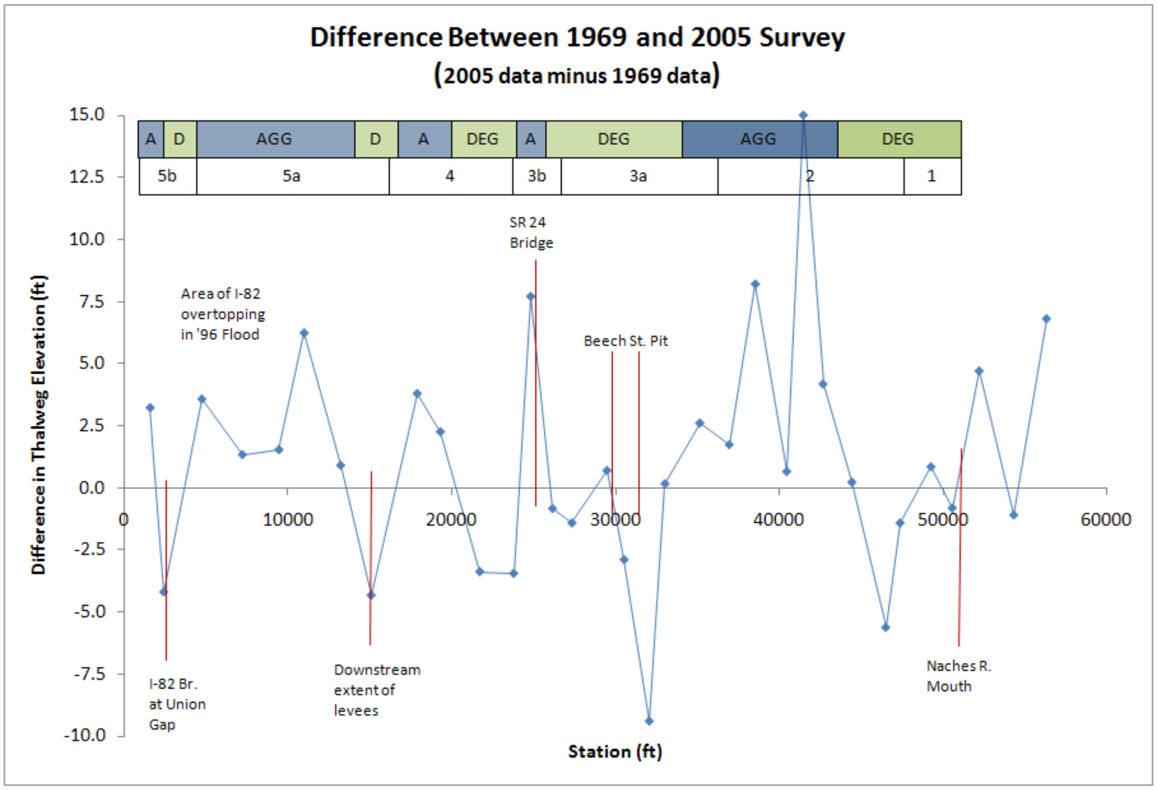

Figure 32: Difference plot using thalweg elevations (2005 data minus 1969 data). Approximate locations of aggradation and degradation are shown in green and blue boxes; approximate segment boundaries are shown below the aggradation/degradation boxes.

2.4.5 Effect of extreme floods on channel morphology

The effects of extreme floods on channel morphology vary within and between river systems based on many factors including climate, hydrology, geology, topography, bank resistance, and vegetation. The largest floods on the Yakima River are able to exert significant changes in channel morphology including both lateral migration, channel avulsion, bed scour and bar formation and erosion. Several large floods in the 1970's, 1996 and 2009 on the Yakima River in the vicinity of Yakima, Washington can be used to observe changes in channel morphology as a result of extreme flooding.

Floods during the 1970's (1972, 1974 and possibly 1978) caused pronounced changes in segment 5a, the furthest downstream reach in the study area (see Figure 19). The changes were most likely initiated by a levee breach along a gravel pit in the western floodplain, which initiated sediment deposition into the gravel pit, headcutting upstream and diversion of the main channel into the western floodplain near I-82. 1979 aerial photography shows an almost complete filling and obliteration of the gravel pits. The previous main channel, located further to the east, was abandoned as the main channel although a small portion of flow was still conveyed down the previous channel network. This channel change was also documented by Dunne (1976), who states that the 1972 flood was responsible for the initial channel avulsion into the gravel pits. While not as significant, other channel changes can also be observed in the upstream study segments due to these floods. Changes include eastward lateral migration in segments 1, 3a, and 4, bar development at the head of a large island in segment 3a and on lateral bars in segment 4, and filling of a gravel pit along the right bank in segment 3b (see Figure 17). As a result of floods during the 1970's, geomorphic parameters generally show an increase in main channel sinuosity from 1966 to 1979, with the exception of segment 1, which shows a slight decrease in sinuosity and segment 5a, which shows a decrease in sinuosity as a result of the channel avulsion into the gravel pits. Most segments also increased in channel complexity, with the exception of segments 3a and 3b. The extent of active bars is noticeably larger in segment 5a due to the abandonment of the previous main channel, while most of the segments experienced small decreases (segment 2 being an exception).

The 1996 flood also exerted significant channel change in the Gap to Gap reach with most of the changes in segments 2 and 3b. In segment 2, bar deposition and lateral erosion upstream of the railroad bridge forced the channel into new positions; 1996 flood photography also shows the channel in these new locations during the flood (Figure 33).

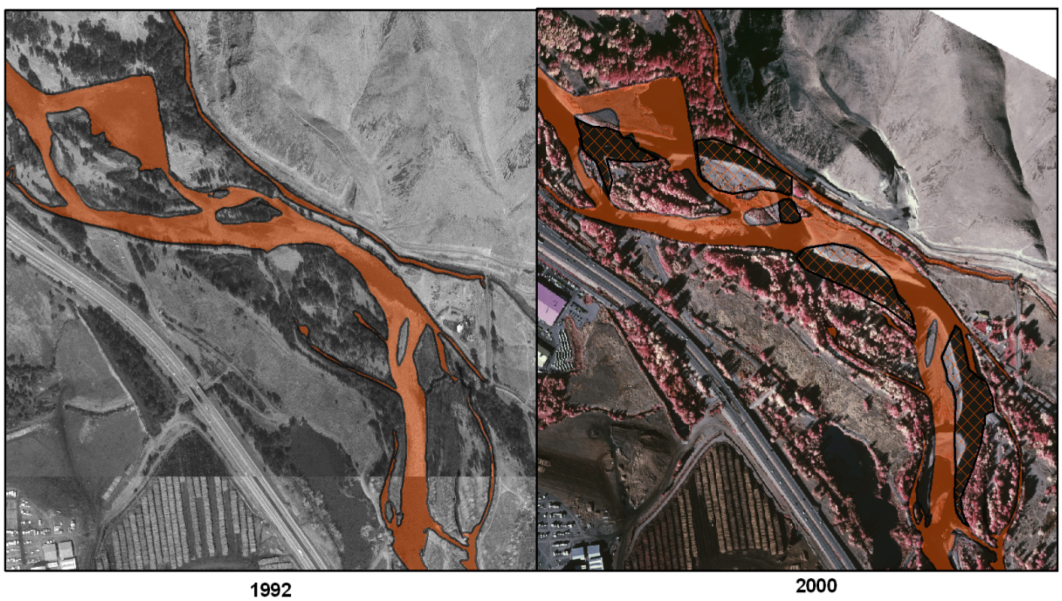

Figure 33: Effects of the 1996 flood in segment 2. 1992 channel is shown in orange; cross hatched polygons on 2000 aerial photograph show areas modified by the 1996 flood.

In segment 3b, a channel avulsion toward the west forced the main channel toward the right bank; the previous main channel still existed as a smaller secondary channel along the left (east) bank (Figure 34). Other channel changes were also observed between 1992 and 2000 in segments 4 and 5a; however, the 1996 flood photography does not show the new channel locations, so it is likely that these changes followed the flood in 1997, which was also a water year of high flows. For example, in segment 4, a shift in the main channel position downstream of Edler Ponds is apparent in 2000, but is not obvious in the 1996 photography. It is possible that deposition during the waning stages of the flood may have shifted the channel to this position or that these changes occurred in 1997. In segment 5a, comparisons between 1992 and 2000 photography show a channel avulsion toward the west near Edler Ponds and filling of the 1992 channel; this area is inundated during the 1996 flood, but does not show an avulsion. Similar channel avulsions exist in this segment that are apparent in 2000, but not in the 1996 flood photos. These changes likely occurred in 1997. Changes in geomorphic parameters, most likely as a result of the 1996 and 1997 flows, show an increase in active bar area from 1993 to 2000, and varied changes in channel complexity. Changes in main channel sinuosity are also varied, but show a large decrease in segment 3b as a result of the channel avulsion.

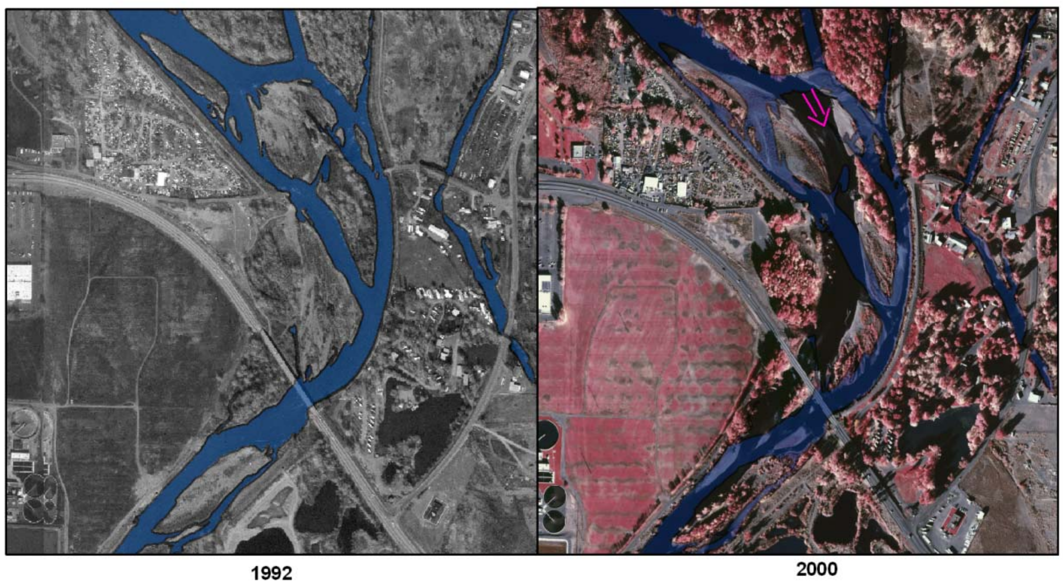

Figure 34: Effects of the 1996 flood in segment 3b. 1992 channel is shown in blue; pink arrow shows the avulsion path.

During the winter of 2009, a flood of 27,700 ft^3/s measured at the Ahtanum gage impacted the study area; field work prior to and following this flood allowed for observations of channel change as well as comparisons of 2008 and 2009 aerial photography. The largest changes were observed in segments 3b and 5a, while minor changes were observed in segments 1, 2, 3a and 4. In segment 3b, the main channel avulsed toward the east into the secondary channel along the outer bend, abandoning the previous main channel path (Figure 35). In segment 5a, point bar progradation combined with lateral migration caused the channel to laterally erode streambanks just downstream of the Edler Ponds area (see Figure 18). Several 2008 channel paths were also filled with sediment in segment 5a, forcing more flow into the western channel path against the highway. Computations of active bar areas showed increases from 2008 to 2009; other parameters were not measured for the 2009 data set.

Figure 35: Effects of the 2009 flood in segment 3b. Blue outline shows the 2008 channel; red crosshatched polygons show the areas filled in with sediment during the 2009 flood.

3 Hydraulic Modeling

The following sections provide detailed methodologies for data collection and modeling the hydraulics of the Gap to Gap reach of the Yakima River. A significant amount of data collection is required as well as determining specific variables and boundary conditions to construct the model. Where appropriate, specific details have been placed into an appendix. River locations throughout the following sections are referenced with the station number, determined by the location of cross sections. River stationing, measured in feet, beginning at the downstream boundary (Wapato Dam) and increasing in the upstream direction. Cross sections and river stationing are shown in Figure 36.

3.1 River bed Bathymetric Survey

River bed topography (bathymetry) is required input for the sediment model. Bathymetry for the study reach had been acquired during two separate surveys. Most of the study reach was surveyed in the summers of 2004 (USGS, Washington Water Science Center), and 2005 (USGS, Columbia River Research Laboratory) for other studies by Reclamation. However bathymetry at each end of the study reach, in Selah and Union Gaps and the mouth of the Naches River, was required for the current study. In 2008 these short portions were surveyed by the USGS, Washington Water Science Center. In addition to boat mounted SONAR, wading surveys were performed in portions of the channel margins and some side channels. These surveys were performed with Real Time Kinematic Global Positioning Satellite (RTK GPS) equipment. Details of the survey can be found in Mastin and Fosness (2009). The bathymetry survey, like all data used in this study, is projected in State Plane WA south, NAD83, NAVD88 with units in feet.

3.2 Projected Hydrologic Scenarios

Although a hydrologic analysis is not part of this study, it is necessary to be aware of the hydrology of the Yakima Basin and more specifically, hydrology for the Gap to Gap reach. Many publications discuss basin hydrology and therefore will not be repeated at length in this report (e.g. USACE, 1970; USACE, 1973, Vaccaro, 1986; Ring and Watson (1999), FEMA 1994; FEMA, 1995; Reclamation, 1998; Snyder and Stanford, 2001; Mastin and Vaccaro, 2002; Stanford et al., 2002; Yakima County, 2007).

Several gages, operated by the USGS and Reclamation, are relevant to this study. Table 5 lists the gages used for analysis in this report. All hydrologic scenarios run in the model use daily average historical gage data. Yakima River discharges were determined using the Yakima River at Umtanum and subtracting the Roza and Selah-Moxee diversions. This discharge is referred to as 'Yakima River at Selah Gap'. Naches River discharges were determined using the Naches River below the Tieton River gage data, adding WOPW, and subtracting CYDW, CIYW, SOUW, CODW (gage names are provided in Table 5). This discharge is referred to as the 'Naches River at the mouth'. In some instances it was necessary to create auxiliary data for diversion and return records during periods of missing data for the Naches diversions. This was accomplished by examining diversions values during previous and following years of the missing data. In many cases the diversions of the previous and following years were used to create an average of the two years to complete the record. The discharge record described was verified with gages in the Gap to Gap reach where possible. For example, combined Naches River at the mouth and Yakima River at Selah Gap discharges were compared to gage data at Yakima River at Terrace Heights and Yakima River above Ahtanum Creek. Satisfactory agreement was achieved with the calculated discharges.

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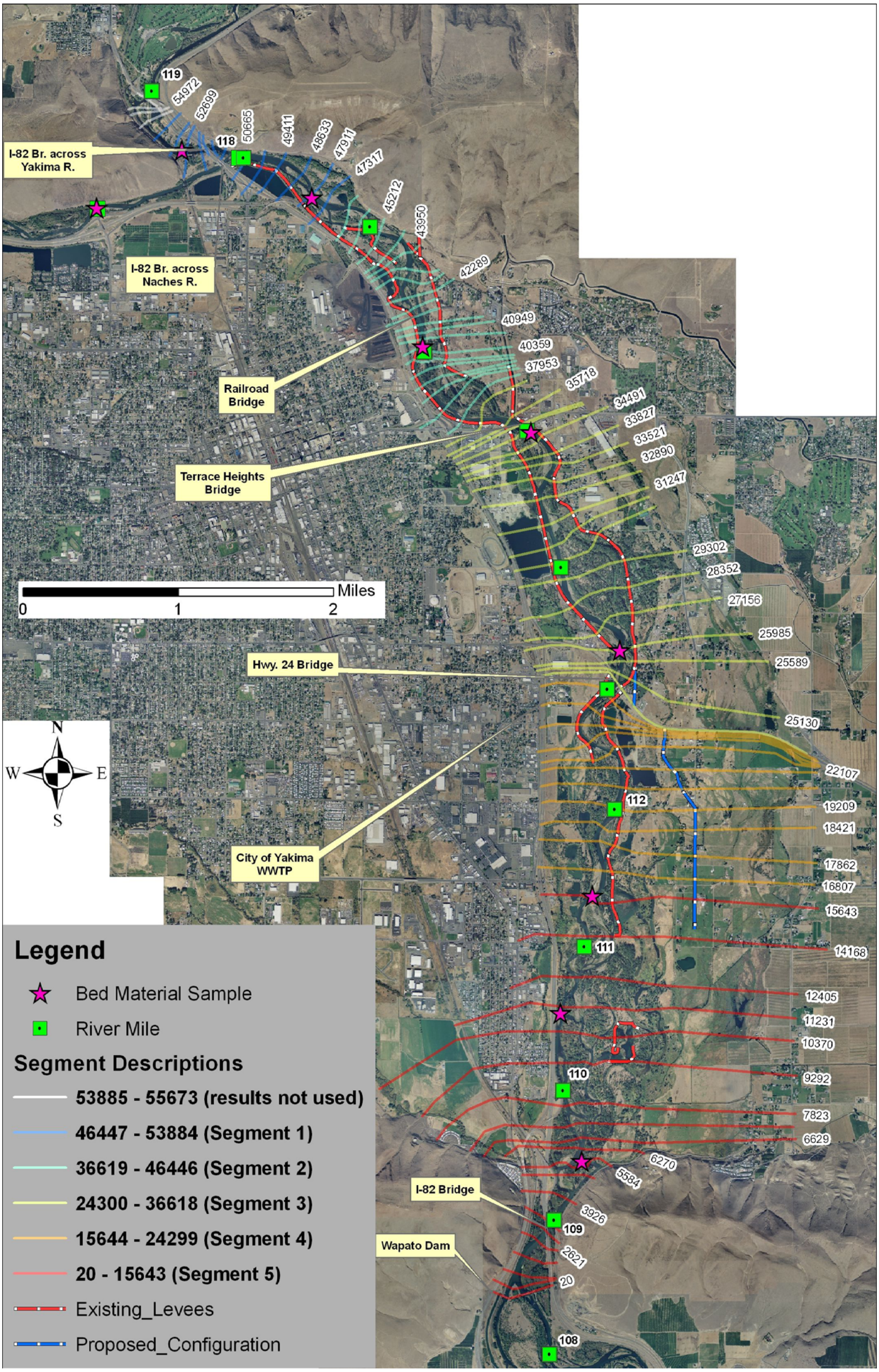

Figure 36: Gap to Gap reach of the Yakima River showing the location of bed material samples, river miles, existing and proposed levee configuration, and cross sections used in the 1-D model. The color coded segments indicate the segments discussed in chapter 2.2 The proposed configuration includes the removal of the Boise-Cascade levee (right bank in the vicinity of River Station 45212) and the setback of DID Levee #1 (left bank downstream of SR 24 Bridge).

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Table 5: Table of stream gages used in this study.

Gage Name	Gage Identifier[1]	Period of Record	
		Begin Date	End Date
Yakima R. abv. Ahtanum Cr.	12500450	10/01/1966	current
Yakima R. at Parker	12505000/PARW	04/25/1908	current
Yakima R. at Union Gap	12503000	10/01/1898 05/18/1963	09/30/1914 09/30/1966[2]
Naches R. blw. Tieton R.	12494000/NACW	10/01/1908	current[3]
Naches R. nr. North Yakima[3]	12499000/NRYW	01/01/1899 09/30/1981	03/31/1915 current[2]
Yakima R. at Umtanum[4]	12484500	10/01/1908	current
Yakima R. at Terrace Hts. Br.	YRTW	4/19/1932 10/01/1981	09/30/1936 07/10/2000
Congdon Canal (Naches R.)	CODW	10/01/1909	current
Cowiche Creek (Naches R.)	CGWW	09/30/1910 10/01/1959	09/30/1915 current[2]
Gleed Diversion (Naches R.)	CYDW	10/01/1954	current[2]
City of Yakima Irrigation (Naches R)	CIYW	10/01/1910 10/01/1965	09/30/1915 current[2]
Selah Moxee Canal (Yakima R)	SEXW	10/01/1910	current
Wapatox Power Canal (Naches R.)	WOPW	04/01/1911	current
Roza Canal at Headworks (Yakima R.)	RZCW	10/01/1940	current
South Naches Channel Canal Company	SOUW	10/01/1976	current

1 –USGS gages indicated by gage number, Reclamation gages indicated by 4 letter identifier. Those gages that were taken over by Reclamation indicate both identifiers.
2 – Significant periods of missing data exist within the indicated period of record
3 – Reclamation in Yakima indicates that data from this gage are unreliable during the period that Reclamation has operated the gage
4 – From 1915 – 1930 discharge during non-irrigation periods is not recorded

Examination of instantaneous peak discharge versus daily average discharge indicated that it was not necessary to shape some of the flood peaks in the daily average on a scale less than 24 hours. A vast majority of the peak values were less than 10% greater than the recorded daily average discharge. This is well within the measurement error and will not affect calculations of sediment transport.

3.2.1 Consideration of Global Climate Change

The changes in climate forecasted for the Yakima Basin indicate a decrease in snowmelt runoff (10% – 23%) assuming an increase in precipitation falling as rain with increasing temperatures (Mastin, 2008). With a reduction in snowmelt runoff, summer streamflows are expected to decrease, and with similar precipitation, winter streamflows are likely to increase. Projected changes in precipitation for the Pacific Northwest vary drastically across results of several global circulation models. Littell et al. (2009) indicate an increase in precipitation for the Pacific Northwest of + 1.3%, with a range of -9% to +12% for the decade of the 2020's. Mastin (2008) assumed no change in precipitation for future warming scenarios within the Yakima Basin. Based on these conclusions, it is difficult to confidently arrive at a near future scenario (25 years) with which to predict changes in sediment transport in the Gap to Gap reach. Figure 37 shows two probable monthly hydrographs, both agreeing that peak spring and summer snowmelt runoff will decrease and protracted high flows increase during the fall and winter months. Although these results are interesting, and likely have significance for ecology, their significance to sediment transport over the next 25 years is limited. The primary significance to sediment transport is the magnitude, duration, and frequency of flooding, which is not yet sufficiently addressed in global climate change scenarios for the basin.

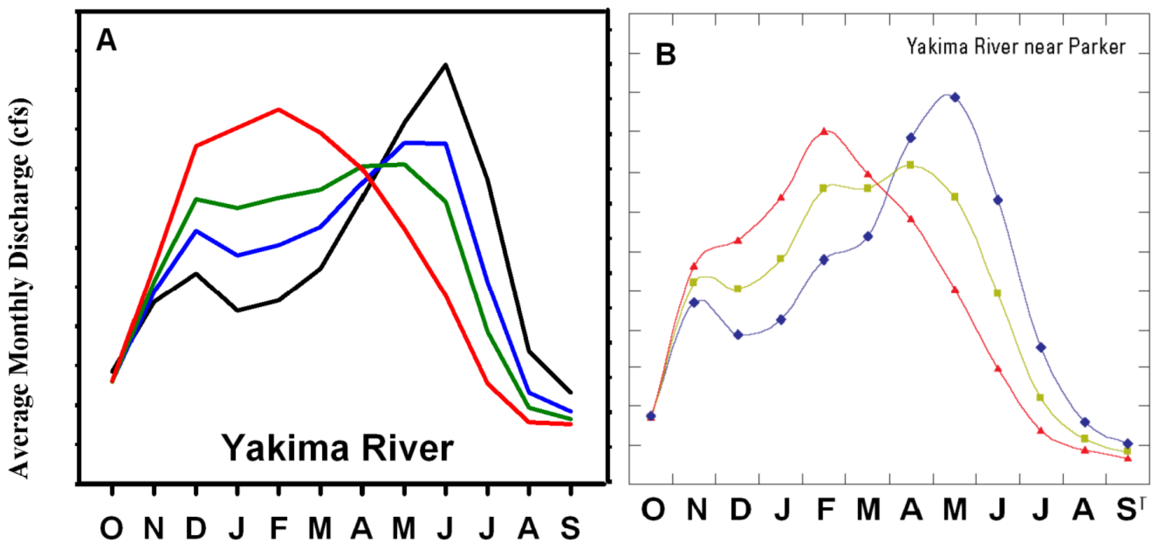

Figure 37: A – Historical (black) and projected hydrograph taken from Littell et al., (2009). Blue line = 2020's, Green line = 2040's, and red line = 2080's. B – Historical (Blue) and projected hydrograph taken from Mastin (2008). Green = an increase in average annual temperature in the Pacific Northwest by 1^{o} C, Red = an increase in average annual temperature in the Pacific Northwest by 2^{o} C.

3.2.2 Wet and Dry 25-Year Hydrographs

To put a bound on predicted sediment transport and channel evolution, probable extremes in basin hydrology were considered by evaluating wet and dry hydrologic scenarios over a 25-year period. An examination of the annual peak discharge record for the Yakima River at Umtanum and Parker, and the Naches River below the Tieton River revealed a decadal oscillation of wet and dry years. A plot of the 10-year running average of annual peaks is shown in Figure 38. This occurrence is not inconsistent with the Pacific Decadal Oscillation as reported by Hamlet and Lettenmaier (2000) and Mantua and Hare (2002), although the oscillation in the Yakima Basin appears to have a shorter period (10 – 20 years) than these authors report for warm and cool periods (20 – 40 years) across the greater Pacific Northwest region, driven by changes in ocean temperature. Nonetheless, the oscillation indicated within the basin is likely a better predictor of near future hydrology in the Yakima Basin than climate change scenarios generated by global circulation models, due to significant uncertainty in quantitative values, particularly for individual basins. Figure 38 is an example of data that were used to determine wet and dry years for the inflow hydrographs. For the purpose of sediment transport and changes in channel morphology, it is more appropriate to base wet and dry years on peak discharges, as opposed to cumulative annual volume, as may be considered for water supply.

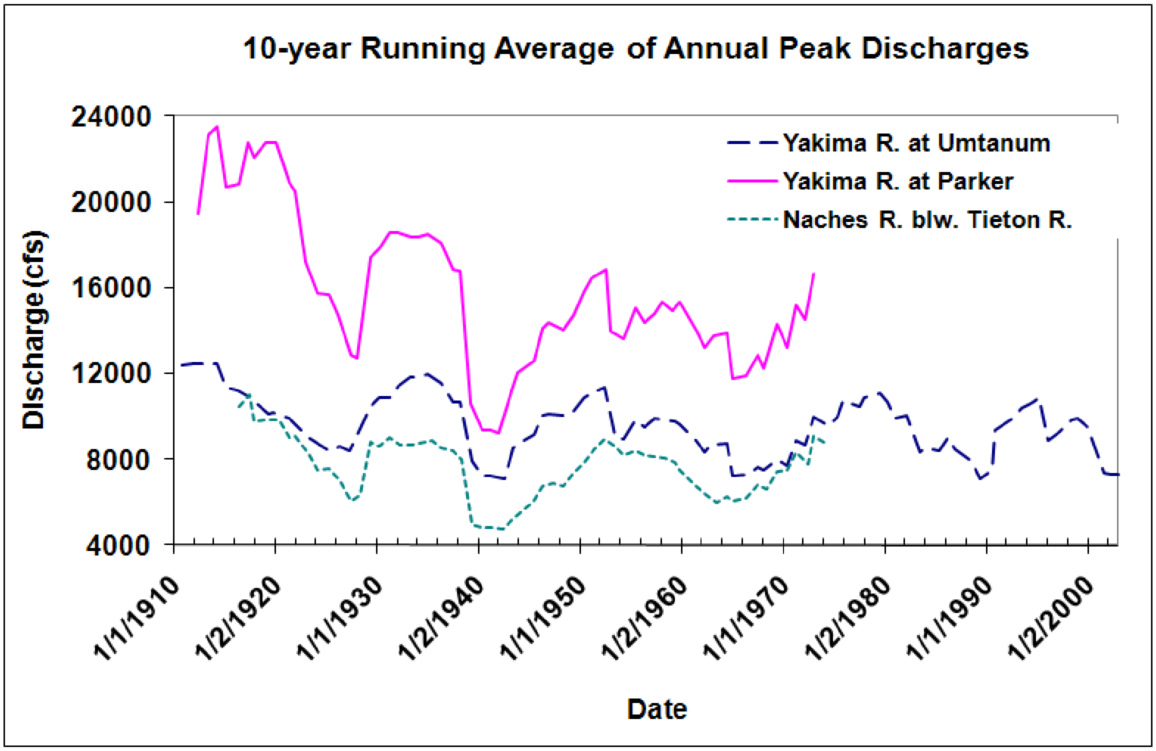

Figure 38: Plot of 10-year running average annual peak discharges from three gages near the Gap to Gap reach.

The above analysis resulted in following water years for wet and dry period hydrographs: Wet Hydrograph; 1909 – 1912, 1931 – 1938, 1945 – 1952, 1974 – 1982; Dry Hydrograph; 1960 – 1972, 1982 – 1990, 1999 – 2004 (Figure 39). These years were linked together to create two 25-year hydrographs.

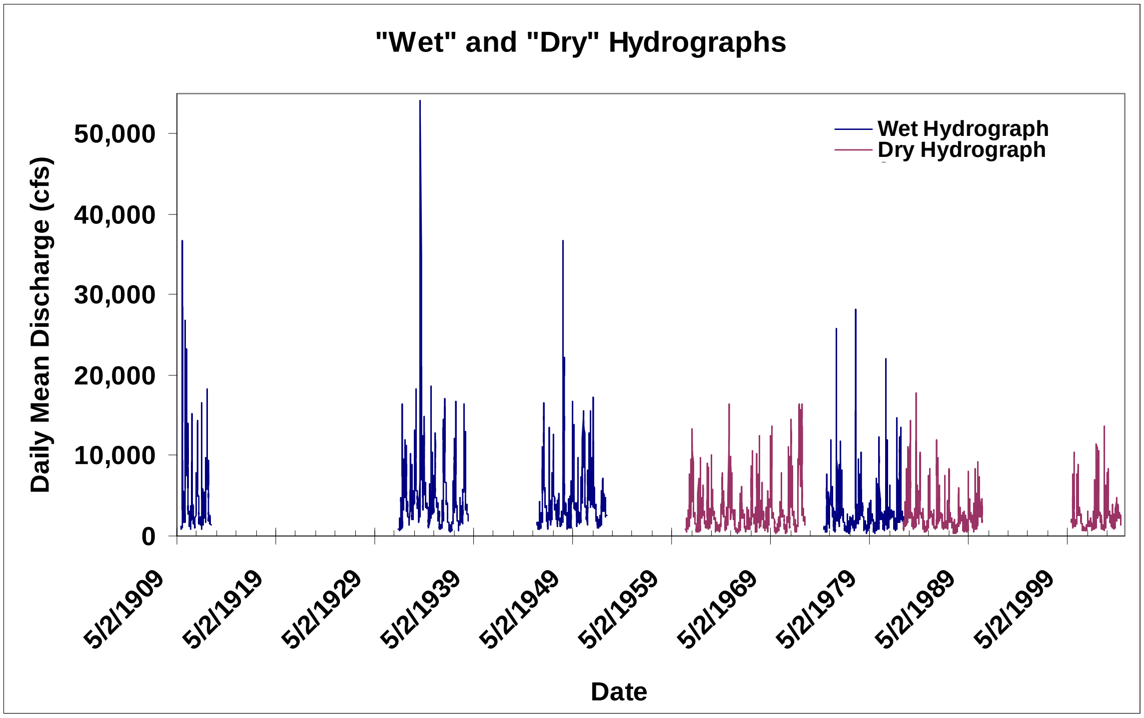

Figure 39: Wet and dry hydrographs for the Gap to Gap reach. Discharges shown were obtained by adding the Yakima River at Selah Gap to the Naches River at the mouth.

3.2.3 Average 25-Year Hydrograph

The intent of the average hydrograph is to project the most probable future hydrology for evaluation of sediment transport. The previous 25 water years, 1985 – 2009, were chosen to represent the most probable future hydrology (Figure 40). Two other consecutive 25 year periods were evaluated for sediment transport. Water years 1960 – 1984 produced very similar values for sediment transport. Water years 1935 – 1959 produced an increase in sediment transport over the 2 more recent 25-year periods, however this period is not likely representative of the future 25-year period, due to changes in climate, precipitation, and perhaps most significantly reservoir operations.

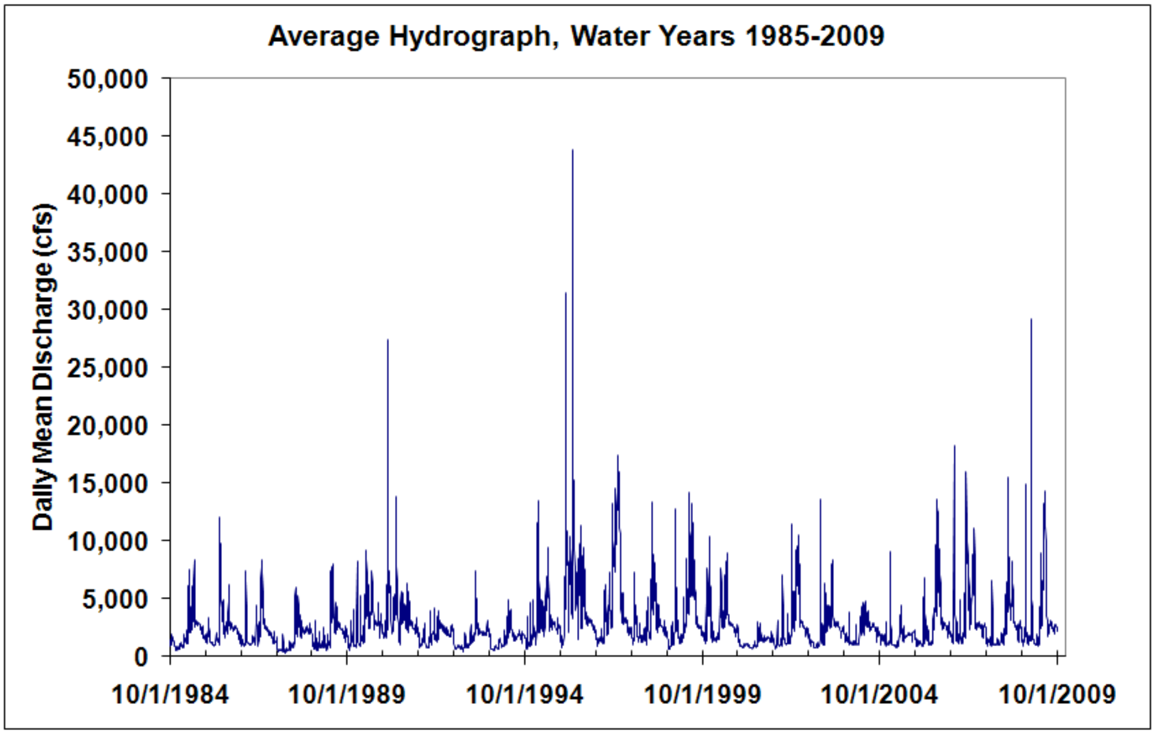

Figure 40: "Average" hydrograph for evaluating future scenarios (Water Years 1985 – 2009).

3.3 Event-Based Hydrology

In addition to future forecasts of hydrology to evaluate sediment transport, evaluating individual events can reveal how floods impact the transport of sediment and changes in channel morphology. A review of the historical flow record indicates that there are four distinct flood types that are worth considering. Although the historical record is being used to model discharges corresponding to specific floods, the results are not a representation of what may have occurred on those specific dates. This is primarily due to dissimilar channel form, the presence or absence of vegetation, changes in land use, and levee configurations compared to the 2005 conditions used for modeling in this study. The discharges used to generate the flood hydrographs used in the sediment model were obtained using the calculated discharges for the Yakima River at Selah Gap and Naches River at the mouth values described in Chapter 3.2.

Four distinct flood events in the record occurred in 1933, 1972, 1974, and 1996. The 1933 flood is the peak of record with respect to the Yakima River at Umtanum, Yakima River below Ahtanum Creek, and Naches River below Tieton River gages. The Parker gage indicates that the peak of record occurred in February of 1996. Regardless of which flood is considered the peak of record, the 1933 flood has the unique characteristic of a very large peak and an extended duration (73 days) compared to other historical floods in the record. For this reason, this hydrograph was evaluated for its effects on sediment transport and is referenced as 'Flood A' (Figure 41). Calculated discharges in the hydrograph indicate a daily average peak of 54,000 ft^3/s. Gage readings from Yakima

River at Parker and Yakima River at Terrace Heights indicate daily average discharges of 49,000 ft^3/s and 46,800 ft^3/s, respectively, on the peak day of the flood.

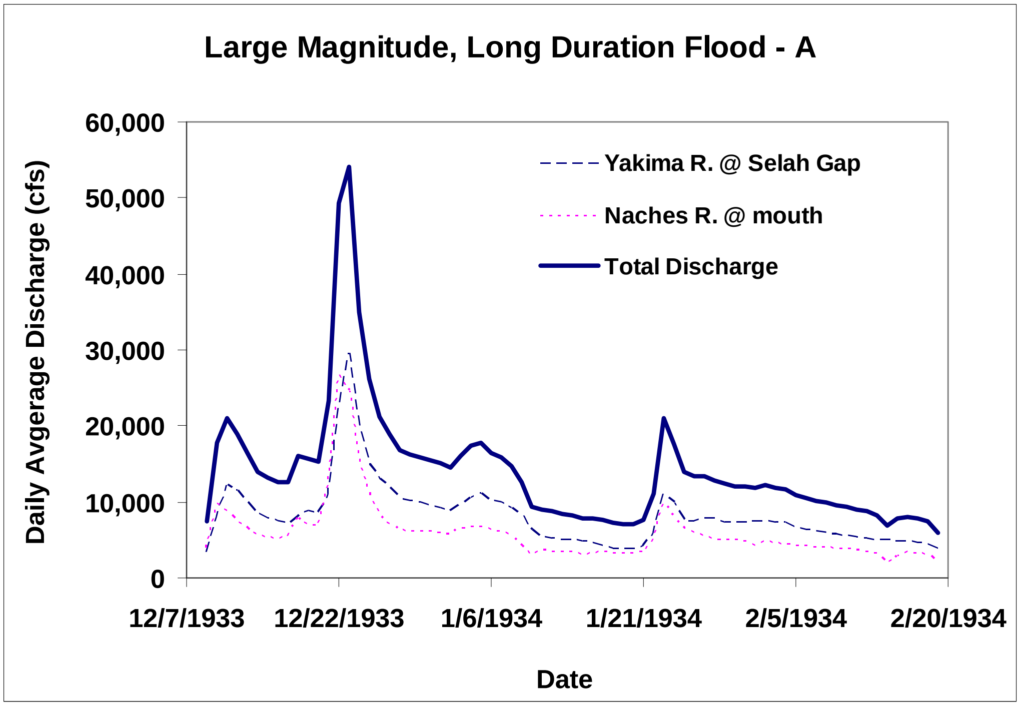

Figure 41: High magnitude, long duration Flood A. Total discharge was obtained by adding Yakima River at Selah Gap and the Naches River at the mouth.

The 1972 flood was a protracted, low peak event that began at the end of February and continued through most of June (122 days). Calculated hydrology indicates the peak discharge during this event was approximately 16,400 ft^3/s, however there were several lesser peaks greater than 14,000 ft^3/s. This event is referenced as 'Flood B' and the hydrograph is shown in Figure 42.

Another distinct flood occurred in 1974, when the discharge in the Naches River was significantly greater than that in the Yakima River at its peak. This was found to occur only once in the historical record. The duration for this flood was 84 days. This hydrograph is referred as Naches Flood C and is shown in Figure 43.

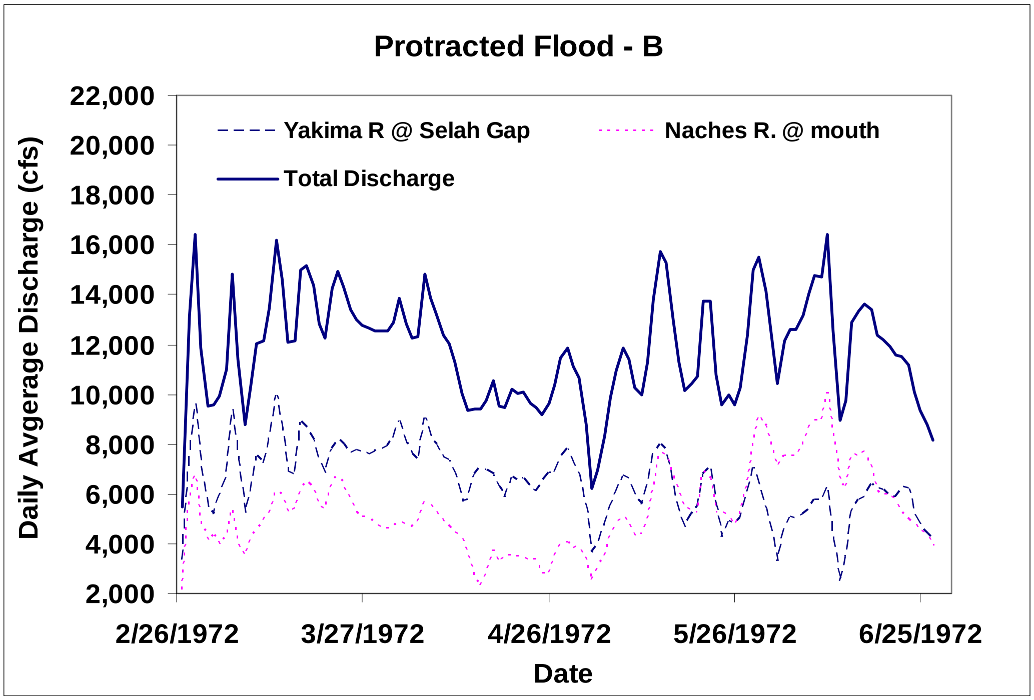

Figure 42: Protracted flood hydrograph for Flood B. Total discharge was obtained by adding the Yakima River at Selah Gap and the Naches River at the mouth.

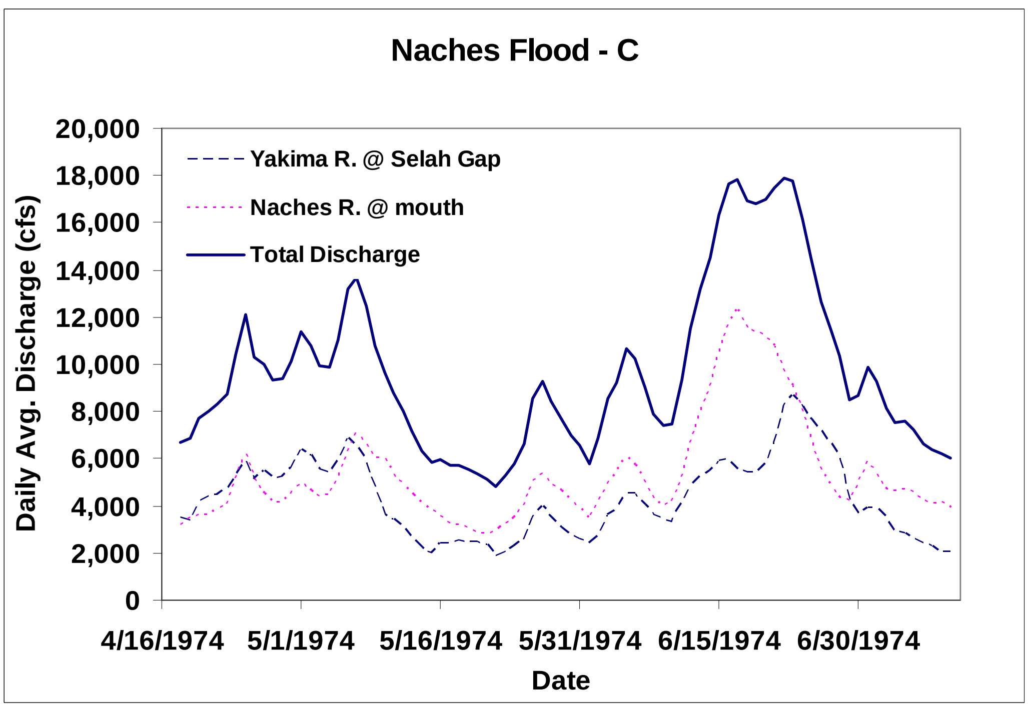

Figure 43: Naches flood hydrograph for Flood C. Total discharge was obtained by adding the Yakima River at Selah Gap and the Naches River at the mouth.

A historical flood of high magnitude and short duration occurred in 1996, and is referenced as Flood D. This hydrograph is shown in Figure 44 The daily average discharge indicated at the Yakima River above Ahtanum Creek gage (44,000 ft^3/s) is nearly identical to the calculated discharge (43,900 ft^3/s). The Yakima River at Parker gage indicates a daily average peak 54,000 ft^3/s daily for the same day. The duration of this flood was 30 days.

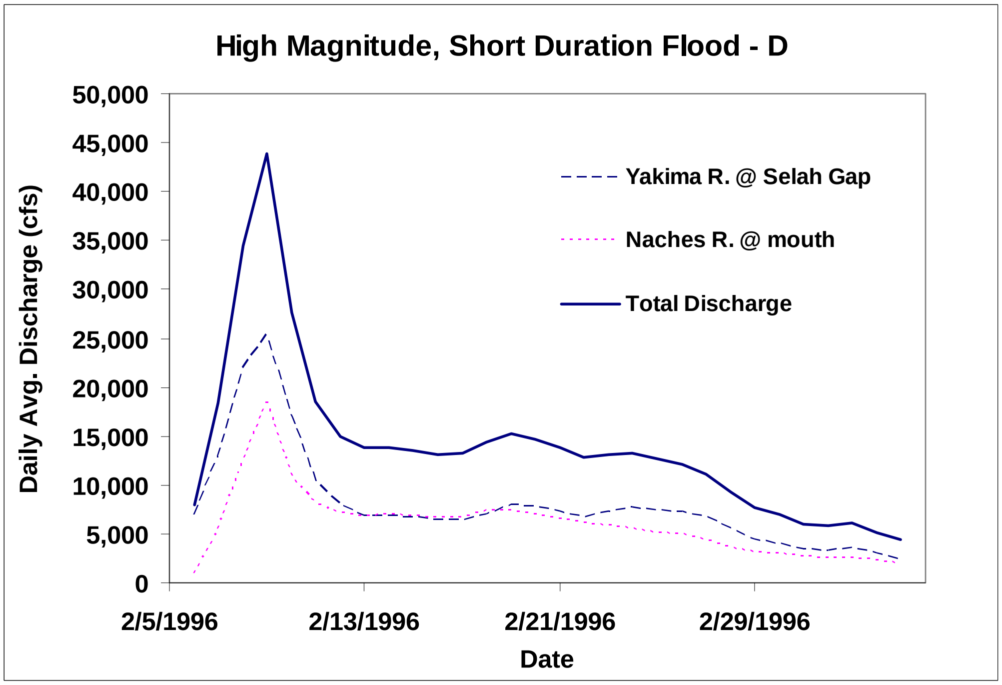

Figure 44: High magnitude, short duration flood D. Total discharge was obtained by adding the Yakima River at Selah Gap and the Naches River at the mouth.

3.4 Construction of the HEC-RAS Model

The primary input to any hydraulic river model is geometry. This, more than any other parameter, determines the validity of the model results. The modeling surface from which the geometry was derived is a 5 ft. raster generated with Arc GIS (ESRI, 2008; ver. 9.3). Because the vast majority of the bathymetry was collected in 2004 and 2005, it was decided that LiDAR from 2005 would be used to represent the out of water portions of the floodplain and terrace. These data were provided by Yakima County, along with corresponding rectified aerial photography. The 2005 LiDAR data were not complete throughout the reach, making it necessary to supplement with LiDAR dated 2002. No portion of the missing 2005 LiDAR was in the active channel. Using the bathymetry and terrestrial LiDAR point data, a Triangulated Irregular Network (TIN) was constructed in Arc GIS, using the channel margins as break lines. A single point data set was created from the TIN and used to construct a raster with 5 ft. spacing, using an Inverse Distance Weighted interpolation scheme.

Upon completion of a satisfactory representation of the terrain within the reach to be modeled, HEC-GeoRAS was used to extract the cross section geometry for input to a HEC-RAS (Hydrologic Engineering Center, 2008) model. This effort resulted in 88 cross sections representing approximately 10 river miles (55,673 ft). The cross section layout can be seen in Figure 36.

A few of the cross sections required adjustment of the geometry for short portions of the channel that were not properly represented by the bathymetry survey. This was limited to areas in the vicinity of the bridges, where the RTK GPS survey was interrupted. Reasonable assumptions were made for the geometry in these portions of the channel based on the survey immediately upstream and downstream of the bridge and photographs taken during site visits at each of the bridges. Bridge piers were represented using the bed geometry, as pressure flow is not considered in the sediment model because modeled discharges do not contact the lower chord of the bridge. An example of the bridge geometry is shown in Figure 45. The width of the piers was estimated based on the photographs taken during data collection. Accounting for bridges in this manner is acceptable for the purpose of this sediment model, as no bridge scour computations are performed, and the primary effect of bridge piers in a 1D model is the loss of cross sectional area.

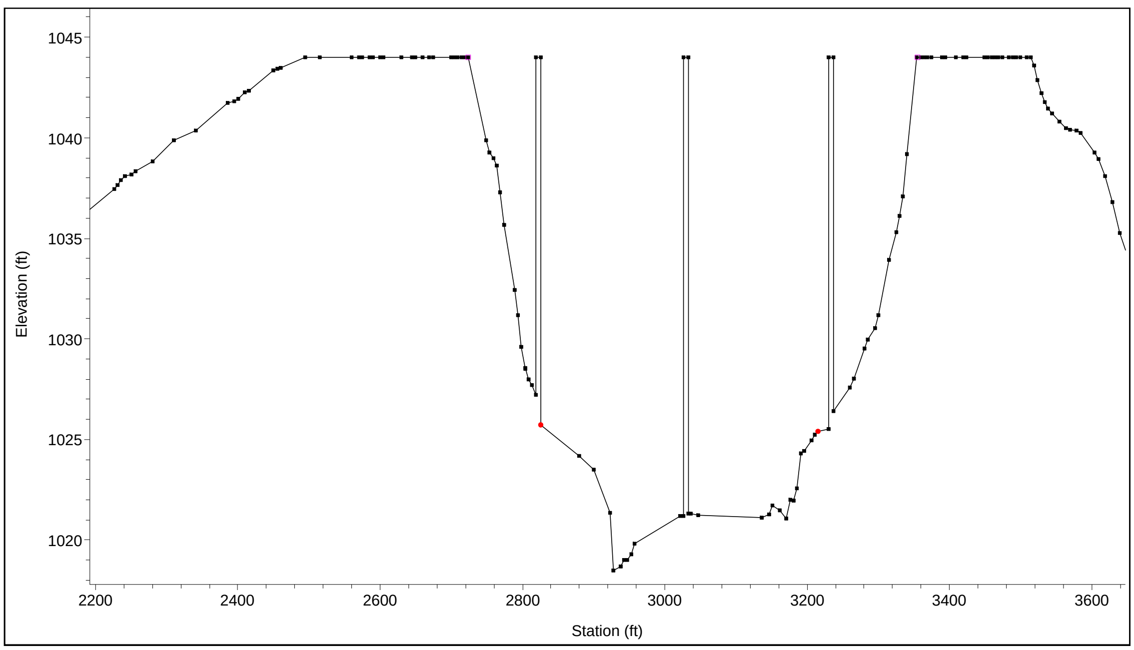

Figure 45: Example of bridge piers digitized into the bed geometry in HEC-RAS for the Terrace Heights Bridge.

Completing the HEC-RAS cross section geometry required refining the location of channel margins and levees, and digitizing the locations of blocked obstructions, and areas of ineffective flow. Roughness values (Manning's *n*) were obtained with HEC-GeoRAS using a series of polygons to represent various conditions in Arc GIS. The Manning's *n* values used in the model are shown in Table 6. In the location of gravel pits, ineffective flow was set at an elevation below the berm or levee surrounding the pit. Once flow overtops the berm, this conveyance was given a low roughness value over the pit, based on the stored water over which the flow is conveyed.

Table 6: Table of Manning's roughness values used in HEC-RAS and the sediment model.

Land Use/cover	Main Channel	Side Chanel	Dense Vegetation	Sparse Vegetation	Gravel Pit
Manning's n	0.037	0.04	0.075	0.045	0.02

3.4.1 Levee Locations

Levees were located at the highest elevation indicated by the geometry for existing conditions. For the proposed removal of the Boise-Cascade levee and setback of the levee in the vicinity and downstream of Hwy 24 (DID levee #1), levees were removed down to the elevation of the surrounding terrain. In the case of the setback levee, a new levee was placed at the same elevation as the existing levee, in an alignment shown in Figure 45 and Figure 46.

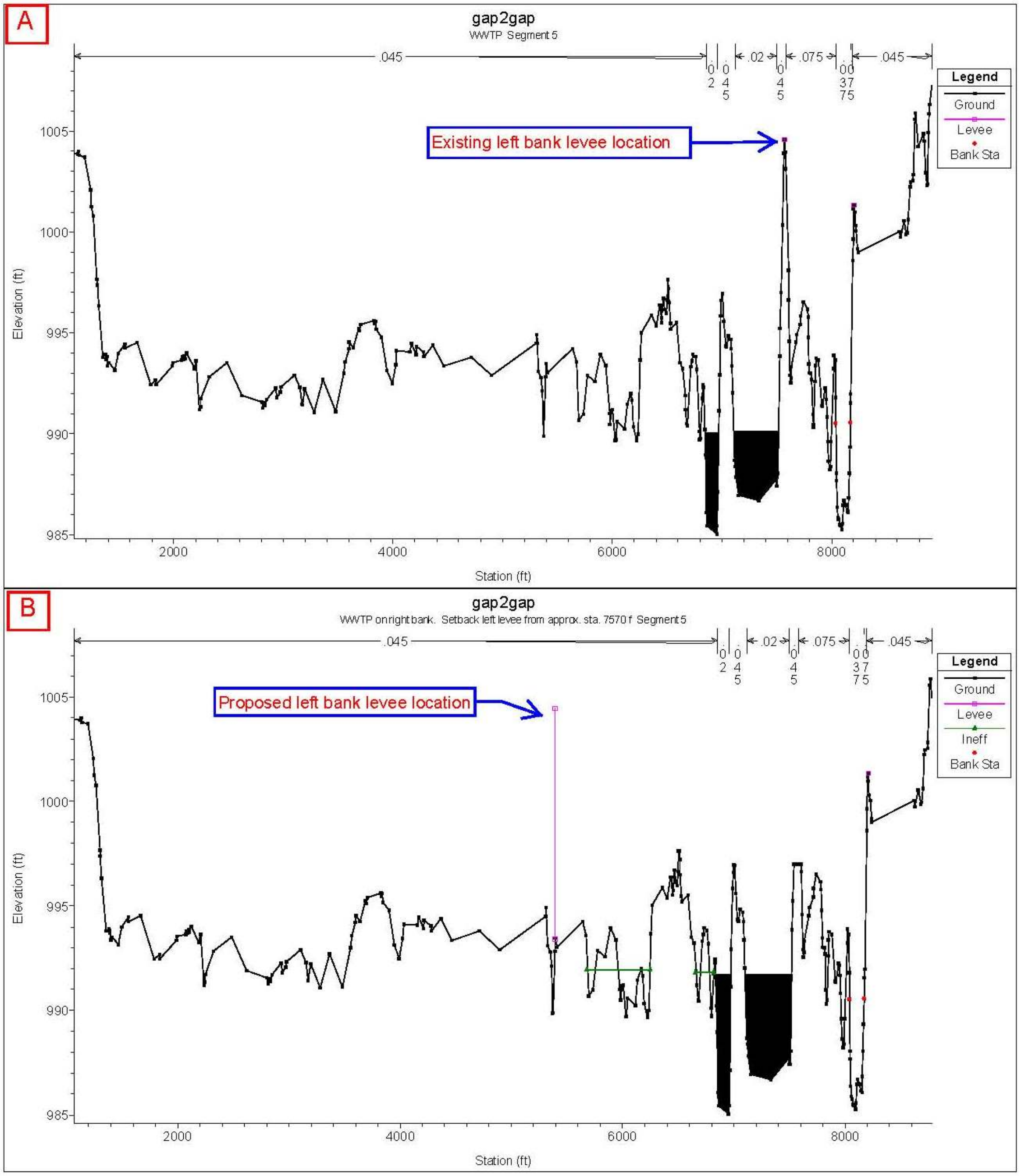

Figure 46: Example of before (A) and after (B) levee setback locations. Note the removal of existing levee down to existing ground elevation.

3.4.2 Model Calibration and Verification

The model was calibrated to water surface elevation measured during the bathymetric survey in 2004. The survey was conducted over 5 consecutive days. The daily average discharge during three consecutive days of the survey was 3,180, 3,240, and 3,220 ft^3/s (measured at USGS gage #12500450, Yakima R. abv. Ahtanum Cr.). The variation in discharge over these days is within measurement error and an average discharge of 3,213

ft^3/s was used in the model for comparison of water surface elevations measured on these three days. Figure 47 shows two plots of modeled and measured water surface elevations.

An initial guess for the main channel roughness was a Manning's *n* value of 0.036, based on a calibration at the Umtanum gage upstream of the site (USGS #12484500) published in Barnes (1967). Minimizing the mean error in modeled and measured water surface elevations resulted in a Manning's *n* value of 0.037 for the main channel. The resulting mean error between measured and modeled water surface elevation is - 0.2 ft, with a standard deviation of 0.6 ft. Figure 49 shows the frequency distribution for the calibration.

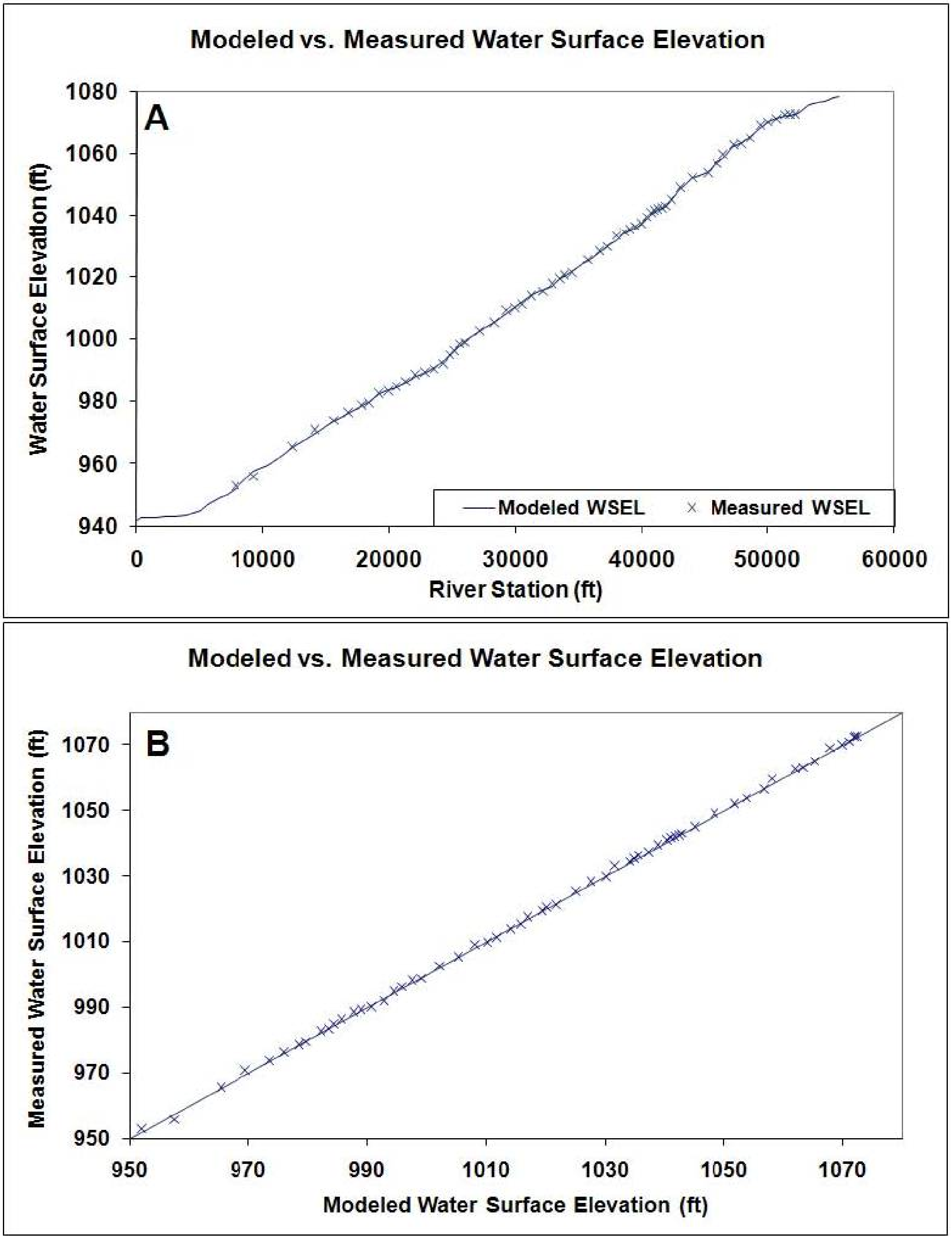

Figure 47: Comparison of modeled and measured water surface elevations. A-Profile of the reach, B-Modeled and measured water surface elevations with a line of perfect agreement.

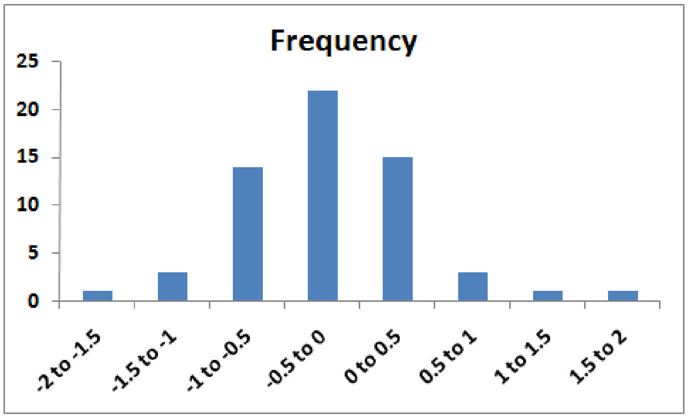

Figure 48: Histogram of model error when results are compared to measured data for the calibration. X-axis shows error bins, Y-axis shows frequency of occurrence.

A stage-discharge relationship at the Yakima R. above Ahtanum Creek gage (USGS #12500450) was used to verify the model calibration. Water surface elevations measured at the gage during the 2004 bathymetry survey were used to convert the published stage data to water surface elevation (Figure 49). This verification provided confidence in the overbank roughness values used in the model, as the largest discharge recorded at this gage was approximately 44,000 ft^3/s (Figure 49). Additionally, locations where modeled discharges overtopped the existing levees during the February 1996 flood were examined using the 1996 aerial photography that was flown during the flood but after the peak. Even though the aerial photographs were taken after the peak discharge, evidence of overtopping is visible through ponded water, an absence of snow cover, and newly formed channel splays in the floodplain. Good qualitative agreement was achieved with this verification.

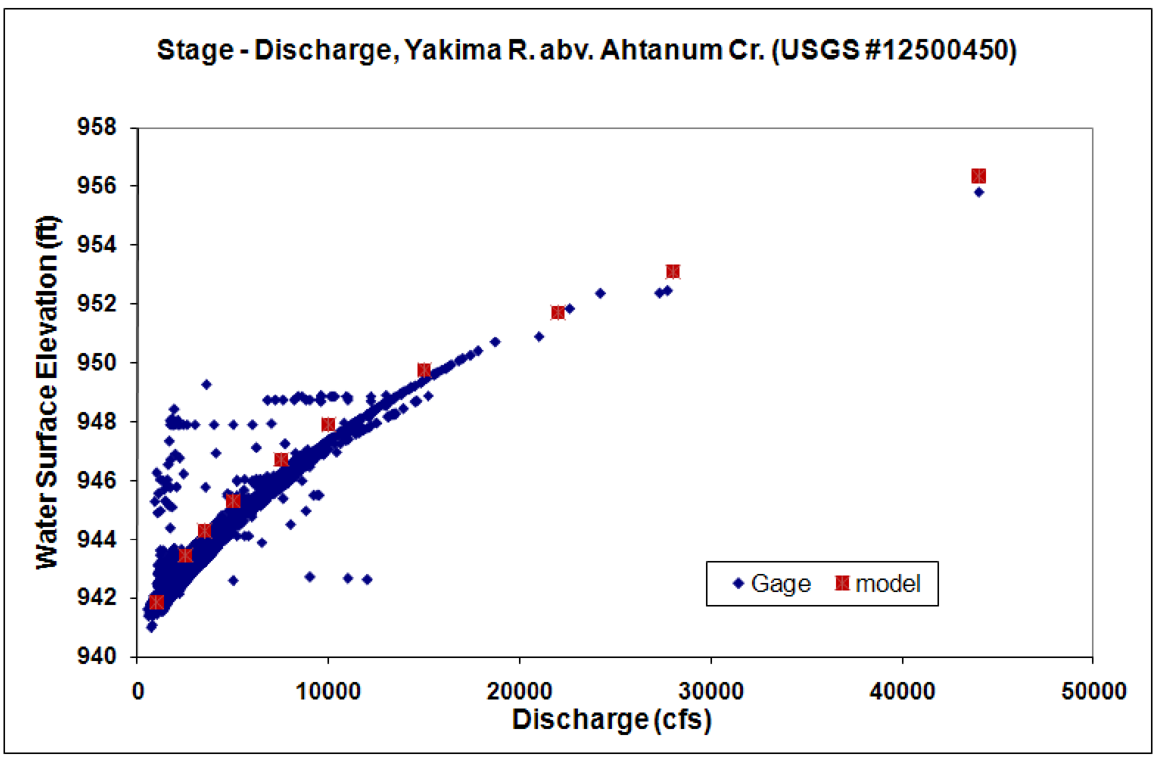

Figure 49: Plot of modeled water surface elevations versus stage recordings.

4 Hydraulic Modeling Results

4.1 Changes Considering Proposed Conditions

The discharge matching the daily peak of Flood D (44,000 ft^3/s, Chapter 3.3) was chosen to evaluate flood results from the hydraulic model. Discharge values were obtained from gage records adjusted for diversions and returns (Chapter 3.2). The initial geometry for the existing and proposed conditions are used for the results displayed, as is the geometry following a 25-year simulation. This will indicate an immediate benefit of the levee setback with respect to reductions of water surface elevation and channel velocities as well as anticipated conditions after 25 years. References to initial existing, initial proposed, final existing, and final proposed conditions indicate the channel geometry immediately following the initial (t=0) proposed changes to levee configurations (initial proposed) and channel geometry following evaluation of the average hydrograph in the sediment model for 25 years (t=25 years, final proposed).

Selected hydraulic properties are used to compare the effects of removing the Boise-Cascade levee and setting back the DID #1 levee in the vicinity and downstream of Hwy. 24. The most relevant hydraulic properties to examine are changes in water surface elevation and main channel velocity. Significant decreases in both these properties can be seen in Figure 50, comparing initial existing and initial proposed conditions. An increase in velocity is seen at the upstream ends of both proposed changes to levee configurations, slight at the Boise-Cascade levee and greater at SR 24. This is due to the loss of a backwater condition created under existing conditions. When the backwater no longer exists, velocities increase in the affected portion of the channel. Additionally, unit stream power is indicative of the energy dissipation within the stream flow. In this report unit stream power is the product of main channel velocity and friction slope (Yang, 1996) and is given per unit weight of water. Consistent with changes to main channel velocity in the vicinity of proposed levee configurations is a change in unit stream power. Figure 51 shows the unit stream power throughout the reach for existing and proposed conditions. Stream power is used in greater detail in Chapter 7.3.1 to evaluate channel energy throughout the study reach, assisting with predictions of future channel condition.

Considering the proposed setback of the DID #1 levee, the indicated decrease in velocity near the City of Yakima's Wastewater Treatment Plant will improve conditions along the right bank levee, that currently act to scour and undermine the riprap. As a result, the erosive forces acting to degrade this levee are expected to decrease. Model results also indicate a significant decrease in water surface elevation near the wastewater treatment plant, lessening the risk for overtopping the right bank levee. This persists through the 25-year simulation, indicating a net decrease in water surface elevations of approximately 3 feet considering the anticipated deposition.

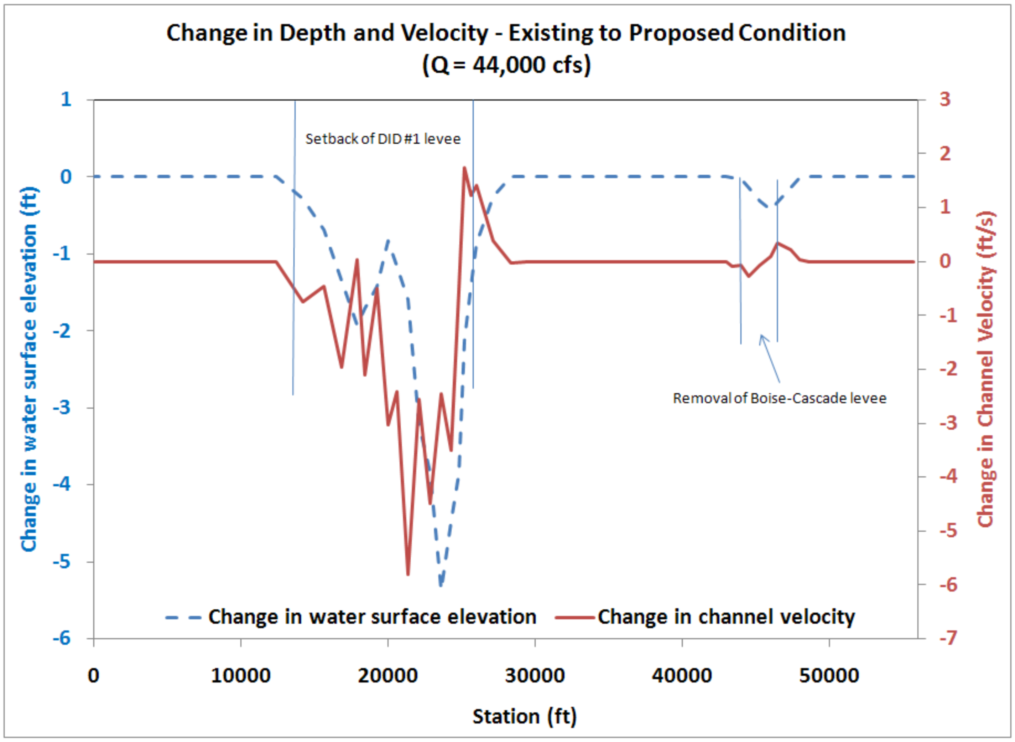

Figure 50: Graph of changes to water surface elevation and main channel velocity considering initial existing and initial proposed conditions.

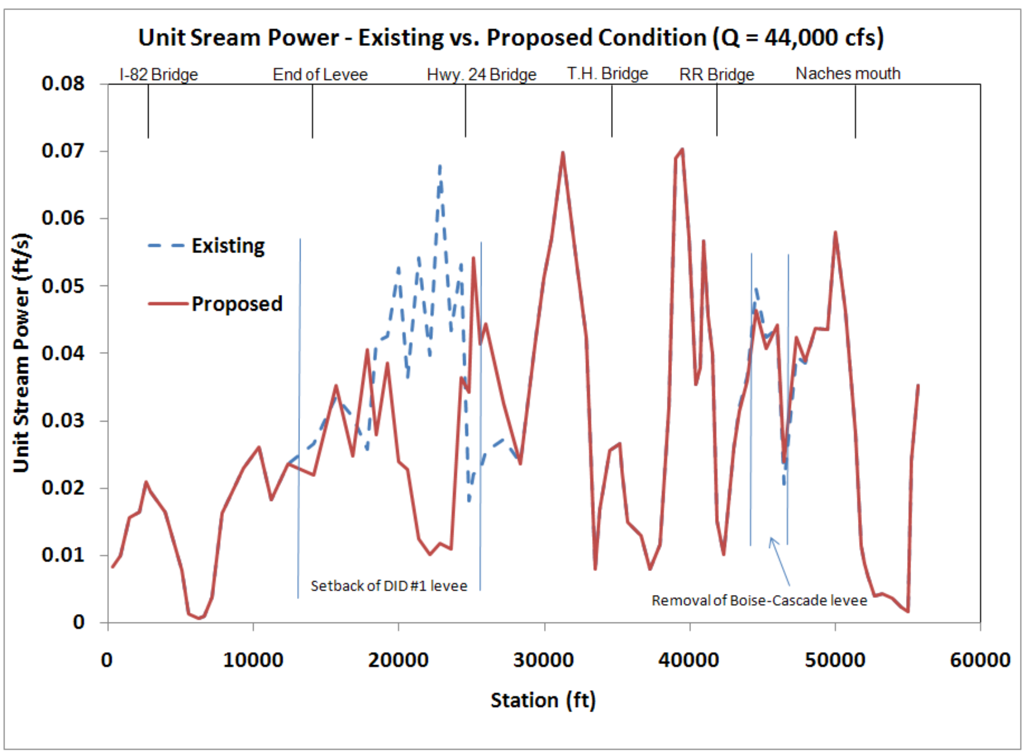

Figure 51: Graph of unit stream power (channel velocity – slope product) throughout the reach. Initial existing and initial proposed conditions are shown. (Stream power units are per unit weight of water, resulting in units of feet per second rather than units of power.)

4.2 Overtopping of Levees

4.2.1 Initial existing and Initial Proposed Conditions

The results of this section are based on the initial existing and the initial proposed conditions. Levees are overtopped under existing and initial proposed conditions in segments 2, 4, and 5. The discharge considered is the peak daily average of the February 1996 flood. These profile plots are shown in Appendix D.

In Segment 2, the Boise-Cascade levee was removed in the proposed conditions. Water surface elevations decrease slightly in this reach as a result of the levee removal (Figure 50), although the right bank levee is overtopped in both scenarios in the vicinity of Stations 43370 through 42997 (Figure 36), which is the levee separating the gravel pit from the river channel. Additionally, the left bank levee is overtopped in both scenarios at Station 38573 (Figure 36). In both existing and initial proposed scenarios the left levee is nearly overtopped at stations 39950 through 409849, with the least amount of freeboard at station 40359. In the existing conditions, the levee point in the model is located at the top of the Boise Cascade levee (stations 46446 through 43950). In the proposed conditions with the Boise Cascade levee removed, the levee top is located at the greenway trail, which is higher than the Boise Cascade levee. This is visible in the plots in Appendix D.

In Segment 4, the right bank levee is overtopped under existing conditions in the vicinity of SR 24 and the City of Yakima Wastewater Treatment Plant (Stations 21331 – 24299, Figure 36). The left bank levee is overtopped in one location, Station 22852. The 2005 LiDAR indicates that the levee in this location is approximately 3 feet lower than at the upstream and downstream locations and overtops in the model as a result. Under the initial proposed scenario, model results indicate that no levees are overtopped in this segment, as water surface elevations are significantly decreased and the existing dip in the levee was not incorporated in the proposed levee height.

Segment 5 shows no change in predicted velocities or water surface elevations (Figure 50), indicating that some inundation of Interstate 82 (station 6629) and Thorp Road (stations 3926 and 5584) will likely exist under existing and proposed conditions.

4.2.2 Final Proposed Conditions

The analysis in this section considers the water surface elevations following the 25-year simulation in the sediment model. No levees are overtopped in segments 1 and 3, similar to the existing and initial proposed conditions. Water surface elevations were obtained in HEC-RAS and are compared by segment in Figure 52 through Figure 56. The final proposed condition uses the geometry (with levee setback) of the SRH-1D model after a 25-year simulation of the average hydrograph. Detailed HEC-RAS profiles for all three conditions, plotted by segment, are shown in Appendix D.

Segment 1 (Figure 52) indicates no change from existing to proposed conditions, however water surface elevations decrease in the upstream half by as much as 1.5 feet. At station 50022 (approximately 1,000 feet downstream of the Naches River mouth) water surface elevations begin to increase following the 25-year simulation.

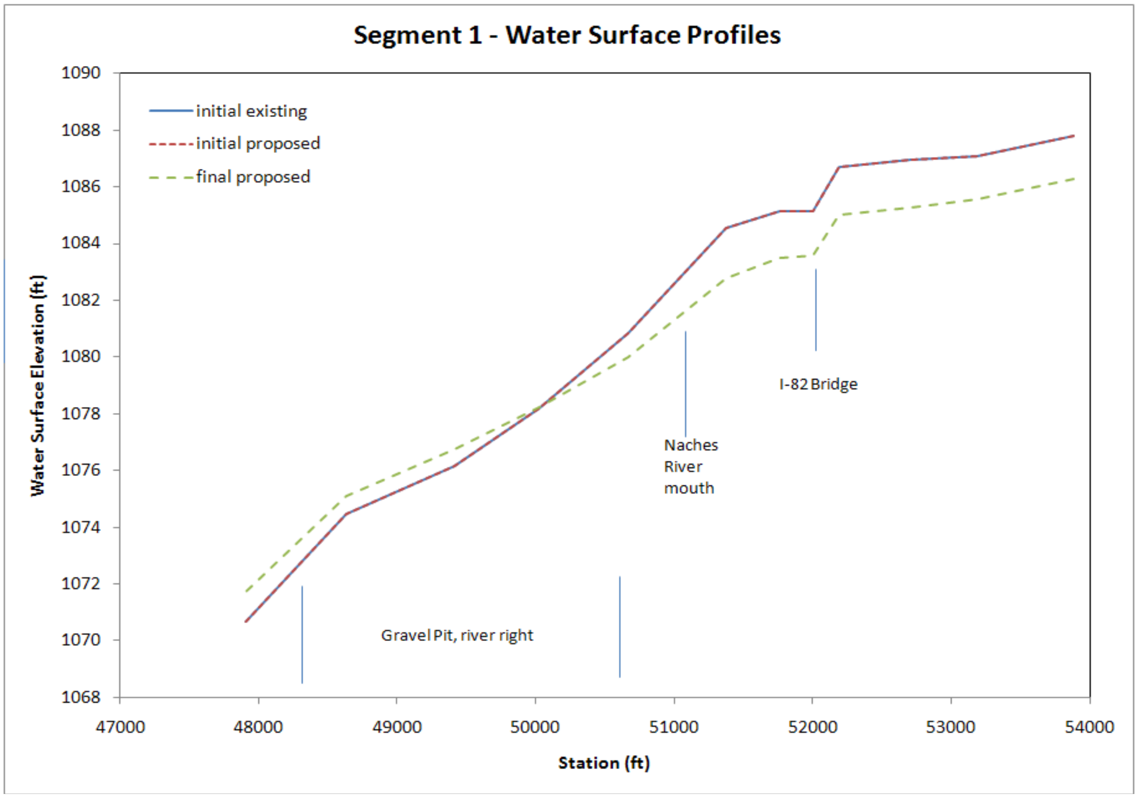

Figure 52: Modeled water surface profiles for segment 1 showing the existing, initial proposed, and final proposed conditions. The discharge is 44,000 ft^3/s.

In segment 2, water surface elevations increase by approximately 1 to 1.5 feet throughout all but the three downstream cross sections (Figure 53). Levees are overtopped at the same locations mentioned above, with the addition of station 40359. Very little freeboard exists through much of this segment along the left bank levee under existing conditions. Following the 25-year simulation, that freeboard decreases.

Water surface elevations for the final proposed conditions in segment 3 decrease as much as 2.6 feet from the initial proposed conditions (Figure 54). Water surface elevations are less for the final proposed conditions throughout the reach.

Segment 4 contains the DID #1 levee setback in the proposed conditions. Water surface elevations in this segment decrease overall following the levee setback (Figure 55) and none of the overtopping that occurs under existing conditions occurs in either the initial or final proposed conditions, however aggradation is expected to negate some of the decrease in water surface elevations. Nonetheless, water surface elevations decrease throughout the segment at the end of the simulation, by as much as 5.5 feet at the wastewater treatment plant.

Very little change occurs in segment 5 under any scenario (Figure 56). The overtopping of I-82 at station 6629 and Thorp Road at stations 3926 and 5584 is still expected to occur into the future. Lateral channel change is expected to occur in this segment in the future with or without the levee setback. The interstate remains vulnerable to attack from the river.

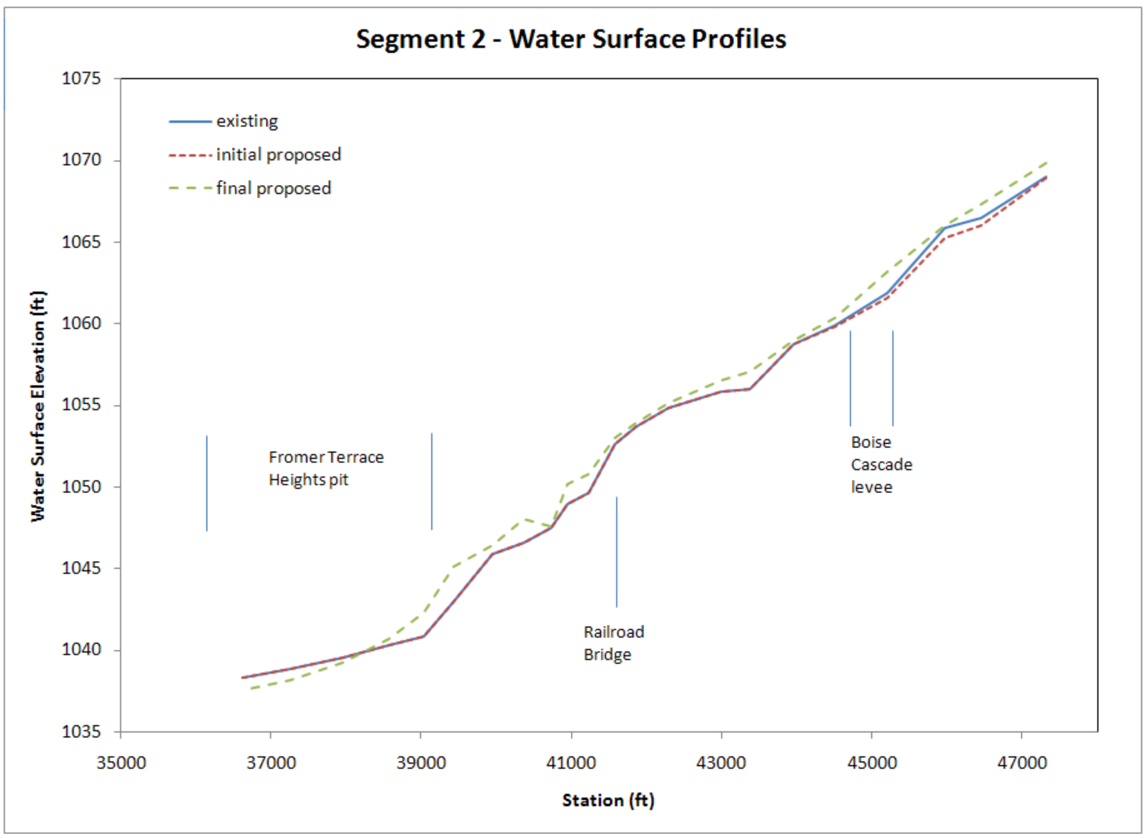

Figure 53: Modeled water surface profiles for segment 2 showing the initial existing, initial proposed, and final proposed conditions. The discharge is 44,000 ft^3/s.

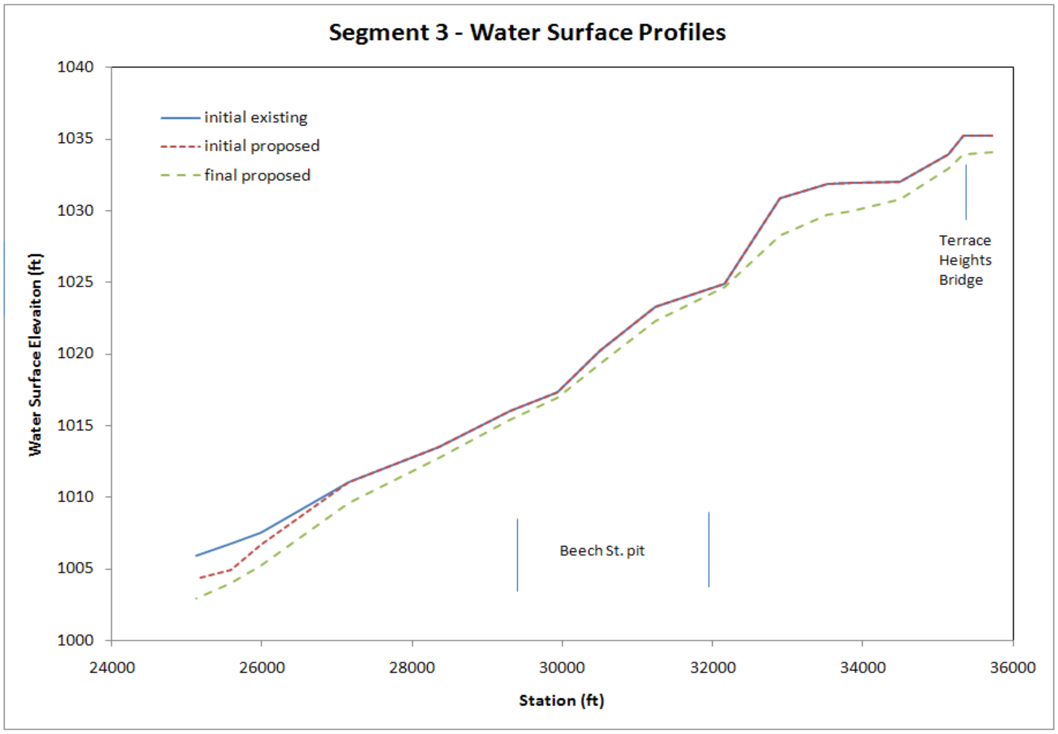

Figure 54: Modeled water surface profiles for segment 3 showing the initial existing, initial proposed, and final proposed conditions. The discharge is 44,000 ft^3/s.

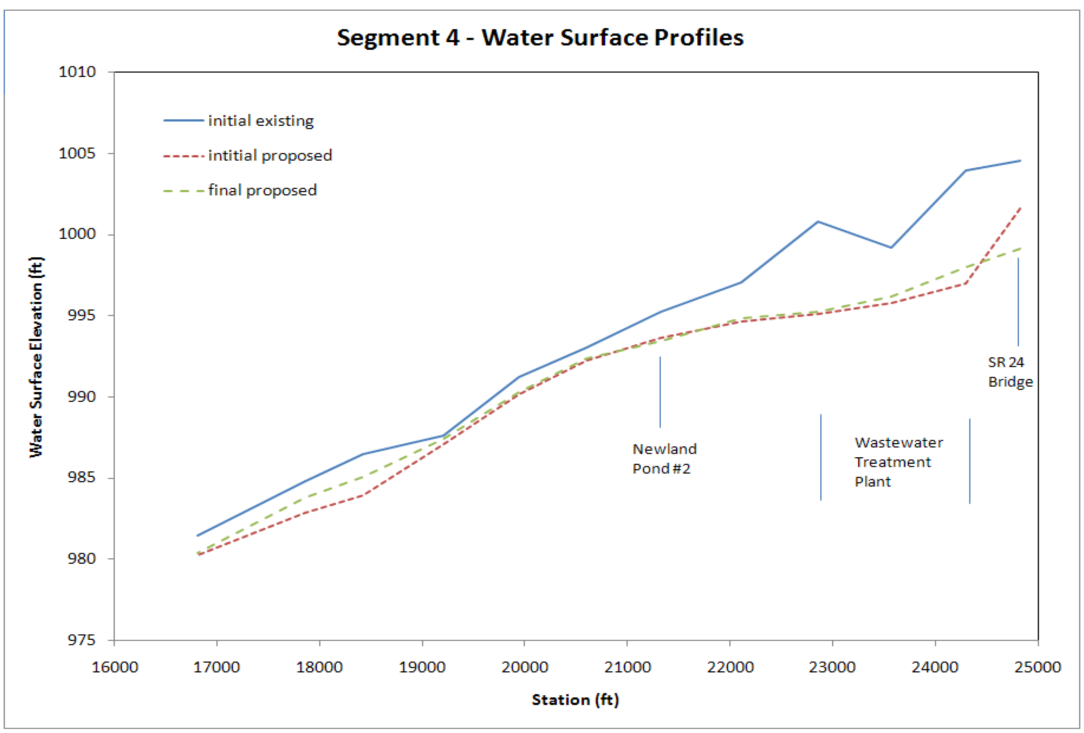

Figure 55: Modeled water surface profiles for segment 4 showing the initial existing, initial proposed, and final proposed conditions. The discharge is 44,000 ft^3/s.

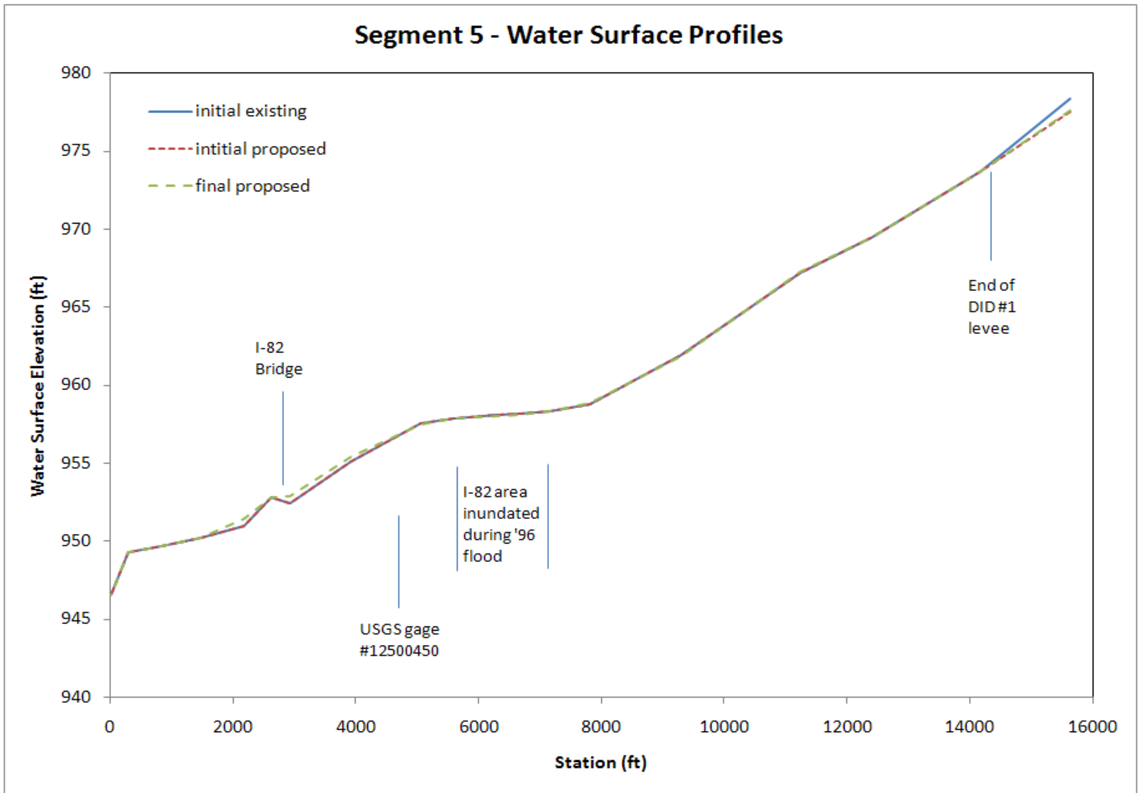

Figure 56: Modeled water surface profiles for segment 5 showing the initial existing, initial proposed, and final proposed conditions. The discharge is 44,000 ft^3/s.

4.3 Determining the Upstream Influence of Wapato Dam

A hydraulic modeling exercise was performed to determine the upstream extent of the hydraulic influence of Wapato Dam. This was performed using the 2005 geometry in HEC-RAS. The original intent was to remove the dam and determine an approximate bed elevation at the same cross section. However, there is significant sediment accumulation in the cross section upstream of the dam, which would result in a sort of artificial control. Considering this, the new downstream boundary was made to be cross section number 827, which is 827 feet upstream of the dam. Moving the boundary to this location does not change the results of the analysis, assuming there would be no downstream control of the hydraulics. This is a safe assumption considering the accumulation would not be there without the dam, the slope through Union Gap does not decrease, and there are no flow constrictions relative to station 827. The boundary condition imposed at the downstream cross section is normal depth with a slope of 0.0025. Using bed survey information upstream and downstream of the dam, the slope varies between 0.0018 and 0.0025, depending on which channel is used downstream to determine the thalweg. A sensitivity analysis was performed by using both 0.0018 and 0.0025 as a slope for the normal depth calculation. The difference in hydraulic conditions between these two assumed slopes does not extend upstream as far as the influence of the dam and thus does not affect the outcome of the exercise.

Two discharges were run in the HEC-RAS model, 2,500 and 28,000 cfs, with and without the dam in place. It is assumed that the entire discharge spills over the dam. Figure 57 shows the results of this analysis, and it is determined that the upstream influence of Wapato Dam is not dependent on discharge and extends to the island near the USGS gage (Yakima River above Ahtanum Creek, #12500450), river station 5052.8. A photograph shows the location in Figure 58.

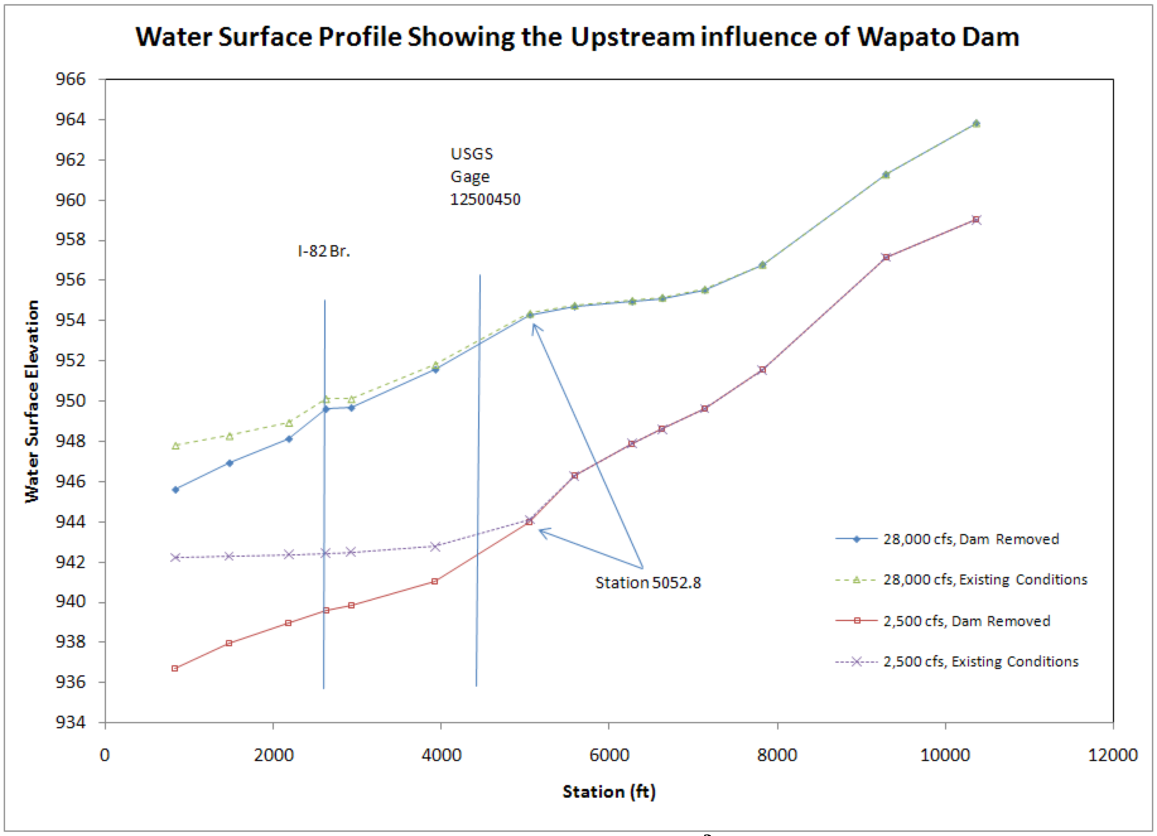

Figure 57: Water surface profiles for 2,500 and 28,000 ft^3/s considering a dam-in and dam-out scenario to determine the upstream influence of Wapato Dam.

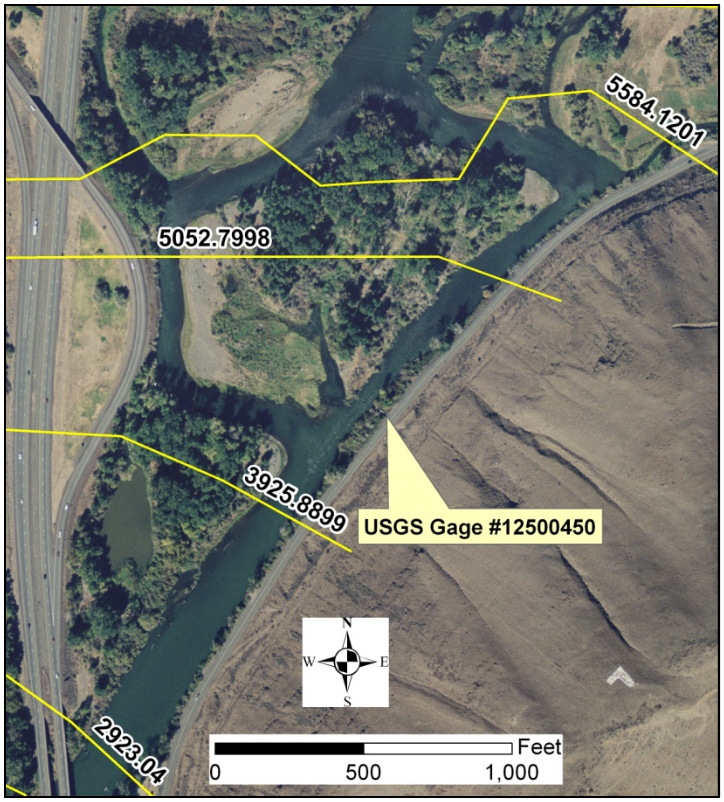

Figure 58: Photograph showing the location of cross section 5052.8, the upstream extent of the influence of Wapato Dam.

5 Sediment Transport Modeling

5.1 Limitations of One-Dimensional Sediment Transport Modeling

Prior to a discussion on sediment transport modeling, the limitations of the sediment transport modeling should be discussed. It is widely recognized that the reliability of sediment transport predictions is largely dependent on the quality of the data available for calibration and verification, as well as data input to the model. Measurements of bed material distributions and sediment transport are subject to large errors and can greatly influence the predictions made with a sediment model. Some specific limitations are explained below.

Sediment transport calculations are based on cross sectional average properties and parameters such as the mean channel velocity may not be representative in complex channels. 1-D sediment models can not represent lateral channel changes, bank erosion processes, meander migration or spatial variations in sediment transport and deposition associated with floodplain sedimentation. The modeled scenarios assume the overall channel alignment remains unchanged over the simulation period. The simulations could not account for complicating factors such as a future channel shift and capture of a gravel pit. This makes the simulation of the DID #1 levee setback relatively artificial since such a channel shift is expected to occur after the levee is removed.

These limitations are not unique to the present study. Furthermore, it is not easy to overcome the limitations by simply using a more sophisticated 2D mobile-bed sediment model. This is because the data requirements for calibrating and verifying 2D models are even greater than a 1D model.

Some of these limitations can be mitigated with a geomorphic analysis, which helps interpret the results of the model by indicating locations of potential channel change through field data collection and observation. Every effort was made to accurately represent field conditions during the data collection process. Input parameters to the sediment model and calibration/verification meet or exceed all accepted criteria by the engineering community.

5.2 Bed Material Data Collection

Bed material data were collected by Reclamation in the summer of 2005 throughout the Yakima Basin, including the Naches River (26 samples total, Mooney, 2008). Four of these samples on the Yakima River and one sample near the mouth of the Naches River are applicable to this study. It was decided that more bed material data were desired for the current study and four more samples were collected on the Yakima River in October, 2008. The locations of these samples are shown in Figure 36 and briefly described in Table 7. These samples were collected during low flow periods, such that there was maximum exposure of and access to bed material.

The process for collecting volumetric bed material samples began with the selection of a site. Most samples were taken from an exposed gravel bar, however some samples were taken in the wetted channel using a barrel (cut from a 55-gal. drum, approximate dimension 24” Dia. x 18” H) when it was more prudent to do so. This is a larger diameter barrel than that described by Hogan et al. (1993) and Milhouse et al. (1995) so that the area is more similar to that used on gravel bars. Procedures very similar to those described in Bunte and Abt (2001) were followed for the barrel sampling. For the purpose of sampling bed material for sediment modeling, a random location on a gravel bar or in the wetted channel is not necessarily appropriate due to spatial sorting. Rather, the sites selected for this effort were based on representing the material in the wetted portion of the channel, determined by observation while wading to the safe limits of depth and velocity. For samples taken on a gravel bar, two 6-foot folding rulers, graduated in inches, were placed over the gravel and a photograph was taken. The surface material was then removed from within the square (Figure 59) and placed into buckets. For the purposes of this sampling effort, surface material was defined as any particle visible from the surface. The buckets of sediment were then transferred to a tarp for sieving and weighing. A rocker sieve with square openings of 32 mm was used to separate material finer than 32 mm. Bed material larger than 32 mm was hand sieved using a gravelometer (template with square openings on half-phi increments, 2 – 180 mm) or measuring the B-axis if material was larger than 180 mm. All material from each individual size class was then weighed with a scale suspended from a tripod (Figure 61) and data were recorded. Bed material smaller than 32 mm was transported to a lab for grain size analysis. Following the removal and sieving of the surface material, the subsurface material was removed to the depth of the largest particle in the surface sample, often requiring a shovel or scoop, and handled in the same way as described for the surface sample. The surface and subsurface samples were not physically combined. This sampling procedure is consistent with that outlined in Church et al. (1987). In most instances, a pebble count was collected in the vicinity of the volumetric sample. If the volumetric sample was collected on a gravel bar, the pebble count procedure was to use a 100-foot tape and sample at regular intervals. If the volumetric sample was collected in-stream with a barrel, the pebble count procedure was an in-stream random walk.

There were several instances where the coarsest fractions required a second volumetric sample at a site in order to obtain a sufficient volume to represent the distribution. Material such as that found in the Yakima and Naches Rivers (i.e. a paved bed with poorly sorted material in the sand through cobble size range) is very difficult to sample representatively (Parker et al., 1982). Bed material data used in this study are in Appendix E.

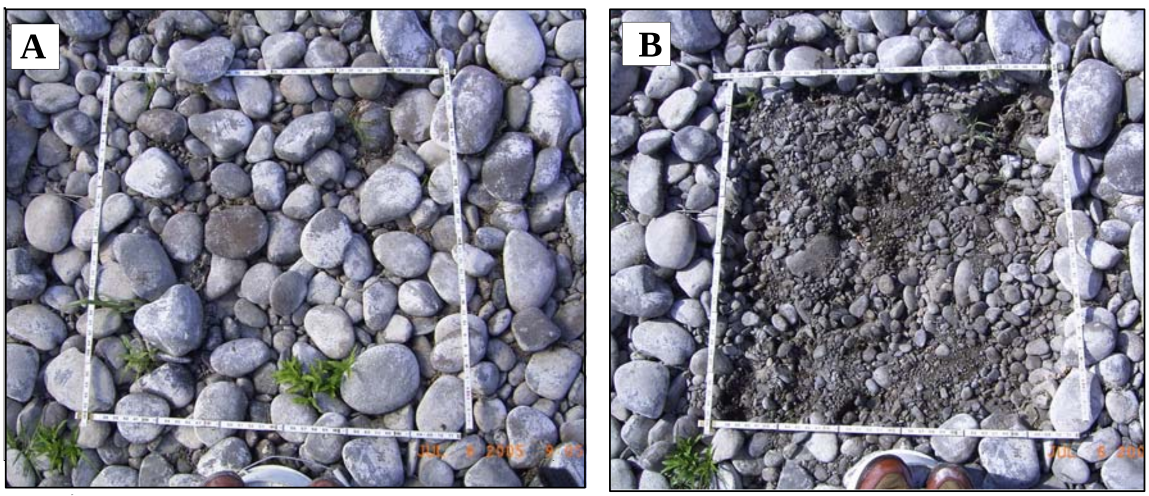

Figure 59: A-Sampling area before surface sample is taken. B-Sampling area after surface sample is taken and prior to collection of the subsurface sample.

Table 7: Table showing sample weights and D_{84}.

River Mile	Surface Sample Weight (lb)	Subsurface Sample Weight (lb)	Total Weight (lb)	D_{84} (mm) Surface - Subsurface
Yakima 118.5	41.9	99.4	141.3	89.7 - 84.9*
Yakima 117.5	150.3	211.0	361.3	178.2 - 302.7*
Yakima 116	369.5	353.8	723.3	165.4 - 156.2
Yakima 115	200.5	160.1	360.6	63.2 - 66.5
Yakima 113.3	157.9	206.3	364.2	112.1 - 122.4
Yakima 111.5	22.2	43.4	65.6	77.3 - 65.1
Yakima 110.5	229.1	274.6	503.7	121.4 - 82.4
Yakima 109.5	223.2	260.8	484.0	95.3 - 104.3
Naches 0.9	334.8	221.9	556.7	146.0 - 116.1
* Sampled with barrel sampler				

Figure 60: Photograph of sediment sampling set-up.

After the grain size analysis was performed in the lab for the smaller size fractions, the data were combined with the field-collected data for the larger size fractions, maintaining the separation of the surface and subsurface data. However, prior to numerical modeling, the surface and subsurface sample distributions were combined to maintain consistency with assumptions in the sediment model (Parker, 1990; Wilcock and Crowe, 2003).

5.3 Construction of the SRH-1D model

The sediment model used for this study is SRH-1D (Huang and Greimann, 2009), developed in-house. The model, user's manual, and tutorial are available at www.usbr.gov/pmts/sediment.

Although large improvements have been made in numerical modeling for fluvial environments, particularly for hydraulics, sediment transport has not enjoyed a similar level of advancement. Uncertainties in sediment transport calculations come from many sources, e.g.; estimates of incoming sediment to the reach, representation of bed material distributions (both spatial and vertical), vertical mixing of sediment layers, and the selection of a reference or critical shear stress. Sediment transport predictions are complicated by mixed size sediments, particularly when the surface composition is coarser than the substrate composition (Wilcock and Crowe, 2003). Indeed, the Yakima River in the Gap to Gap reach is a paved gravel bed stream, defined as requiring rather infrequent stages for complete activation, although bed motion is a normal event in that the bed is active for at least several days in most years (Parker et al., 1982).

5.3.1 Sediment Model Input

5.3.1.1 Geometry

The geometry for the sediment model was converted from HEC-RAS format for input to SRH-1D. Roughness values, levee locations, blocked obstructions, and areas of ineffective flow are all maintained and honored in SRH-1D. The Naches River is treated as a lateral input for sediment and flow.

5.3.1.2 Boundary Conditions

5.3.1.2.1 Downstream Boundary

The downstream boundary condition is a stage-discharge table taken from the HEC-RAS model. This table is based on critical depth at Wapato Dam in Union Gap. The configuration of the dam considers updates to the dam in 2007 using design drawings by Geomax, provided by Chane Salois of the Yakama Nation. Upstream boundary conditions are the input of flow and sediment at the upstream end of the Yakima River in Selah Gap and input of flow and sediment from the Naches River. All other tributaries in the reach are not significant enough contributors of flow and sediment to be considered.

5.3.1.2.2 Sediment Input

Sediment input to the reach is coupled with flow using a table that provides sediment discharge in tons per day and associated distribution by percent in each size class. Incoming sediment loads were determined using a sediment transport capacity program based on the sediment routines in SRH-1D (Huang, unpublished report, 2009). Transport capacity for incoming sediment loads was evaluated on the Naches and Yakima Rivers using reach averaged hydraulics from four cross sections and bed material distributions taken in the vicinity.

In 2008, at the request of Yakima County, the USGS gathered bed load and suspended load measurements from the Interstate 82 bridges (Figure 36) across both the Naches and Yakima Rivers (USGS, 2008) at the upstream end of the reach. These data can be seen in Appendix F. The sediment measurements provided valuable data for more accurate estimates of the incoming load and model parameters. The sediment measurements were collected during the peak of spring runoff in 2008, which provided low transport rates of bedload on the Naches River (peak sample discharge was 9,300 ft^3/s) and very low transport rates on the Yakima River (peak sample discharge was 6,710 ft^3/s). The sediment transport reference shear stress and hiding factor was calibrated to match these measurements. Figure 61 and Figure 62 show the computed and measured bed material loads for the Yakima and Naches Rivers, respectively. Incoming sediment load for the Yakima River at discharges greater than 15,000 ft^3/s (Figure 61) indicates a decrease beyond 15,000 ft^3/s and is due to a backwater effect caused by the I-82 Bridge. The flow does not contact the low chord, rather main channel velocities become retarded as the constriction begins to affect the hydraulics at the profile. The peak value of the sediment load input to the model was held constant for all discharges higher than 15,000 ft^3/s (dashed line in Figure 61). Sensitivity to the variation in incoming sediment load was tested and is explained in Chapter 5.4. This effect is not seen in the Naches River data because measurements, and therefore transport capacity, were not evaluated in a cross section significantly affected by a constriction for discharges evaluated.

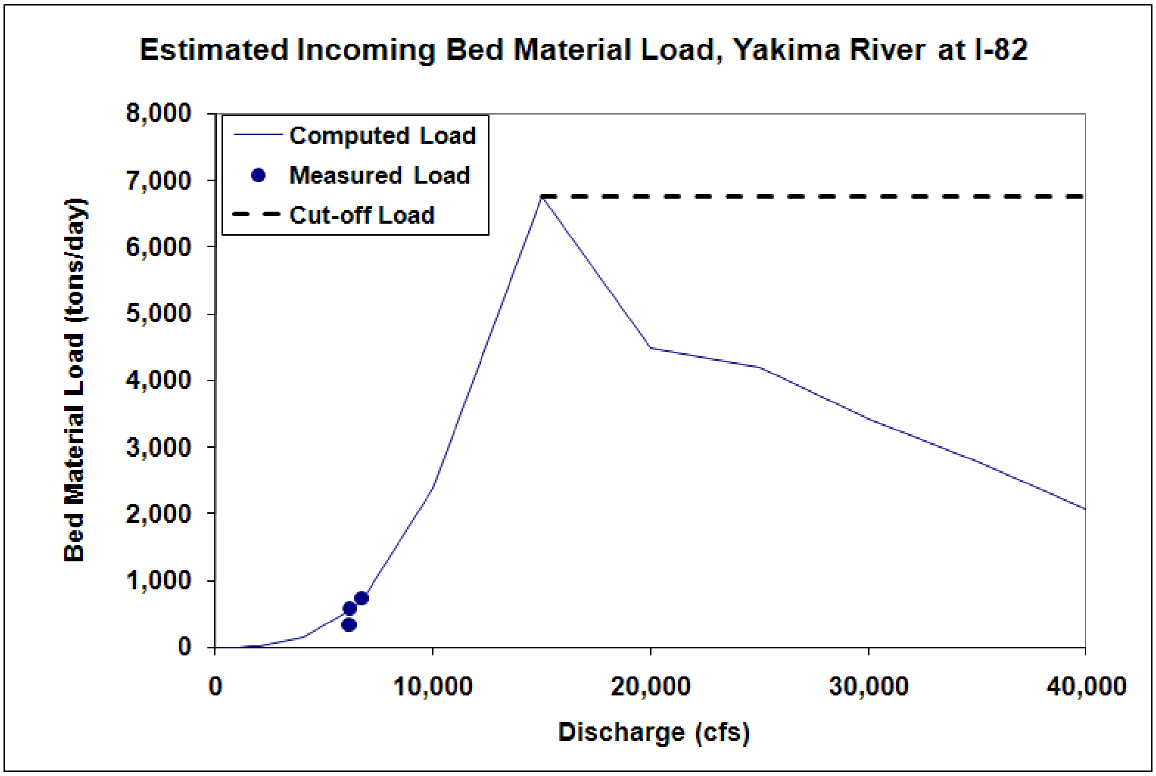

Figure 61: Computed and measured incoming bed material load on the Yakima River. The dashed line indicates a peak value of bed material load used as the incoming load for all discharges greater than 15,000 ft^3/s. The occurrence of a decreasing load is a result of a backwater condition at the I-82 Bridge in Selah Gap.

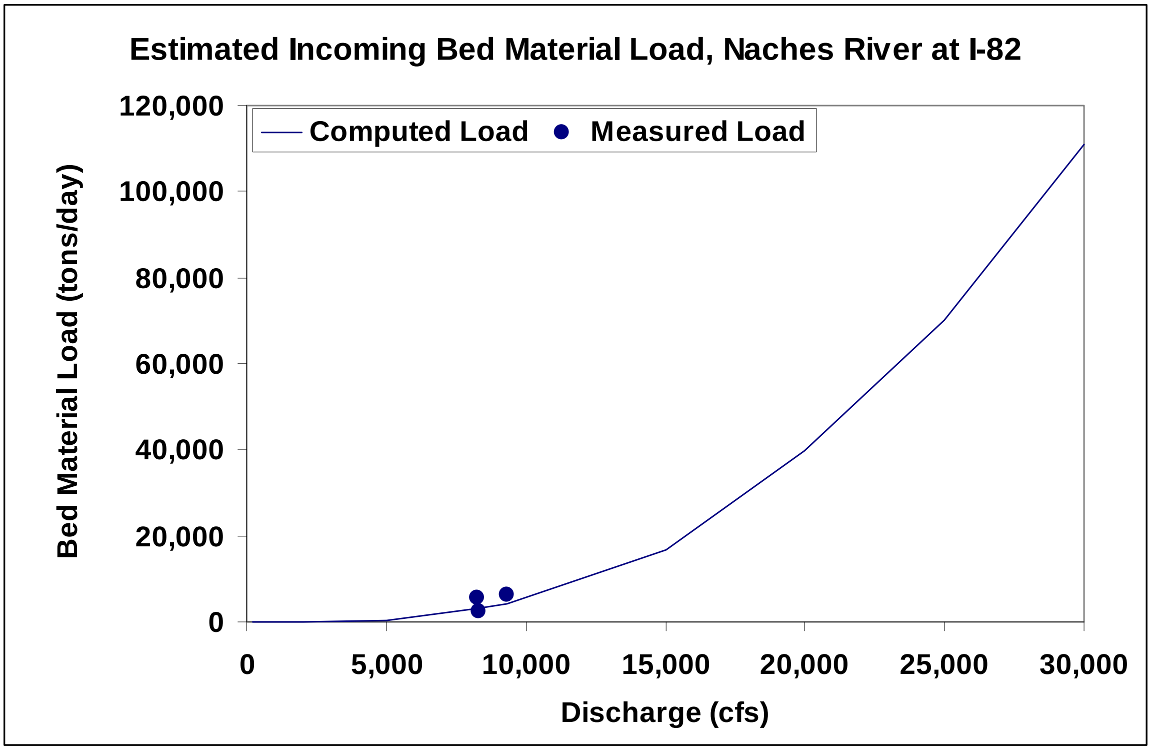

Figure 62: Computed and measured incoming bed material load on the Naches River.

It is important to discuss the various types of sediment load. The following definitions are taken from the Sedimentation Engineering Manual (ASCE, 1975) and Chang (1988). These terms are used throughout the report.

*Wash load** – comprised primarily of silt and clay particles (< 0.0625 mm) that are washed through the channel , with an insignificant fraction contained in the bed material

*Suspended load** – particles transported in the body of the flow by turbulent mixing processes for an appreciable length of time

Bed load – particles moving on or near the bed by rolling, sliding, or saltating along the bed at velocities less than that of the surrounding flow

Bed material load – includes all sizes of bed material readily found in the bed (generally > 0.0625 mm for gravel bed streams)

Total load – the sum of bed load and suspended load, or the sum of bed material load and wash load

(*Suspended sediment measurements include suspended load and wash load.)

All modeled sediment quantities in this study are reported as *bed material load*, as it is the transport of this material that is responsible for the morphology of the Yakima River in the Gap to Gap reach, with respect to sediment transport. Moreover, sediment transport predictions of silt and clay sized particles have a much greater uncertainty due to their highly variable distribution in the floodplain and the interactions of chemical and biological processes that are not completely considered in sediment transport models. Additionally, fine sediment is stored in the banks and floodplains as opposed to the bed and is extremely difficult to sample representatively. Sediment measurements at the upstream boundaries of the reach indicate that approximately 86% and 64% of the Yakima and Naches Rivers' suspended sediment (respectively) was *wash* load. These same measurements indicate that the *bed* load (generally considered to be > 2 mm) is approximately 6% and 15% of the *total* load on the Yakima and Naches Rivers, respectively.

The calculation of sediment transport is performed by size class. The size classes are divided according to the Wentworth scale (Table 8), beginning with fine sand and extending through the large cobble size class. Many sediment transport formulae were considered in the sediment transport capacity modeling at the upstream boundaries. These included Meyer-Peter and Muller (1948) as modified by Wong and Parker (2006), Ackers and White (1973) with updated coefficients by HR Wallingford (1990), Engelund and Hansen (1966), Brownlie (1981), Parker (1990), Wilcock and Crow (2003), and Wu et al. (2000). The Parker (1990) and Wilcock and Crowe (2003) formulae were combined with the Engelund Hansen formula for better representation of transport for sand sized particles (Table 8). With this correction, all but the Meyer-Peter Muller formula consider *bed material load*. Meyer-Peter Muller is a *bed load* formula. The Parker (1990) and Wilcock–Crowe (2003) formulae, combined with the Engelund - Hansen most closely matched the measured data. This combination of transport formulae comes about for two primary reasons; 1) Sediments with large deviations tend to have bimodal size distributions (as is the case in this study), with a principal gravel mode and a secondary sand mode (Kuhnle, 1992; Wilcock, 1992). In these cases sand is preferentially transported at smaller discharges (Wilcock, 2001) and may be better modeled using difference relationships (Kuhnle, 1992), 2) Both the Parker and Wilcock-Crowe formulae are written for *bed* load, and including the Engelund-Hansen equation provides a complete *bed material* load equation. More information regarding these equations can be found in Huang and Greimann, (2009) Although the Parker and Wilcock-Crowe formulae, combined with Engelund - Hansen, proved to be more closely matched to measured data than other formulae, it was discovered that this coupling did not provide the desired match. The combination of these formulae in SRH-1D is written in such a way that the hiding factors affect the transport of the finer fractions (i.e. sand). When the Engelund – Hansen formula is de-coupled from the Parker and Wilcock–Crowe formulae, transport relationships are more appropriate for the conditions on the Yakima and Naches Rivers, so much so that large adjustment of the coefficients (reference shear stress and hiding factor) from default values was not necessary. This decoupled method is what was used for determining the incoming loads and for the entire model of the Gap to Gap reach. Appendix G expands this explanation of this formulation. Future references to the combined equations will be Parker-EH and Wilcock-EH.

Table 8: Table showing the Wentworth size classes used in the sediment model.

	Class Name	Size Range (mm)
Sand	Very Fine Sand	0.0625 – 0.125
	Fine Sand	0.125 – 0.25
	Medium Sand	0.25 – 0.5
	Coarse sand	0.5 – 1.0
	Very Coarse Sand	1 – 2
Gravel	Very Fine Gravel	2 – 4
	Fine Gravel	4 – 8
	Medium Gravel	8 – 16
	Coarse Gravel	16.0 – 32
	Very Coarse Gravel	32 – 64
Cobble	Small Cobbles	64 – 128
	Large Cobbles	128 – 250

It was requested that the sediment measurements on the Yakima and Naches Rivers were collected during the rising limb, peak, and the falling limb of the runoff hydrograph. This was accomplished on the Naches River, however two measurements were made on the falling limb of the hydrograph for the Yakima River. This is understandable considering the difficulty in obtaining these measurements and the error in predicting the time and date of peak runoff. Table 9 shows the dates and discharges for the sediment measurements.

Table 9: Table of dates and discharges for the sediment measurements on the Yakima and Naches Rivers at the Interstate 82 bridges at the upstream end of the study reach.

Yakima River		Naches River	
Date	**Discharge**	**Date**	**Discharge**
May 17, 2008	6,710 ft^3/s	May 17, 2008	8,250 ft^3/s
May 18, 2008	6,170 ft^3/s	May 18, 2008	9,300 ft^3/s
May 20, 2008	6,130 ft^3/s	May 20, 2008	8,290 ft^3/s

For the purpose of calibration and determination of incoming load, the lower two discharges on the Yakima River were assumed to be representative of a 6,150 ft^3/s discharge. Similarly, the lower two discharges on the Naches River were assumed to be representative of a discharge of 8,270 ft^3/s. Each of these pairs of discharges differs by less than 1%.

The incoming load on the Yakima River was best defined by the Wilcock-EH formula, however a better fit was accomplished by further separating the formula by using different values of the reference shear stress and the hiding factor for sand and gravel size particles. Figure 63 shows the calibration results for the Yakima Rivers. The reference shear stress and hiding factor used for sand size particles were 0.024 and 0.05 respectively. Reference shear stress and hiding factor values for gravel size particles were 0.035 and 0.5, respectively. The purpose of these efforts is to account for the bimodal distribution of sediment being transported.

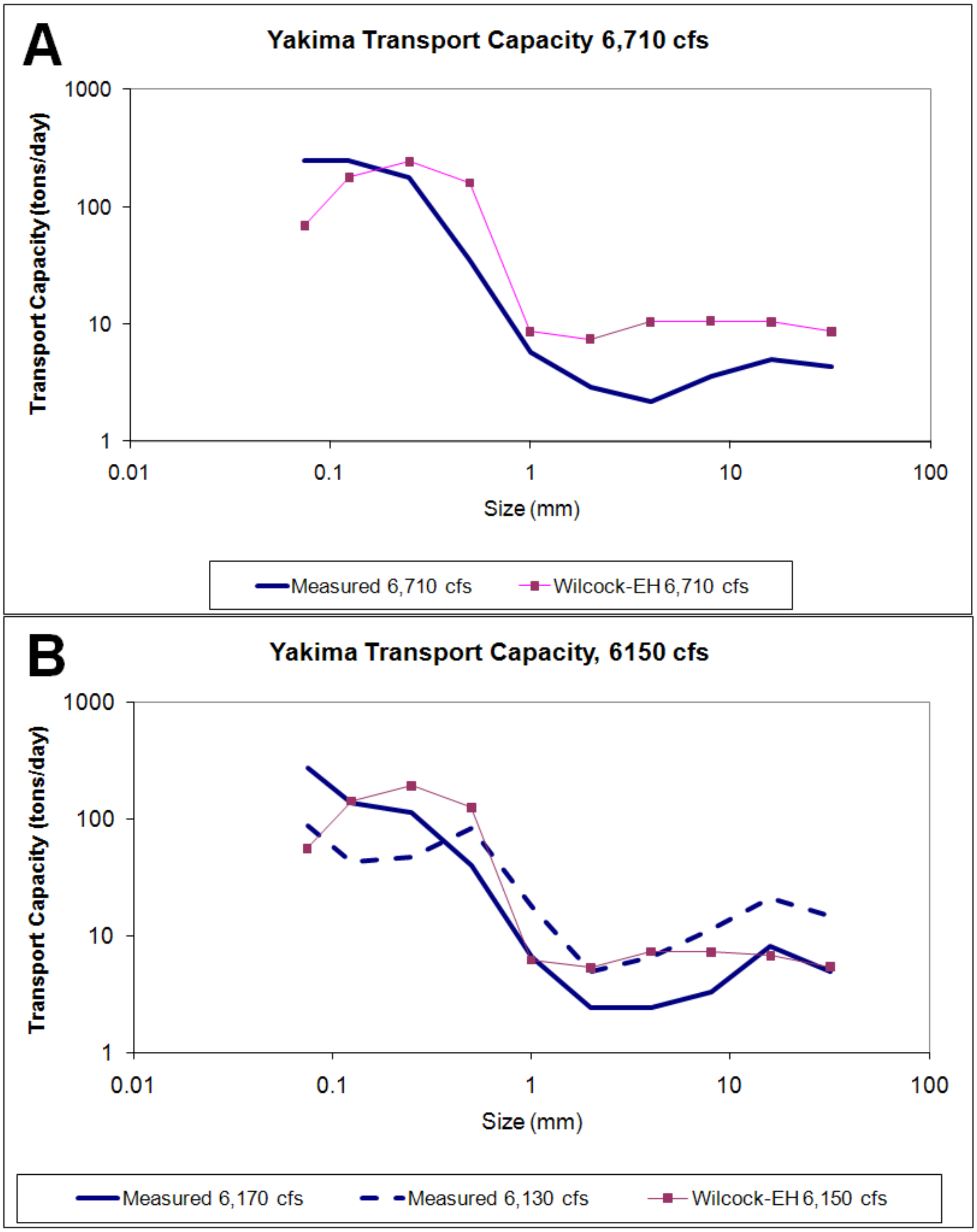

Figure 63: Comparisons of incoming sediment load, measured vs. modeled. A – Peak of measurement, 6,710 ft^3/s. B – Lower discharges, modeled at 6,150 ft^3/s.

A similar approach to modeling incoming loads was used for the Naches River. However, it was discovered that the Wilcock-EH formula could not account for the much larger sand load, making it necessary to describe the sand size sediment using the Parker-EH formula. Both distributions in the Yakima and Naches Rivers appear very similar, although overall loads for the Naches are approximately an order of magnitude greater.

Parameters regarding the reference shear stress and hiding factor for the Naches River are as follows: sand sized transport – Parker-EH, 0.035 and 0.8; gravel size transport, Wilcock-EH, 0.021 and 0.33 (Figure 64).

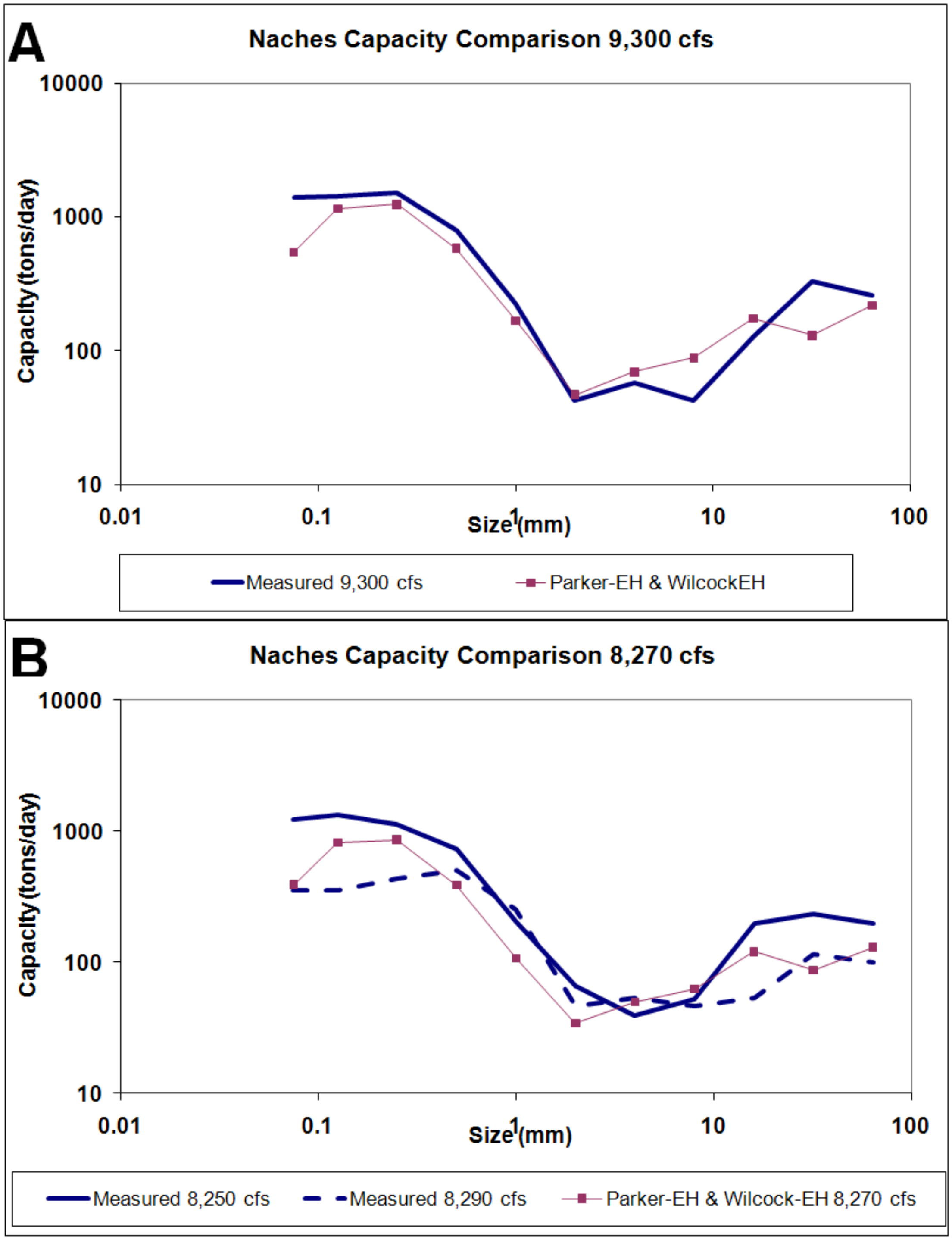

Figure 64: Comparison of the incoming sediment load from the Naches River, measured vs. modeled. A – Peak of measurement at 9,300 ft3/s. B – Rising (8,250 ft3/s) and falling (8,290 ft3/s) limbs of the runoff hydrograph.

It should be noted that transport rates during measurements on the Yakima River are very near the initiation of significant bed motion. The table input for the sediment model for incoming load was constructed by separating sand and gravel size sediment based on the formulation stated above. This effort was required so that accuracy in modeling the incoming gravel load was not accomplished by sacrificing accuracy for the incoming sand load, and vice versa.

5.3.1.2.3 Discharge/Hydrology Input

All discharges modeled for this study are assumed to be steady flow and are input to the model in table format, with two columns of time in hours and discharge in cubic feet per second. The Gap to Gap model has two locations where flow and sediment are input, at the upstream end in Selah Gap and at the mouth of the Naches River (river station 50665, Figure 36). A separate table is specified for each flow input. All hydrologic scenarios described in Chapter 3.2 were modeled for sediment transport.

5.3.2 Bed Material Input

A decreasing trend in bed material size can be observed in Figure 65. This can be attributed to two factors; 1.) the Naches River contributes sediment of sizes considerably greater than the incoming sediment in the mainstem Yakima River at the upstream end of the reach, thus there is a local source of coarse material that becomes mixed with the finer material of the Yakima River bed material. The Yakima has very limited ability to transport the largest size classes coming from the Naches River, leaving much of the coarsest material in the upstream portion of the Gap to Gap reach, and 2.) although there is no trend of a decrease in channel slope, there is a decrease in transport capacity (Figure 66). In spite of every attempt to sample the bed material representatively, it is likely that local variations are contained in the data. Because the sediment model more accurately addresses trends over multiple cross sections, a synthetic sediment distribution was created for input to the model (Figure 67). This is accomplished by inserting synthetically derived bed material distributions, using the trend lines (Figure 66) at each end of the reach and letting the model interpolate bed composition for each cross section throughout the reach. This methodology represents the decreasing trend without incorporating actual samples that could result from local anomalies, which might negatively affect model results. The synthetic bed material distribution was only applied downstream of the Naches River mouth. Bed material sampled from the Yakima River in Selah Gap upstream of the Naches River mouth was used to represent this short reach. The significant change in bed composition downstream of the Naches River mouth can be seen in Figure 67.

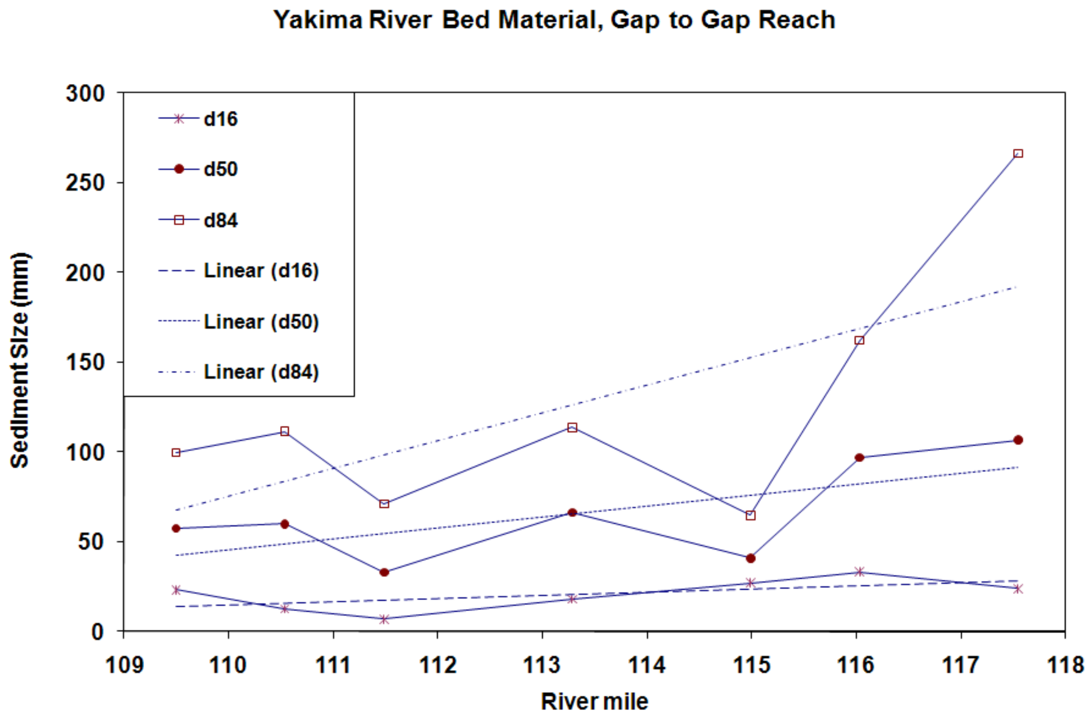

Figure 65: Graph of bed material distribution throughout the Gap to Gap reach. Dashed lines are a linear fit to d_{84}, d_{50}, and d_{16}. Data upstream of the Naches River mouth are not shown.

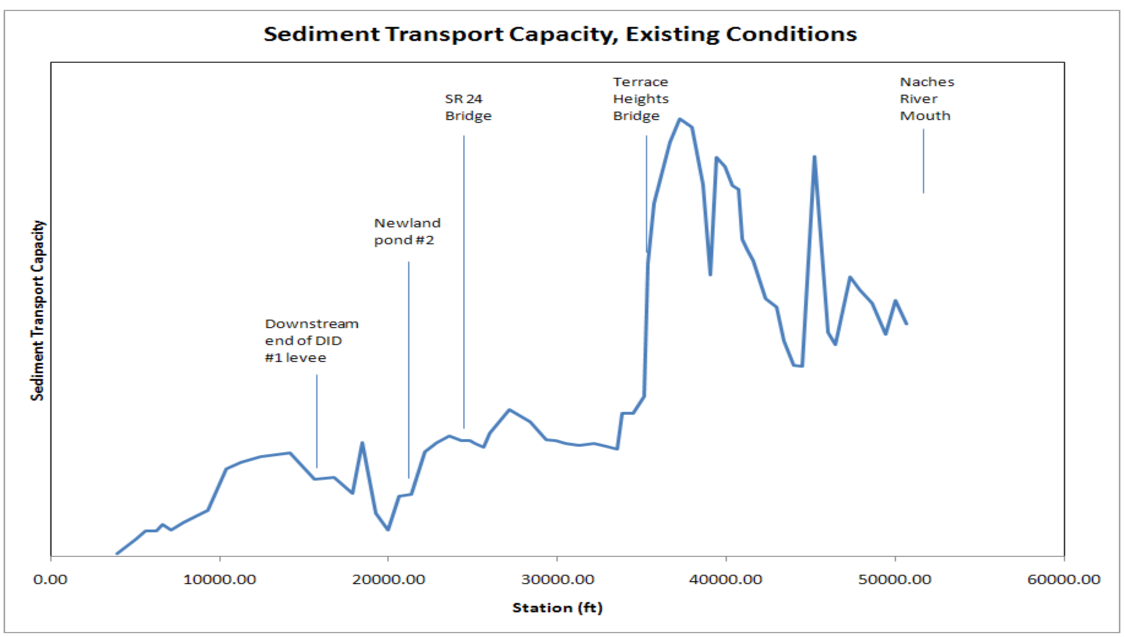

Figure 66: Sediment transport capacity through the Gap to Gap reach using the last time step from the sediment model representing the existing conditions. The units have been left off the Y-axis because this value will vary with channel conditions and discharge. The plot is meant to demonstrate one reason for the decrease in bed material size throughout the reach.

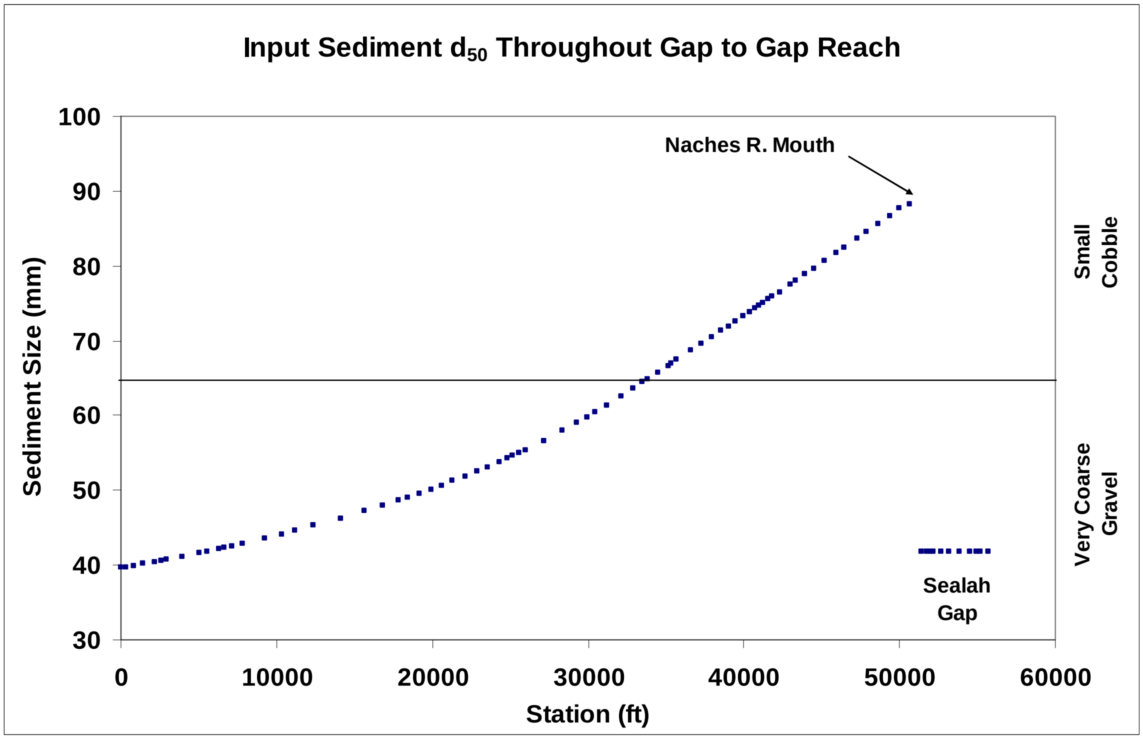

Figure 67: Synthetic bed material d_{50}.

5.3.3 Transport Equation

Based on the calibration of the incoming sediment load, it was determined that the Wilcock-Crowe (2003) bedload formula, combined with the Engelund-Hansen bed material load formula, most appropriately matches the sediment transport conditions in the Yakima River in the Gap to Gap reach. The Wilcock-EH formula is capable of handling the bimodal transport of the bed material and best represents the transport of the coarsest fractions of the bed material. The Parker-EH formula predicted the sand fractions well, however, it fell short of capturing the transport of the coarsest material. While the Parker-EH formula will likely better represent the average annual load than will the Wilcock-EH equation, the coarsest fractions of the transported bed material are responsible for the morphology of the channel. Therefore, the greatest priority for determining the most appropriate transport equation was given to the transport of gravel and cobble size sediment.

5.4 Model Sensitivity

The sediment model was tested for sensitivity to time step, incoming sediment load on the Yakima River, and the transport equation variables for reference shear stress and hiding factor. The time step sensitivity was tested by decreasing the time step value and evaluating the change in results. Because an improper value of the time step will most likely manifest itself in a local instability, the thalweg profile was used to evaluate time step sensitivity, with values ranging from 0.05 - 5 hours. Differences in the thalweg elevation for each cross section in the model were compared with the values resulting from the 0.05-hour results, looking for the largest deviations in elevation. This analysis indicated that a 0.5-hour time step was the most appropriate when balancing model error and run time efficiency. The incoming sediment load was evaluated using both the 'computed load' and the 'cut-off load' for the Yakima River as shown in Figure 61. Average annual bed material load changes by less than 1% for existing conditions. Differences in the change to mean bed elevation (aggradation/degradation) show a maximum of 0.26 ft., with 83% of the difference less than 0.1 ft. Differences between the incoming load values are imperceptible (< 0.1 ft.) when reach-averaged values are examined in the results chapter (Chapter 6). Sensitivity to the reference shear stress and hiding factor was evaluated with results of change in mean bed elevation, changes to the final bed material composition, and average annual load. The mean bed elevation includes those bed elevations that are between the bank points, as configured in the cross section geometry. Two hydrologic scenarios were used to evaluate the sensitivity; a one year hydrograph that includes a 30-day flood with a magnitude of approximately 44,000 ft^3/s, and another hydrograph with the previous 25-years (water years 1985 – 2009). Further details are in Appendix H.

5.5 Sediment Model Verification

While predictions of aggradation and degradation are not verifiable in a reasonable time frame, there are measures that can be taken to increase confidence in sediment modeling results. One such way is to model past conditions and verify results with a current survey. However, a comparison between 1969 and 2005 surveys indicates significant changes to the floodplain between the surveys that are not well represented with 1-D modeling. No less than five gravel pits have been captured and filled in the time period between surveys. These gravel pits span the study reach, including the triangular pit near the Naches River mouth, the Terrace Heights pit just upstream of the Terrace Heights Bridge, the SR 24 pit, and two pits downstream of the DID #1 levee in segment 5. This negates the usefulness of such an exercise for this study, as these changes would not be replicated in a sediment model. Without a significant change to slope and levee configuration over the 35 years between the surveys, it can be reasonably assumed that the composition of the bed material with respect to grain size distribution has not changed significantly (at least not within available methods to representatively sample coarse bed material). The extension of what is now the DID #1 levee by approximately one mile is the only noteworthy change with respect to width restrictions. Therefore, a reasonable prediction of future bed composition will not be expected to dramatically change throughout the reach, assuming limited change in river training structures such as levees. For this reason, future scenarios evaluating bed composition for verification were evaluated with the existing levee configuration. Figure 68 shows the a comparison of the synthetic bed material d_{50}, the measured d_{50}, and the final d_{50} after simulating water years 1985 – 2009 using the existing levee configuration. It can be seen that the model tended to return to a bed composition similar to the measured data.

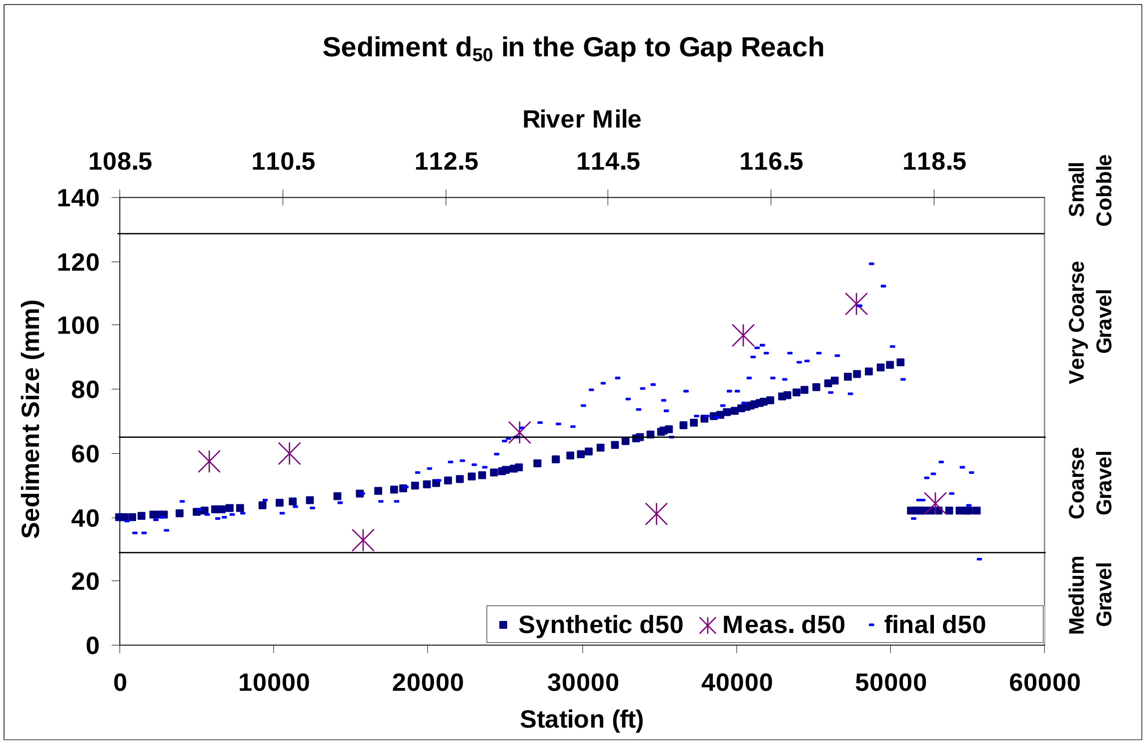

Figure 68: Graph of the synthetic d_{50}, measured d50, and d_{50} after 25-years of simulation (final d_{50}).

It is noteworthy that the modeled d_{50} of the bed material sample located at station 38,455 (River Mile 115) is the only location that is not within the same size class (e.g. coarse gravel) as the measured data. This is most probably a demonstration of a non-representative bed material sample. This location is just downstream of the Terrace Heights Bridge (Figure 36). The channel geometry at this site forces a significant amount of the flow against the rip-rapped left bank, creating a rather wide thalweg. The sample was taken on an exposed mid-channel bar, and erosional forces create a condition where the material in the thalweg is likely much coarser than that sampled. That this occurred demonstrates the benefit of using a synthetic distribution as input to the model, as abrupt changes in bed material can result in inaccuracies in model results.

In an effort to verify sediment model results, predicted sediment load was checked against suspended sediment measurements taken at the Yakima River above Ahtanum Creek gage for verification. 241 such samples are reported during the period 1975 – 1993. Although modeled estimates are reasonably close to measured data, predicted suspended sediment values were consistently low compared to measured data. This is not unexpected and occurs for a few reasons: 1.) The history of the water and sediment sampled at a given time is unknown and unlikely to match results from the model using an arbitrary hydrograph, 2.) Suspended sediment measurements include fine fractions of sediment (i.e. silt and clay), not simulated when modeling bed material load. This portion of the suspended load normally constitutes a very significant fraction of the overall sample. Archived sediment samples did not report the size breakdown of sediment sampled, 3). The model does not accurately represent sand-sized fractions (< 2 mm) of sediment eroded from the banks and floodplain surfaces, and as such will not match measured samples that include sediment from these origins, 4.). Because the primary focus of the sediment model is future channel form, modeling coarse fractions (gravel and cobble) was emphasized, at the possible expense of accuracy in the finer (sand) fractions of the overall sediment load. For these reasons, verification with measured suspended sediment may not produce satisfactory results. Predictions of average annual total load will be made using these measured data and is discussed in Chapter 6.1

Modeling the existing condition also indicates no significant trend in aggradation or degradation throughout the reach, which is consistent with the measured data from 1969 to 2005 and no significant change to reservoir operations.

6 Sediment Transport Modeling Results

The sediment modeling effort was focused on simulating transport conditions through the next 25 years. The results discussed in this chapter reflect this time frame.

6.1 Average Annual Load

The average annual sediment load can be calculated using 241 suspended sediment measurements collected at the Yakima River above Ahtanum gage between 1975 and 1993. By fitting a power curve through these data (Figure 69) a rating curve can be obtained with which an average annual *suspended* load can be determined. These data were evaluated for temporal trends but none were found. If the assumption is made that *bed load* is approximately equivalent to 10% of the *suspended* load (Chapter 5.3.1.2.2), values of average annual *total load* can be obtained. Using the rating curve obtained with the power fit, and increasing the value by 10% to account for *bed load*, average annual *total* load evaluated over the data collection period is estimated to be 80,000 tons per year. If the rating curve is evaluated over the water years 1985 – 2009 the average annual *total* load is 96,000 tons/year.

The modeled results for average annual *bed material* load indicate approximately 19,000 tons/year for the existing levee configuration and approximately 17,000 tons/year for the proposed condition using the 1985 – 2009 hydrograph (more details presented in Chapter 6.2.1). This is a predicted decrease of about 10% over 25 years assuming the proposed levee configuration. If the 10% decrease is assumed for the *total* load calculations, 86,000 tons/year is the projected *total* load over the next 25 years. This represents an imperceptible change considering model error. The calculated *bed material* load can be compared to the measured *total* load if it is assumed to contain 75% wash load (see Chapter 5.3.1.2.2). With this assumption, measured *bed material* load is approximated to be 24,000 tons/year, which is considered relatively similar to the modeled results, considering typical errors in sediment transport calculations and measurements. The assumption of wash load consisting of material finer than 0.0625 mm is debatable for gravel bed rivers and can influence the verification of the sediment model. However, finer material measured as suspended load, including wash load, is primarily eroded form the banks and floodplain. These process are not represented in a 1-D sediment model, as the focus is limited to channel processes and bed material (see limitations of sediment modeling at the beginning of this chapter).

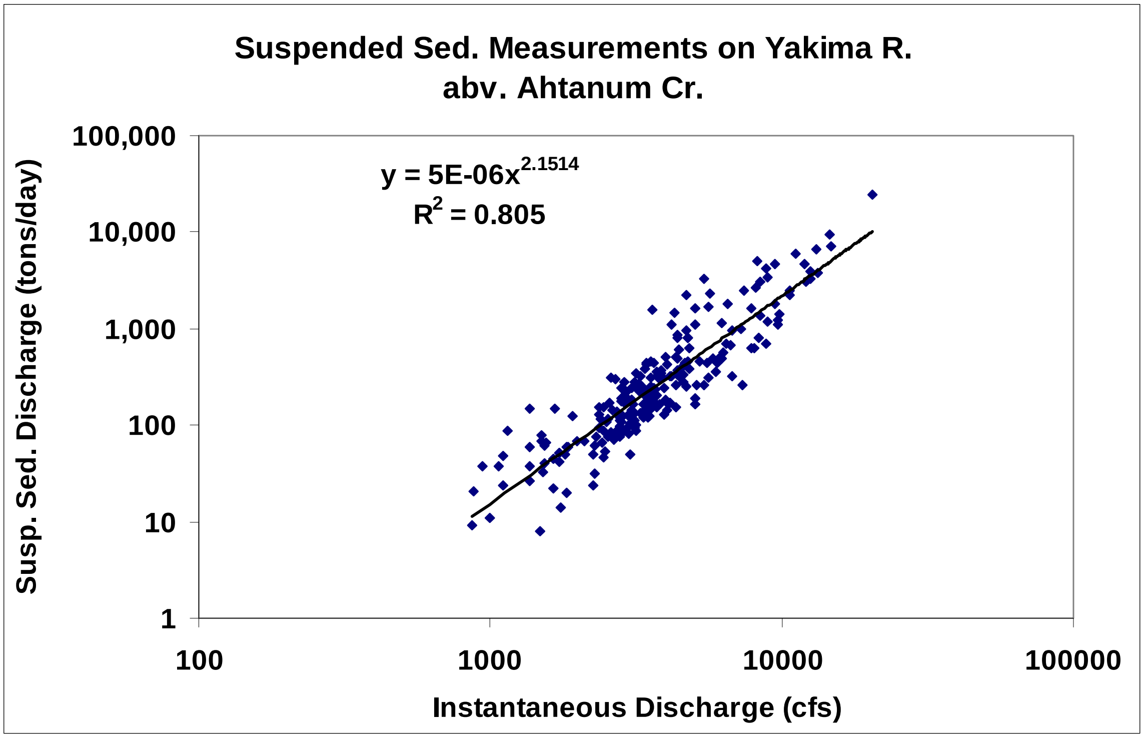

Figure 69: Plot of suspended sediment measurements taken over a 19 year period (1975 – 1993). The line through the points is a power fit to the data (shown on a log-log scale).

6.2 Location of Projected Aggradation and Degradation

Locations of predicted aggradation and degradation in the study reach are best defined by short reaches, or segments, that display similar trends. These quantities are limited to the channel as opposed to the channel and floodplain. Results from the first four upstream cross sections have been ignored, as they are too close to the boundary to be reliable. The segments were determined based on similar values of deposition or erosion at adjacent cross sections and coincide with reaches independently identified in the geomorphic assessment (Chapter 2.2). The segment-averaged change in mean bed elevations are shown in Figure 70. These values represent the predicted vertical change within the channel over the next 25 years using the historical hydrograph from 1985 - 2009. Predicted vertical change will often result in lateral erosion or avulsion, considering the lack of a trend in vertical channel change over the past few decades (Chapter 2.4) and no knowledge of significant future changes to hydrology or dam operation. The relevance of these results with respect to sediment modeling is discussed below. Some discussion of implications for future channel change based on deposition and erosion is discussed in the following paragraphs, however a more in depth discussion of future channel condition takes place in Chapter 7.3.

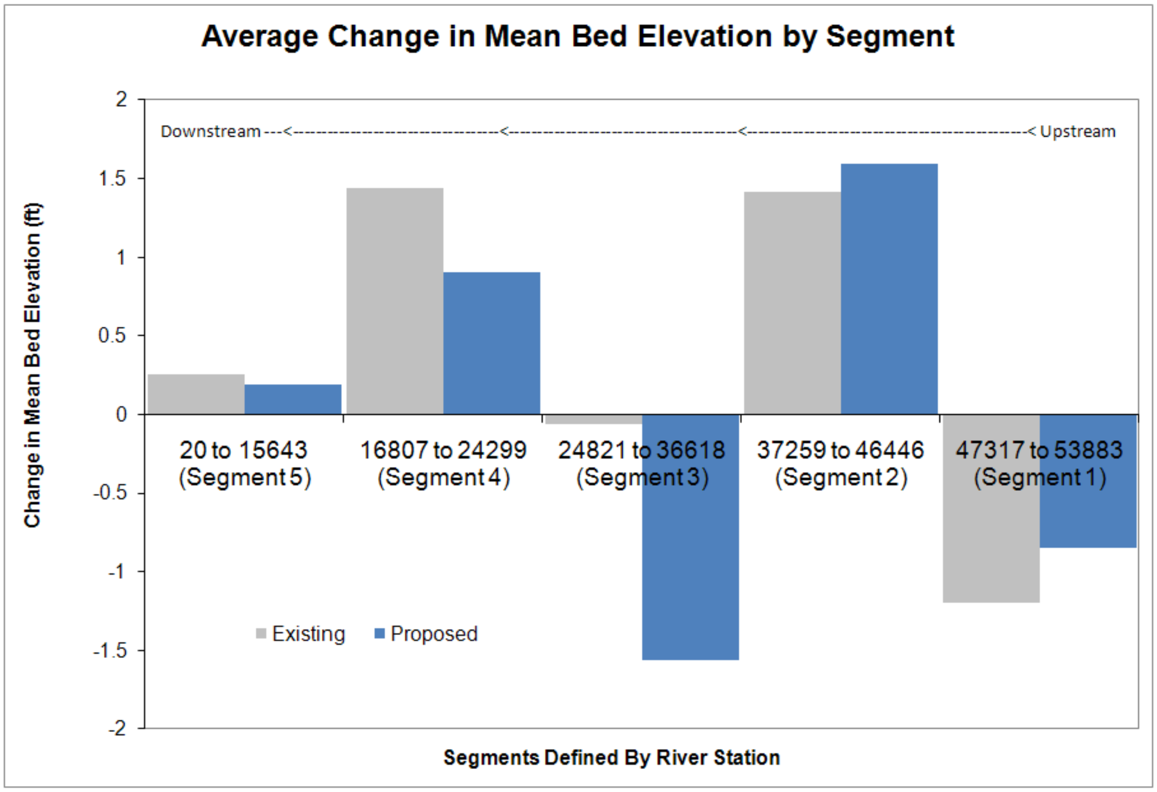

Figure 70: Plot of projected reach-averaged aggradation and degradation. Reaches are defined on the horizontal axis and are the station number in feet with the downstream portion of the reach at the left of the chart.

A more detailed means of displaying the change in the sediment model predictions is to show the profiles of mean bed elevation over time. Plots shown in Figure 71 through Figure 75 depict the model results considering the proposed condition. These data help to identify temporal trends in erosion and deposition and addresses the expected channel stability at the end of the simulation. A mean bed elevation at the end of the simulation that is significantly different from the prior data point may indicate that aggradation or degradation might be expected to continue beyond the simulated period.

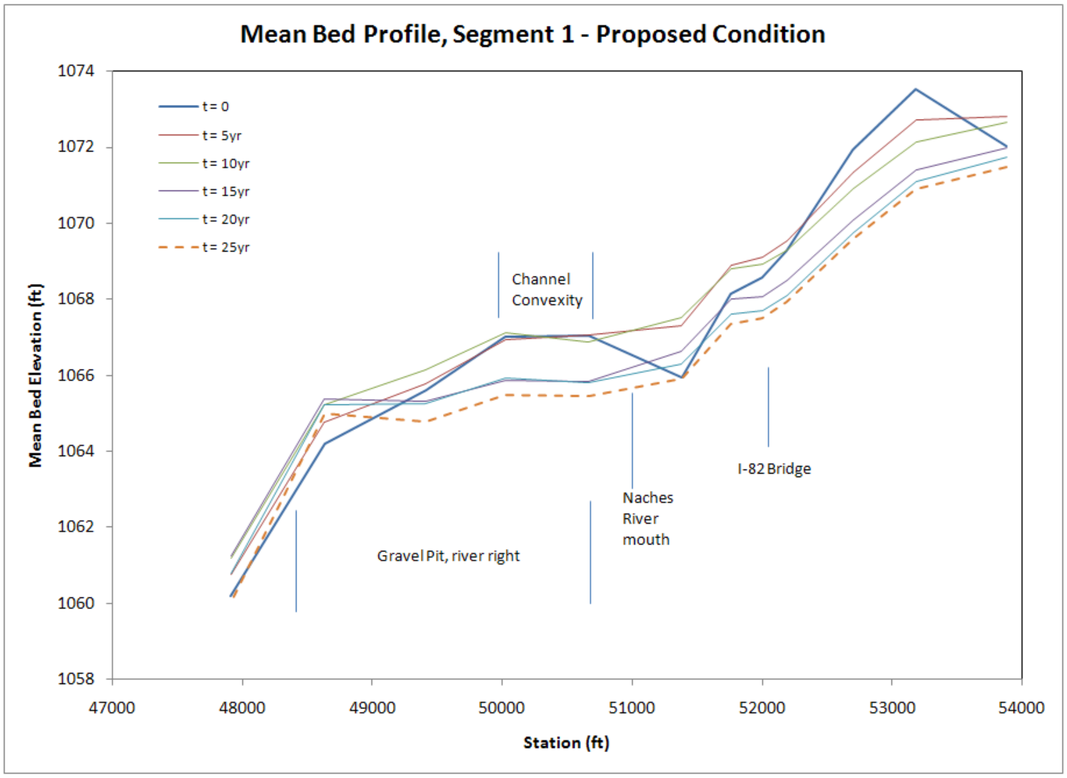

Figure 71: Profile of mean bed elevations in segment 1 throughout the modeling period.

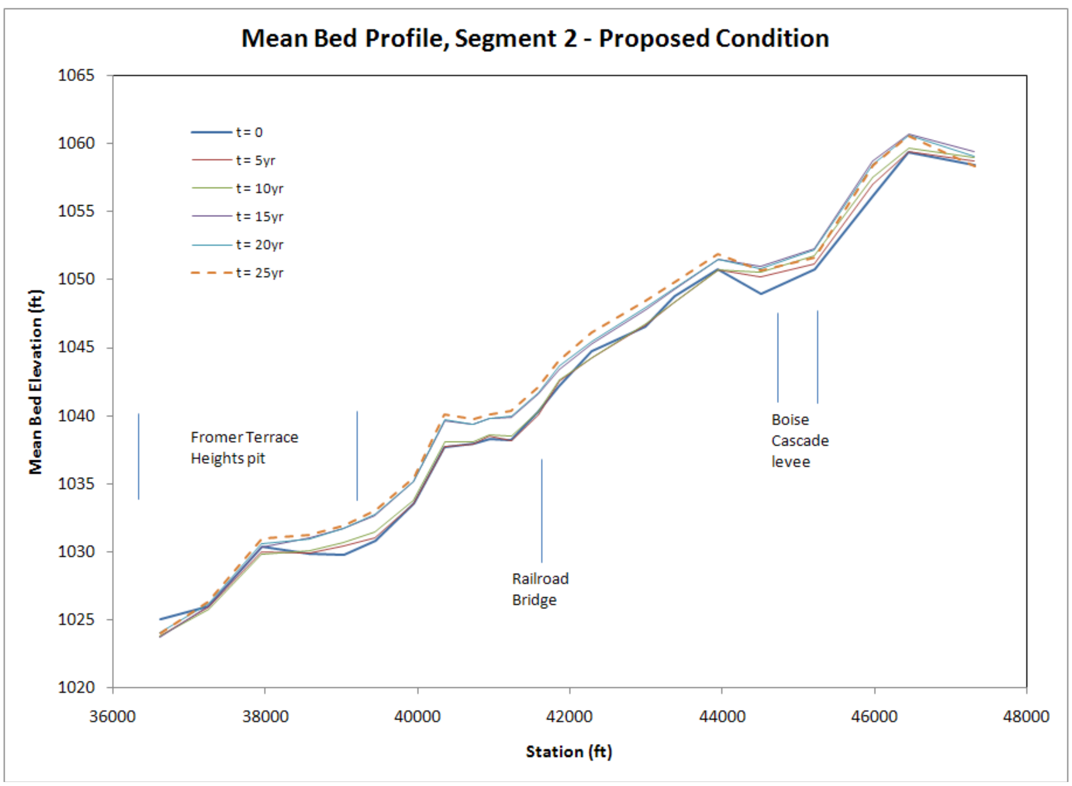

Figure 72: Profile of mean bed elevations in segment 2 throughout the modeling period.

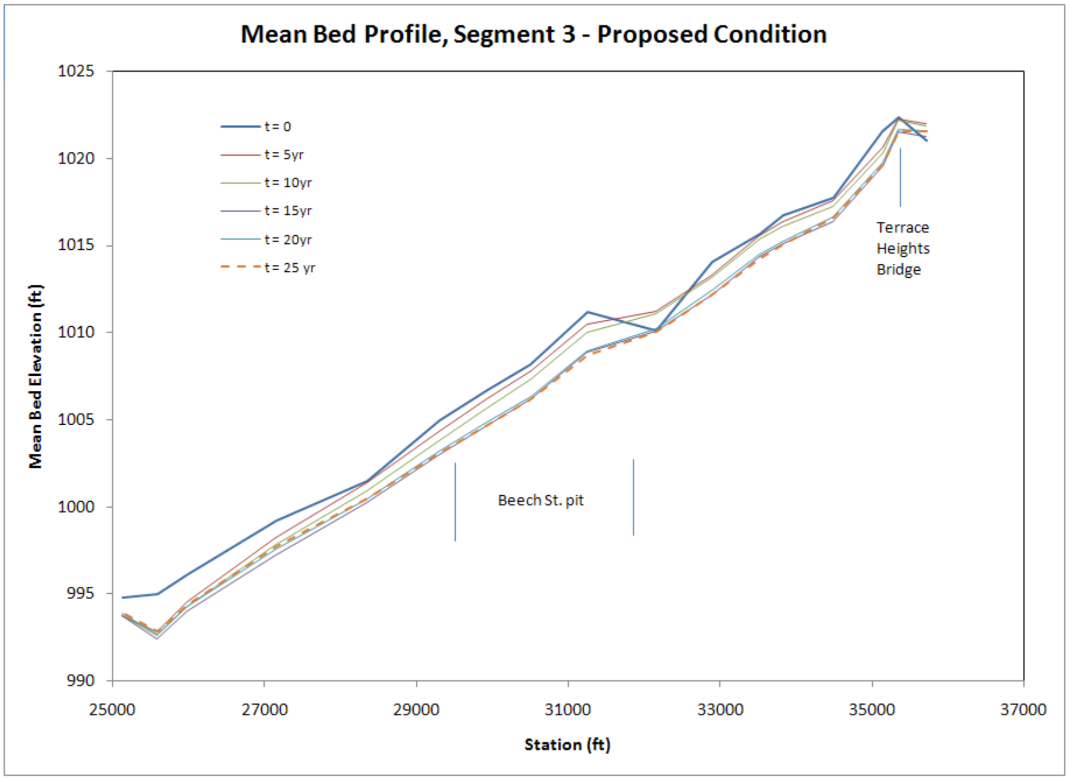

Figure 73: Profile of mean bed elevations in segment 3 throughout the modeling period.

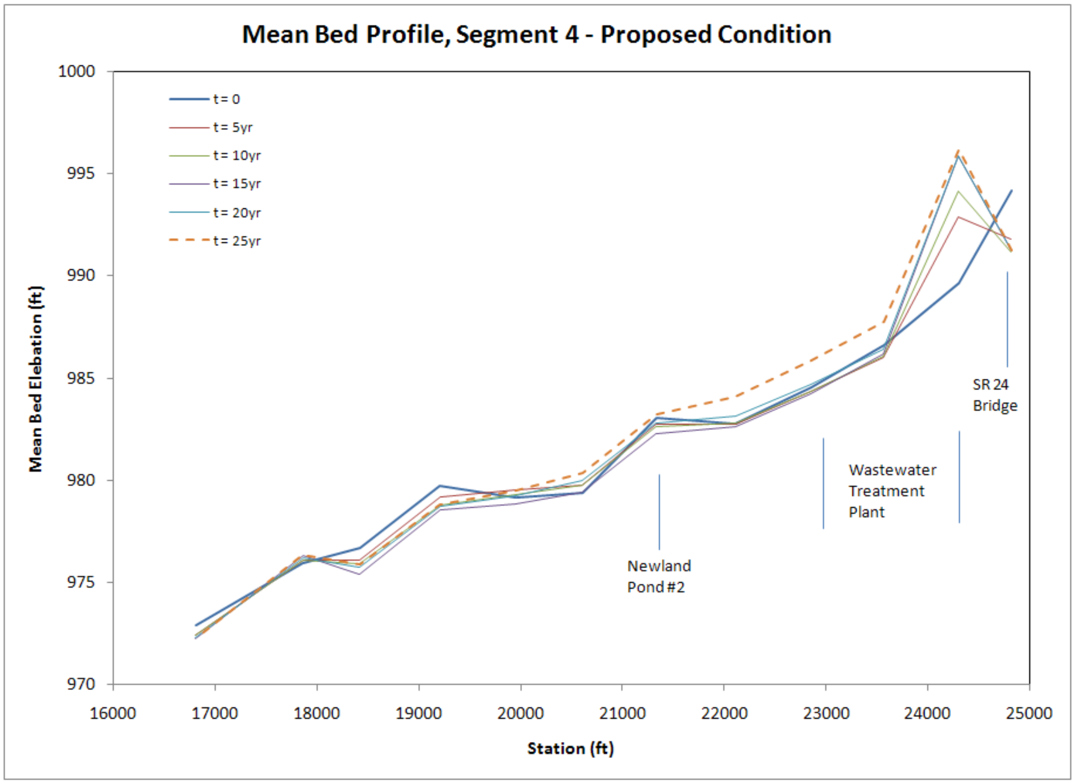

Figure 74: Profile of mean bed elevations in segment 4 throughout the modeling period.

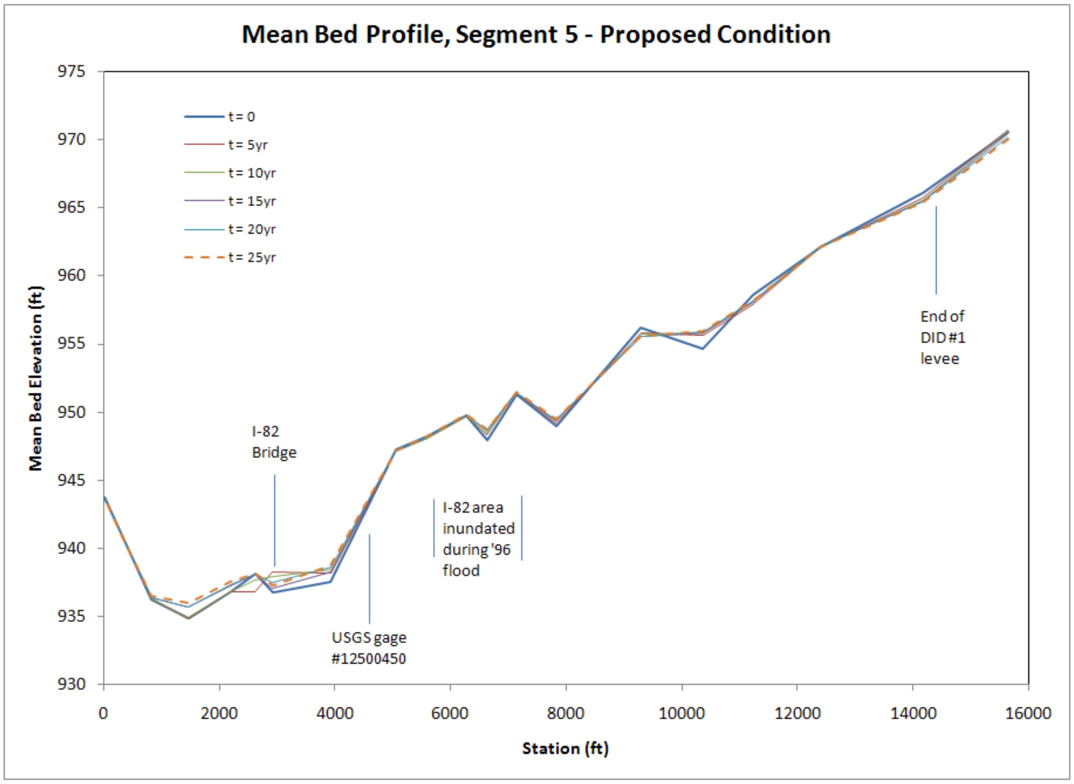

Figure 75: Profile of mean bed elevations in segment 5 throughout the modeling period.

Segment #1 straddles the Naches River mouth and model results indicate a segment average degradation of approximately one foot. Just downstream of the mouth of the Naches River is a large deposit resulting in a channel convexity, that exists in both the 1969 and 2005 channel surveys (see survey profile, Figure 31). This channel convexity is a result of the decreased ability of the Yakima River to transport the large sediment brought in from the Naches River. This delta could fluctuate vertically or even longitudinally to some extent depending upon relative contributions of sediment and flow from the Naches and Yakima Rivers. The convexity essentially presents itself as a large riffle in the river, which tend to be eroded in 1-D sediment models, as is the case shown in Figure 71. Although the predicted degradation is representative of the reach, it is expected that the large channel convexity downstream of the mouth of the Naches River will remain under an existing scenario or the proposed conditions. The reason for slightly less degradation in the proposed scenario is due to an adjustment of slope in segment 2 following the removal of the Boise Cascade levee. The difference in erosion between the existing and proposed scenario is limited to the downstream half of segment 1.

Model results indicate that segment #2 experiences the most aggradation in the study reach (Figure 70). It is anticipated that some of the aggradation in this segment will likely result in lateral channel change, as opposed to an overall increase in channel elevation. However, the deposition could encroach on existing levee freeboard. Deposition at and just upstream of the Boise Cascade levee, upstream of the railroad bridge, and at the upstream end of the former Terrace Heights pit (Figure 72) are likely to cause lateral channel changes. Recent lateral erosion is noted in this segment, discussed further in Chapter 7.3. The slight increase in aggradation in segment #2 under the proposed versus existing conditions can be attributed to the removal of the Boise-Cascade levee and the resulting decrease in sediment transport capacity. The difference is likely not significant.

The downstream half of segment #3 indicates the largest difference between existing and proposed conditions. Most of the change seen in this reach is a result of the loss of a backwater effect, resulting in an adjustment to the channel slope following the levee setback in the vicinity of SR 24. With the DID #1 levee setback under proposed conditions, sediment transport capacity increases upstream of the bridge, allowing for approximately 2 feet of degradation for approximately 6,000 feet upstream of the SR 24 Bridge. This degradation extends upstream past the Beech St. pit (Figure 73), which is a point of concern considering the increased opportunity for undermining of the bank protection along the pit on the right bank. Model results indicate negligible change to mean bed elevations in this reach under existing conditions.

Sediment model results in segment #4 between the SR 24 Bridge and the downstream end of the wastewater treatment plant are somewhat misleading. Under existing conditions, more than 1 ft. of deposition is indicated, although this is not anticipated. The scoured channel between SR 24 and Newland Pond #2 (Figure 74) appears as a pool in a 1-D model and complex flow patterns around the bend (cross sections 22107 – 24299, Figure 36) partially responsible for the current scour condition are not well represented. Under proposed conditions, some channel and floodplain deposition is anticipated, primarily resulting from the degradation in the downstream half of segment 3 combined with the reduced energy following levee setback. The large peak in the predicted mean bed profile just downstream of SR 24 (Figure 74) is an artifact of the model due to the sudden expansion caused by the levee setback and the inability of the model to replicate the energy around the bend near the wastewater treatment plant. The anticipated aggradation scenario under the proposed conditions is that the volume of sediment seen in the first cross section downstream of SR 24 will be deposited throughout the channel between the SR 24 Bridge and Newland Pond #2.

The least aggradation or degradation predicted throughout the study reach under either the existing or proposed scenarios is in segment #5, less than an average of 0.5 feet (Figure 70 and Figure 75). Significant aggradation is not anticipated in this segment over the 25-year evaluation, but the reach will remain highly active with respect to lateral channel position. Localized deposition is likely to cause lateral channel movement upstream of the USGS gage (Yakima River above Ahtanum Creek, #12500450). Minimal dredging of the pool at Wapato Dam has taken place in the past and a site visit and discussions with Chane Salois (Yakama Nation) indicate that gravel-sized sediment is being transported past the dam, based on observations of accumulating gravel behind recently (2007) constructed engineered riffles downstream of the dam. Flow conditions were not conducive to conducting pebble counts during the site visit however this could be performed in the future to learn what sediment sizes are passed over Wapato Dam.

Care must be taken to insure that fluvially deposited gravel, as opposed to manually reworked sediment, is sampled.

Figure 76 details the predicted future change in mean bed elevations of the main channel for existing and proposed conditions. The relative change in mean bed elevation is a result of a running average over three cross sections. Results reflect the average hydrograph projected over the next 25 years. The choice of the five segments becomes apparent when one examines the alternating aggradation and degradation from upstream to downstream. Note the large peak in mean bed elevation at cross section 24299 for the proposed scenario, which is one cross section downstream of SR 24 Bridge. This is the same peak seen in the mean bed profile in segment 4 (Figure 74). The occurrence of this spike has been explained previously in this chapter. Some aggradation is seen downstream of the DID #1 levee in segment 5, which is expected to manifest itself as localized deposition, possibly leading to lateral channel change. Much of this reach also indicates little or no erosion.

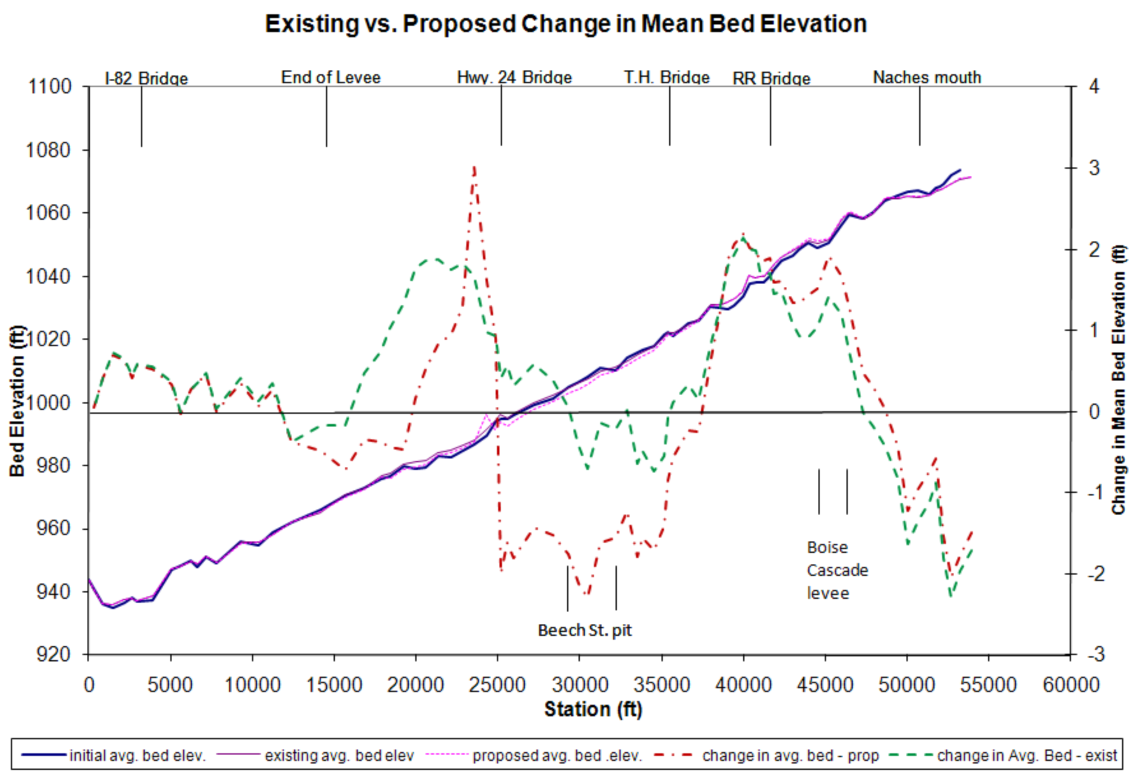

Figure 76: Plot of the model results using the 25-year average hydrograph. Shown are the profiles and relative change in the mean bed elevation (average hydrograph) for existing and proposed conditions.

6.2.1 Consideration of Wet and Dry 25-year Hydrographs

The sediment modeling results of the 25-year wet and dry hydrographs (Chapter 3.2) indicate limited difference between dry and average hydrographs (maximum difference is 0.5 ft.) and more significant difference between wet and average hydrographs (max difference > 2 ft.). Table 10 shows the sediment modeling results of all three hydrographs considering the existing and proposed conditions.

Table 10: Table showing the projected aggradation/degradation considering the 25-year wet, dry, and average hydrographs.

	Change in mean bed elevation (ft)					
Segment #	Existing Conditions			Proposed Conditions		
	dry	average	wet	dry	average	Wet
1	-1.0	-1.2	-3.5	-0.7	-0.9	-3.5
2	1.4	1.4	0.1	1.4	1.6	-0.1
3	0.0	-0.1	0.7	-1.1	-1.6	-1.3
4	1.4	1.4	3.5	0.4	0.9	4.4
5	0.3	0.3	0.6	0.3	0.2	0.5

Under a wetter than average hydrologic scenario, channel change is expected to be greater than an average or dryer period, as the volume of sediment transported under a wetter than average scenario is significantly greater. The average annual *bed material* load transported through each segment also differs little between the dryer than average and average. Modeled bed material load averaged over the five segments is displayed in Table 11. It is apparent that under all hydrologic scenarios the upstream portion of the Yakima River within the study reach transports much more sediment than the downstream portion. Sediment transport capacity decreases significantly downstream of the Terrace Heights Bridge, indicating that the large material coming into the reach from the Naches River is unable to be transported through the entire reach. This conclusion is verified by the significant decrease in d_{84} (Figure 65).

Table 11: Table showing sediment model results for average annual bed material load within each segment for the three 25-year hydrologic scenarios evaluated.

	Average Annual Bed Material Load for Each Segment (tons/year)					
Segment #	Existing Conditions			Proposed Conditions		
	dry	average	wet	dry	average	wet
1	25,093	29,914	83,654	24,461	29,237	83,271
2	27,151	34,514	104,869	21,475	27,820	101,962
3	14,228	18,333	73,423	13,732	20,397	88,152
4	7,548	9,563	35,768	6,267	9,062	43,431
5	1,980	2,499	6,503	1,845	2,188	4,742

6.3 Event-Based Sediment Transport Results

Event-based hydrologic scenarios were modeled to increase understanding of the effect various flood types have on sediment transport within the Gap to Gap reach of the Yakima River. The hydrologic scenarios were defined previously in Chapter 3.3.

Results for the event-based sediment modeling considering existing conditions are shown in Figure 77. The most significant difference among the various floods is the amount of *bed material* transported over the duration of the floods, a factor of three. Modeled changes to mean bed elevations indicate little change among the four scenarios. Event based sediment modeling results considering the proposed condition are shown in Figure 78. The change in *bed material* load is insignificant between the two scenarios, as is the difference in mean bed elevation, with one exception, the three cross sections (23567, 24299, and 24821) in the vicinity of SR 24. The results of the proposed conditions at this location are not necessarily representative of fluvial processes in this area, as the indicated degradation near the bridge and the sudden deposition immediately downstream will occur over greater longitudinal distances following levee setback. Predictions of channel change at this location are expected to be similar to the segment averages as discussed in Chapter 6.2. Additional observations and predictions are discussed in Chapter 7.3.

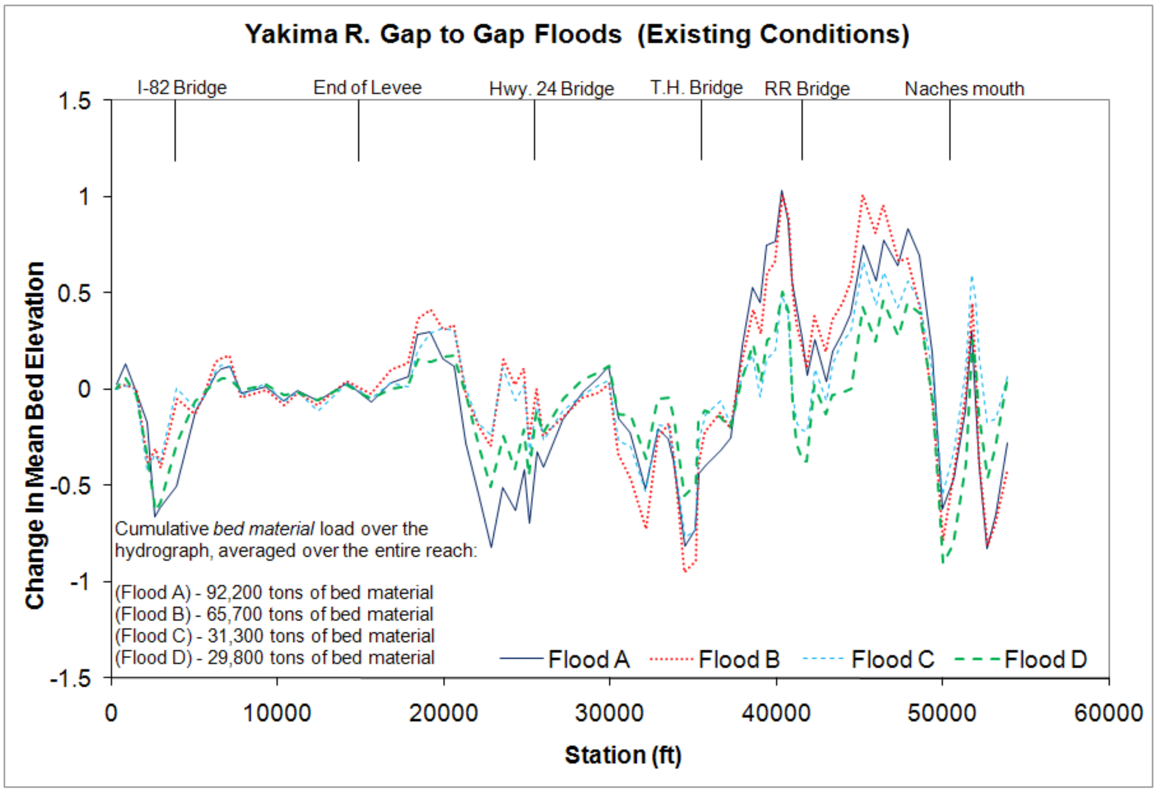

Figure 77: Chart showing the results of the event-based sediment modeling, existing conditions.

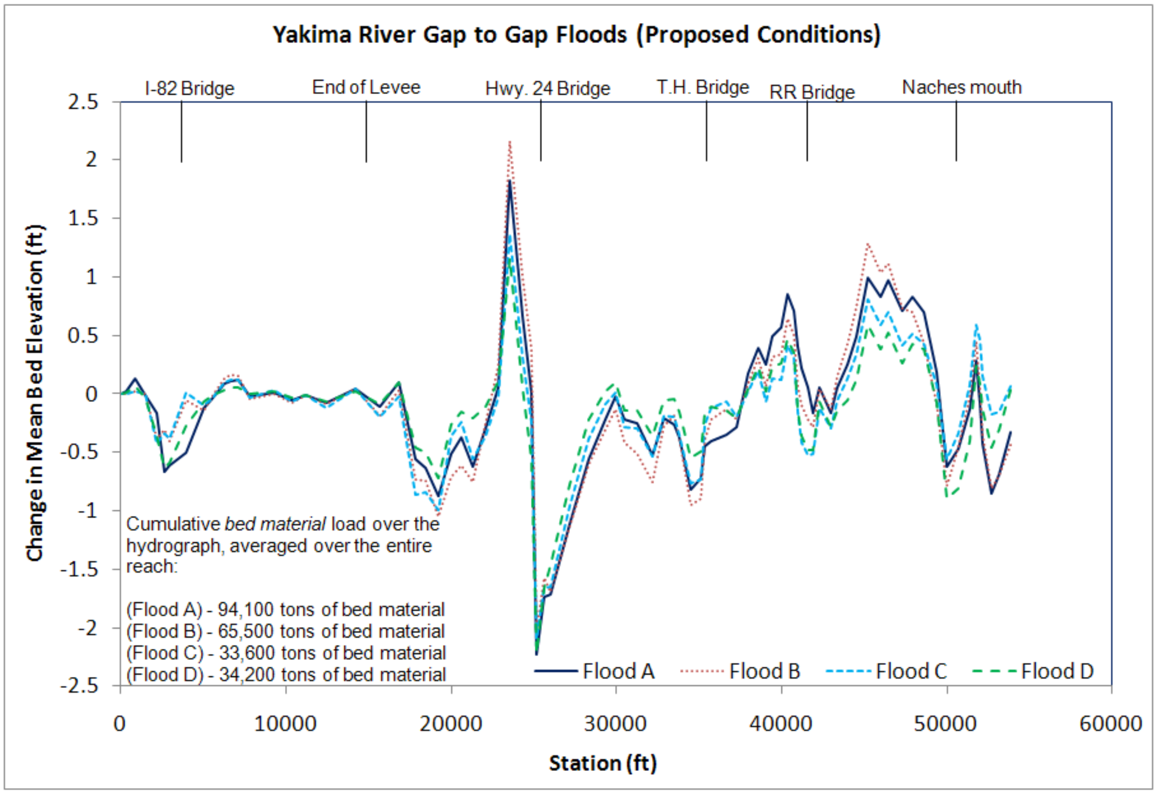

Figure 78: Chart showing the results of the event-based sediment modeling, proposed conditions.

7 Discussion

7.1 Trends in geomorphic parameters

Historical trends were analyzed in the Gap to Gap reach in order to understand whether the channel had historically undergone adjustments in bed elevations. Comparison of cross section data and thalweg elevations from 1969 and 2005 along the length of the study reach indicate that historical aggradation in the channel and floodplain is most consistent in segments 2 and 5a. Other areas of historical bed aggradation include segment 3a from Beech Street pit to Old SR24 where the vertical accretion of floodplain sediments can be observed. Areas of historical bed degradation are located in segment 1, upstream of Beech Street pit (part of segment 3a), segment 4 and part of segment 5b. Cross sections with the largest aggradation based on changes in cross sectional area correspond to the locations of captured gravel pits.

Lateral channel changes, including lateral channel migration and channel avulsion, have been significant historically and are described by channel segment in Chapter 2.2. Some channel segments were observed to be more laterally active in the recent past (last 5 years) than other segments based on field observations between 2008 and 2009 and comparison to 2005 photography. Stable segments include segment 1, segment 3a, segment 4 and segment 5b. Dynamic segments include segment 2, segment 3b and segment 5a. Segments 3a and 4 have had anthropogenic modifications that have acted to fix the channel in place, causing local scour against levees and revetments and channel simplification from multiple flow paths to a single dominant flow path. Segment 5b is located in Union Gap and is controlled by bedrock outcrops adjacent to the channel. Dynamic reaches have either had in-channel modifications to which the channel is responding or have not degraded and are able to more readily make lateral adjustments. For example, segment 2 has changed in several areas where historical gravel pits have been reincorporated into the active channel. In the Terrace Heights gravel pit, several breaches of the gravel pit berms have allowed for multiple channels to form a complex channel network that continues to rework sediment in this area.

Based on observations of historical gravel pit capture in the Gap to Gap reach, the Yakima River is able to reclaim itself due to its mobile sediment load and a flood regime that is geomorphically effective in modifying the active channel. This is an observation that has been previously mentioned by several authors that have worked in this reach (i.e., Stanford et al., 2002; Clark, 2003; Eitemiller et al., 2002). Observations of the capture of shallow gravel pits both from in-stream mining and floodplain mining on the Yakima River as well as other rivers show that pit captures can act to increase channel complexity following their reconnection (Norman et al 1998). However, pit captures also disrupt sediment continuity upon breaching, causing a depletion of sediment in the channel as the pit is filled, and may initiate headcutting and incision upstream of the pit and channel scour and lateral instability downstream of the pit. The gravel pits discussed in Chapter 2.2 are reincorporated into the active channel within one or two decades once they are breached. These captured pits were shallow and likely filled rapidly; however, deeper pits, should they be captured, may have more protracted consequences for sediment continuity in the study reach.

Channel complexity, as measured by the nodal analysis and channel length measurements, continues to increase in segment 5a through 2008 measurements as the channel continues to recover from gravel pit captures during the 1970’s, which simplified the channel network. Channel complexity in other segments shows an overall decrease through the historical period, with the exception of segment 1, which has remained relatively similar. The return to former levels in 1927 is unlikely in these reaches due to levees and revetments that will remain in locations near critical infrastructure, residential development and deeply mined gravel pits.

Channel sinuosity showed the greatest decreases in segments 5a and 3a from 1927 to 2009. These decreases are mostly due to channel avulsions into gravel pits along I-82 during the 1970’s in segment 5a. In segment 3a, levees that cut off former 1927 meanders acted to fix the channel against the levee in a straight (less sinuous) channel pattern. Increases in channel sinuosity from 1927 to 2009 are greatest in segment 2, where the 1927 main channel was considerably straighter than the channel in 2009.

7.2 Comparison to previous geomorphic analyses

In 1976, Dunne et al prepared a report in preparation for the development of the Yakima River Regional Greenway. In the report, the authors outlined changes in slope of the floodplain and fluvial terrace in the Gap to Gap reach, showing a steeper gradient in the upstream portion of the reach and transitioning to a lower gradient near the SR24 Bridge. Dunne et al attributes this change in gradient to a higher rate of uplift along Yakima Ridge at the upstream end of the reach when compared to Ahtanum Ridge at the downstream end. Studies that have explored tectonic activity related to the basalt ridges have found that faults along Ahtanum Ridge and Toppenish Ridge have been active during the late Pleistocene and Holocene, exhibiting displaced sediments that are 13,000 years old and younger (Reidel et al 1993; Geomatrix, 1988). Yakima Ridge is not mentioned in these publications, indicating that it was either not investigated or that associated faults do not have any expression or offsets that would indication Quaternary deformation.

While the slope of the floodplain and terrace does appear to show a break at Highway 24 based on the measurements of Dunne et al, the slope of the longitudinal profile along the channel of the Yakima River shows a less dramatic change (Table 12 and Figure 79). The bedrock constriction at Union Gap has maintained a long-term control on the gradient of the upstream fluvial landforms by restricting the conveyance capacity through the gap and forcing larger flows to backwater behind the constriction and deposit overbank sediments in floodplain areas. In order to maintain sediment continuity, channel avulsions are more common across the broad floodplain surface and sediment deposition in the floodplain occurs across a wider area than in upstream segments. Supporting statements from Entrix (2010) also note that channel migration increases as the river approaches the constrictions at the gaps and tends to decrease downstream of the gaps.

Table 12: Slope measurements of fluvial landforms and main channel thalweg.

Location	Terrace (Dunne et al 1976)	Floodplain (Dunne et al 1976)	Channel thalweg (this study)
Upstream of SR 24	0.0045	0.0036	0.0029
Downstream of SR 24	0.0027	0.0024	0.0024
Average	0.0036	0.0030	0.0027

In their report, Dunne et al. (1976) also made predictions of channel change by the year 2000, or approximately 25 years after the completion of their study. Stable and unstable zones are identified along with possible areas for channel avulsion. A few of the areas identified by Dunne et al. (1976) have experienced avulsions; these are primarily in segment 2, in which the channel has avulsed into the triangular gravel pit and Terrace Heights pit. However, the avulsions have created either split flow or multiple channels in the vicinity of the gravel pits rather than abandonment of the previous main channel. Other areas that Dunne et al. highlighted as potential avulsion areas have not experienced major channel change, partially because levees and revetments have prevented them from doing so.

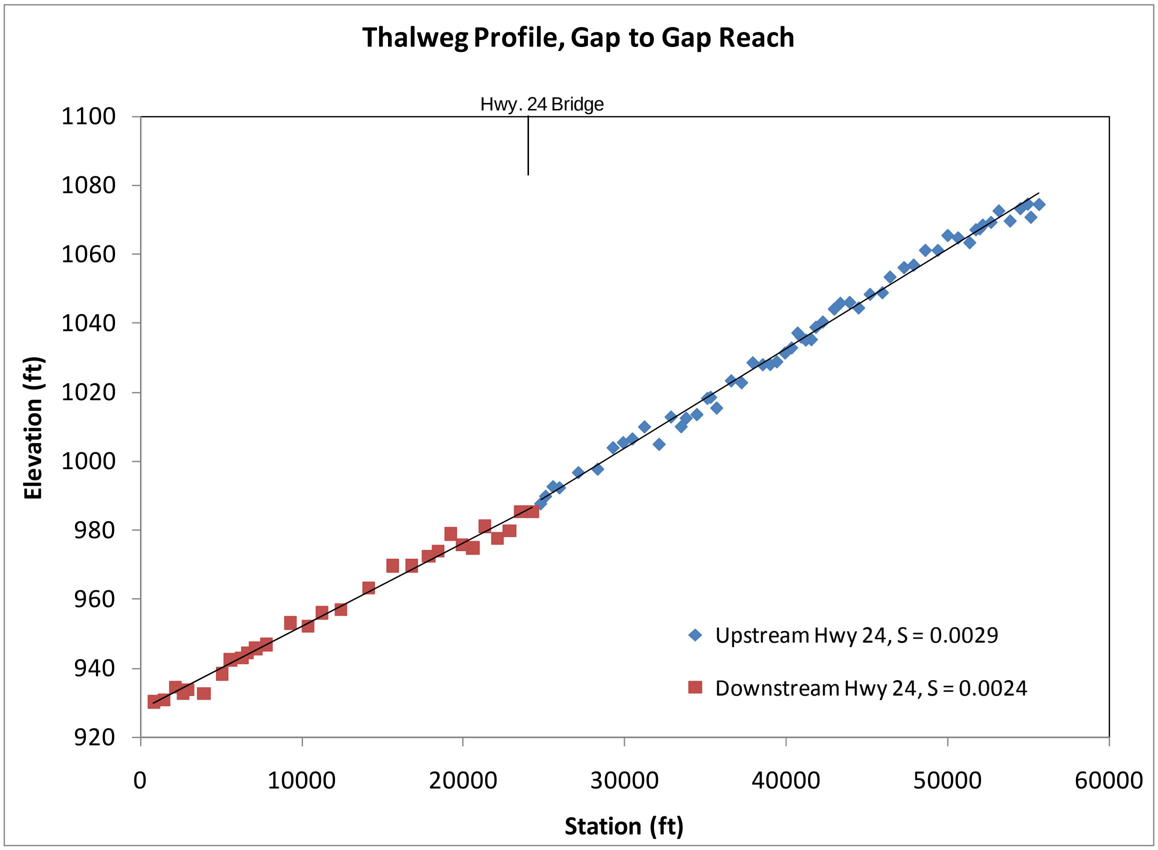

Figure 79: Thalweg profile, Gap to Gap reach

This study attempts to add information to existing studies rather than duplicate any previous work. However, some overlap of work was necessary for the understanding of river processes. Mapping of the younger floodplain generally corresponds to the previously mapped geomorphic floodplain (Clark, 2003; Eitemiller et al., 2002) and has very similar boundaries. Deposits that comprise this map unit range in age from historical to about 300 years old based on radiocarbon dating of charcoal in the floodplain deposits. The older floodplain boundary generally corresponds to the delineation of the Holocene floodplain as mapped by Eitemiller et al. (2002) with some modifications. Paleochannels visible on its surface are hypothesized to be between 300 and 700 years old based on limited radiocarbon dating, indicating that the main channel of the Yakima River has been located in the eastern floodplain within the last 700 years among other locations. In general, deposits that form the older floodplain outside of the obvious paleochannels are estimated to be late Holocene in age. The active floodplain, as mapped by Clark (2003), corresponds to the area that can be actively modified by the river channel and therefore only includes areas between existing levees. This map unit will change as levees are setback and removed along the Yakima River. A map unit that corresponded to Clark's active floodplain was not delineated during this study.

Channel morphology is described differently than the channel types in Eitemiller et al. (2002). This study uses the term anabranching to define channel morphology in the Gap to Gap reach. Similar to Nanson and Knighton's (1996) Type 5 anabranching river, the

Yakima River in this reach can be described as a laterally active system with a gravel-dominated bed, multiple flow paths and semi-stable islands (Nanson and Knighton, 1996). This channel type has characteristics that are transitional between meandering and braided. It may have single thread reaches between anabranching reaches and commonly has a dominant channel, which may be braided. Bank material is typically gravel with a sand and silt cap. The term meandering is not used for the reach just upstream of Union Gap (as in Eitemiller et al., 2002) because multiple flow paths exist in this area that are more typical of an anabranching planform.

7.3 Future Channel Condition

Based on the scope of the study, future channel conditions are predicted for a period of 25 years. Some of the observations noted in the geomorphic study may be of a more immediate nature, while others are anticipated over the 25-year period.

For the geomorphic study, locations of potential change following the levee setback were identified based on field observations during 2008 and 2009 field work as well as historical photo analysis from 2005 to 2009. The locations identified as areas of potential lateral erosion, channel avulsion, or both are based solely on recent observations of channel dynamics and are not currently part of the channel network. Areas that have a high potential for lateral erosion are areas that were observed to be currently experiencing bank retreat or failure of rip rap along outer channel bends. Areas that have a high potential for channel avulsion are areas that show channel erosion along their streambanks or that have significant channel splays and incipient channels on bar surfaces. Unstable areas are those areas in the floodplain that are likely to become part of the main channel due to lateral erosion or avulsion. Avulsions are difficult to predict and can be dependent on flow magnitude, sediment load and other perturbations that may act as catalysts for an avulsion, such as large woody debris. Changes in future channel form will be dependent on flow magnitudes and sediment volumes that develop in any given year rather than over a particular time period. Areas that are highlighted as having the greatest potential for channel avulsion or lateral erosion following the levee setback should be assessed for any critical areas that should be protected to prevent undesired channel change. These areas only apply to the initial period following the levee setback and for the first major flood along the river. The potential areas for channel change would need to be reassessed following the first major channel avulsion or lateral erosion event that modifies the channel geometry. The results of the sediment model compliment the geomorphic analysis by indicating anticipated aggradation or degradation, changes to bed composition, and sediment loads carried through the reach. These factors affect the nature of channel change.

To demonstrate the variability in slope throughout the reach, channel slope was evaluated based on the segment breaks (Figure 80). These slope breaks aid the following discussion of future channel condition in each of the segments.

The following discussion is broken down into five segments that were introduced in Chapter 2.2. The segments identified in the geomorphic study are nearly identical to segments identified in the sediment model based on degradation and aggradation (Section 4.2). Minor adjustments were made to the segment definitions (Figure 36) determined by the geomorphic study and the sediment modeling results to make them agree, which facilitates the following discussion of future channel condition using the results of both studies.

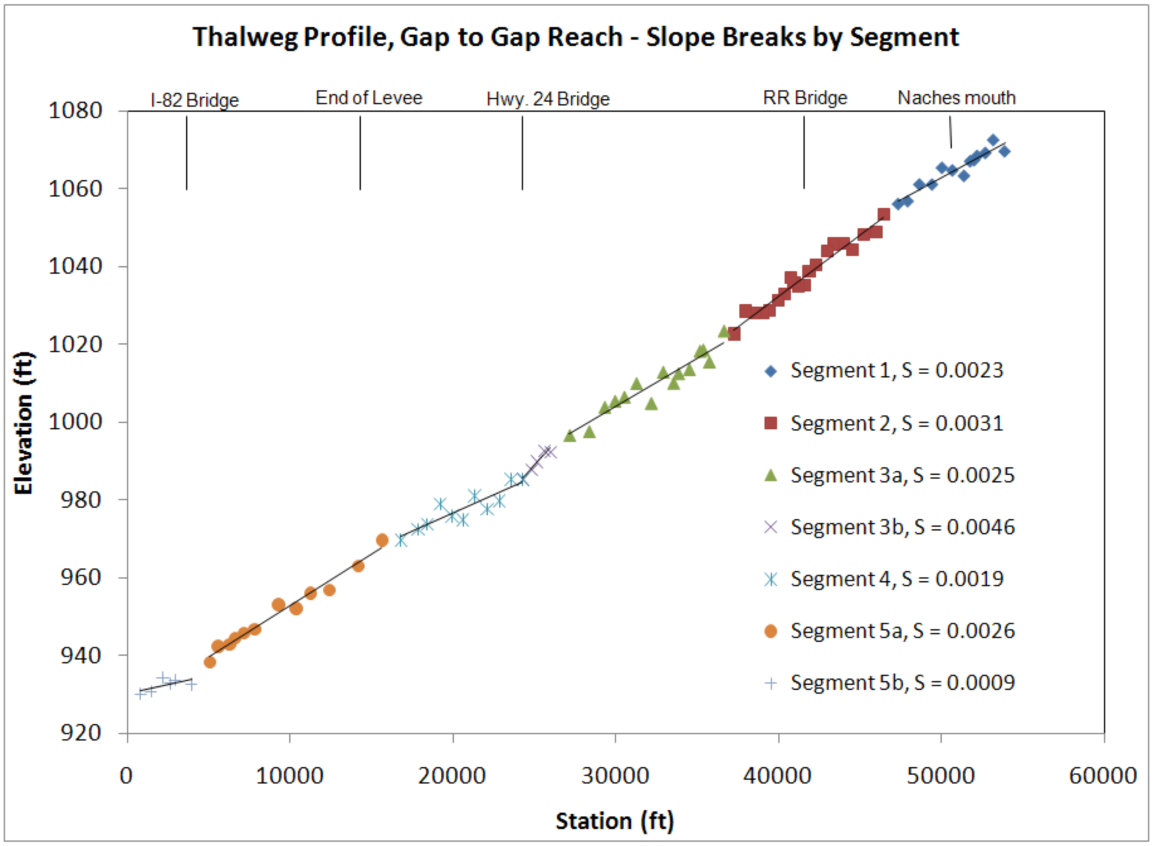

Figure 80: Thalweg profile showing slope by segment breaks.

7.3.1 Evaluating Stream Energy and the Potential for Channel Change

Unit stream power has been used for evaluating the energy throughout the Gap to Gap reach. The underlying assumption is steady, uniform flow with no change in the physical properties of water. Unit stream power then reduces down to the product of velocity and friction slope per unit weight of water and measures the rate of energy dissipation (Yang, 1996). Stream power has been evaluated using a discharge that coincides with that of February 9, 1996 (~44,000 cfs) with a running average using the values of the cross sections immediately upstream and downstream of the cross section of interest. It is reasonable to correlate locations of high energy dissipation with locations of greater potential for channel dynamics (Stanford et al., 2002; Lorang et al., 2005), although correlating high stream power with bank erosion can sometimes be overstated, primarily due to the lack of similarly located bank erosion properties. Areas of low stream power may indicate potential deposition, also signifying locations for potential channel change. This is particularly true downstream of the DID #1 levee in segment 5a. It is important to state that the following evaluation is only indicative of *potential* channel change, and changes in one location may negate or exacerbate changes in another.

Field observations independent from the modeling analysis have been combined with stream power to arrive at a more informed prediction of potential channel change. These changes can include vertical and/or lateral changes in the channel. Unstable areas have notable gravel splays and channels carved into their surfaces or are located along the outside of eroding channel banks; their locations relative to the current main channel and recent deposition make them possible candidates for avulsion or erosion in the future during large floods. Erosion areas are areas located along the outer bends of the main channel or channel branch that were noted to be experiencing levee erosion or rip rap failure. Potential avulsion points or paths are those locations which are the most likely to experience a channel avulsion based on the observed erosion of channel banks or the presence of channel splays and incipient channels on the bar surfaces. The avulsion paths typically follow abandoned historical channels or areas where floodplain channels are likely to be captured by the main channel. T he following discussion is broken into the 5 segments defined in Chapter 2.2.

7.3.1.1 Segment 1

This segment includes no changes to levee configuration and there is no change in stream power from existing to proposed conditions. The low values of stream power at and upstream of the I-82 Bridge over the Yakima River are due to a backwater effect caused by the constriction at the bridge at discharges greater than 15,000 cfs. This segment contains the channel convexity explained in Chapter 6.2 and this feature is expected to remain as a result of sediment deposition from the Naches River. This feature is the cause of the high stream power visible in Figure 81. No areas in segment 1 were identified in the geomorphic study as likely to undergo lateral channel change in the near future. However, the channel convexity may change vertically and/or longitudinally in the future depending on flooding conditions but lateral movement of the channel is unlikely due to its confinement at this location. This assessment assumes competent bank protection between the river and the gravel pit on the right. No active erosion was observed along the gravel pit levee on river right.

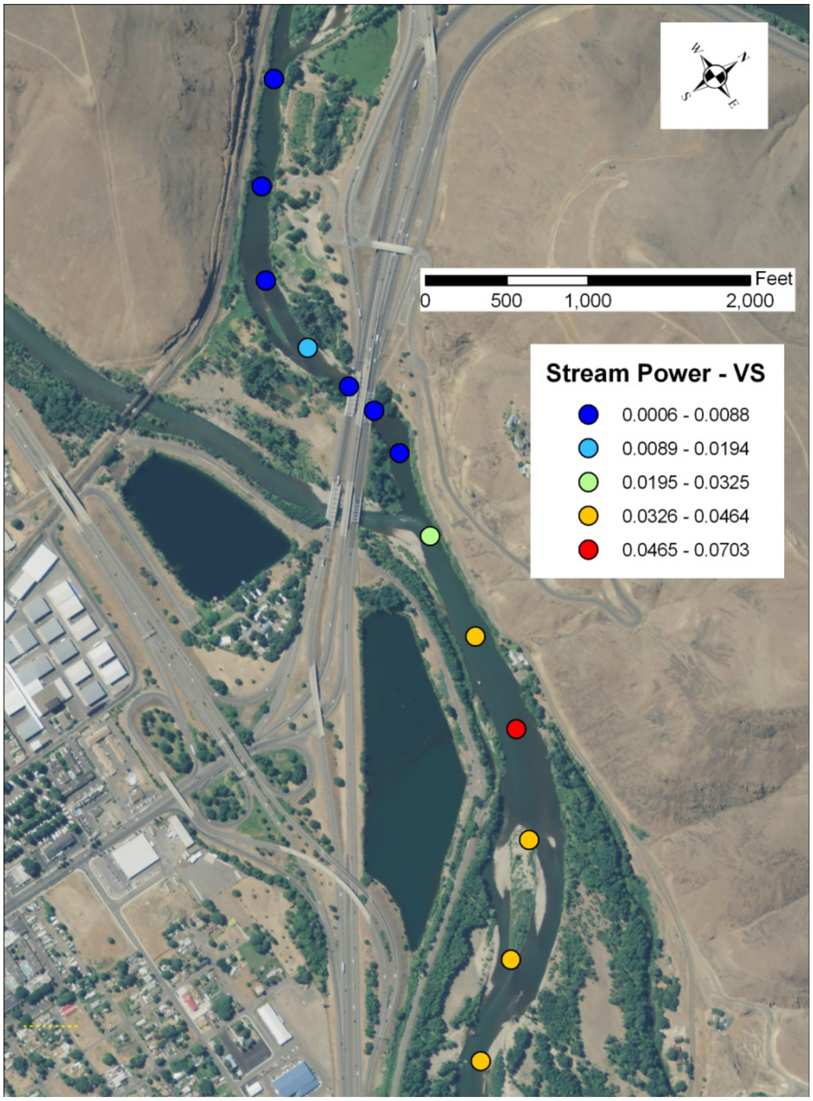

Figure 81: Aerial photograph of segment 1, showing the stream power through the reach. Stream power was determined with the initial proposed conditions, although there are no differences in this segment between existing and initial proposed. No areas of potential change or erosion were identified in this reach.

7.3.1.2 Segment 2

In segment 2, the proposed condition includes the removal of the Boise Cascade levee (see Figure 82). The river channel continues to erode the levee near the river access point on the right bank upstream of the Boise Cascade levee where the left branch channel takes an abrupt turn to the east and encounters the levee road. These areas are at risk for continued lateral erosion and avulsion. Results from the sediment model indicate approximately 0.5 feet of increased aggradation in the vicinity of the Boise-Cascade levee following its removal, which may increase the probability of channel change at this location.

Under proposed conditions, stream power increases slightly following the removal of the Boise Cascade levee due to the loss of a mild backwater effect (see Figure 82). Stream power in the channel decreases slightly along the length of the Boise Cascade levee because flow accelerations are no longer present. Downstream of the levee, stream power values from proposed and existing conditions match. These changes are shown in Figure 51. Upstream of the railroad bridge, flows are retarded by the constriction for approximately 1,500 feet. Observations identify an unstable area upstream of the bridge on river right. This location is vulnerable to attack from upstream during floods, as flows inundate the gravel pit on the right, and possibly from the main channel. For approximately 1 mile upstream of the railroad bridge, 1 to 2 feet of aggradation is anticipated over the next 25 years under both the existing and proposed conditions, further indicating a laterally active channel. With continued erosion along river left, a 1949 channel path could potentially be reactivated by an avulsion.

Downstream of the railroad bridge, top widths decrease from approximately 900 feet at the bridge to 700 feet where the stream power peaks locally (Figure 82). Here observations indicate an unstable area on river left that coincides with this increase in stream power, indicating the potential for channel change under either the existing or proposed scenarios.

Continuing downstream, stream power values remain high as the river flows against I-82. Again, this is true for both existing and proposed conditions. Here flow is constricted until it reaches lower floodplain elevations toward Terrace Heights Bridge. Geomorphic observation identifies the right bank as an erosional area and an unstable portion of the floodplain on river left. High stream power values are of greater significance on river right along the levee, as continued bank erosion is likely. Model predictions do not indicate significant aggradation or degradation here.

Sediment model results indicate much of segment 2 as aggrading in the future (Figure 70 and Figure 73). Excess sediment deposition will likely exacerbate lateral erosion and channel avulsion in this segment.

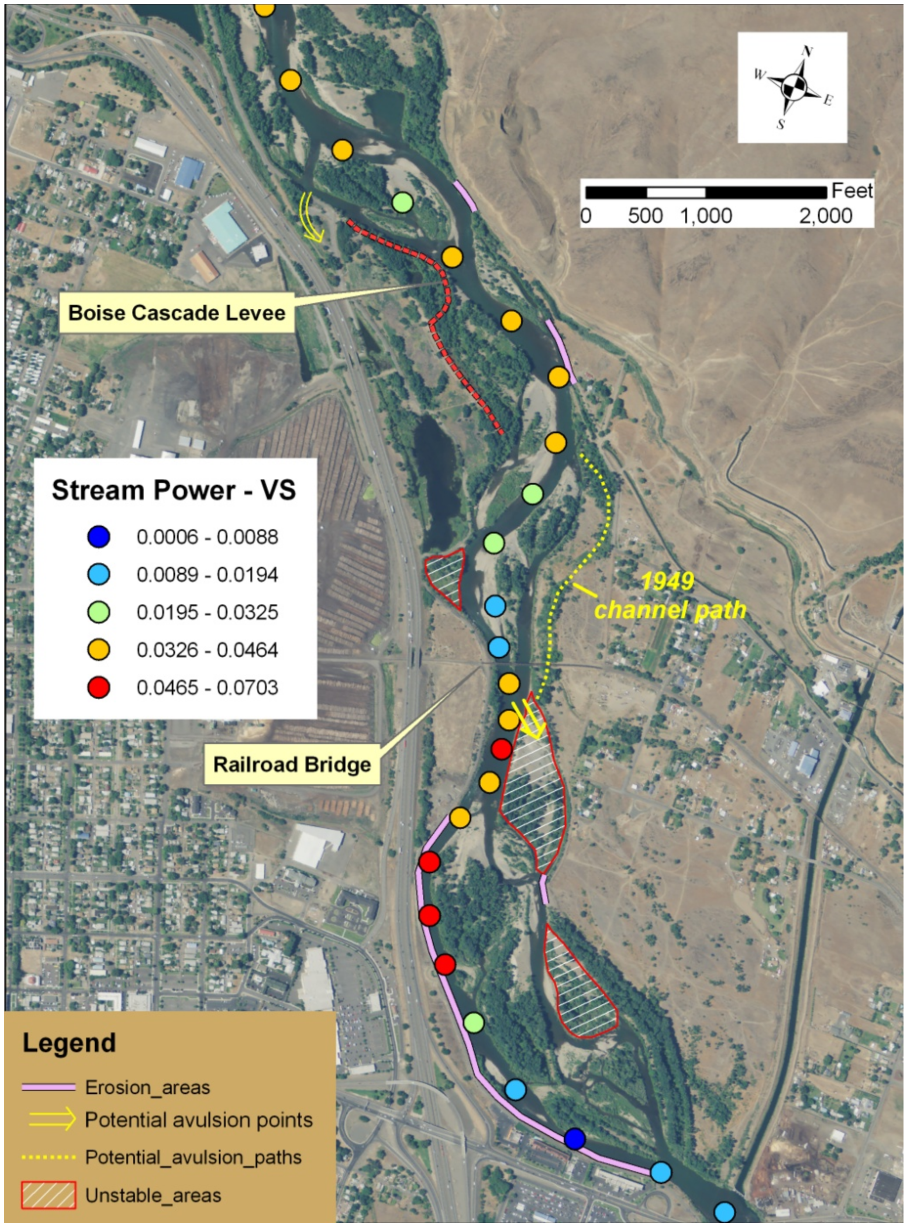

Figure 82: Aerial photograph showing stream power values for the initial proposed condition in segment 2. Also shown are areas of potential channel change. Values of stream power change in this reach between existing and initial proposed conditions. See Figure 51 for differences between the two scenarios.

7.3.1.3 Segment 3

In segment 3a, there are no changes to levee configurations in the proposed conditions and stream power through this reach remains unchanged from the existing to the proposed conditions. Downstream of the Terrace Heights Bridge, erosion of the left bank levee has been observed (Figure 83). This location coincides with moderate levels of stream power and bed elevations are expected to degrade in the future, approximately 1 foot for existing conditions and 2 feet for proposed conditions (Figure 76), posing increased risk to the levee on river left.

As the river approaches the levee on river right upstream of the Beech Street pit, velocities, and therefore stream power, begin to increase dramatically as flow is concentrated against the levee upstream of the Beech Street pit. This finding agrees with that of Lorang et al. (2005), however the current analysis indicates high stream power values along the entire length of the Beech Street pit while Lorang et al. (2005) indicate low stream power values. The main channel continues to scour the rip rap along the Beech Street pit and will continue to be a risk for lateral erosion; this area was formerly occupied by a western channel branch in 1927 prior to the levee construction. If the levee is not maintained, this area could be at risk for avulsion. Hydraulic model results show this area to have some of the highest unit stream power values in the study reach (Figure 51), further indicating the likelihood of erosion near the upstream end of the Beech Street pit.

Beginning at the downstream end of the Beech Street pit, top widths increase significantly and stream power is reduced. Sediment model projections indicate some degradation along the Beech Street pit (up to 0.7 feet) under the existing scenario. For proposed conditions, much more degradation is anticipated (up to 2 feet). Continued degradation along this levee will weaken and undermine the existing bank protection. Because of the significant depth and volume of the Beech Street pit, an avulsion to the west at this location could be catastrophic with respect to infrastructure both upstream and downstream of the pit. Sampling bed material in the river channel along the Beech Street pit is not possible due to excessive depths and velocities. It is possible that the bed material in this location is coarser than that represented in the sediment model, in which case the model may be over predicting degradation. Geomorphic observations that include sediment deposition on river left at the upstream end of the Beech Street pit, bar building along the levee on river right and streambank erosion on the opposite (left) bank indicate that channel change is currently taking place in this reach, although not as dramatic as some other reaches. A potential avulsion point is located at the upstream end of the eastern floodplain that reflects the recent sediment deposition and channel adjustments downstream; this avulsion could follow previous side channels that were active historically.

In Segment 3b, the proposed setback of the KOA levee causes stream power to increase upstream of the SR 24 Bridge, as the backwater effect of the constriction is removed (see Figure 51). The setback of this levee could also allow the channel to laterally erode this area and shift toward the east. Based on the many historical channel changes in this reach and increased stream power, it is likely that the main channel will continue to shift in the future between its multiple channels. The longitudinal profile (Figure 32 and Figure 80) indicates some historical aggradation for approximately 3,500 ft. upstream of SR 24, which will likely be degraded to match the channel slope immediately upstream under proposed conditions. Examining the model results for the existing conditions, aggradation is expected to continue near the KOA levee.

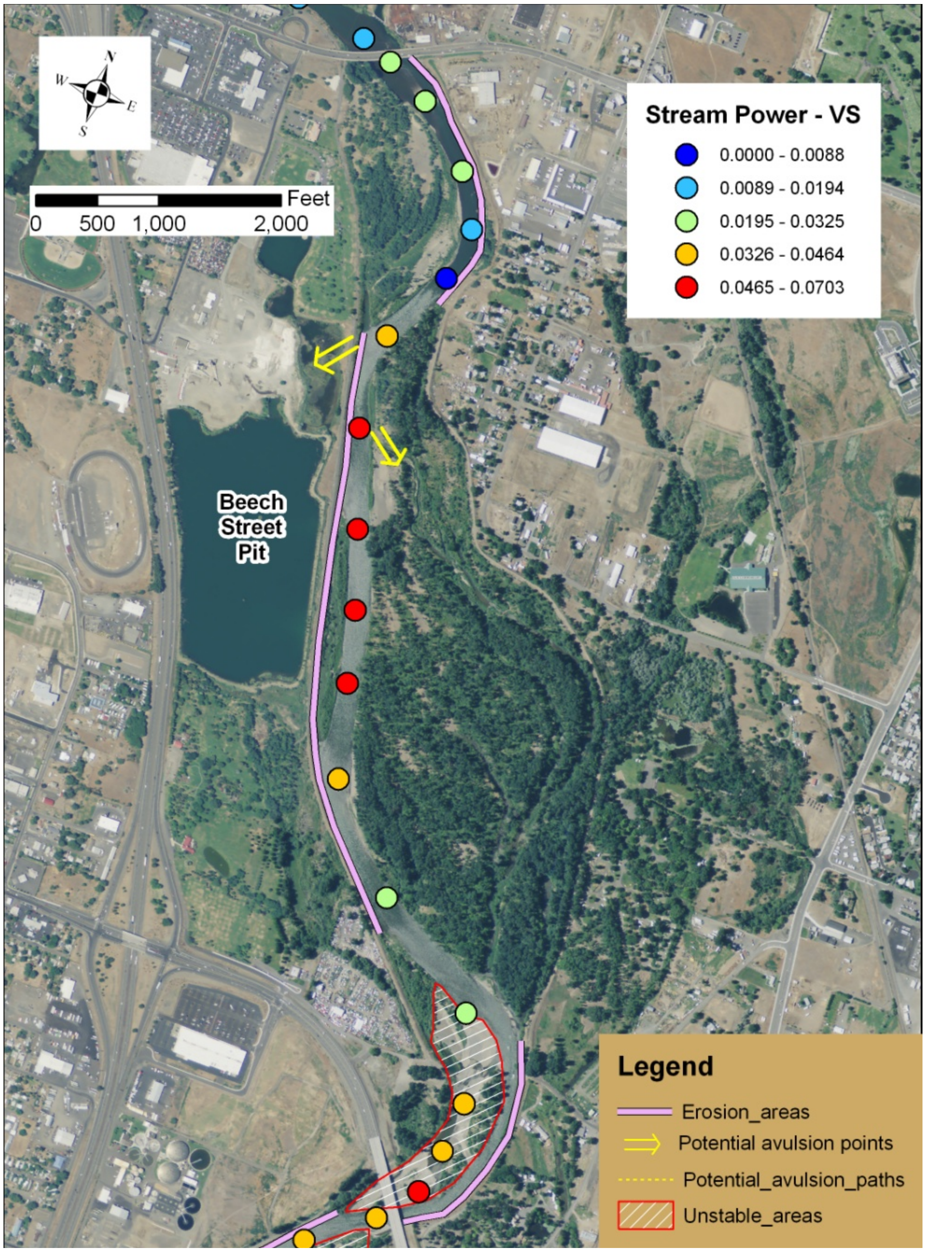

Figure 83: Aerial photograph showing stream power values for the initial proposed condition in segment 3. Also shown are areas of potential channel change. Values of stream power increase at the downstream 4 points in this segment between existing and initial proposed conditions. All other values remain unchanged. See Figure 51 for differences between the two scenarios.

7.3.1.4 Segment 4

Segment 4 is the location of the greatest physical change under the proposed conditions, and as such, indicates the greatest change in stream power (Figure 51). Under existing conditions, stream power values are high, which is in contrast with the findings of Lorang et al. (2005). Model results in this study indicate that the bend along the wastewater treatment plant experiences the highest velocities in the Gap to Gap reach, making it difficult to justify low stream power values. Although the sediment model results indicate deposition in one cross section downstream of SR 24 Bridge (shown in Figure 76), main channel deposition is anticipated over a few thousand feet throughout the bend, as transport capacity is reduced following levee setback. Sediment model results indicate approximately two feet of aggradation in this vicinity, thus maintaining the significant decrease in stage indicated previously.

At the downstream end of the bend, where the river turns south, erosion has been observed and an avulsion point identified. This avulsion point agrees with the findings of Lorang et al. (2005), where they also defined locations of potential channel avulsion. Here, proposed conditions indicate a significant decrease in stream power compared to existing conditions, and future sediment conditions are expected to aggrade slightly. Downstream of this point, stream power values remain moderate, although lower under initial proposed conditions.

Segment 4 has been a laterally stable reach during the historical period with little channel change. As it is narrowly constrained in most areas by levees and revetments, it has also not had much opportunity to change its position. Several gravel pits exist in this reach that will become accessible by overbank flows and channel processes following the levee setback. These pits include the Newland ponds and other unnamed gravel pits downstream of the Newland ponds. The waste water treatment outfall is also located in this reach along the right bank. Continued erosion of the right bank at the location of the wastewater treatment plant is likely under existing conditions, however setting back the levee on the left bank decreases these erosional forces. Areas of specific concern in segment 4 are discussed in the following paragraphs.

7.3.1.4.1 Newland Ponds and other gravel pits on left bank

Newland Pond #1 (Figure 85) is located on the inside bend just downstream of SR24 Bridge. This pond has a maximum depth of 30 ft and an average depth of 11.9 ft (WADNR, 2004). While a split flow channel existed in this area in 1927, the eastern branch channel was located within the floodplain and east of the levee as it exists currently. Following levee removal, it will be possible for the main channel to avulse into this pond, which would disrupt sediment continuity for a significant period due to the depth of the pit. The integrity of SR 24 Bridge would come into question should an unplanned avulsion occur into this pit. An upstream migrating head-cut would likely occur, severely degrading the channel bed and possibly undermining the bridge piers. Similar erosion patterns were observed during an avulsion of the Yakima River into the Selah pits in February 1996 (Norman et al., 1998). A plan should be in place to prevent a sudden avulsion into Newland Pond #1. Smaller and shallower pits, labeled the “A Ponds” (Figure 85) are not expected to capture enough gravel to be problematic. The existing channel is likely low enough in elevation to maintain a regular surface connection in the event of an avulsion but may be subject to aggradation due to decreased energy through the channel following an avulsion. This type of situation may be controlled through engineering to maintain flow conveyance and grade control through a western channel.

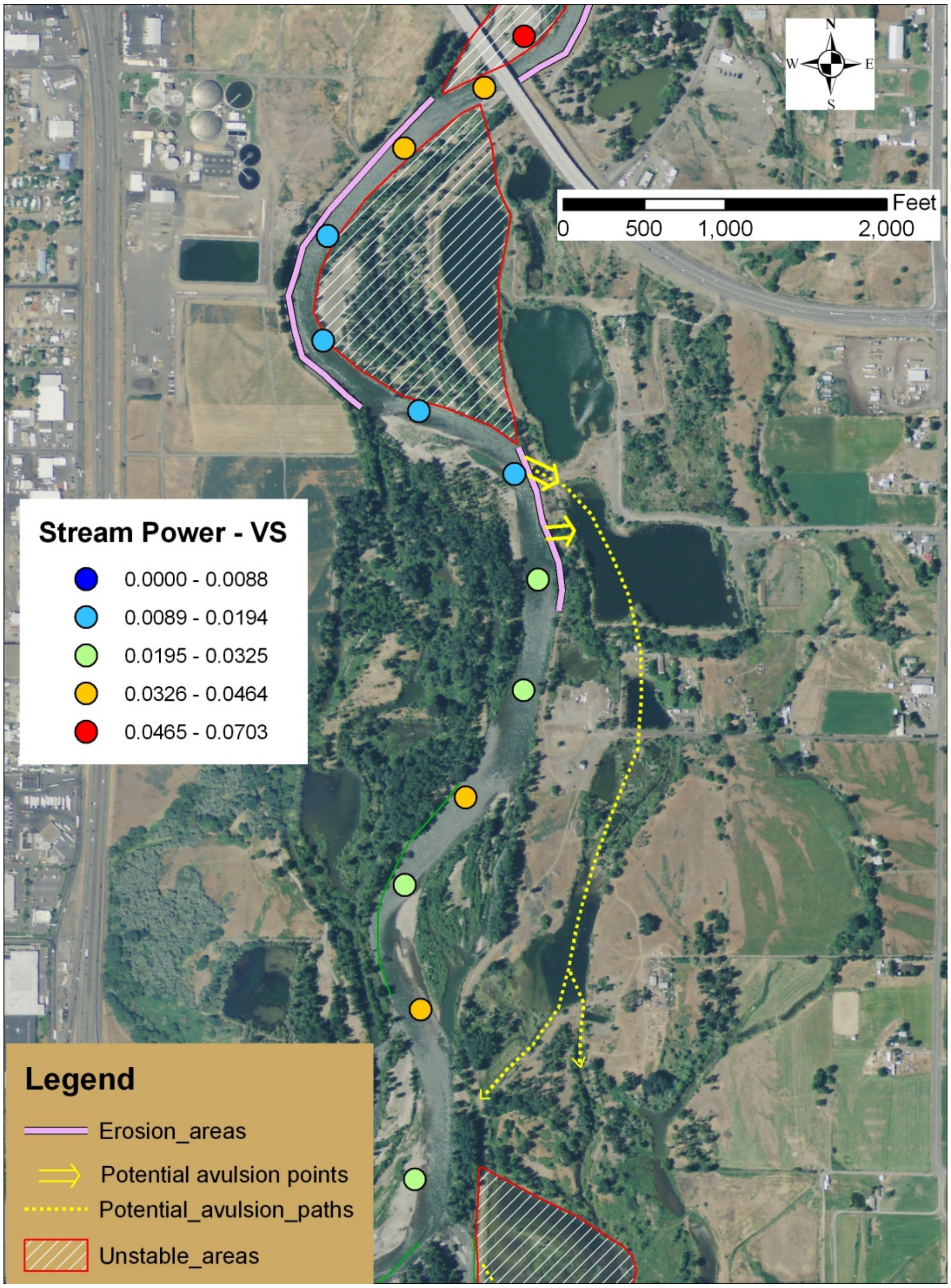

Figure 84: Aerial photograph showing stream power values for the initial proposed condition in segment 4. Also shown are areas of potential channel change. Values of stream power decrease significantly in this segment between existing and initial proposed conditions. See Figure 51 for differences between the two scenarios.

Following the levee setback, Newland Pond no. 2 (Figure 85) and an adjacent gravel pit in segment 4 (B Pond) are likely to be captured (points 4-1 and 4-2). The time span over which capture may occur depends largely on the future hydrology as well as the method of levee setback. If the majority of the levee is removed from the area, channel flows will sooner access the floodplain and work to laterally erode the walls of the gravel pits. Regardless of the method of levee setback, the area is likely to laterally erode in the future and fill in with sediment. This process would be similar to the capture of Edler Pond no. 3 (see Figure 18). However, it is also possible for channel avulsions to take place in this area following the breaching of the gravel pit berms. The depths of these pits are not recorded in the Gravel Mining Impact Study; based on their areal coverage, the pits are assumed to be of similar depth to that of Newland Pond no. 1. Upon a breach of the pit, sediment deposition into the pit may initiate headcutting upstream and cause a sediment starved flow downstream of the pit to scour and erode laterally. Some small pits with nearby relict channels (C and D ponds) could be inundated downstream of Newland Pond no. 2 (Figure 85), which may initiate headcutting and avulsion of the main channel to the east through these larger pits. It is recommended that the depth of at least the larger pits in segment 4 be determined prior to the levee setback.

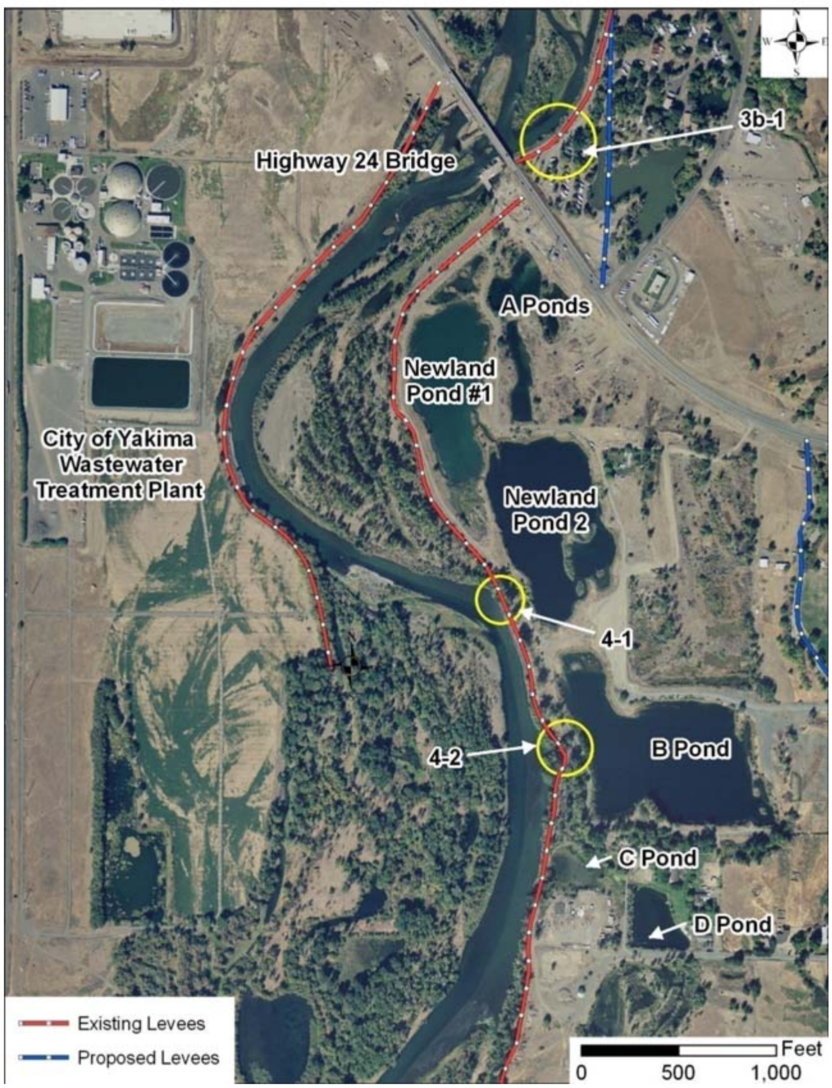

Figure 85: Site map of the Newland Pond area. Flow is from north to south in the photo.

7.3.1.4.2 Waste water treatment plant outfall

The waste water treatment plant outfall is located along the right bank and discharges into the Yakima River downstream of the SR24 Bridge. Following levee setback, it will be possible for the channel to avulse toward the east, forming a split flow channel similar to 1927. Relief between the thalweg and point bar adjacent to Newland Pond no.1 is greater than that of bars in other areas, making this bar less accessible by floods and therefore a lesser risk for avulsion. However, bed changes at the upstream end of the point bar following the levee setback upstream of SR 24 could make this scenario more plausible. In the event of a split channel in this location following levee removal, a frequent surface connection on the right bank is likely to maintain itself, therefore providing a potential location for discharge and dilution of effluent.

7.3.1.5 Segment 5a

Segment 5a contains no changes to levee configurations in the proposed scenario. The area near Edler Pond no. 3 (Figure 86) continues to evolve through bar progradation and accentuation of the right bank meander bend. The low bank and location of a small channel to the west makes this an area of continued lateral erosion or potential channel avulsion and was also noted by Lorang et al., (2005) as having a high avulsion potential. It is possible that the main channel could avulse or a side channel could develop by headcutting during higher discharges from the existing springbrook along I-82 and into the main channel. Model results indicate only slight degradation in this vicinity under either scenario. Downstream of this location, stream power moderates as top widths increase, and some degradation is indicated by the model results under either scenario.

Throughout segment 5a, multiple avulsion areas are possible following levee set back; most of these occur along the eastern side of the main channel, as the main channel is currently located at its westernmost extent along the I-82 embankment. An area of high potential for avulsion can be found in the floodplain to the east of the main channel in which extensive channel splays and channel widening of secondary channels has been occurring in the last 5 years. Stream power values in this location are moderate, and are likely to change locally with shifting channel position. As the channel continues to erode laterally, greater amounts of sediment and discharge may be directed into these channels and continue to widen them until one becomes the main channel. The levee setback will also allow access to several abandoned historical channels as possible avulsion areas. Channel changes at the upstream end of segment 5a will impact the potential avulsion areas in the downstream portion of segment 5a. If changes are slow to occur at the upstream end, channel avulsions at downstream points are likely. During field work, the channel bed along Interstate 82 was observed to be building, elevating the stage of the discharge against the highway embankment; large woody debris was also observed to be depositing in this reach. The sediment model does not account for woody debris and as such, does not identify significant aggradation here. If the trend in sediment deposition continues in this reach, an avulsion to the east is likely in the future. Cross sections near this location show that the 2005 channel bed is lowest in the main channel against I-82; however, this is the only channel with bathymetric data, suggesting that other wetted channels are lower than they appear in the survey and conservatively have depths of 1-2 ft greater than the cross sections portray. Lateral channel change in segment 5a is dependent on incoming loads from upstream, as local accumulations often dictate channel avulsions. Should one or more of the pits in segment 4 capture the channel or otherwise

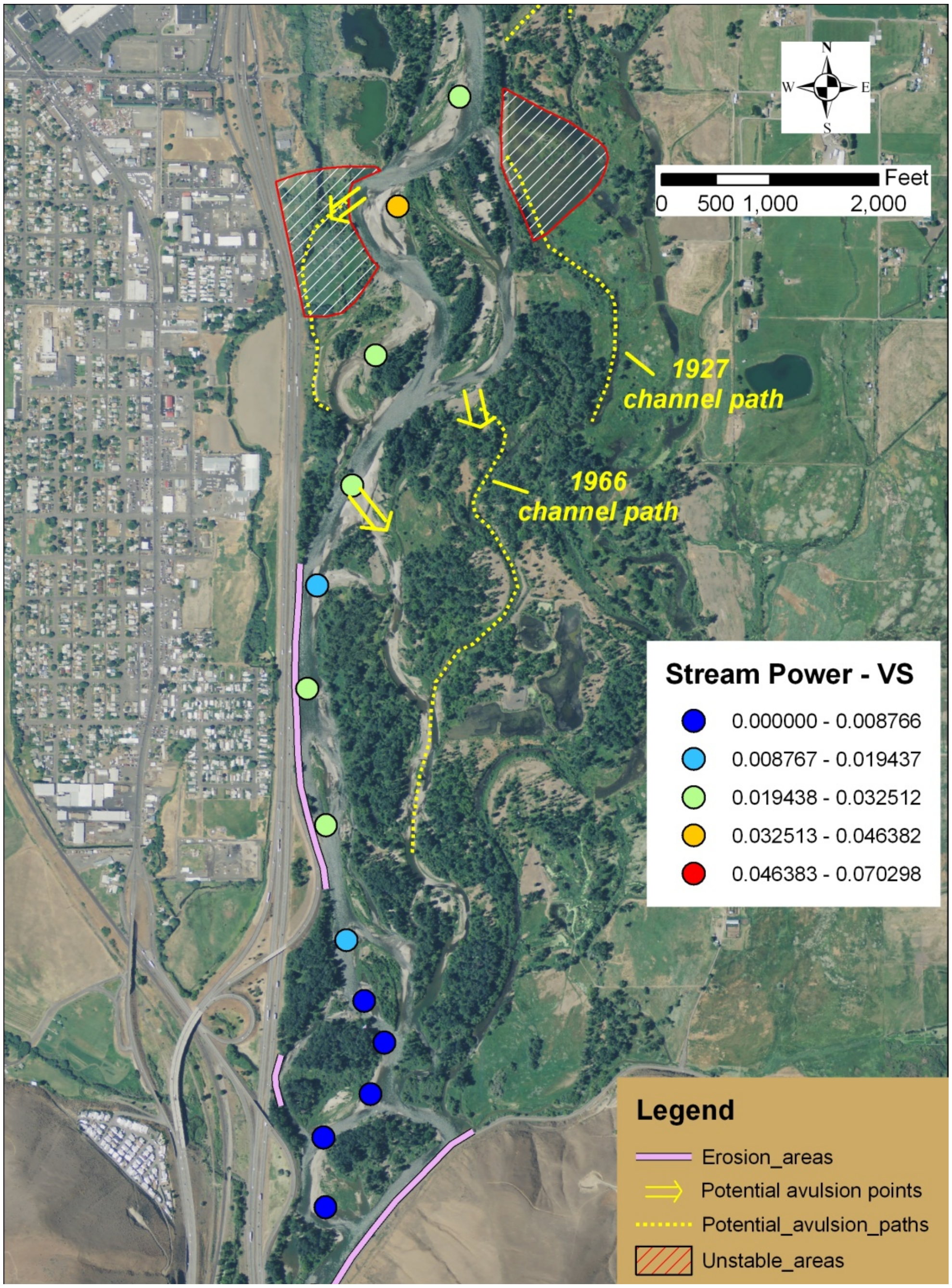

Figure 86: Aerial photograph showing stream power values for the initial proposed condition in segment 5. Also shown are areas of potential channel change. Values of stream power decrease only for the two northern points of the segment between existing and initial proposed conditions. Values elsewhere remain unchanged. See Figure 51 for differences between the two scenarios.

become a sediment sink, lateral channel change in segment 5a will be affected. Sediment model results in segment 5 indicate some aggradation, which is interpreted as indicating localized deposition in the future.

Avulsions, as stated before, are highly dependent on the future hydrology in the Gap to Gap reach. Large-magnitude discharges will exact greater change in the reach by mobilizing greater amounts of sediment and exerting greater shear stress on the channel bed and banks. The unconsolidated nature of deposits along the main channel in the Gap to Gap reach and the high sediment load will allow for frequent lateral channel shifts and fluctuations in bed elevations. This combination allows the channel to modify itself, creating a variety of physical conditions in the channel and thus a variety of habitat.

7.3.1.6 Segment 5b

Segment 5b is located in Union Gap and stream power values are low. This portion of the channel is influenced by the backwater from Wapato Dam. The main channel has been in a similar location historically and is bounded by bedrock. No areas in segment 5b were identified in the geomorphic study as likely to undergo lateral channel change in the near future due to the bedrock control in this reach as well the need to maintain the current channel position under the I-82 Bridge. Sediment model results indicate the channel may aggrade slightly (< 1 foot, Figure 75). The cross section comparison of 1969 and 2005 indicates that the mean bed elevation within the channel has degraded in sections 209, 210, and 211 (Figure 29). It appears that Wapato Dam is able to pass medium to large gravel, as evidenced by the accumulation of upstream gravel in newly constructed grade control features (pers. Communication, Chane Solois).

7.4 DID#1 Levee: anticipated impacts and recommendations

The DID#1 Levee setback will reconnect a large expanse of the eastern floodplain that has been isolated from floodplain and channel processes since at least 1979. Several abandoned channels and gravel pits exist in the area that will be reconnected. Channel change is anticipated to occur in areas where the current main channel or secondary channel branches are located near the gravel pits and relict channels. These changes are expected to enhance the recovery of channel complexity, especially in segment 4 where levees and revetments have restricted channel movement for much of the historical period. Water surface elevations and channel velocities will be reduced, not only relieving pressure on west side revetments but also reducing the flooding hazard. An examination of the sediment model results indicates that aggradation in the vicinity of the wastewater treatment plant is likely, but not so much aggradation occurs as to increase flooding risk over the current conditions.

The levee setback is also anticipated to increase inundation of the eastern floodplain downstream of the SR24 Bridge between the new levee alignment and the Yakima River. Any structures located to the west of the new levee alignment should be evaluated for flooding posed by the levee realignment. The levee setback is expected to cause some degradation in the vicinity and upstream of the new SR 24 Bridge due to the loss of a backwater condition. A scour analysis is beyond the scope of this study but it is assumed that this was performed during the design phase of the bridge. Deposition is likely downstream of the bridge due to the temporary increase in sediment load. However the large scour pool that currently exists in this area can accommodate a large volume (~ 15,000 yd^3) of sediment. The anticipated aggradation of approximately 2 feet along the levee near the wastewater treatment plant will not negate the decrease in stage of more than 5 feet following the levee setback.

This study recommends that the old DID#1 Levee should be mechanically removed to surrounding elevations in order to facilitate a more rapid reclamation of floodplain areas that have been disconnected from the main channel for 30 years. A rehabilitation plan for Newland ponds 1 and 2 should be in place prior to the removal of the existing levee due to the hazard posed by a sudden channel avulsion. In order to protect the City of Yakima Sewage Treatment Plant, the revetment along the right bank should be maintained and monitored during large floods, particularly the first large flood that occurs following the levee setback.

7.5 Boise-Cascade Levee: Anticipated impacts and recommendations

Removal of the Boise-Cascade Levee in Segment 2 will allow for greater connection of the river to its floodplain along the right bank. While larger floods currently overtop the levee in some locations along its length, the removal of the levee will allow for smaller discharges to contribute to floodplain reworking and will reduce the potential for surface scour when floods overtop the levees with a large head differential. Lateral erosion and channel avulsion are possible, particularly if the main channel switches to the smaller right branch channel that presently flows along the Boise-Cascade Levee. It is also possible that smaller channels may form in the area, creating a greater variety of habitat. Some small gravel pits exist behind the levee, but are not anticipated to capture enough sediment to disrupt channel processes for any significant amount of time.

Periodic surveys of the longitudinal profile through the Gap to Gap reach will greatly aid in monitoring future channel conditions. Floodplain conditions can be monitored through continued acquisition of aerial photography and LiDAR.

7.6 Other Recommendations

Some key recommendations are put forth for consideration. These recommendations are based on observations and evaluation of geomorphic, hydraulic, and sediment transport data throughout the study.

A plan for the likely avulsion of Newland pits should be in place prior to the setback of the DID #1 levee. An unplanned avulsion could prove damaging to infrastructure and ecology and will disrupt sediment continuity for decades. Norman et al. (1998) discuss the occurrence of a sudden avulsion into one of the Selah pits in February 1996, where an upstream migrating knickpoint eroded an estimated 300,000 yd^3 of river sediment from the channel and caused approximately 8,000 feet of channel to be abandoned after the floodwaters receded. A planned or engineered avulsion will not necessarily prevent this occurrence but will greatly reduce the risk. An engineered avulsion could include the excavation of a channel at the upstream and downstream ends of the pit, allowing natural sedimentation to fill the pit over time. Connecting the pit at the upstream and downstream ends creates conditions that will more rapidly evolve into a lotic environment more conducive to native species. The volume of sediment intentionally trapped by the pit should be balanced by the needs of downstream reaches to avoid sediment starvation. Grade control at the upstream and downstream ends should be planned, as this will greatly reduce the potential for unchecked erosion. Available floodplain sediment should be used to partially fill the pits, which could be accomplished by adding sediment to the bottom of the pit to reduce the difference between the channel thalweg and the bottom of the pit, thus reducing the potential for an upstream migrating knickpoint. Alternatively, the available sediment could be added to the sides to create a narrower pit, increasing velocities and changing the transport dynamics within the pit, perhaps more rapidly advancing the submerged delta. Adding sediment to the sides of the pit could also more rapidly create a lotic environment. Multi-dimensional, mobile bed sediment modeling will assist with decisions such as the width and invert elevation of inlet and outlet channels and benefits to filling from the sides or from the bottom. Norman et al. (1998) recommends connecting pits at the downstream end only, which will also reduce the potential for failure of the berm surrounding the pit by equalizing the water surface elevations on both sides of the berm, thus reducing the head differential across the berm. The process suggested by Norman et al. (1998) is less expensive to construct but has some drawbacks: 1.) the environment created is lentic, which might benefit some native species but will also benefit non-native species that prey on or compete with natives, and 2.) the pit will take much longer to fill with natural sediment, and may never completely fill.

A periodic collection of surface topography, aerial photography and bathymetry in the Gap to Gap reach is suggested as part of a monitoring program. To reduce costs, the bathymetry survey can be limited to a thalweg profile as opposed to complete coverage of the bed, which will largely accomplish the goals of the monitoring program. Monumented cross sections should be used to monitor the same locations at every interval. These monuments can be electronic and maintained in a Geographical Information System (GIS), e.g. the location of the 1969 cross sections. Permanently mounted monuments are recommended at several key locations throughout the reach to maintain a physical record of cross section locations. The bathymetric survey can provide insight to aggradation/degradation and potential changes in slope. There are already two data points (1969 and 2005) at the location of the 1969 cross sections as a result of this study. The aerial photographs can be used for monitoring changes in planform, vegetation encroachment, channel complexity, and other geomorphic parameters.

A pebble count downstream of Wapato Dam will provide insight regarding the transport of sediment through Union Gap. The D84, D50, and D16 should be compared to similar data upstream of the dam. This comparison will help define what portion of sediment flowing into Union Gap and approaching the dam is transported over the dam. Grade control structures were constructed below the dam in 2007 and filled in during the January 2009 high flow. Gravel sized particles are said to have filled the volume behind the structures (personal communication, Chane Salois, Yakama Nation), implying that gravel is transported across the dam.

Segments 2 and 5 have been identified as locations where levees are either being overtopped or are nearly so at a 44,000 ft^3/s discharge. Both segments are predicted to aggrade over the next 25 years. For this reason the adequacy of the levee system protecting Yakima and Union Gap should be evaluated.

8 Conclusions

This study has reported the findings of a geomorphic and sediment transport investigation designed to provide insight to future channel condition over the next 25 years. Although the overarching focus is the proposed removal of the Boise-Cascade levee and the setback of the DID #1 levee, observations, evaluations, and predictions have been made throughout the study reach.

Sediment transport modeling under existing and proposed conditions predicts aggradation of the channel bed in segments 2 (triangular gravel pit to Terrace Heights bridge), 4 (SR24 bridge to Newland Pond no. 2) and 5 (downstream of levees), with the largest amount of aggradation in segment 2. These values represent the predicted vertical change within the channel over the next 25 years using the historical hydrograph from 1985 – 2009. Historical cross section and longitudinal profile comparisons also indicate that segments 2 and 5 have undergone channel and floodplain aggradation during the historical period (1969-2005). Recent geomorphic observations combined with model predictions indicate that segments 2 and 5 will continue to experience sediment deposition in the channel and floodplain areas with lateral movement anticipated. In segment 4, some channel and floodplain deposition is anticipated under proposed conditions, primarily resulting from sediment made available through erosion in the downstream half of segment 3 combined with the reduced energy following levee setback. This segment has experienced few lateral changes within the last 5 years and has experienced degradation historically due to levee restrictions along the channel. The setback of levees in this segment is predicted to initiate both vertical and lateral change, discussed further below.

Sediment transport modeling under existing and proposed conditions indicates channel bed degradation for segment 1 (Naches River to triangular gravel pit) and in segment 3 (Terrace Heights bridge to SR24 bridge). Some, but not all, of the degradation indicated in segment 1 is a result of the model eroding the channel convexity located downstream of the Naches-Yakima River confluence, although it believed that this convexity will persist. Most of the change seen in segment 3 under proposed conditions is a result of the loss of a backwater effect following the levee setback in the vicinity of SR 24. With the

DID #1 levee setback, sediment transport capacity increases upstream of the bridge, allowing for approximately 2 feet of degradation for approximately 6,000 feet upstream of the SR 24 Bridge. This degradation extends upstream past the Beech Street pit, which is a point of concern considering the increased opportunity for undermining of the bank protection along the pit on the right bank. Historically, the channel and floodplain have also degraded in segment 1 and in segment 3 from Terrace Heights bridge to the Beech Street pit. Historical aggradation in segment 3 is reflected in vertical accretion in the eastern floodplain opposite Beech Street pit and multiple avulsions due to sediment storage and backwatering effects upstream of SR24 bridge. Sediment transport modeling predicts that the levee setback will reverse the historical aggradational pattern in the downstream portion of segment 3, particularly just upstream of the SR24 bridge.

An unplanned capture of the river by a significantly deep gravel pit following the levee setback in segment 4 could temporarily disrupt sediment continuity through the downstream portion of the study area. With proper planning and engineering of gravel pit rehabilitation, the setback of the DID #1 levee will provide a decreased risk of flood damage in the vicinity and downstream of SR 24 without negatively impacting nearby infrastructure or channel processes. The removal of the Boise-Cascade levee will not negatively affect the risk of flood damage and is likely to improve habitat by allowing more frequent interaction with the floodplain. Additionally, the proposed conditions will improve aquatic and riparian habitat by allowing for increased channel-floodplain interaction and increased channel complexity.

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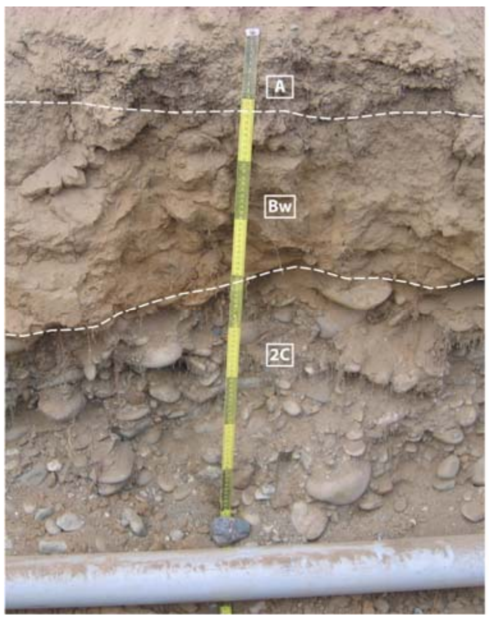
10 APPENDIX A

Soil Descriptions

FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK1 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/28/2009 **Slope** <1° **Aspect** backhoe trench
Map Unit Qa1 **Parent Material** sandy and gravelly alluvium
Location N46°36’11.2”; W 120°27’26.3”; behind university medical center building
Quadrangle Yakima East **Township/Range** T13NR19E **Section** 21NE1/4 **Elevation** ~1172 ft

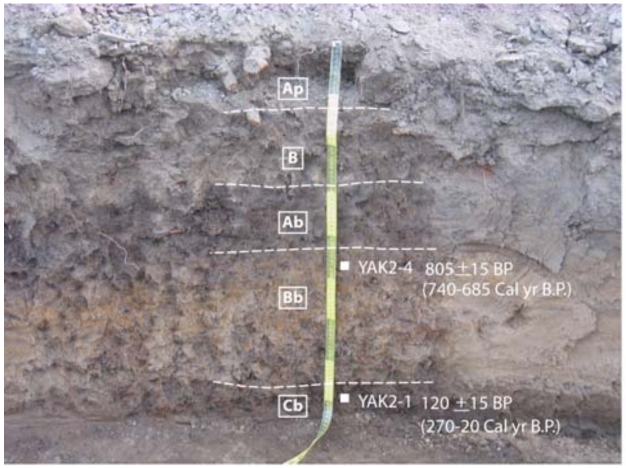
Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-12 (12)	aw	3cgr	L	none	ss	ps	sh	0	none	10YR3/2M 10YR5/2D
Bw	12-45 (33)	aw	2csbk	f-mSL	none	so	po	sh	0	none	10YR3/3M 10YR5/4D
2C	45-94 (49)	--	sg	vcLS	none	so	po	lo	50-75	e-	10YR3/2M 10YR5/3D



FIELD DESCRIPTIONS OF SOIL PROPERTIES
Profile No. YAK2 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/28/2009 **Slope** <1° **Aspect** backhoe trench
Map Unit Qa1 **Parent Material** fine-grained alluvium
Location N46°36'10.4"; W120°27'25.1"; behind university medical center building
Quadrangle Yakima East **Township/Range** T13N R19E **Section** 21 NE1/4 **Elevation** ~1185 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
Ap	0-13 (13)	aw	2mpl-1cabk	SiCL	none	s	p	so	0	none	10YR3/2M
B	13-30 (17)	aw	2msbk	SiCL	none	s	p	so	0	none	10YR3/2M
Ab	30-44 (14)	cw	1mgr-3msbk	SiC	none	vs	vp	--	0	none	10YR2/2M
B	44-75 (31)	cw	1csbk	SiC	none	vs	vp	--	0	none	10YR3/3M
C	75-87 (12)	--	m	SiC	none	vs	vp	--	0	none	10YR3/2M

Notes: Ap horizon is most likely a plowpan; dry color for all horizons and dry consistency were not described for the lowermost three horizons because the soil was too moist.

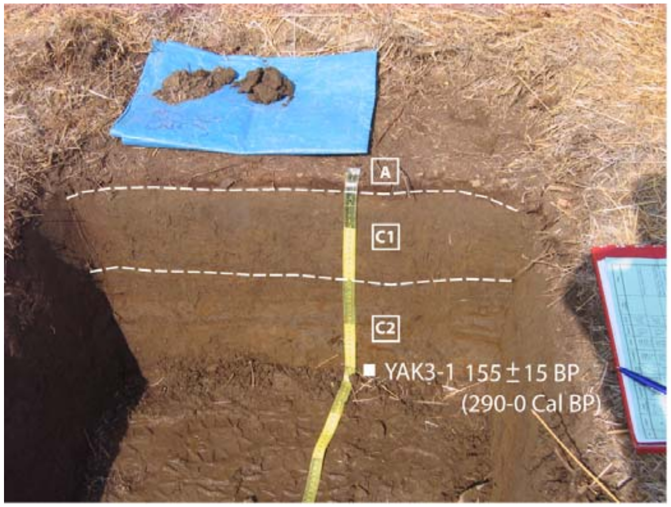


FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK3 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/29/2009 **Slope** <1° **Aspect** Pit
Map Unit Qa2 **Parent Material** sandy alluvium
Location N46°33’27.0”; W120°27’22.5”; younger floodplain along east side of Blue Slough
Quadrangle Yakima East, WA **Township/Range** T12NR19E **Section** 4 SW1/4 **Elevation** ~960 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-4 (4)	aw	1mgr	fSL	none	so	po	so	0	none	10YR3/2M 10YR4/2D
C1	4-20 (16)	as	m-1msbk	L	none	ss	ps	so	0	none	10YR4/2M
C2	20-43 (23)	--	m	mLS	none	so	po	--	0	none	10YR3/3M
				CL		s	p	--		none	10YR3/2M

Notes: dry consistence not described for C2 horizon because soil was too moist; dry color not described for C1 and C2 horizons because soil was too moist. C2 horizon has alternating sand and clay beds.



FIELD DESCRIPTIONS OF SOIL PROPERTIES
Profile No. YAK4 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/29/2009 **Slope** <1° **Aspect** pit
Map Unit Qa2 **Parent Material** sandy alluvium
Location N46°32'44.6"; W120°27'20.2"; floodplain near southern end of Reclamation property
Quadrangle Yakima East **Township/Range** T12NR19E **Section** 9 NW1/4 **Elevation** ~960 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-7 (7)	aw	2mgr	L	none	ss	ps	sh	0	none	10YR2/2M 10YR4/2D
A2	7-18 (11)	aw	2mpl	SiC	none	vs	vp	sh-h	0	none	10YR3/1M 10YR4/2D
B	18-38 (20)	cs	1msbk	C	1fpf	s	vp	h	0	none	10YR3/2M
Cox	38-48 (10)	as	m	fSL	none	so	po	--	0	none	10YR3/3M mottled
2Cox	48-52 (4)	--	m	SiC	none	vs	p	--	0	none	10YR3/2M mottled

Notes: 4 cm thick charcoal-rich bed at base of A2 unit, associated with oxidized sand bed; soil moist below a depth of 18 cm

FIELD DESCRIPTIONS OF SOIL PROPERTIES

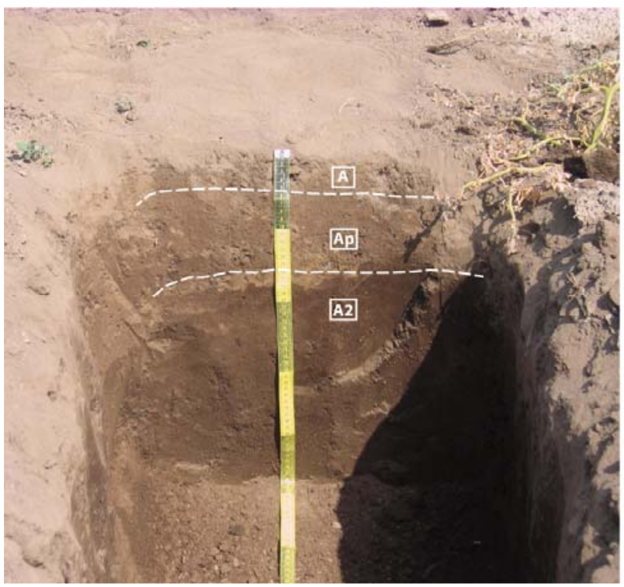
Profile No. YAK5 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/29/2009 **Slope** <1° **Aspect** pit

Map Unit Qa1 **Parent Material** sandy alluvium

Location N46°32'47.5"; W120°26'46.3"; older floodplain, southeast corner of Reclamation property

Quadrangle Yakima East **Township/Range** T12NR19E **Section** 4NE1/4 **Elevation** ~1029 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-6 (6)	aw	1fgr-1msbk	L	none	ss	ps	so	0	none	10YR3/2M 10YR5/2D
Ap	6-17 (11)	aw	2fsbk	L	none	ss	ps	sh	0	none	10YR3/2M 10YR4/2D
A2	17-49 (32)	--	2csbk	L	none	s	ps	sh	0	none	10YR2/2M 10YR4/2D



FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK6 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/29/2009 **Slope** <1° **Aspect** pit
Map Unit Qa1 **Parent Material** sandy alluvium
Location N46°34'08.4"; W120°26'43.8"; older floodplain in proposed gravel mining area, south of navigational beacon
Quadrangle Yakima East **Township/Range** T13NR19E **Section** 34NE1/4 **Elevation** ~1560 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-9 (9)	as	3fgr	SiC	none	vs	p	so	0	none	10YR2/2M 10YR3/2D
A2	9-28 (19)	as	3mgr	SiC	none	vs	vp	--	0	none	10YR2/1M
B	28-57 (29)	aw	1csbk	SiCL	none	s	p	--	0	none	10YR4/2M mottled
2Cox	57+	--		rounded gravelly alluvium at base of pit; iron staining noted on bottom of gravel							

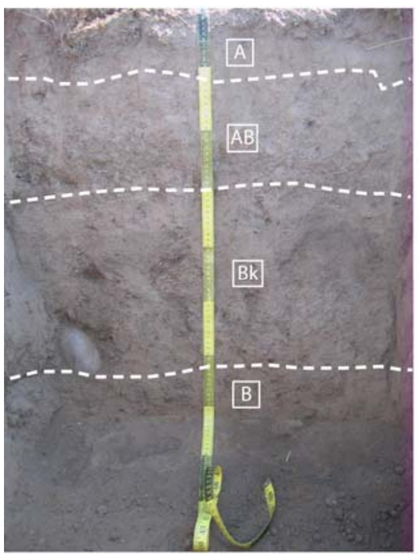
Notes: soil moist below depth of 8cm; dry consistence and dry color not described below this depth.

FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK7 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/29/2009 **Slope** <1° **Aspect** pit
Map Unit Qap **Parent Material** fine-grained alluvium
Location N46°32’25.5”; W120º28’38.8”; Ahtanum Creek floodplain; just west of powerlines in undeveloped field at Fullbright Park
Quadrangle Yakima East **Township/Range** T12NR19E **Section** 8SW1/4 **Elevation** ~960 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	$CaCO_3$ Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-12 (12)	ai	3fgr-2cpl	L	none	ss	ps	sh	<10	none (e)	10YR3/2M 10YR5/2D
AB	12-30 (18)	aw	3cgr-2fsbk	SiCL	none	s	p	sh	<10	none (e)	10YR2.5/2M 10YR5/2D
Bk	30-63 (33)	cw	2mgr-1csbk	SiCL	1fpo	vs	p	sh	10-25	I (e)	10YR3/2M 10YR5/2D
B	63-73 (10)	--	1msbk	SiCL	none	vs	p	sh	10	none	10YR3/2M 10YR5/2D

Notes: Bk horizon has filamentous coarbonate coatings on undersides of clasts

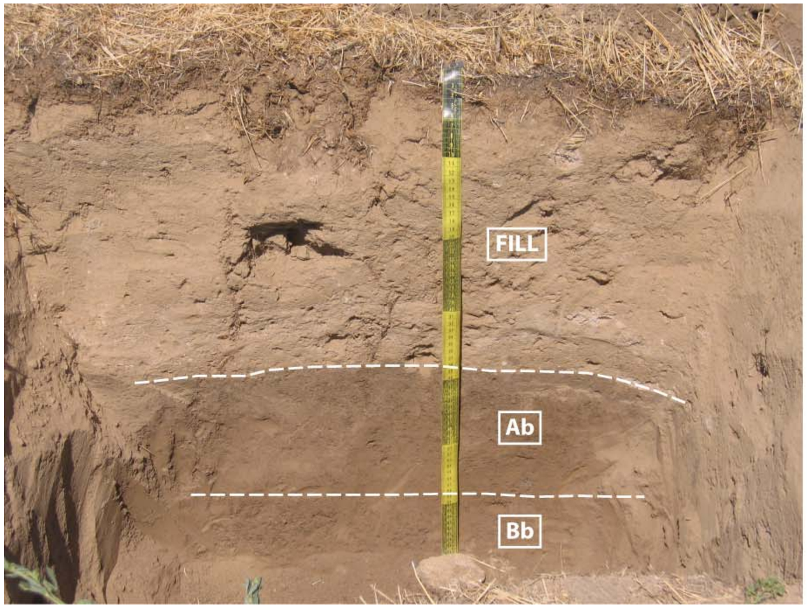


FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK8 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/30/2009 **Slope** <1° **Aspect** pit
Map Unit Qa1 **Parent Material** sandy alluvium
Location N46°04'37.9"; W120º28'06.6"; older floodplain alluvium in field south of sewage treatment plant
Quadrangle Yakima East **Township/Range** T13NR19E **Section** 32NE1/4 **Elevation** ~1000 ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence: Stickiness	Consistence: Plasticity	Consistence: Dry	Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
FILL	0-40 (40)	as			not described				10	none (ev)	10YR6/3D
Ab	40-58 (18)	cw	1msbk	L	none	ss	ps	so	0	none	10YR3/2M 10YR4/2D
Bb	58-72 (14)	--	2cgr	SL	none	ss	po	so	0	none	10YR3/2M 10YR4/2D

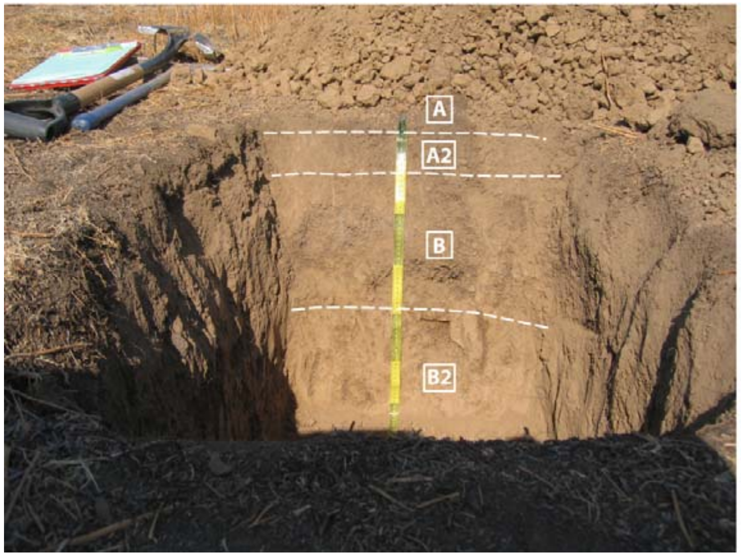
Notes: upper horizon is composed of calcareous fill with broken concrete and angular pieces of carbonate



FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK9 **Described by** Jeanne Godaire, Ralph Klinger **Date** 7/30/2009 **Slope** <1° **Aspect** pit
Map Unit Qt1 **Parent Material** sandy alluvium
Location N46°34'21.5"; W120º28'14.8"; terrace along highway south of sewage treatment plant
Quadrangle Yakima East **Township/Range** T13NR19E **Section** 32NE1/4 **Elevation** ~ 1000 ft

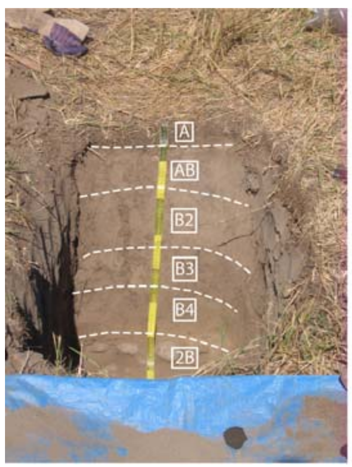
Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-4 (4)	as	sg	fSL	none	so	po	lo	0	none	10YR2/2M 10YR3/3D
A2	4-13 (9)	cw	2cgr-1msbk	L	none	ss	ps	sh	<10	none	10YR3/3M 10YR4/2D
B	13-39 (26)	as	3cgr-2msbk	CL	none	s	p	h	<10	none	10YR3/3M 10YR5/3D
B2	39-62 (23)	--	3m-csbk	L	none	ss	ps	h	0	none	10YR3/3M 10YR5/3D mottled



FIELD DESCRIPTIONS OF SOIL PROPERTIES

Profile No. YAK10 **Described by** Jeanne Godaire, Ralph Klinger **Date** 9/24/2009 **Slope** <1° **Aspect** pit
Map Unit Qt2 **Parent Material** sandy alluvium
Location N46°33'21.8"; W120º26'35.4"; younger terrace, northeast corner of Reclamation property
Quadrangle Yakima East **Township/Range** T12NR19E **Section** 4 East 1/2 **Elevation** ~ 960ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-6 (6)	aw	2mpl	mSL	none	so	po	sh	0	none	10YR2/2M 10YR4/2D
AB	6-17 (11)	cw	2fgr-2m- csbk	L	none	ss	ps	sh	0	none (e)	10YR2/2M 10YR4/2D
B2	17-32 (15)	cs	1msbk	L	none	s	ps	sh	0	none (e)	10YR3/2M 10YR4/2D
B3	32-55 (23)	cw	2cgr- 2msbk	L	none	s	ps	sh	0	none	10YR2/2M 10YR4/2D
B4	55-69 (14)	aw	2fsbk	L	none	s	ps	sh-h	0	none	10YR3/2M 10YR4/2D
2B	69-75 (6)	--	1fsbk	L	none	ss	ps	so	25	none	10YR3/2M 10YR4/2D



FIELD DESCRIPTIONS OF SOIL PROPERTIES

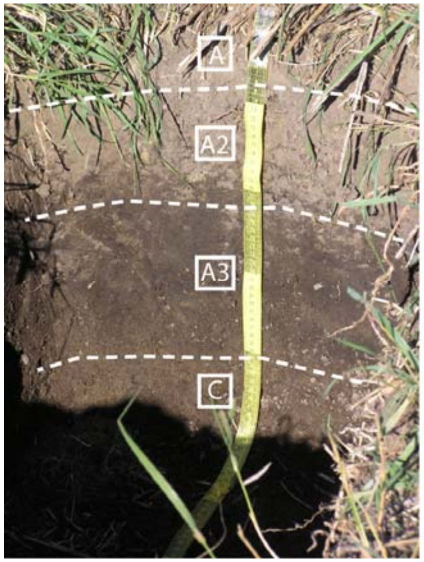
Profile No. YAK11 **Described by** Jeanne Godaire, Ralph Klinger **Date** 9/24/2009 **Slope** <1° **Aspect** pit

Map Unit Qa1 **Parent Material** fine-grained alluvium

Location N46°33'21.2"; W120º26'39.8"; older floodplain, northeast corner of Reclamation property

Quadrangle Yakima East **Township/Range** T12NR19E **Section** 4 East1/2 **Elevation** ~ 960ft

Horizon	Depth (Thickness) cm	Boundaries	Structure	Texture	Clay Films	Consistence			Gravel %	CaCO3 Morphology (effervescence)	Color (moist/dry)
						Stickiness	Plasticity	Dry			
A	0-8 (8)	aw	1fgr-2msbk	L	none	ss	ps	so	0-10	none	10YR3/2M 10YR4/2D
A2	8-23 (15)	as	1fgr-2msbk	CL	none	s	p	so	0	none	10YR2/1M 10YR4/2D
A3	23-41 (18)	as	2msbk	SiCL	none	s	p	sh	0	none	10YR2/1M 10YR4/2D
C	41-55 (14)	--	sg	cSL	none	so	po	lo	0-10	none	10YR3/2M 10YR6/2D



11 APPENDIX B

Radiocarbon Data

CHARCOAL IDENTIFICATION AND AMS RADIOCARBON DATING OF SAMPLES FROM ALONG THE YAKIMA RIVER, YAKIMA, WASHINGTON

By

Kathryn Puseman

With Assistance from
Wendy White
and
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PaleoResearch Institute
Golden, Colorado

PaleoResearch Institute Technical Report 09-115

Prepared For

Bureau of Reclamation
Denver, Colorado

January 2010

INTRODUCTION

A total of eighteen charcoal samples and four bulk soil samples from soil pits or trenches on stream terraces adjacent to the Yakima River in eastern Washington were floated to recover organic fragments suitable for radiocarbon analysis. These samples were collected for a study of Holocene terrace chronology along the Yakima River. Botanic components and detrital charcoal were identified, and potentially radiocarbon datable material was separated. Six radiocarbon dates were obtained.

METHODS

Flotation and Identification

The charcoal samples were water-screened through a 250 micron mesh and allowed to dry. Samples initially were examined under a binocular microscope at a magnification of 10x. Charcoal fragments were separated from the water-screened sample matrix and broken to expose fresh cross, radial, and tangential sections. Charcoal fragments were examined under a binocular microscope at a magnification of 70x and under a Nikon Optiphot 66 microscope at magnifications of 320-800x.

The bulk samples were floated using a modification of the procedures outlined by Matthews (1979). Each sample was added to approximately 3 gallons of water, then stirred until a strong vortex formed. The floating material (light fraction) was poured through a 150 micron mesh sieve. Additional water was added and the process repeated until all floating material was removed from the sample (a minimum of five times). The material that remained in the bottom (heavy fraction) was poured through a 0.5-mm mesh screen. The floated portions were allowed to dry.

The light fractions were weighed, then passed through a series of graduated screens (US Standard Sieves with 2-mm, 1-mm, 0.5-mm and 0.25-mm openings) to separate charcoal debris and to initially sort the remains. The contents of each screen then were examined. Charcoal fragments were separated from the rest of the light fraction and broken to expose fresh cross, radial, and tangential sections. Charcoal fragments were examined under a binocular microscope at a magnification of 70x and under a Nikon Optiphot 66 microscope at magnifications of 320-800x. The weights of each charcoal type were recorded. The material that remained in the 2-mm, 1-mm, 0.5-mm, and 0.25-mm sieves was scanned under a binocular stereo microscope at a magnification of 10x, with some identifications requiring magnifications of up to 70x. The material that passed through the 0.25-mm screen was not examined. The heavy fractions were scanned at a magnification of 2x for the presence of botanic remains. Remains from the light and heavy fractions were recorded as charred and/or uncharred, whole and/or fragments.

Macrofloral remains, including charcoal, were identified using manuals (Core, et al. 1976; Martin and Barkley 1961; Panshin and Zeeuw 1980; Petrides and Petrides 1992) and by comparison with modern and archaeological references. The term "seed" is used to represent seeds, achenes, caryopses, and other disseminules. Because charcoal and possibly other botanic remains were to be sent for radiocarbon dating, clean laboratory conditions were used during flotation and identification to avoid contamination. All instruments were washed between samples, and samples were protected from contact with modern charcoal.

AMS Radiocarbon Dating - Charcoal and Wood

Wood and charcoal samples submitted for radiocarbon dating are identified and weighed prior to selecting subsamples for pre-treatment. The remainder of each sample, if there is any, is permanently curated at PaleoResearch. The subsample selected for pre-treatment is first subjected to hot (at least 110 °C), 6N hydrochloric acid (HCl), with rinses to neutral between each HCl treatment, until the supernatant is clear. This removes iron compounds and calcium carbonates that would hamper removal of humate compounds later. Next the samples are subjected to 5% potassium hydroxide (KOH) to remove humates. Once again, the samples are rinsed to neutral and re-acidified with pH 2 HCl between each KOH step. This step is repeated until the supernatant is clear, signaling removal of all humates. After humate removal, each sample is made slightly acidic and left that way for the next step. Charcoal samples (but not wood samples) are subjected to a concentrated, hot nitric acid bath, which removes all modern and recent organics. This treatment is not used on unburned or partially burned wood samples because it oxidizes the submitted sample of unknown age.

Each submitted sample is then freeze-dried using a vacuum system, freezing out all moisture at -98 °C. Each individual sample is combined with cupric oxide (CuO) and elemental silver (Ag^{o}) in a quartz tube, then flame sealed under vacuum.

Standards and laboratory background samples also are treated in the same manner as the wood and charcoal samples of unknown age. A radiocarbon “dead” EUA wood blank from Alaska that is more than 70,000 years old (currently beyond the detection capabilities of AMS) is treated using the same chemical processing as the samples of unknown age in order to calibrate the laboratory correction factor. Standards of known age, such as Two Creeks wood that dates to 11,400 RCYBP and others from the Third International Radiocarbon Intercomparison (TIRI), are also processed simultaneously to establish the laboratory correction factor. Each wood standard is run in a quantity similar to the submitted samples of unknown age and sealed in a quartz tube after the requisite pre-treatment.

Once all the wood standards, blanks, and submitted samples of unknown age are prepared and sealed in their individual quartz tubes, they are combusted at 820 °C, soaked for an extended period of time at that temperature, and then slowly allowed to cool to enable the chemical reaction that extracts carbon dioxide ($C0_2$) gas.

Following this last step, all samples of unknown age, the wood standards, and the laboratory backgrounds are sent to the Keck Carbon Cycle AMS Facility at the University of California, Irvine, where the $C0_2$ gas is processed into graphite. The graphite in these samples is then placed in the target and run through the accelerator, which produces the numbers that are converted into the radiocarbon date presented in the data section. Dates are presented as conventional radiocarbon ages, as well as calibrated ages using Intcalc04 curves on Oxcal v.3.10.

RADIOCARBON REVIEW

When interpreting radiocarbon dates from non-annuals such as trees and shrubs, it is important to understand that a radiocarbon date reflects the age of that portion of the tree/shrub when it stopped exchanging carbon with the atmosphere, not necessarily the date that the tree/shrub died or was burned. Trees and shrubs grow bigger each year from the cambium, where a new layer or ring of cells is added each year. During photosynthesis, new cells take in atmospheric carbon dioxide, which includes radiocarbon. The radiocarbon taken in will reflect the radiocarbon present in the atmosphere during that season of growth. Once the sapwood in a tree has been converted into heartwood, the metabolic process stops for that inner wood. Once this happens, no new carbon atoms are acquired, and the radiocarbon that is present starts to decay. Studies have shown that there is little to no movement of carbon-bearing material from one ring to another. As a result, wood from different parts of the tree will yield different radiocarbon dates. The outer rings exhibit an age close to the cutting or death date of the tree, while the inner rings will reflect the age of the tree. Because the younger, outer rings burn off first when a log or branch is burned, it is the older, inner rings that typically are what is left remaining in a charcoal assemblage (Puseman 2009; Taylor 1987).

DISCUSSION

The Yakima River study sites are located near Yakima, Washington. Local vegetation in the area consists of riparian taxa along the terraces and floodplain, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.), while the upland parts of the basin support conifer forests. Charcoal and bulk soil samples were collected from soil pits and trenches on the stream terraces along the river.

YAK1

Charcoal samples YAK1-1 and YAK1-2 were recovered from the Bw horizon at depths of 35 cm and 41 cm, respectively (Table 1). Sample YAK1-1 did not contain any charcoal or other charred material. Sample YAK1-2 yielded seven small fragments of charred parenchymous tissue weighing less than 0.0001 g (Table 2, Table 3). “Parenchyma is the botanical term for relatively undifferentiated tissue, composed of many similar thin-walled cells...which form a ground tissue that surrounds other tissues. Parenchyma occurs in many different plant organs in varying amounts. Large fleshy organs such as ...roots and stems are composed largely of parenchyma. ...The vegetative storage parenchyma in swollen roots and stems stores starch and other carbohydrates and sugars ...” (Hather 2000:1). Recovery of parenchymous tissue might reflect charred root or stem tissue. One piece of charcoal weighing less than 0.0001 g was too small for identification and too small for radiocarbon dating.

YAK2

Sample YAK2-4 was taken from a depth of 47 cm. This sample contained nine fragments of Salicaceae charcoal weighing 0.0240 g, reflecting a member or members of the willow family such as willow and cottonwood. Several small fragments of unidentified hardwood charcoal also were present, including a few slightly vitrified fragments. Vitrified charcoal has a shiny, glassy appearance due to fusion by heat, possibly as a result of burning fresh wood with a higher sap content. The Salicaceae charcoal was selected for AMS radiocarbon dating. This charcoal returned a date of 805 ± 15 RCYBP (PRI-09-115-YAK2-4), with a two-sigma calibrated age range of 740-685 CAL yr. BP (Table 4, Figure 1).

Sample YAK2-3 from a depth of 55 cm also contained a fragment of charred parenchymous tissue weighing 0.0029 g. In addition, the sample yielded several fragments of Salicaceae charcoal weighing 0.0044 g and several fragments of hardwood charcoal too small for identification weighing 0.0103 g.

Sample YAK2-2 was collected from a depth of 64 cm. This sample contained 11 fragments of Salicaceae charcoal weighing 0.0120 g, reflecting growth of willow and/or cottonwood.

Several fragments of Asteraceae charcoal were noted in sample YAK2-1 from a depth of 78 cm, indicating the presence of a woody member of the sunflower family. This charcoal was selected for AMS radiocarbon dating, resulting in a date of 120 ± 15 RCYBP (PRI-09-115-YAK2-1). The two-sigma calibrated age range for this date is 270-210 and 150-20 CAL yr. BP (Figure 2).

YAK3

Sample YAK3-3 represents charcoal from Unit 2 at a depth of 26 cm. This sample contained a charred bark scale fragment weighing 0.0003 g, as well as three pieces of conifer charcoal weighing 0.0006 g.

Sample YAK3-1 from a depth of 40 cm in Unit 2 contained several fragments of Salicaceae charcoal weighing 0.0090 g. One piece of partially charred unidentified hardwood charcoal exhibited rounded edges. The Salicaceae charcoal was submitted for AMS radiocarbon dating. A date of 155 ± 15 RCYBP (PRI-09-115-YAK3-1) was returned for this charcoal, with a two-sigma calibrated age range of 290-250, 230-130, and 40-(-1) CAL yr. BP (Figure 3).

Several fragments of incompletely charred periderm (bark) fragments weighing 0.0140 g were noted in sample YAK3-2 from a depth of 42 cm in Unit 2. Two pieces of uncharred Salicaceae root wood reflect a willow or cottonwood root.

YAK4

Sample YAK4-1 was taken from a charcoal bed at a depth of 15-17 cm. This sample contained two pieces of Asteraceae charcoal weighing 0.0135 g, three Rosaceae twig charcoal fragments weighing 0.0248 g, several pieces of Salicaceae charcoal weighing 0.2574 g, and probable *Salix* twig fragments weighing 0.5063 g. These charcoal types represent a woody member of the sunflower family, a woody member of the rose family, probable willow, and possibly another member of the willow family. A charred thorn fragment also was noted. A portion of the probable *Salix* twig charcoal was selected for AMS radiocarbon dating. This charcoal returned a modern, post-bomb age range of February-July 1958, February-March 1987, and November 1987-June 1990 at the two-sigma level (Figure 4).

Sample YAK4-2 was recovered from the B horizon at a depth of 33 cm. This sample contained five fragments of unidentified hardwood root charcoal weighing 0.2517 g.

Samples YAK4-3 and YAK4-4 were collected from the Cox horizon at depths of 46 and 40-42 cm, respectively. A charred periderm (bark) fragment weighing 0.0006 g was present in sample YAK4-3, as well as six pieces of hardwood charcoal too small for identification and weighing 0.0002 g. Sample YAK4-4 consisted of uncharred periderm fragments weighing 0.2490 g. A portion of these uncharred bark fragments were processed for AMS radiocarbon dating, resulting in a date of 100 ± 15 RCYBP (PRI-09-115-YAK4-4). The two-sigma calibrated age range for this date is 260-220 and 140-30 CAL yr. BP (Figure 5).

YAK5

Samples YAK5-2 and YAK5-1 were taken from depths of 21 cm and 49 cm, respectively, in the A2 horizon. Neither sample yielded charcoal or other organic remains suitable for radiocarbon dating.

YAK6

Sample YAK6-1 was recovered from the B horizon at a depth of 50 cm. This sample contained four fragments of charcoal too small for identification and weighing less than 0.0001 g.

YAK8

One piece of uncharred Asteraceae wood weighing 0.0015 g was present in sample YAK8-1 from the Ab horizon at a depth of 54 cm. This wood fragment yielded a modern, post-bomb, two-sigma calibrated age range of March 1956-August 1957 (Figure 6).

YAK10

Charcoal sample YAK10-1 was taken from a depth of 54 cm. This sample contained a few uncharred rootlets from modern plants and a small amount of rock/gravel, but no organic remains suitable for radiocarbon dating.

Bulk sample YAK10-2 was collected from a Holocene terrace at a depth of 32-55 cm. One piece of charred vitrified tissue weighing 0.0008 g might reflect charcoal or other charred plant tissue too vitrified for identification. An uncharred Cheno-am perisperm fragment and a moderate amount of rootlets represent modern plants in the area. The charcoal record consisted of a single piece of conifer charcoal weighing 0.0002 g. In addition, the sample contained an insect puparia fragment, a small amount of rock/gravel, a snail shell, and a few sclerotia. Sclerotia are commonly called "carbon balls." They are small, black, solid or hollow spheres that can be smooth or lightly sculpted. These forms range from 0.5 to 4 mm in size. Sclerotia are the resting structures of mycorrhizae fungi, such as *Cenococcum graniforme*, that have a mutualistic relationship with tree roots. Many trees are noted to depend heavily on mycorrhizae and may not be successful without them. "The mycelial strands of these fungi grow into the roots and take some of the sugary compounds produced by the tree during photosynthesis. However, mycorrhizal fungi benefit the tree because they take in minerals from the soil, which are then used by the tree" (Kricher and Morrison 1988:285). Sclerotia appear to be ubiquitous and are found with coniferous and deciduous trees including *Abies* (fir), *Juniperus communis* (common juniper), *Larix* (larch), *Picea* (spruce), *Pinus* (pine), *Pseudotsuga* (Douglas fir), *Acer pseudoplatanus* (sycamore maple), *Alnus* (alder), *Betula* (birch), *Carpinus caroliniana* (American hornbeam), *Carya* (hickory), *Castanea dentata* (American chestnut), *Corylus* (hazelnut), *Crataegus monogyna* (hawthorn), *Fagus* (beech), *Populus* (poplar, cottonwood, aspen), *Quercus* (oak), *Rhamnus fragula* (alder bush), *Salix* (willow), *Sorbus* (chokecherry), and *Tilia* (linden). These forms originally were identified by Dr. Kristiina Vogt, Professor of Ecology in the School of Forestry and Environmental Studies at Yale University (McWeeney 1989:229-230; Trappe 1962).

A charred *Arctostaphylos* seed fragment weighing 0.006 g was present in bulk sample YAK10-3 from a depth of 55-69 cm, reflecting manzanita in the area. The sample also contained three fragments of conifer charcoal weighing 0.0001 g and two pieces of hardwood charcoal too small for further identification weighing 0.0005 g. In addition, the sample yielded an insect puparia, uncharred Cheno-am seeds and rootlets from modern plants, and a moderate amount of sclerotia.

YAK11

Sample YAK11-1 consists of bulk soil from a depth of 23-41 cm. This sample contained a variety of charred remains, including two *Chenopodium* seed fragments, three unidentified seed fragments weighing 0.0007 g, two pieces of parenchymous tissue weighing 0.0006 g, three fragments of vitrified tissue weighing 0.0012 g, four fragments of Asteraceae charcoal weighing 0.0096 g, two unidentified root charcoal fragments weighing 0.0068 g, a piece of oxidized and vitrified charcoal weighing 0.0073 g, and a piece of charcoal too vitrified for identification weighing 0.0035 g. The sample also contained uncharred seeds and rootlets from modern plants, a moderate amount of sclerotia, insect chitin, insect puparia, and a rodent tooth fragment.

Two pieces of Rosaceae wood weighing 0.0027 g were noted in sample YAK11-2 from a depth of 41-55 cm. Several uncharred seeds and a moderate amount of rootlets represent modern plants in the area. Recovery of several insect chitin fragments, insect puparia, and numerous worm casts indicate subsurface disturbance from insect and earthworm activity. A moderate amount of sclerotia also were noted.

SUMMARY AND CONCLUSIONS

Identification of charcoal samples and flotation of bulk samples from study sites along the Yakima River in eastern Washington resulted in recovery of charcoal and other charred botanic remains suitable for radiocarbon analysis. Salicaceae charcoal was noted in five samples, reflecting local willow and/or cottonwood. Salicaceae charcoal in sample YAK2-4 yielded the oldest date of 805 ± 15 BP. Salicaceae charcoal in sample YAK3-1 returned a date of 155 ± 15 BP, while a modern post-bomb age range of February-July 1958, February-March 1987, and November 1987-June 1990 was returned for a charred probable *Salix* twig fragment in sample YAK4-1. Asteraceae charcoal in three samples and uncharred Asteraceae wood in two samples indicate the presence of a woody member or members of the sunflower family. Asteraceae charcoal in sample YAK2-1 yielded a date of 120 ± 15, and Asteraceae wood from sample YAK8-1 yielded a modern, post-bomb age range of March 1956-August 1957. Four samples contained charred, incompletely charred, or uncharred bark/periderm fragments. A date of 100 ± 15 BP was returned for uncharred bark fragments in sample YAK4-4. Other charcoal types reflect the presence of conifers, a woody member of the rose family, and unidentified hardwoods. A charred *Arctostaphylos* seed fragment indicates the presence of manzanita, while two charred *Chenopodium* seed fragments note the presence of goosefoot plants. Radiocarbon dates from the Yakima River samples suggest that much of the charred material in this area is the result of historic and modern fires.

TABLE 1
PROVENIENCE DATA FOR SAMPLES FROM ALONG YAKIMA RIVER, WASHINGTON

Sample No.	Depth (cm)	Provenience/ Description	Analysis
YAK1-1	35	Charcoal, Bw horizon	Charcoal ID
YAK1-2	41	Charcoal, Bw horizon	Charcoal ID
YAK2-4	47	Charcoal	Charcoal ID AMS ^{14}C Date
YAK2-3	55	Charcoal	Charcoal ID
YAK2-2	64	Charcoal	Charcoal ID
YAK2-1	78	Charcoal	Charcoal ID AMS ^{14}C Date
YAK3-3	26	Charcoal, Unit 2	Charcoal ID
YAK3-1	40	Charcoal, Unit 2	Charcoal ID AMS ^{14}C Date
YAK3-2	42	Charcoal, Unit 2	Charcoal ID
YAK4-1	15-17	Charcoal bed	Charcoal ID AMS ^{14}C Date
YAK4-2	33	Charcoal, B horizon	Charcoal ID
YAK4-3	46	Charcoal, Cox horizon	Charcoal ID
YAK4-4	40-42	Charcoal, Cox horizon	Charcoal ID
YAK5-2	21	Charcoal, A2 horizon	Charcoal ID
YAK5-1	49	Charcoal, A2 horizon	Charcoal ID
YAK6-1	50	Charcoal, B horizon	Charcoal ID
YAK8-1	54	Charcoal, Ab horizon	Charcoal ID AMS ^{14}C Date
YAK10-1	54	Charcoal	Charcoal ID
YAK10-2	32-55	Bulk soil from Holocene terrace	Macrofloral
YAK10-3	55-69	Bulk soil from Holocene terrace	Macrofloral
YAK11-1	23-41	Bulk soil from Holocene terrace	Macrofloral
YAK11-2	41-55	Bulk soil from Holocene terrace	Macrofloral

TABLE 2
MACROFLORAL REMAINS IN SAMPLES FROM ALONG THE YAKIMA RIVER, WASHINGTON

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK1-1	Water-screened Sample Weight						4.953 g
35 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	NON-FLORAL REMAINS:						
	Sand					X	
YAK1-2	Water-screened Sample Weight						0.066 g
41 cm	FLORAL REMAINS:						
	Parenchymous tissue			7			<0.0001 g
	CHARCOAL/WOOD:						
	Unidentifiable - small			1			<0.0001 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK2-4	Water-screened Sample Weight						4.766 g
47 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Salicaceae**	Charcoal		9			0.0240 g
	Unidentified hardwood	Charcoal		14			0.0481 g
	Unidentified hardwood - slightly vitrified	Charcoal		8			0.0572 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK2-3	Water-screened Sample Weight						2.739 g
55 cm	FLORAL REMAINS:						
	Parenchymous tissue			1			0.0029 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Salicaceae	Charcoal		12			0.0044 g
	Unidentified hardwood - small	Charcoal		13			0.0103 g
	NON-FLORAL REMAINS:						
	Sand					X	

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK2-2	Water-screened Sample Weight						0.413 g
64 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Salicaceae	Charcoal		11			0.0120 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK2-1	Water-screened Sample Weight						0.598 g
78 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Asteraceae**	Charcoal		29			0.0155 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK3-3	Water-screened Sample Weight						0.395 g
26 cm	FLORAL REMAINS:						
	Bark scale			1			0.0003 g
	CHARCOAL/WOOD:						
	Conifer	Charcoal		3			0.0006 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK3-1	Water-screened Sample Weight						0.592 g
40 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Salicaceae**	Charcoal		16			0.0090 g
	Unidentified hardwood - rounded	Charcoal		1pc			0.0056 g
	NON-FLORAL REMAINS:						
	Sand					X	

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK3-2	Water-screened Sample Weight						1.179 g
42 cm	FLORAL REMAINS:						
	Periderm			10pc			0.0140 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Salicaceae root	Wood				2	0.0303 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK4-1	Water-screened Sample Weight						9.85 g
15-17 cm	FLORAL REMAINS:						
	Thorn			1			0.0049 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Asteraceae	Charcoal		2			0.0135 g
	Rosaceae twig	Charcoal		3			0.0248 g
	Salicaceae	Charcoal		14			0.2574 g
	Salix twig**	Charcoal		12			0.5063 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				3	
	Sand					X	
YAK4-2	Water-screened Sample Weight						1.73 g
33 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood root	Charcoal		5			0.2517 g
	NON-FLORAL REMAINS:						
	Sand					X	
YAK4-3	Water-screened Sample Weight						0.229 g
46 cm	FLORAL REMAINS:						
	Periderm			1			0.0006 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		6			0.0002 g
	NON-FLORAL REMAINS:						
	Sand					X	

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK4-4	Water-screened Sample Weight						0.759 g
40-42 cm	FLORAL REMAINS:						
	Periderm**					41	0.2490 g
	Rootlets					X	
	NON-FLORAL REMAINS:						
	Sand					X	
YAK5-2	Water-screened Sample Weight						0.19 g
21 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	NON-FLORAL REMAINS:						
	Sediment					X	
YAK5-1	Water-screened Sample Weight						4.98 g
49 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	NON-FLORAL REMAINS:						
	Sediment					X	
YAK6-1	Water-screened Sample Weight						0.52 g
50 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentifiable - small	Charcoal		4			<0.0001 g
	NON-FLORAL REMAINS:						
	Sediment					X	
YAK8-1	CHARCOAL/WOOD:						
54 cm	Asteraceae**	Wood				1	0.0015 g
YAK10-1	Water-screened Sample Weight						0.79 g
54 cm	FLORAL REMAINS:						
	Rootlets					X	Few
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Few

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK10-2	Liters Floated						2.00
32-55 cm	Light Fraction Weight						9.47 g
	FLORAL REMAINS:						
	Vitrified tissue			1			0.0008 g
	Cheno-am	Perisperm			1		
	Rootlets					X	Moderate
	Sclerotia				X		Few
	CHARCOAL/WOOD:						
	Conifer	Charcoal		1			0.0002 g
	NON-FLORAL REMAINS:						
	Insect	Puparia			1		
	Rock/Gravel					X	Few
	Snail shell				1		
YAK10-3	Liters Floated						2.00
55-69 cm	Light Fraction Weight						5.26 g
	FLORAL REMAINS:						
	Arctostaphylos	Seed		1			0.0006 g
	Cheno-am	Seed				3	
	Rootlets					X	Moderate
	Sclerotia				X		Moderate
	CHARCOAL/WOOD:						
	Conifer	Charcoal		3			0.0001 g
	Unidentified hardwood - small	Charcoal		2			0.0005 g
	NON-FLORAL REMAINS:						
	Insect	Puparia			1		
	Rock/Gravel					X	Few

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK11-1	Liters Floated						1.20
23-41 cm	Light Fraction Weight						2.452 g
	FLORAL REMAINS:						
	Chenopodium	Seed		2	7	49	
	Unidentified	Seed		3			0.0007 g
	Parenchymous tissue			2			0.0006 g
	Vitrified tissue			3			0.0012 g
	Scirpus	Seed			2		
	Unidentified	Bract				1	
	Rootlets					X	Moderate
	Sclerotia				X		Moderate
	CHARCOAL/WOOD:						
	Asteraceae	Charcoal		4			0.0096 g
	Unidentified root	Charcoal		2			0.0068 g
	Unidentifiable - oxidized	Charcoal		1			0.0073 g
	Unidentifiable - vitrified	Charcoal		1			0.0035 g
	NON-FLORAL REMAINS:						
	Insect	Chitin			2	13	
	Insect	Puparia			4	1	
	Rock/Gravel					X	Few
	Rodent tooth					1	
YAK11-2	Liters Floated						1.20
41-55 cm	Light Fraction Weight						0.883 g
	FLORAL REMAINS:						
	Amaranthus	Seed			3	2	
	Chenopodium	Seed			2		
	Cirsium	Seed			1		
	Unidentified	Seed			1	1	
	Rootlets					X	Moderate
	Sclerotia				X		Moderate
	CHARCOAL/WOOD:						
	Asteraceae	Wood				2	0.0027 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
YAK11-2	NON-FLORAL REMAINS:						
41-55 cm	Insect	Chitin				24	
	Insect	Puparia			17		
	Mica					X	Numerous
	Rock/Gravel					X	Moderate
	Worm casts				X	X	Numerous

W = Whole
F = Fragment
X = Presence noted in sample
g = grams
pc = Partially charred
** = Submitted for AMS ^{14}C Dating

TABLE 3
INDEX OF MACROFLORAL REMAINS RECOVERED IN SAMPLES FROM
ALONG THE YAKIMA RIVER, WASHINGTON

Scientific Name	Common Name
FLORAL REMAINS:	
Amaranthus	Pigweed, Amaranth
Arctostaphylos	Bearberry, Manzanita, Kinnikinnick
Cheno-am	Includes goosefoot and amaranth families
Chenopodium	Goosefoot, Pigweed
Cirsium	Thistle
Periderm	Technical term for bark; Consists of the cork (phellum) which is produced by the cork cambium, as well as any epidermis, cortex, and primary or secondary phloem exterior to the cork cambium
Parenchymous tissue	Relatively undifferentiated tissue composed of many similar thin-walled cells–occurs in different plant organs in varying amounts, especially large fleshy organs such as roots and stems
Scirpus	Bulrush, Three-squares
Vitrified tissue	Charred material with a shiny, glassy appearance due to fusion by heat
Sclerotia	Resting structures of mycorrhizae fungi
CHARCOAL/WOOD:	
Asteraceae	Sunflower family
Conifer	Cone-bearing, gymnospermous trees and shrubs, mostly evergreens, including the pine, spruce, fir, juniper, cedar, yew, hemlock, redwood, and cypress
Rosaceae	Rose family
Salicaceae	Willow family
Salix	Willow
Unidentified hardwood	Wood from a broad-leaved flowering tree or shrub
Unidentified hardwood - small	Wood from a broad-leaved flowering tree or shrub, fragments too small for further identification
Unidentified hardwood - slightly vitrified	Wood from a broad-leaved flowering tree or shrub, exhibiting a shiny, glassy appearance due to fusion by heat

TABLE 4
RADIOCARBON RESULTS FOR SAMPLES FROM ALONG THE YAKIMA RIVER, WASHINGTON

Sample No.	Sample Identification	AMS ^{14}C Date*	1-sigma Calibrated Date (68.2%)	2-sigma Calibrated Date (95.4%)	$\delta^{13}C$** ($^o/_{oo}$)
PRI-09-115-YAK2-4	Salicaceae charcoal	805 ± 15 RCYBP	730-695 CAL yr. BP	740-685 CAL yr. BP	-25.8
PRI-09-115-YAK2-1	Asteraceae charcoal	120 ± 15 RCYBP	270-220 150-130 120-70 40-20 CAL yr. BP	270-210 150-20 CAL yr. BP	-26.8
PRI-09-115-YAK3-1	Salicaceae charcoal	155 ± 15 RCYBP	280-260 220-170 160-140 30-10 CAL yr. BP	290-250 230-130 CAL yr. BP	-27.0
PRI-09-115-YAK4-1	cf. *Salix* twig charcoal	1.1674 ± 0.0020 fM	December 1987, October 1988-October 1989	Feb -July 1958, Feb.-March 1987, Nov. 1987-June 1990	-29.3
PRI-09-115-YAK4-4	Bark - uncharred	100 ± 15 RCYBP	260-220 140-110 80-30 CAL yr. BP	260-220 140-30 CAL yr. BP	-29.0
PRI-09-115-YAK8-1	Asteraceae wood	1.0691 ± 0.0016 fM	September 1956-July 1957	March 1956-August 1957	-22.1

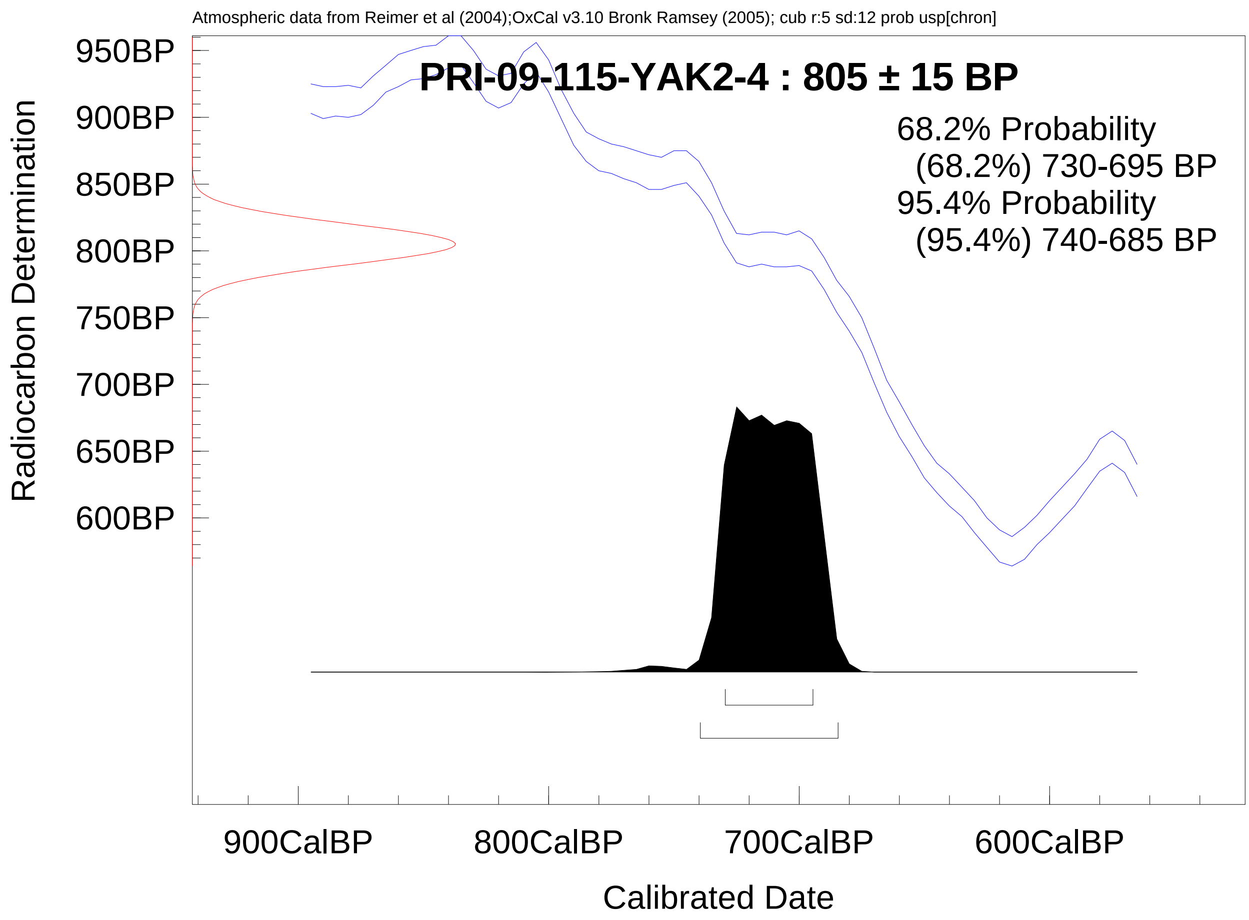
* Reported in radiocarbon years at 1 standard deviation measurement precision (68.2%), corrected for $\delta^{13}C$

** $\delta^{13}C$ values are measured by AMS during the ^{14}C measurement for use during the ^{14}C calculation and should not be used for dietary or paleoenvironmental interpretations.

fM = fraction Modern. Recent dates (falling within the time after atomic testing began) are reported as fraction Modern because calibrations can only be done using fraction Modern for this time period. Years BP are calculated as prior to 1950, not prior to today's date.

FIGURE 1. PRI RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK2-4
Sample Identification: Salicaceae charcoal
Conventional AMS ^{14}C Date: 805 ± 15 RCYBP
1-sigma Calibrated Date (68.2%): 730-695 CAL yr. BP
2-sigma Calibrated Date (95.4%): 740-685 CAL yr. BP
$\delta^{13}C$ ($^{o}/_{oo}$): -25.8 (Measured for ^{14}C calculation, not valid for dietary or paleoenvironmental interpretations)



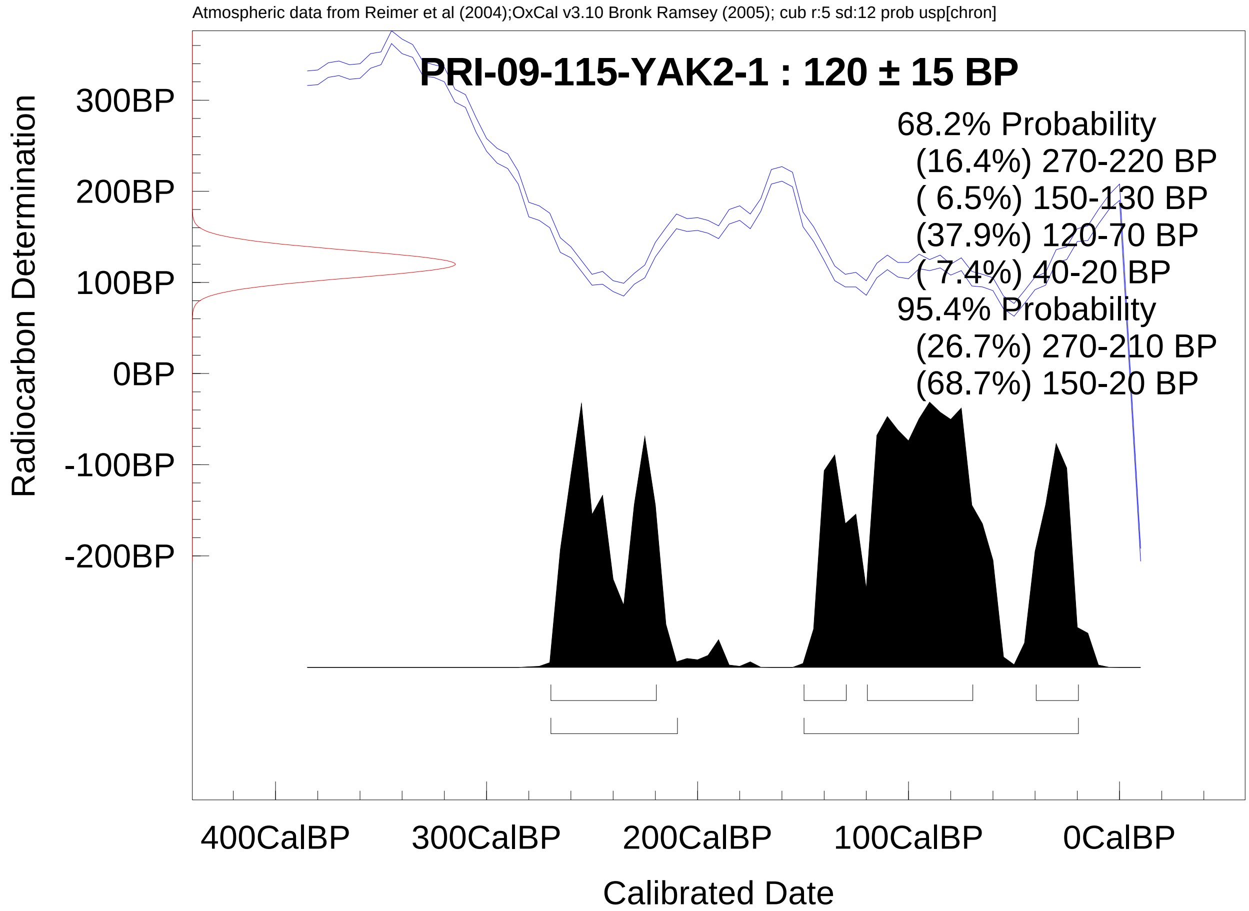
Intercept Statement. PaleoResearch Institute utilizes OxCal3.10 (Bronk Ramsey, 2005) for radiocarbon calibration, which is a probability-based method for determining conventional ages. We prefer this method over the intercept-based alternative because it provides our clients with a calibrated date that reflects the probability of its occurrence within a given distribution (reflected by the amplitude (height) of the curve), as opposed to individual point estimates (Telford 2004). As a result, the probability-based method offers more stability to the calibrated values than those derived from intercept-based methods that are subject to adjustments in the calibration curve (Telford 2004).

References

Telford, R. J., E. Heegaard, and H. J. B. Birks, 2004, *The Holocene* 14(2), pp. 296-298.

FIGURE 2. PRI RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK2-1
Sample Identification: Asteraceae charcoal
Conventional AMS ^{14}C Date: 120 ± 15 RCYBP
1-sigma Calibrated Date (68.2%): 270-220; 150-130; 120-70; 40-20 CAL yr. BP
2-sigma Calibrated Date (95.4%): 270-210; 150-20 CAL yr. BP
$\delta^{13}C$ ($^{o}/_{oo}$): -26.8 (Measured for ^{14}C calculation, not valid for dietary or paleoenvironmental interpretations)



Intercept Statement. PaleoResearch Institute utilizes OxCal3.10 (Bronk Ramsey, 2005) for radiocarbon calibration, which is a probability-based method for determining conventional ages. We prefer this method over the intercept-based alternative because it provides our clients with a calibrated date that reflects the probability of its occurrence within a given distribution (reflected by the amplitude (height) of the curve), as opposed to individual point estimates (Telford 2004). As a result, the probability-based method offers more stability to the calibrated values than those derived from intercept-based methods that are subject to adjustments in the calibration curve (Telford 2004).

References

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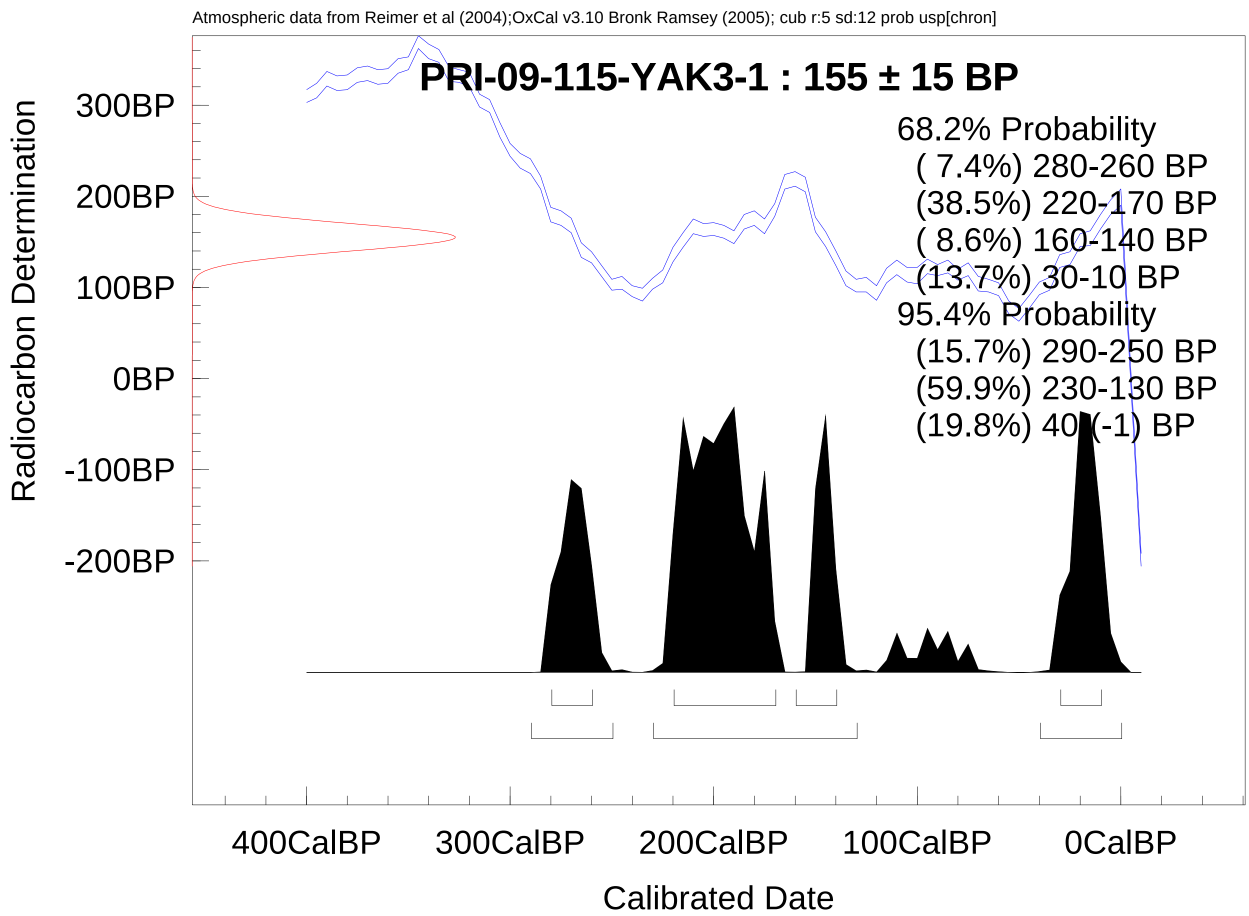
FIGURE 3. PRI RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK3-1
Sample Identification: Salicaceae charcoal
Conventional AMS ^{14}C Date: 155 ± 15 RCYBP
1-sigma Calibrated Date (68.2%): 280-260; 220-170; 160-140; 30-10 CAL yr. BP
2-sigma Calibrated Date (95.4%): 290-250; 230-130; 40-(-1) CAL yr. BP
$\delta^{13}C$ ($^{o}/_{oo}$): -27.0 (Measured for ^{14}C calculation, not valid for dietary or paleoenvironmental interpretations)



Intercept Statement. PaleoResearch Institute utilizes OxCal3.10 (Bronk Ramsey, 2005) for radiocarbon calibration, which is a probability-based method for determining conventional ages. We prefer this method over the intercept-based alternative because it provides our clients with a calibrated date that reflects the probability of its occurrence within a given distribution (reflected by the amplitude (height) of the curve), as opposed to individual point estimates (Telford 2004). As a result, the probability-based method offers more stability to the calibrated values than those derived from intercept-based methods that are subject to adjustments in the calibration curve (Telford 2004).

References

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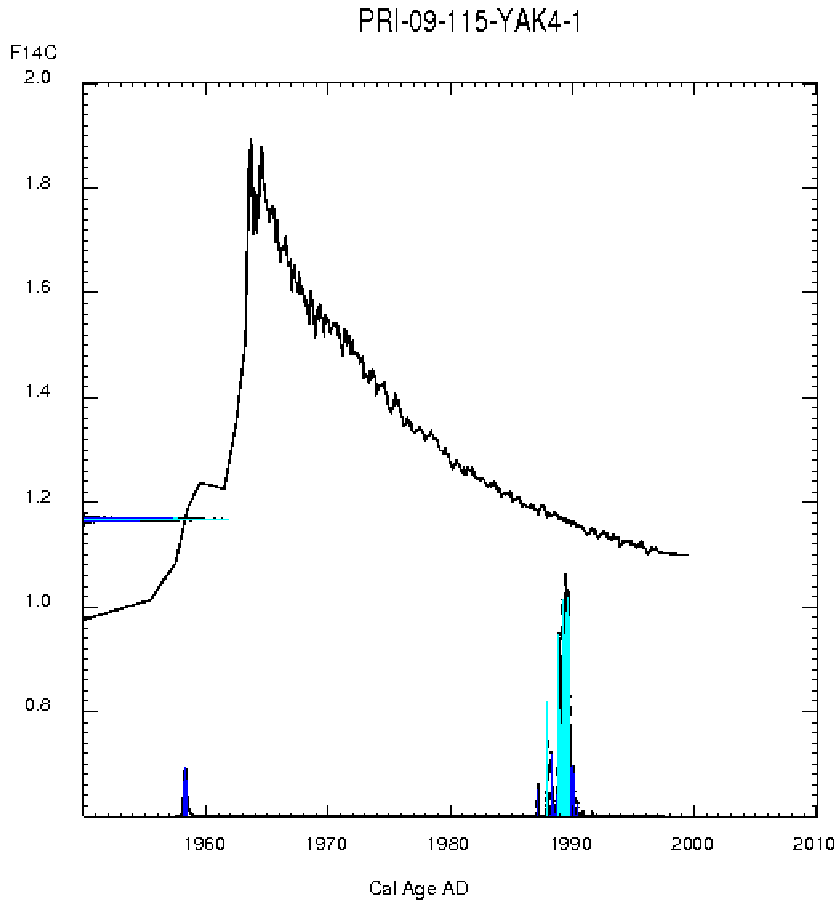
FIGURE 4. PRI CALIBOMB RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK4-1
Sample Identification: cf. *Salix* twig charcoal
Calibration of with NH_zone2.14c dataset

1-sigma Calibrated Date:	Probability:	2-sigma Calibrated Date:	Probability:
December-December 1987	01.43%	February-July 1958	07.28%
October 1988-October 1989	98.57%	February-March 1987	01.60%
		November 1987-June 1990	91.13%



References

Hua, Q. and M. Barbetti, 2004, Review of Tropospheric Bomb ^{14}C Data for Carbon Cycle Modeling and Age Calibration Purposes", *Radiocarbon* 46:1273-1298.

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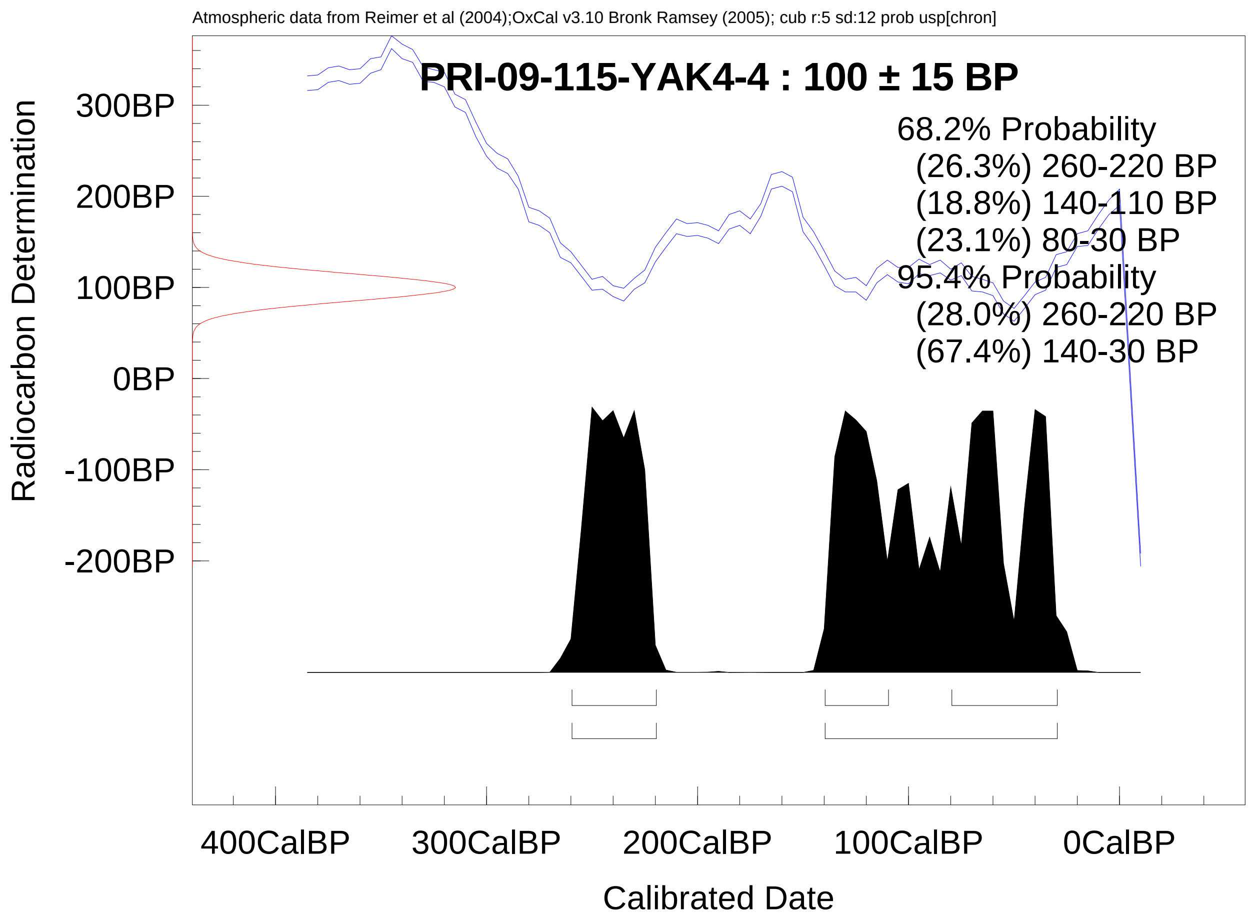
FIGURE 5. PRI RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK-4-4
Sample Identification: Bark - uncharred
Conventional AMS ^{14}C Date: 100 ± 15 RCYBP
1-sigma Calibrated Date (68.2%): 260-220; 140-110; 80-30 CAL yr. BP
2-sigma Calibrated Date (95.4%): 260-220; 140-30 CAL yr. BP
$\delta^{13}C$ ($^{o}/_{oo}$): -29.0 (Measured for ^{14}C calculation, not valid for dietary or paleoenvironmental interpretations)



Intercept Statement. PaleoResearch Institute utilizes OxCal3.10 (Bronk Ramsey, 2005) for radiocarbon calibration, which is a probability-based method for determining conventional ages. We prefer this method over the intercept-based alternative because it provides our clients with a calibrated date that reflects the probability of its occurrence within a given distribution (reflected by the amplitude (height) of the curve), as opposed to individual point estimates (Telford 2004). As a result, the probability-based method offers more stability to the calibrated values than those derived from intercept-based methods that are subject to adjustments in the calibration curve (Telford 2004).

References

Telford, R. J., E. Heegaard, and H. J. B. Birks, 2004, *The Holocene* 14(2), pp. 296-298.

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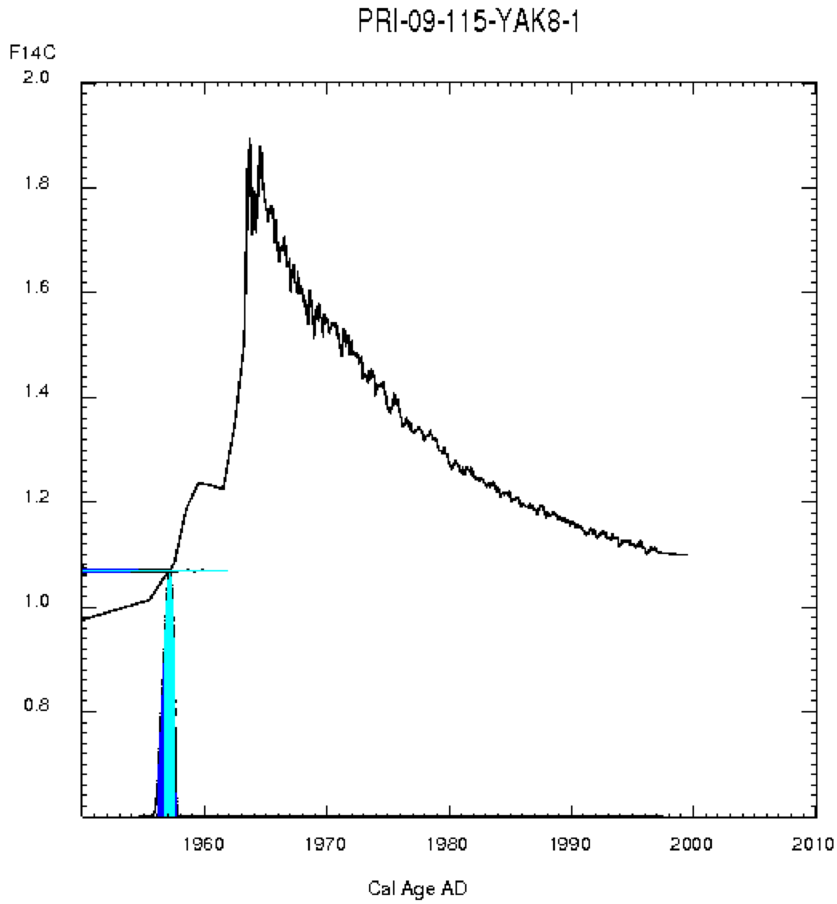
FIGURE 6. PRI CALIBOMB RADIOCARBON AGE CALIBRATION

Laboratory Number: PRI-09-115-YAK8-1
Sample Identification: Asteraceae wood
Calibration of with NH_zone2.14c dataset

1-sigma Calibrated Date:	Probability:	2-sigma Calibrated Date:	Probability:
September 1956-July 1957	100.00%	March 1956-August 1957	100.00%



References

Hua, Q. and M. Barbetti, 2004, Review of Tropospheric Bomb ^{14}C Data for Carbon Cycle Modeling and Age Calibration Purposes", *Radiocarbon* 46:1273-1298.

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12 APPENDIX C

Vertical Adjustment of 1969 Cross Section Data

Procedures used to align the 1969 U.S. Army Corps of Engineers Cross Sections with current topography and bathymetry of the Gap-to-Gap Reach.

Joel Freudenthal, Fish and Wildlife Biologist, Yakima County Public Services
Duncan Kincaid, Engineering Technician, Yakima County Public Services
Michael Martian, Director, Yakima County Geographic Information Services

Historical cross sections of the Gap-to-Gap reach, developed as part of a floodplain study in 1969, could provide an opportunity to evaluate vertical and horizontal changes in this reach when compared to current conditions. This appendix describes the procedures used to reproduce the 1969 the vertical and horizontal alignments of these cross sections to allow evaluation of channel and floodplain conditions since 1969.

1969 Cross Sections

The 1969 U.S. Army Corps of Engineers cross sections were surveyed as a component of a report entitled “Flood Plain Information, Yakima and Naches Rivers, Yakima-Union Gap, Washington” dated May 1970. In that report, the Corps evaluates the Federal Project Levees (constructed in 1947-48), the newly constructed US 12 (now I-82) along the Yakima River, and the proposed US 12 along the Naches river relative to historical floods of record, the Standard Project Flood (180,000 cfs, more than a 500 year flood) and the Intermediate Regional Flood (the 100 year flood, calculated at 79,000 cfs). The cross sections were used to calculate the elevation of both flood discharges at the cross section locations.

The Flood Plain Information report contains a series of plates on which the locations of the cross sections are shown. The cross sections on the Yakima River begin (downstream) at the Sunnyside Irrigation District Diversion Dam (RM 104), and end near Selah (RM 117), there are 40 cross sections shown in this distance, of which 28 are of interest in the project area. Yakima County GIS had used these plates to create a GIS shapefile of the 1969 cross sections (which are similar to the current FEMA Flood Insurance Rate Map cross sections) in 2005. In 2008, during a search of the Yakima County archives, plots of the 1969 cross sections were found. There were a total of 5 plots (each containing multiple cross sections), each on engineering vellum 36” wide by 6-10 feet long. These plots were then scanned into electronic images and converted to a variety of formats for this project.

The first plot of the cross sections had the following Legend:

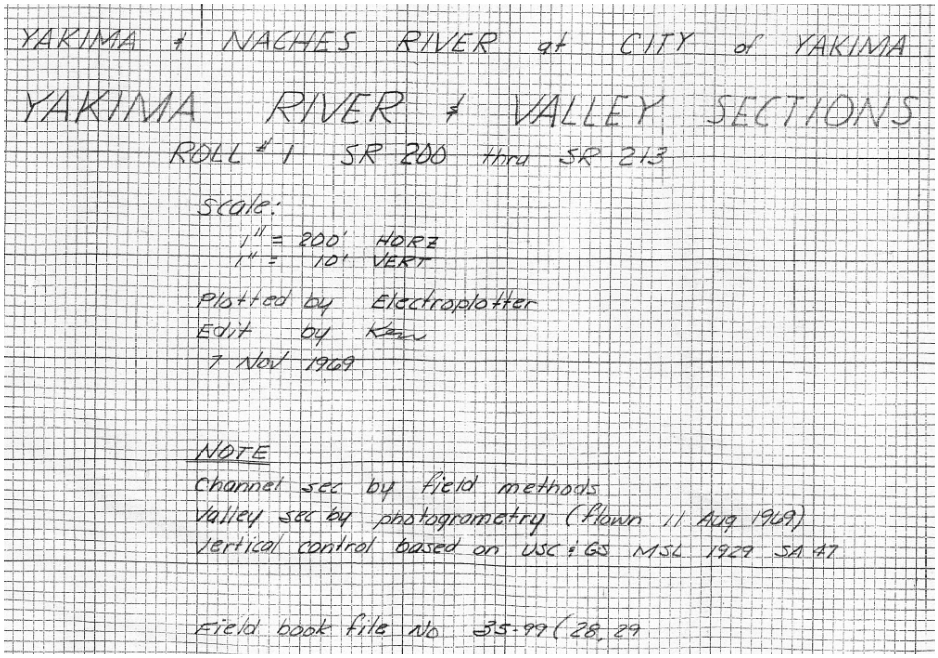


Figure 1 – Legend of 1969 Corps Sections Plot Sheets

SR # denotes the cross section number, this plot contains cross sections 200 (the most downstream plot) to number 213, upstream of Union Gap. The cross sections used the datum of MSL 1929, S.A. 47. This denotes the Coastal and Geodetic Survey's 1929 datum, with a Special Adjustment for the Columbia River Region that resulted in a correction of several thousandths of a foot for the gravitational effect of the Columbia River. These terms were combined in 1973 to National Geodetic Vertical Datum 1929 (NGVD 29). The Legend notes that the sections were plotted by electroplotter, and that the valley sections were determined through photogrammetry, while the channel sections were determined by field methods. An example of a cross section is shown below.

Figure 2 – Cross Section # 209

The hand drawn symbols on the plot show the locations of the instruments in the field, and intermediate lines shown turning points or inflection points in the cross section. From this cross section it can be determined the extent of the cross section that was determined through field methods (area between colored stars), and the extent by photogrammetry. On all cross sections, at least one specific ground elevation is given, and one or several surface water elevations are given. The Legend also references field books in which the survey data were recorded, both Yakima County and Denver Technical Services Center asked the Corps Seattle District if they could locate the referenced field books. After several attempts and through several different parts of the Corps – Survey, Emergency Management, Planning – those field books could not be located.

Modern Cross Sections

"Modern" topography and bathymetry consisted of a merged dataset of 2005 Lidar data, and bathymetric collected by USGS in 2005 and 2008. The vertical datum for this data set is NAVD 88, which in the Gap-to-Gap area is approximately 3.51 feet higher than the MSL 1929 datum. With these data, cross sections were developed with GIS software by selecting a cross section alignment, buffering that alignment by 20 feet on either side of the line, and selecting all raw surface and bathymetry points that lied within the 40 foot strip. These data were then loaded into road design software (Eaglepoint) to generate a triangulated irregular network (TIN), and then a profile based on the center line (the cross section alignment) of the TIN. This procedure allowed the generation of a very fine scale cross section on the ground section, and usually multiple points in the bathymetric section in the channel. This approach was chosen to maximize the number of potential "match points" along the modern topography, to allow a more detailed comparison with the 1969 cross sections. The 1969 cross sections were then also loaded into the road design software (as graphics) and could be compared to the "modern" cross sections.

Alignment and Evaluation Process –

Iteration One - The simplest process for comparison and evaluation of the cross section alignment was simply to lay the cross section locations generated by Yakima County GIS (based on the plates in the Flood Plain Information report) and compare. This approach was attractive as the 1969 cross sections had to be long enough to encompass the standard project flood, and most of these cross sections were very long, some over 2 miles. Given the length of the cross sections, many areas covered by the cross sections (some agricultural fields, but also the surrounding slopes of the valley) had not seen any topographic change since 1969, allowing the cross sections to be "tied" to known locations of the same elevation. This comparison proved to be very inaccurate in the majority of cross sections, with portions of the 1969 cross sections generated by photogrammetry extremely inaccurate. It appeared that these inaccuracies were from 3 causes: 1) the GIS cross sections did not match the locations of the 1969 cross sections in the valley, and appeared in most cases to be upstream by several hundred feet; 2) the cross sections change in alignment, and even minor errors in alignment (transferring the alignment from the field books, then to a rectified photo, then to production of the plates in the report, then from the report to a GIS shapefile) across a long cross section created large horizontal and vertical errors and; 3) the accuracy of the photogrametrically determined cross sections was much less (estimated RMSE of 2.5 feet) than the Lidar data (RMSE of .5 feet), which prevented matching elevations at either end of the cross sections. This process was rejected as lacking accuracy.

Iteration 2 - After consultation with Hilldale and Godaire, we decided that the comparison analysis should be limited to those portions of the 1969 cross sections that had been determined with field methods. Since there is a relatively accurate conversion factor of 3.51 feet for the two vertical datums, and each cross section has at least one ground shot (often on the shoulder of I-82), it should be possible to find those locations on the 2005 Lidar datasets as a starting point for the cross sections. Then, using the cross section stationing information on the 1969 cross sections plots, to lay out the length and alignment of the different "legs" of the cross section using high resolution 1971 aerial photography available on the Yakima County GIS. The 1971 photos are very comparable to conditions in 1969 as there were no major floods in the intervening years. This exercise also proved to lack accuracy as use of the conversion factor resulted in several hundred feet of horizontal error upstream and downstream of the actual cross section location based on the 1971 photos and fitting the 1969 cross section "legs" and topography to those photos. These errors in alignment were large for those cross sections downstream from SR 24 that were tied to I-82, but and less severe in the upper portion of the reach. This process was also rejected as lacking accuracy or consistency in method.

Iteration 3 - At that point, it was decided to simply try to match the topography shown in the 1969 cross sections to the georeferenced 1971 photos, and cut the modern cross sections based on that alignment. Basically, the procedure was to take the best attempt at matching the "shot" portion of the cross sections, so at a minimum, the two sets of cross sections could be compared graphically. Once the best fit for each cross section was found, then evaluate if additional numeric comparisons could be made. Typically, this consisted of taking a given cross section, looking at its rough location, and matching:

- topographic features such as the distance from I-82 or the Right Federal Levee to the Yakima River
- the width of the main channel and side channels,
- the distance between side channels
- the elevation of topographic feature such as levees, roads and valley walls
- and a general rule to cross major channels at a right angle to allow the (1969) flow model to develop flow/stage curves.

The turning points shown in the hand annotations on the cross sections determined the length of the various legs and helped to set the angle of those legs. Oftentimes the "legs" of the cross sections would begin or end at a local high point (a road, old levee, ditchbank spoils) that were discernable on the 1971 photos and the 2005 Lidar data. This was a labor-intensive and iterative process that had to be repeated for 3-8 times for each cross section. After an initial alignment was laid out on the GIS, it was checked with a cross section cut on the 2 foot contours from the LIDAR data, which is a feature of ARC/Gis. If there were differences, the cross section alignment was altered and checked again against current data. Once a satisfactory result had been achieved, the process of generation of the bare earth data 40 foot swath, importation of those points into Eaglepoint, and generation of a modern cross section was completed. Upon comparison of those more detailed and georeferenced cross sections with the 1969 cross sections, the cross section would either be accepted as matching elevation and alignment, or refined yet again, and in some cases an additional 3 times until a satisfactory match was generated.

This process resulted in acceptable graphical comparisons with the exception of two cross section, # 209 and #216. Both Cross Sections really never fit conditions in the floodplain, but the length and therefore the alignment of the cross section is correct. Cross Section 209 is shown above, and there is a large hump with the hand annotation "dense brush" written above. There is presently such a hump in this vicinity, but its height is only about 5 feet (based on bare earth LIDAR), and is vegetated with the same trees as those in 1969, which indicated that a significant elevation loss is unlikely. Horizontally, the current Hump lies some 150-200 feet west (right on the cross section), not in the location shown on the cross section. This cross section was located entirely based on the main and side channel widths, the distances between channels, the total distance of the cross section, and a field visit to the slope below I-82 which is the eastern terminus of the cross section that was gathered by "field methods".

Cross section #216 is similar (Figures 3 and 4). Possibly this cross section was hand-labeled incorrectly, it appears that the eastern (right hand) portion of this cross section has the square angles and coarse detail (especially lack of depiction of the bathymetry of the side channels) of the portions of this and other cross sections that were generated by photogrammetry, but the hand annotations indicate that this area was surveyed by field methods. There is no indication in the 1971 photo of either riverine or anthropogenic processes that would have accounted for the 10 foot rise shown on the cross section plot between the river and the side channels on the right side of the photos.

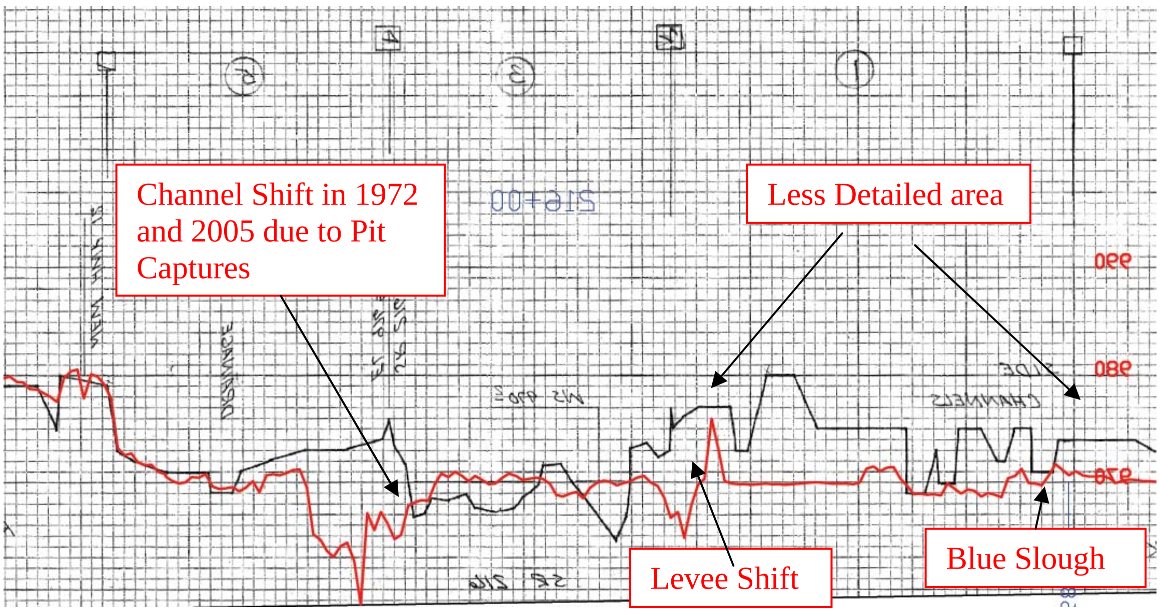


Figure 3 – Graphical Comparison on 1969 (black) and 2005 (Red) Cross Sections #216. (Plot has been reversed to allow comparisons with photos below) Note hand annotations of instrument locations at top of plot, and change in character of right portion of 1969 cross section.

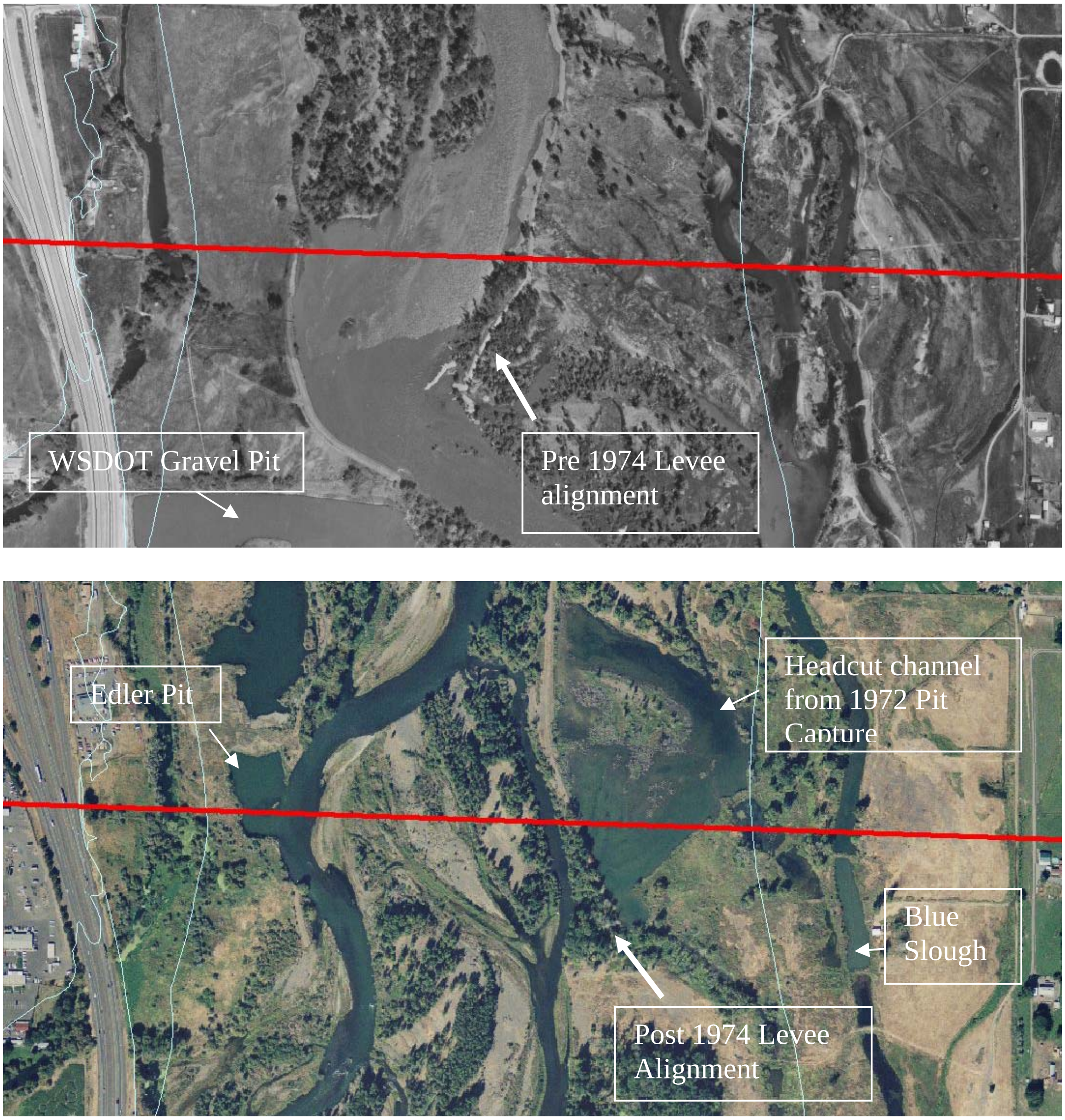


Figure 4 – Cross Section #216 (red) overlaid on 1971 (upper) and 2005 (lower) air photos. Note change in position of river; change in channel configuration as a result of gravel pit capture in 1972 (WSDOT pit) and 2003 (Edler Pit); relocation of levee; stability of Blue Slough alignment.

Cross Section #216 is an example of the elements that were used for the graphical comparison. The overall angle of the cross section is based on crossing the Yakima River (as it existed in 1969) at a right angle; the upstream/downstream position was based on fitting the cross section to the shape of I-82, the distance from I-82 to the levee and river channel on river right in 1971, and the position of Blue Slough on river right. This cross section also illustrates the large changes in cross section that have occurred in Segment 5.

Cross Section # 214 required the most radical modification of alignment of any of the cross sections. The alignment developed by Yakima County GIS, based on the scanned and rectified images from the Corp's Floodplain Information Report. When compared to the cross section plots, it was obvious that this cross section alignment was located 500-600 feet upstream of the location where the actual cross section was located.

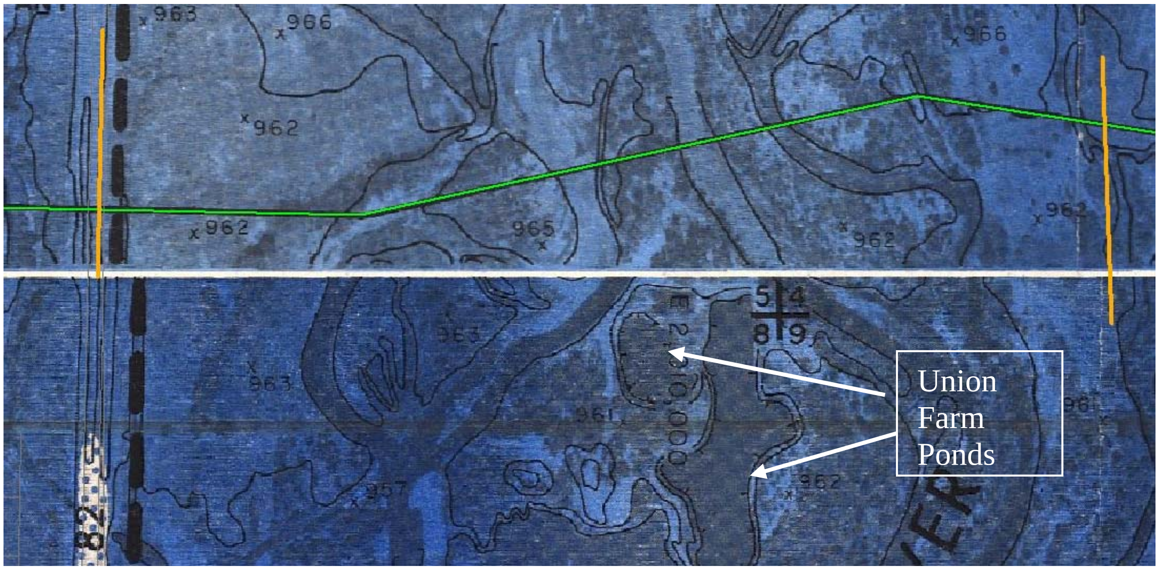


Figure 5 – Section of Geo-rectified map showing a portion of cross section 214. Green line is the cross section alignment originally developed by Yakima County GIS, overlain on the cross section alignment shown on the map. Orange bars on left and right indicate the extent of the cross section gathered by "field methods".

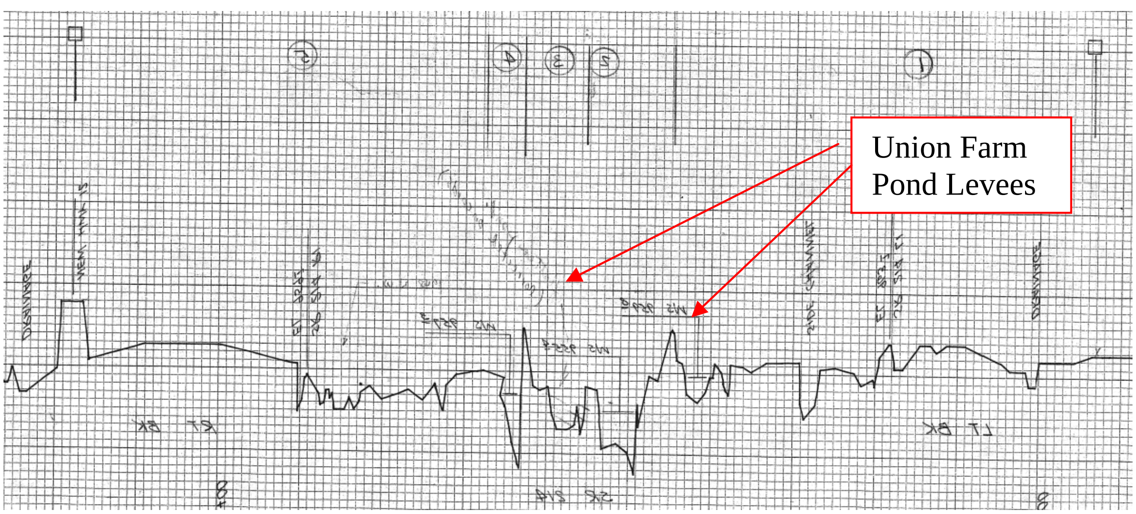


Figure 6 – Plot of Cross Section 214. Cross Section image is reversed to allow comparison with the map above. Note levees in middle of cross section.

As you can see above, the cross section plot shows that the cross section alignment included the Union Farm Pond levees. The Corp's Floodplain Information map and the cross section alignment developed by GIS both are too far upstream to include the Union Farm levees. Also note that the alignment above does not cross the main channel of the river at a right angle, as would be necessary for numerical flow models. Using the information in the cross section plot, a new alignment was developed after several iterations; both the new alignment and the cross section comparison are shown below.

Figure 7 – Alignment of cross section 214 over lain on 2005 photo. Green line is alignment from Corps Study, red line is new alignment based on fitting the cross section plot to topography.

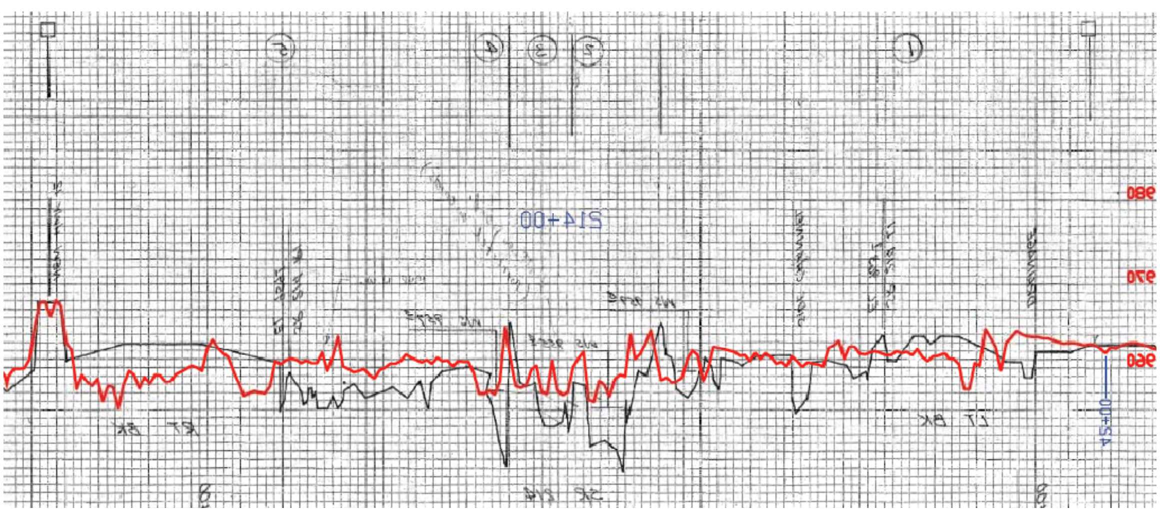


Figure 8 – Graphical comparison of Corps cross section with graphically fitted alignment. Cross section is reversed to allow for comparison with photos.

Numerical Comparisons

The majority of the 1969 cross sections (except for 5) referenced either the I-82 road prism, constructed several years before, or the Yakima Project Federal Levee system constructed in 1947. As-built drawings of the levee system using the NGVD 1929 vertical datum were available for both the Federal Levee system and I-82, and these data were then used to check either for local variation or overall differences between the 2005 Lidar bare earth data, the as-builts, and the Corps cross sections. Comparison of the 2005 bare earth points with both the I-82 and Levee as-builts showed that the 3.51 foot correction was applicable and both data sets matched within hundredths of a foot in the project area. There were a total of four locations shown on the 1969 cross sections that could be resurveyed to determine the difference between the 2005 and 1969 data sets. 3 of these points were on old bridge abutments that still exist in the middle of the Gap-to-Gap reach, all 3 points matched exactly (with the correction). The fourth point was the location of the instrument at cross section 201 just downstream of Sunnyside Diversion Dam on the top of a concrete and rock wall. This point did not match the 1969 data by +.86 feet, and there is no indication that the wall had been modified since 1969 or even earlier, as this wall appears in photos of the dam in the 1933 flood which are contained in the Floodplain Report itself. This indicated that there may be some variance between the 1969 Corps vertical data and NAVD 88. At the very low gradients present in the river system and valley, an error of that magnitude would result in the cross sections being shifted several hundred feet, generally downstream.

In order to evaluate this difference, the elevations of 1-82 or the Federal Levees were then compared between the 1969 and 2005 datasets, and a correction specific to each cross section was generated, for each “shot” portion of the cross section that referenced either I-82 or the Federal Levees. This process was used to minimize bias in comparison of the cross sections since both the freeway and levees parallel the river and have a similar gradient to the river, and it was possible using the as-builts for both structures to determine the actual elevation in 1969 a specific location along the cross section alignment developed through the graphical process defined above. If that 1969 elevation was lower than the elevations shown on the 1969 plots, the correction for the modern datum for that cross section would be less than the standard 3.51 feet (converting from NGVD 29 to NAVD 88), if that 1969 elevation was higher, the correction was greater.

As mentioned before several cross sections did not include the entire road prism of I-82 or the Federal Levees in the cross section.

- The first two cross sections in the Project Area, 209 and 210 (in the Union Gap) did not include I-82, but were shot from US 97 on the other side of the Gap. US 97 has been completely rebuilt since 1969, and as-builts for the former alignment were not available. There are also two railroad grades in the cross sections, the UPRR and the NPRR. The UPRR has been abandoned, but the NPRR (now BN) is still in existence, and these cross sections were referenced to the NPRR tracks (actually the corner of the prism that supports the track), which have been maintained in a consistent elevation in the vicinity of the cross sections.

- Cross Section #217 matches very well graphically along its entire length, but the elevation shown for I-82 is high by 4 feet (when compared both to the Lidar data and I-82 as-builts) after correction, even though the slope and elevation rise of the I-82 road prism shown on the cross section matches exactly with the current slope and elevation, which have not changed since construction in 1962. The accuracy of the location and alignment of this cross section is arguably the best of any cross section in the dataset due to the very short area along the length of the freeway that the cross section could be located within –the location of the Shanno Ditch/Drain undercrossing . Without access to the actual survey books used by the Corps, the reason for this discrepancy is unknown.

- Cross Sections 219, 220 and 221 also did not include reference to I-82 or the Federal Levees in the portions of the cross sections gathered by field methods. Section 219 was therefore matched to the 1971 air photo and the standard correction was used. This cross section has changed dramatically both in-channel and with the construction of a portion of the DID #1 levee after the 1974 flood, the scale of these changes relative to the degree of uncertainty for the datum are sufficient to accurately detect that a large change has occurred in this cross section. At Cross Section 220, the location of the surveying instrument was discernable, adjacent to the City of Yakima Wastewater Treatment Plant outfall. This area has changed since 1969, most notably after the 1996 flood. The City of Yakima was able to supply a survey of the area (from 1979) and the access road on which the instrument was located, these elevation matched precisely with the correction of 3.51 feet. Cross section #221 again did not have any other references than the cross sections themselves, and was fit to the 1971 photos, and the standard correction of 3.51 feet was used. Given that both the downstream (#220) and upstream (#222, with shot bridge abutments) cross sections both met the standard correction of 3.51 feet with good to excellent control, application of the standard correction for this cross section was acceptable.

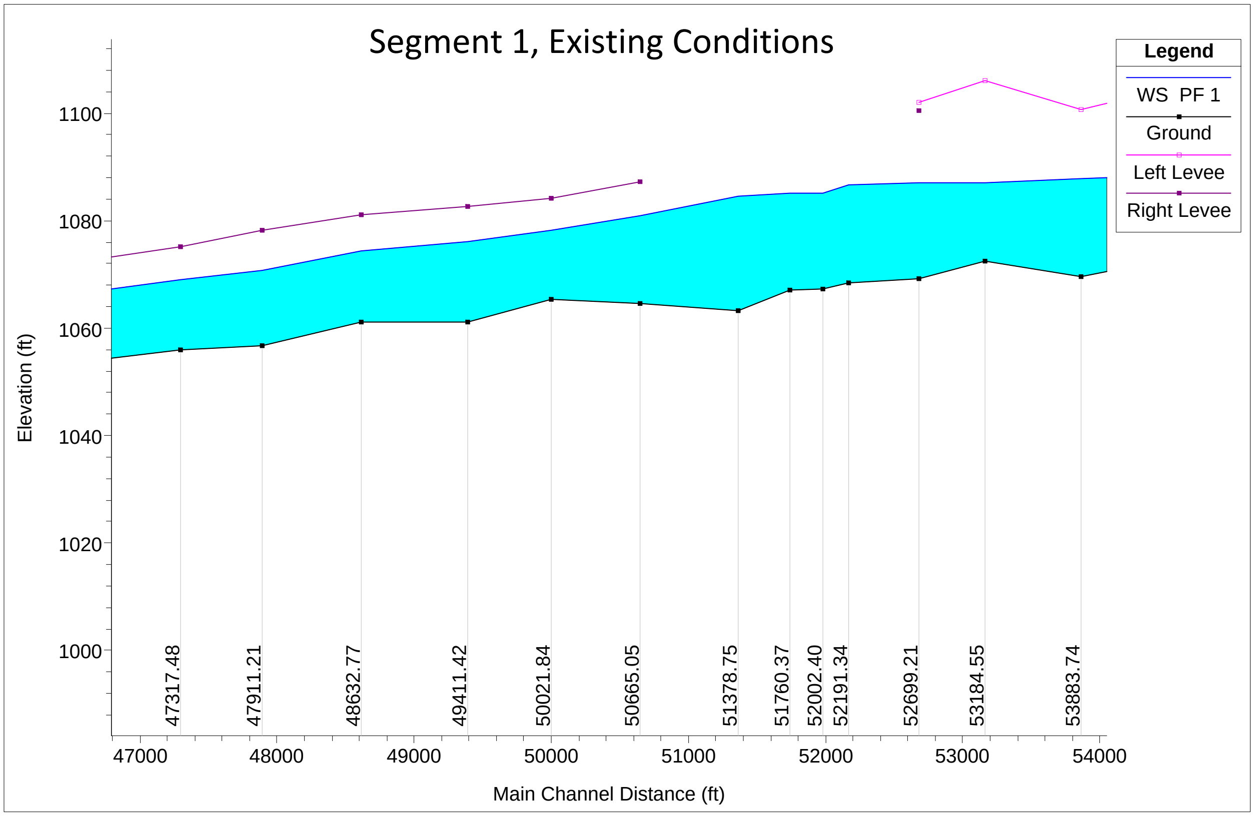
Ideally, the numerical comparisons of the cross sections would be used for two purposes in the current study, and also for future uses. In the current study, the datum corrections for each cross section could be used to calculate changes in the elevation of the thalweg, channel, or floodplain elevations in the period from 1969 to 2005, and to get a quantitative estimate of the change. The accuracy of the correction can be estimated by the calculation of the Root Mean Square Error (RMSE) for the set of cross sections used in the analysis. RMSE is analogous to the Standard Error, and is an unbiased estimator if the error in the dataset, these errors could arise from the inability to exactly locate the endpoints of the cross sections, differing methodologies of survey, differing datums, error in the geoid model, errors in the accuracy of the plots relative to the registration on the engineering vellum the plots were printed on, conversion of survey data to the plots, or errors reading elevations from the plots. RMSE for the entire dataset was 1.36 feet. With the exception of Cross Section 217, where the correction was large due to the large difference between the Corps elevation of I-82 relative to the LIDAR and as-built elevations of I-82, the corrections are normally distributed around a mean correction of approximately 3.2 feet. Because the correction for Cross Section 217 is inexplicably and significantly larger than that of other cross sections, it is considered an outlier to the dataset and has been removed. If Cross Section 217 is removed from the dataset, the RMSE for the corrections of the remainder of the cross sections in the dataset becomes .84 feet. To estimate the accuracy of a comparison of the 1969 cross section to current topography at multiple points (assuming the error in the Corps field methods at each cross section was zero, and assuming both the I-82 and Federal Levee as-builts had zero error) the RMSE of the Lidar data (.5 feet) would have to be added, giving an overall estimate of the accuracy of the comparisons to be approximately +/- 1.4 feet.

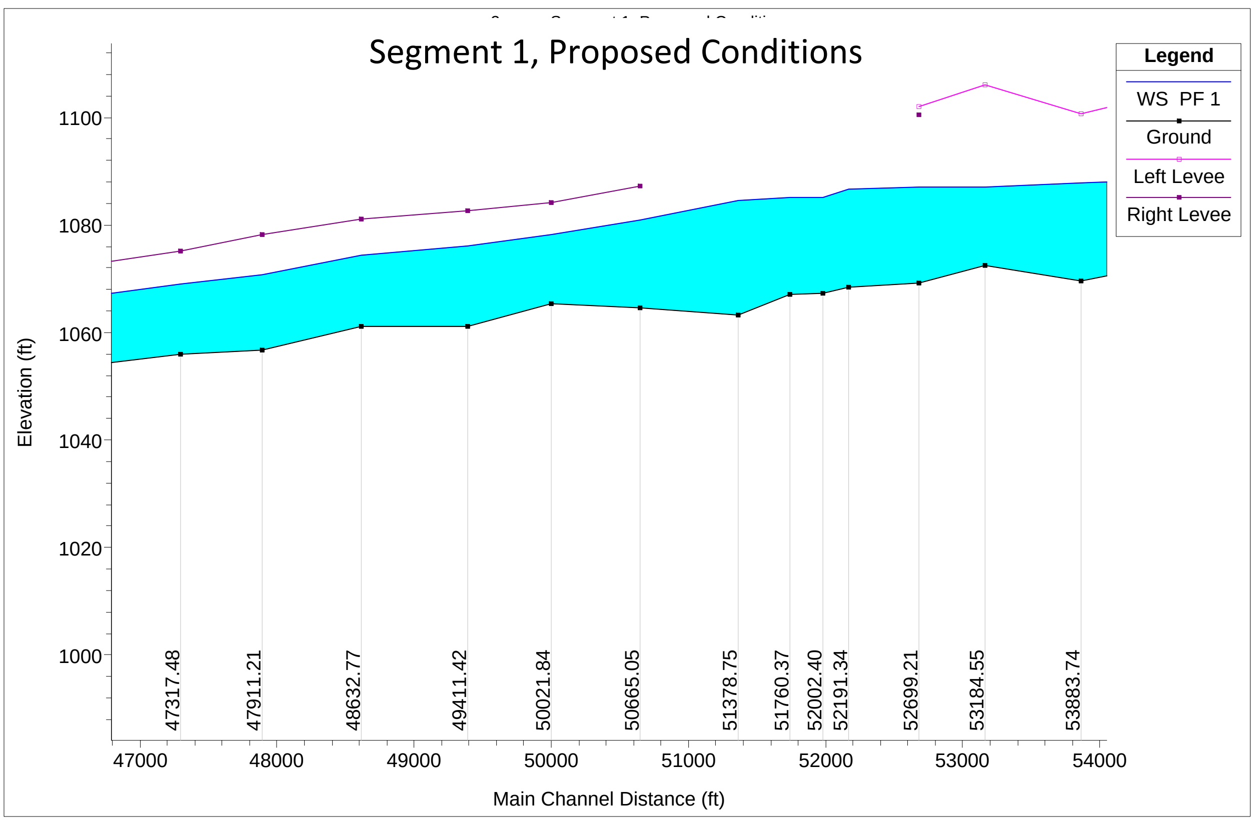
Use of the 1969 cross section data in the present report and future reports should keep the following considerations in mind-

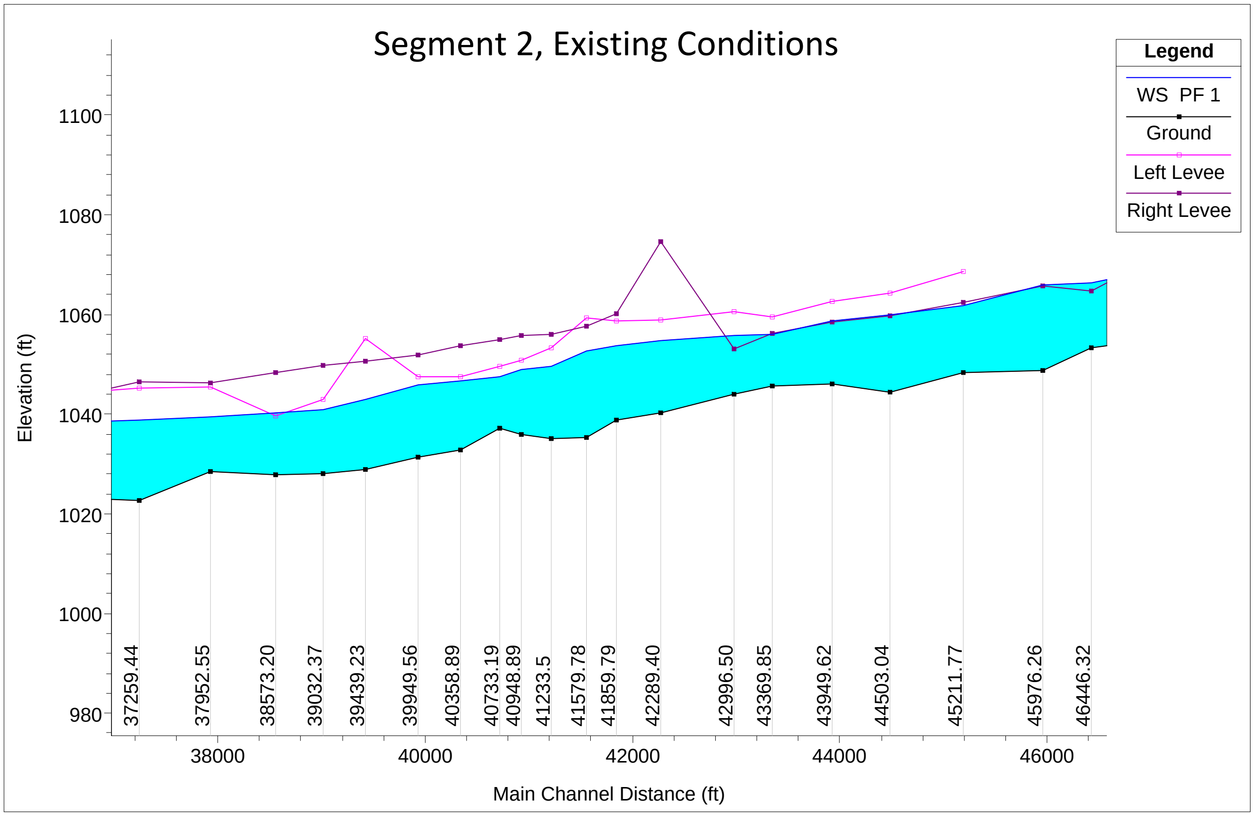
- With the exception of Cross Section 209 and 216, all of the cross sections should be usable for graphical comparison of change over time.
- With the exception of Cross Section 217, all cross sections should be usable for numerically-based comparisons of change over time.

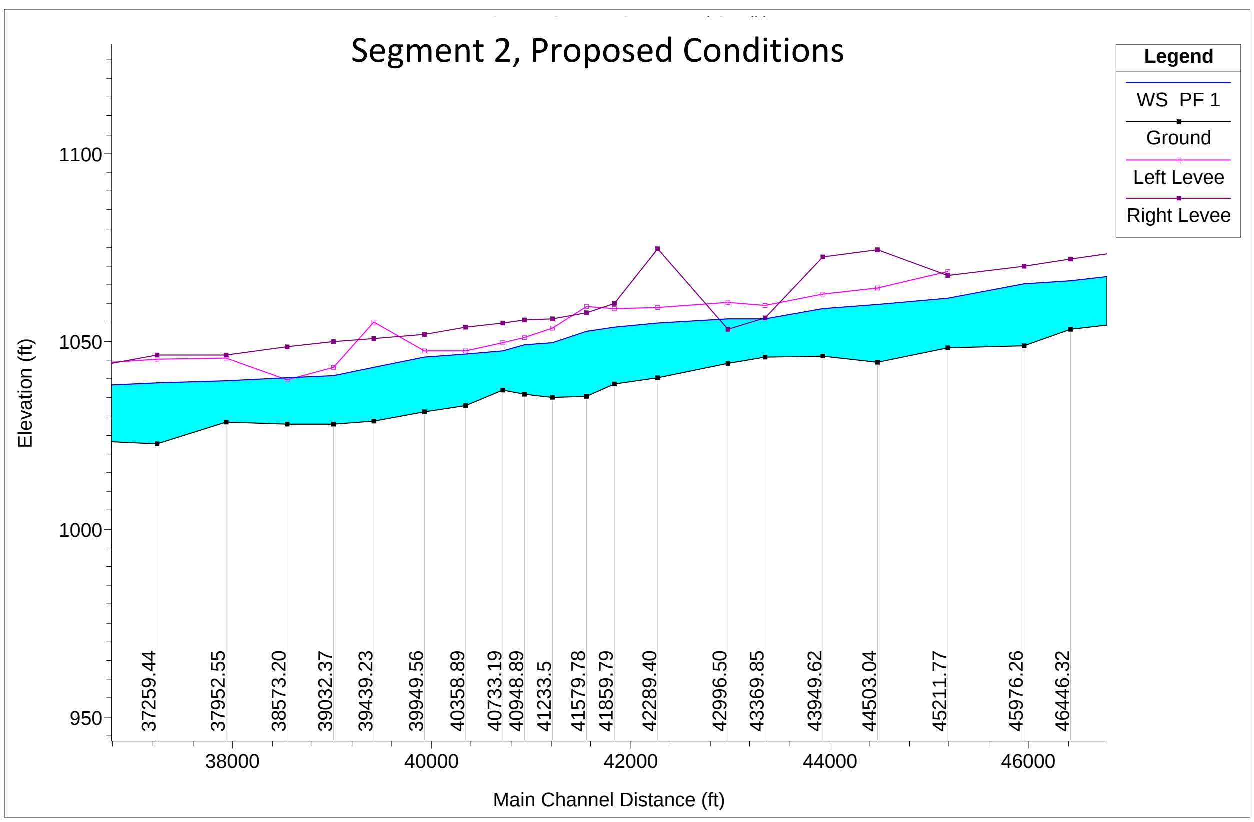
13 APPENDIX D

Water Surface Profiles from HEC-RAS


Segment 1, Existing Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1100
1080
1060
1040
1020
1000
47317.48
47911.21
48632.77
49411.42
50021.84
50665.05
51378.75
51760.37
52002.40
52191.34
52699.21
53184.55
53883.74
47000
48000
49000
50000
51000
52000
53000
54000
Main Channel Distance (ft)


Segment 1, Proposed Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1100
1080
1060
1040
1020
1000
47317.48
47911.21
48632.77
49411.42
50021.84
50665.05
51378.75
51760.37
52002.40
52191.34
52699.21
53184.55
53883.74
47000
48000
49000
50000
51000
52000
53000
54000
Main Channel Distance (ft)


Segment 2, Existing Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
Main Channel Distance (ft)
37259.44
37952.55
38573.20
39032.37
39439.23
39949.56
40358.89
40733.19
40948.89
41233.5
41579.78
41859.79
42289.40
42996.50
43369.85
43949.62
44503.04
45211.77
45976.26
46446.32


Segment 2, Proposed Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
Main Channel Distance (ft)
37259.44
37952.55
38573.20
39032.37
39439.23
39949.56
40358.89
40733.19
40948.89
41233.5
41579.78
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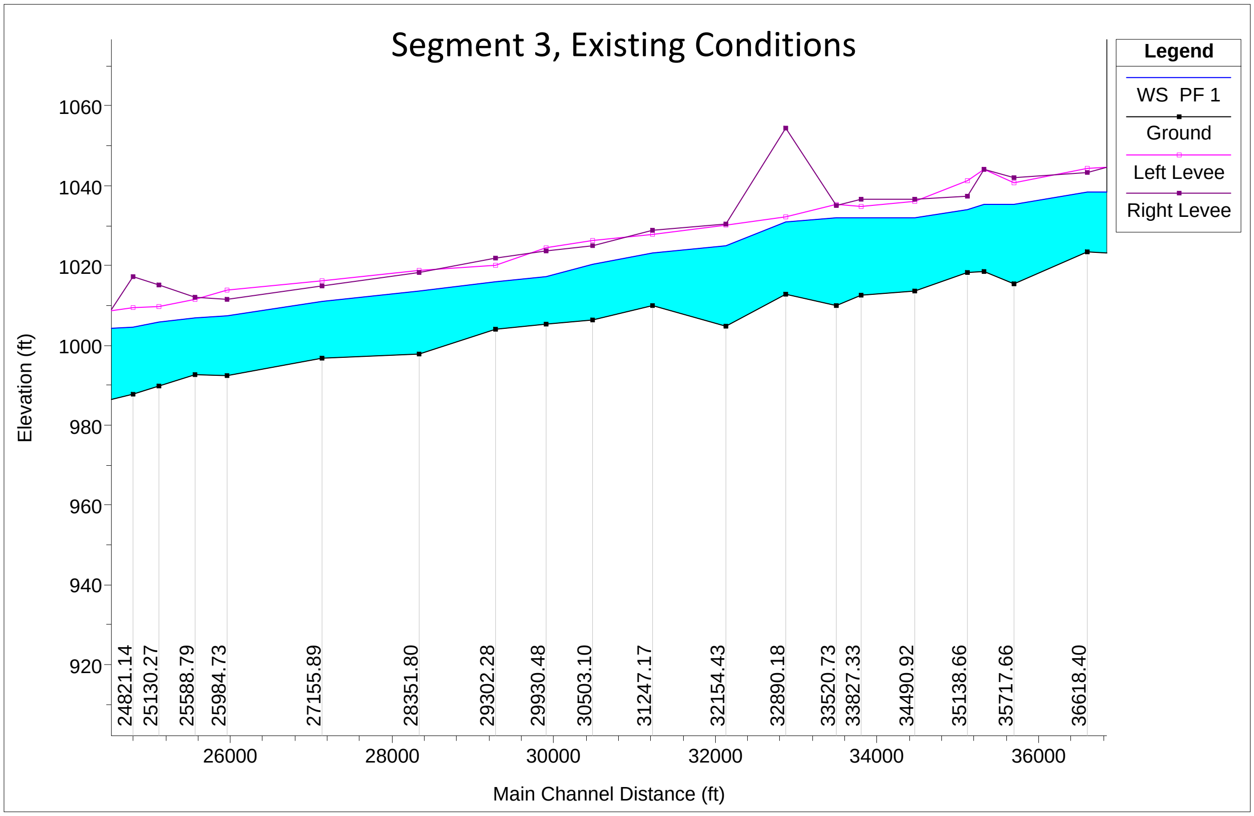
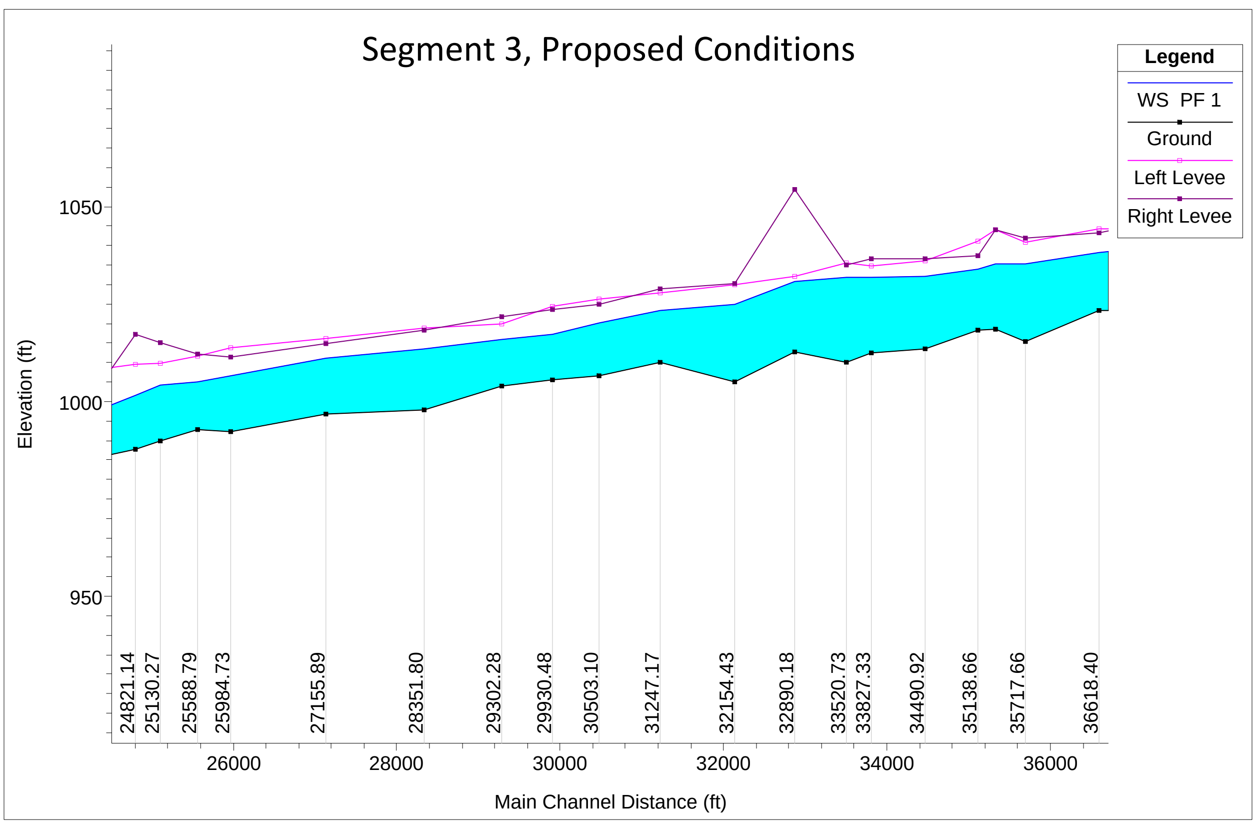
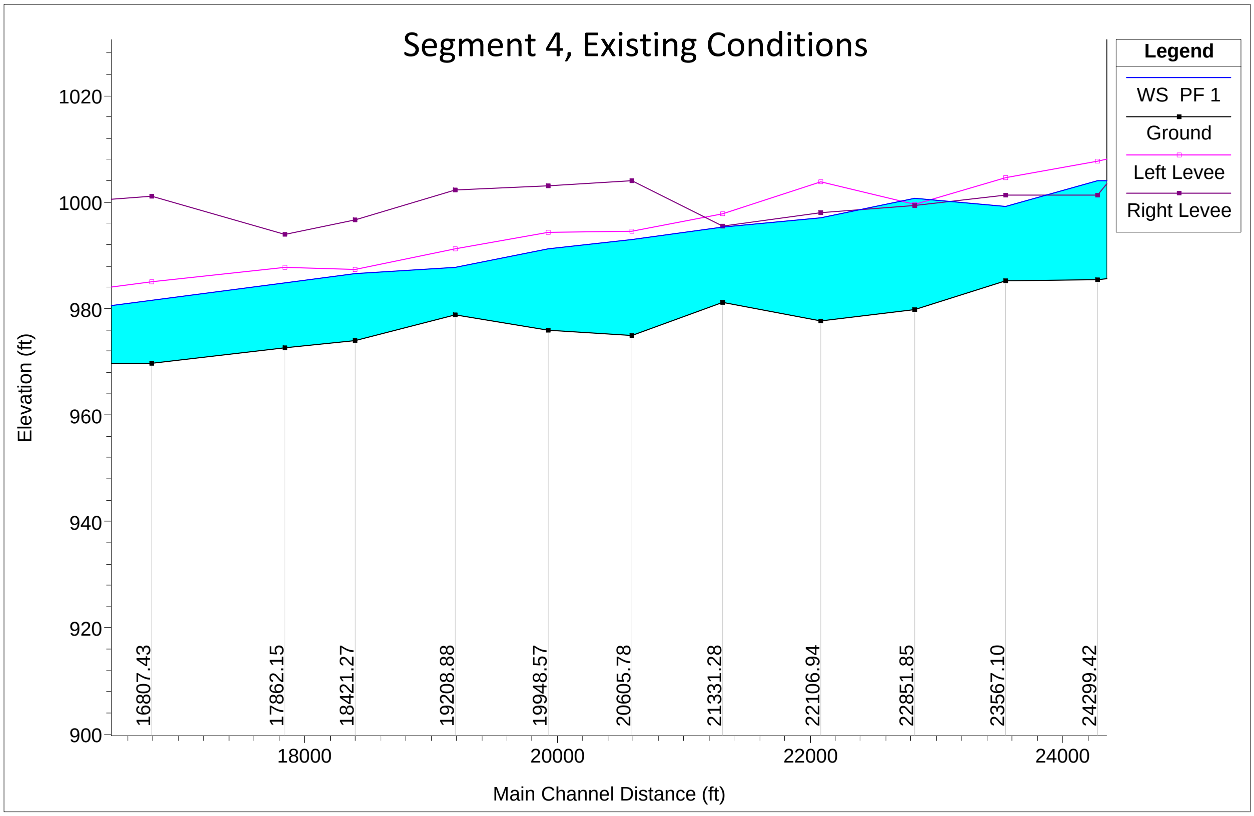
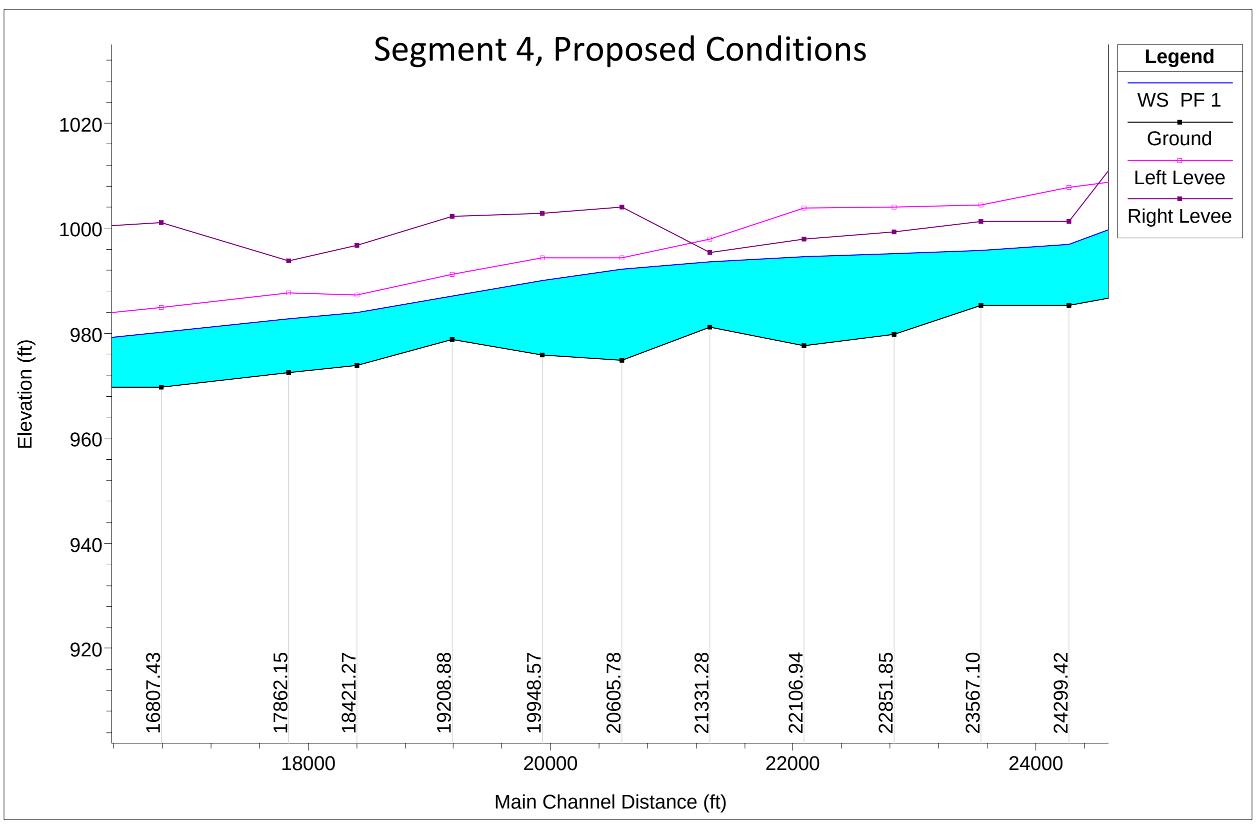
42289.40
42996.50
43369.85
43949.62
44503.04
45211.77
45976.26
46446.32


Segment 3, Existing Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1060
1040
1020
1000
980
960
940
920
24821.14
25130.27
25588.79
25984.73
27155.89
28351.80
29302.28
29930.48
30503.10
31247.17
32154.43
32890.18
33520.73
33827.33
34490.92
35138.66
35717.66
36618.40
26000
28000
30000
32000
34000
36000
Main Channel Distance (ft)

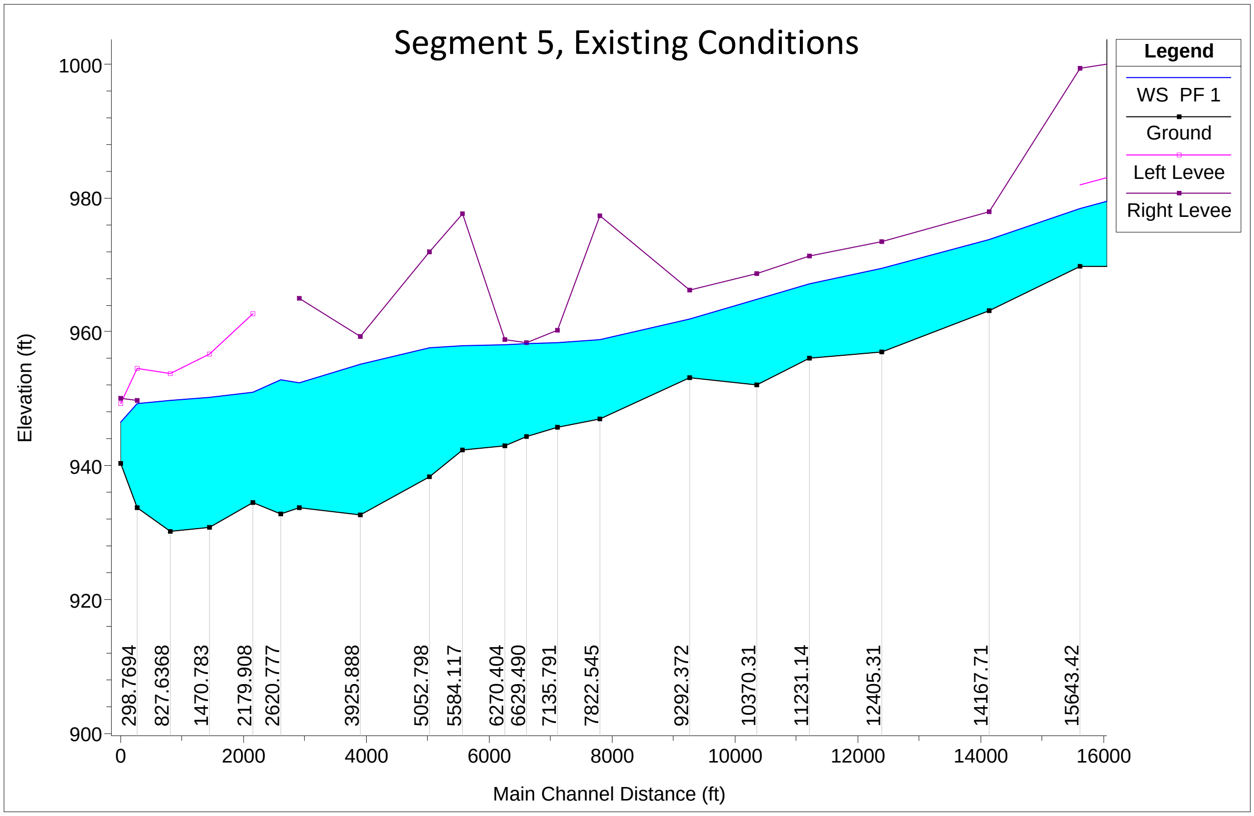

Segment 3, Proposed Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1050
1000
950
24821.14
25130.27
25588.79
25984.73
27155.89
28351.80
29302.28
29930.48
30503.10
31247.17
32154.43
32890.18
33520.73
33827.33
34490.92
35138.66
35717.66
36618.40
26000
28000
30000
32000
34000
36000
Main Channel Distance (ft)



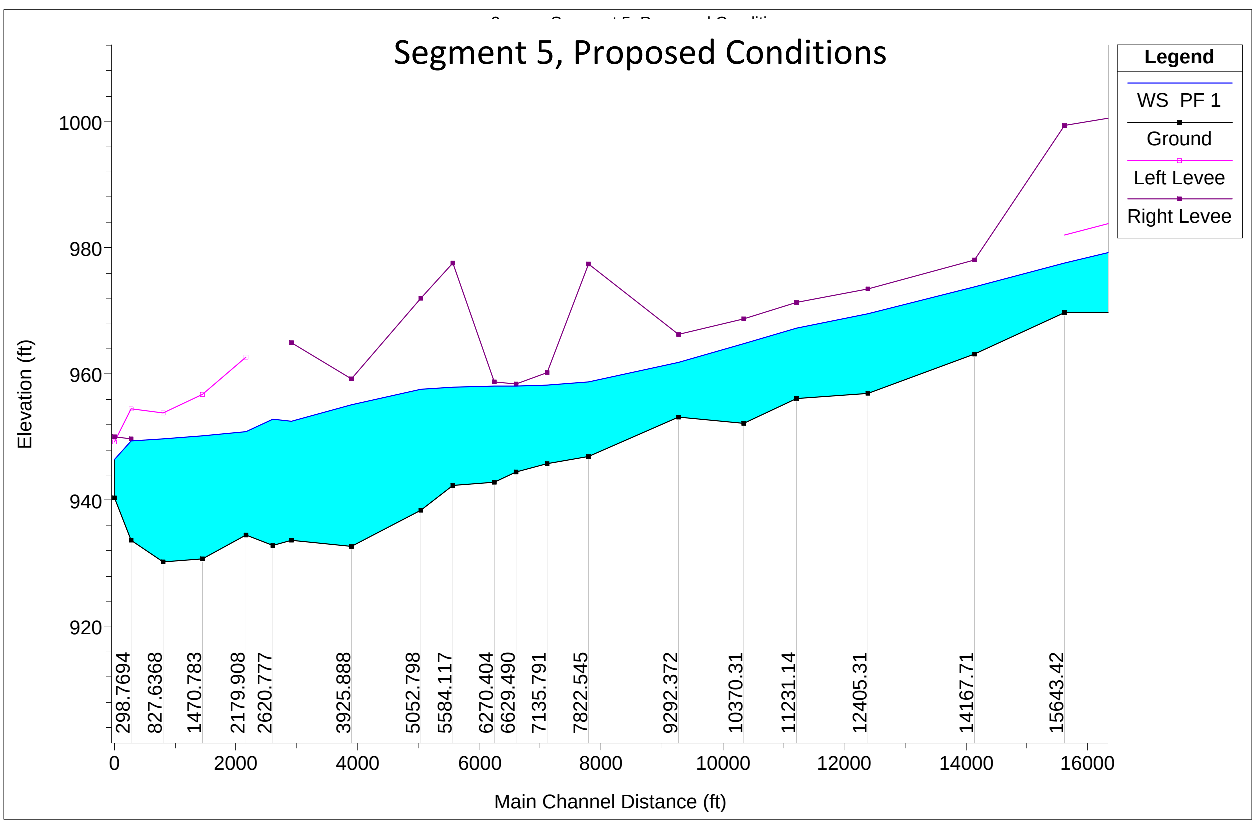
Segment 4, Existing Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1020
1000
980
960
940
920
900
16807.43
17862.15
18421.27
19208.88
19948.57
20605.78
21331.28
22106.94
22851.85
23567.10
24299.42
18000
20000
22000
24000
Main Channel Distance (ft)



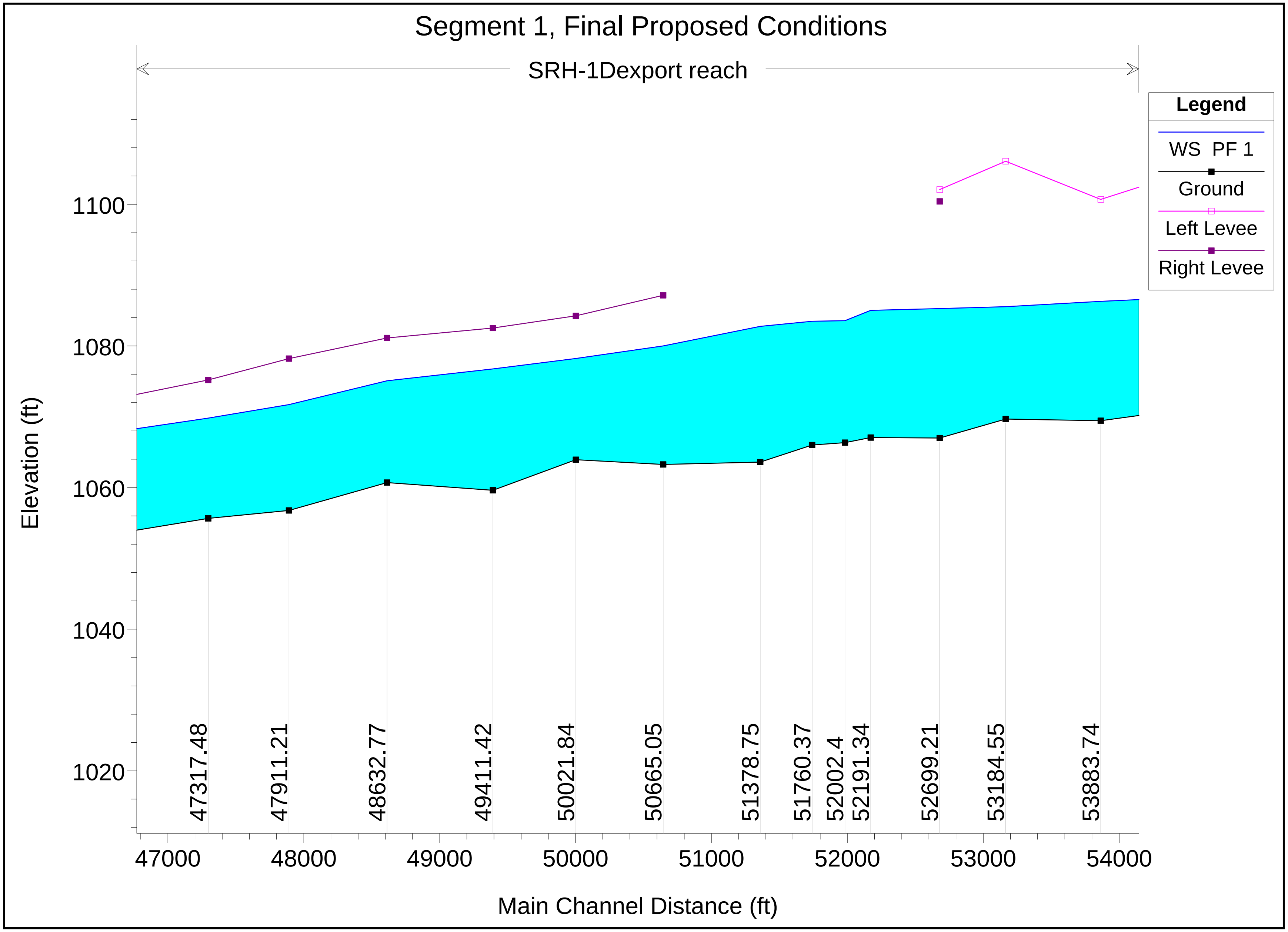
Segment 4, Proposed Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1020
1000
980
960
940
920
16807.43
17862.15
18421.27
19208.88
19948.57
20605.78
21331.28
22106.94
22851.85
23567.10
24299.42
18000
20000
22000
24000
Main Channel Distance (ft)

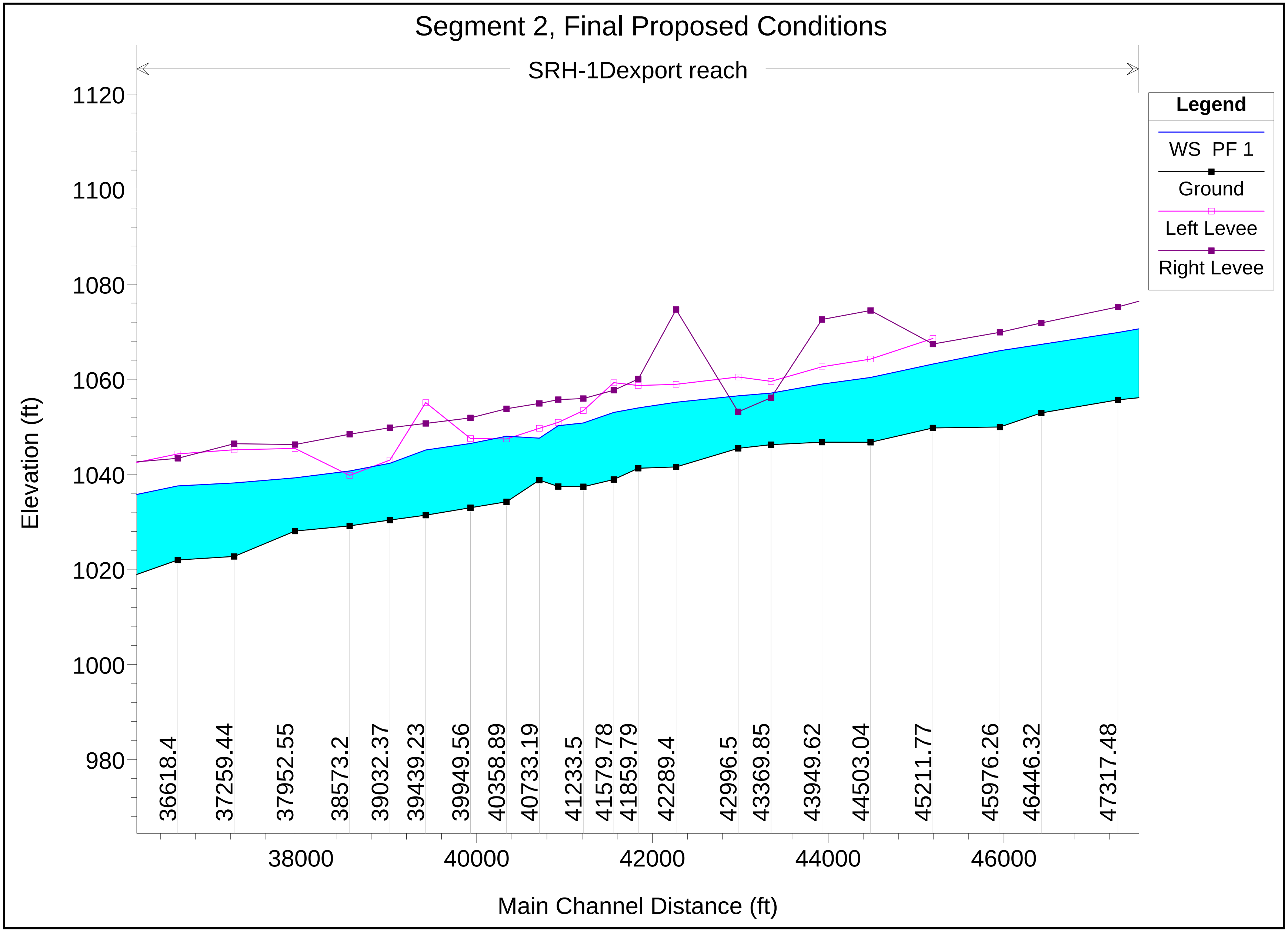


Segment 5, Existing Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1000
980
960
940
920
900
298.7694
827.6368
1470.783
2179.908
2620.777
3925.888
5052.798
5584.117
6270.404
6629.490
7135.791
7822.545
9292.372
10370.31
11231.14
12405.31
14167.71
15643.42
0
2000
4000
6000
8000
10000
12000
14000
16000
Main Channel Distance (ft)

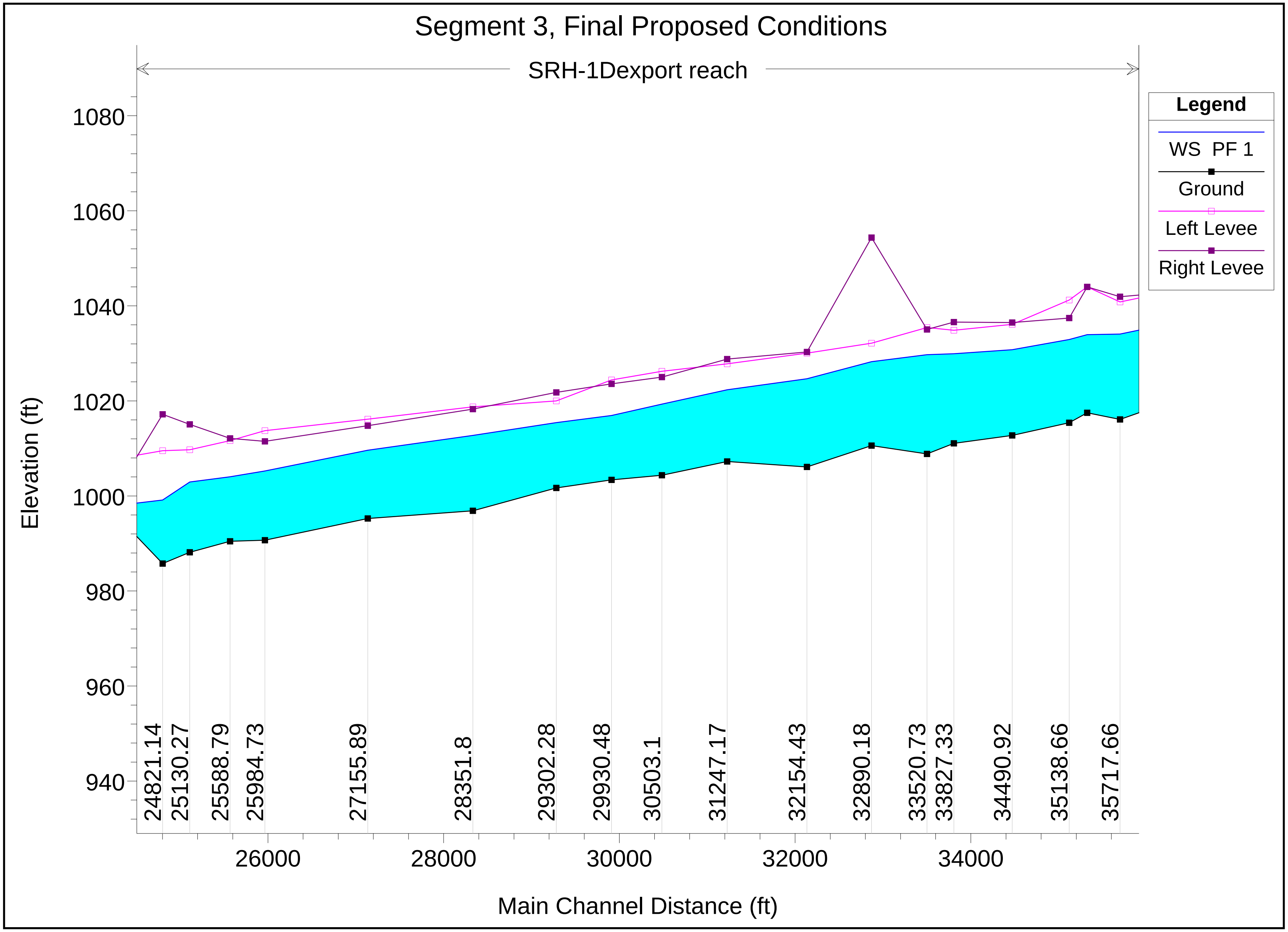


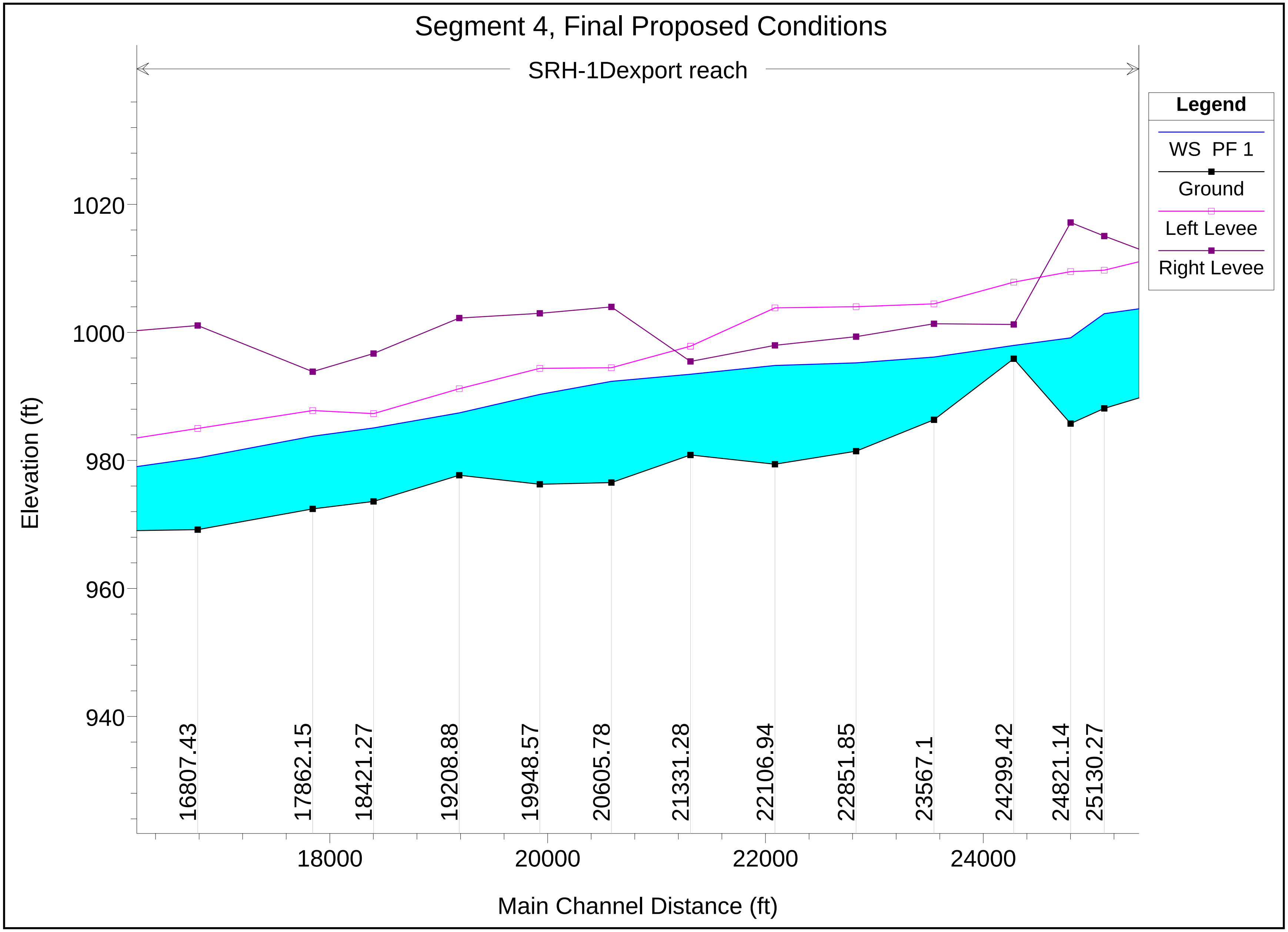
Segment 5, Proposed Conditions
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1000
980
960
940
920
298.7694
827.6368
1470.783
2179.908
2620.777
3925.888
5052.798
5584.117
6270.404
6629.490
7135.791
7822.545
9292.372
10370.31
11231.14
12405.31
14167.71
15643.42
0
2000
4000
6000
8000
10000
12000
14000
16000
Main Channel Distance (ft)


Segment 1, Final Proposed Conditions
SRH-1Dexport reach
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1100
1080
1060
1040
1020
47317.48
47911.21
48632.77
49411.42
50021.84
50665.05
51378.75
51760.37
52002.4
52191.34
52699.21
53184.55
53883.74
47000
48000
49000
50000
51000
52000
53000
54000
Main Channel Distance (ft)

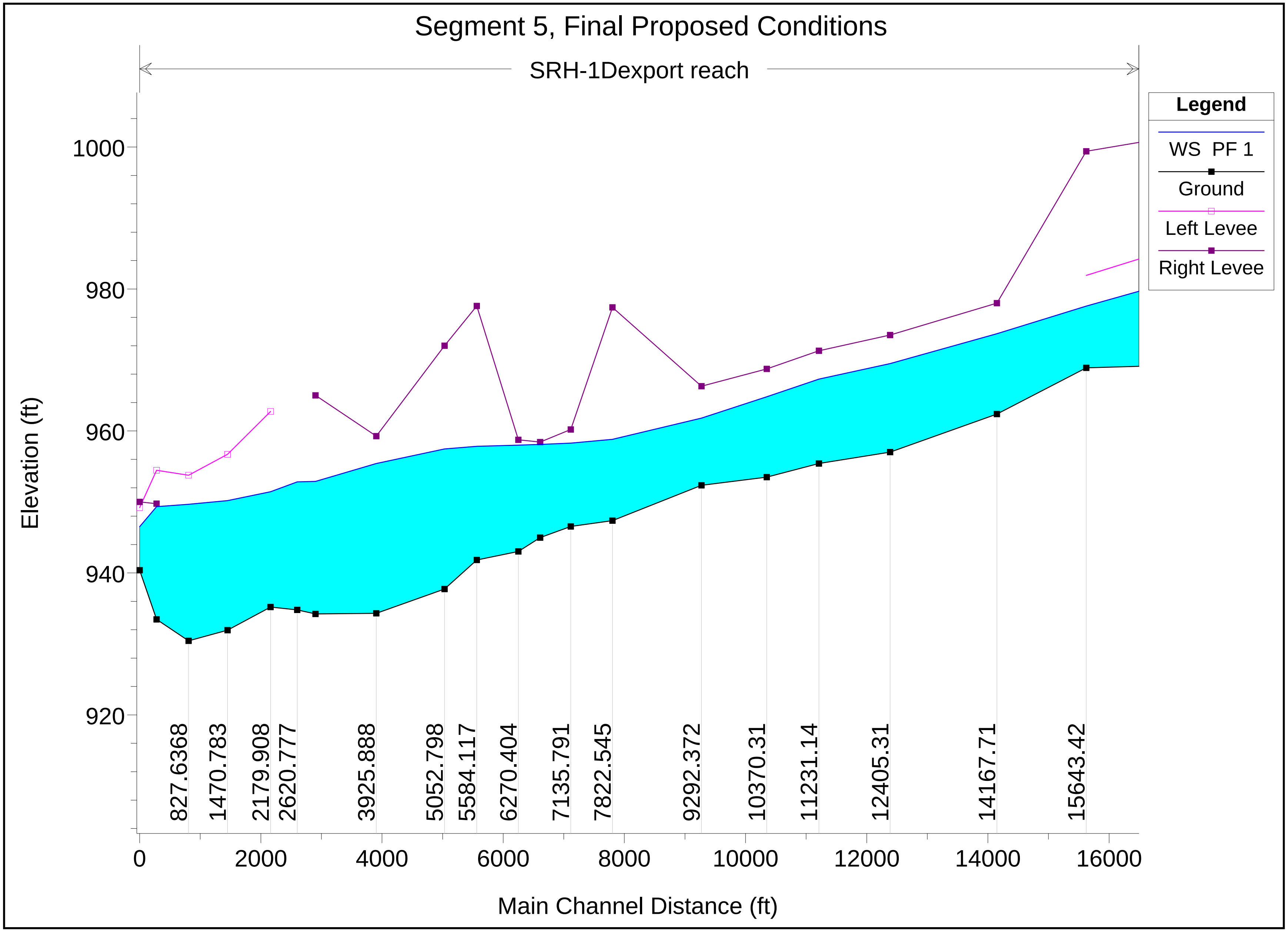


Segment 2, Final Proposed Conditions
SRH-1Dexport reach
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1120
1100
1080
1060
1040
1020
1000
980
36618.4
37259.44
37952.55
38573.2
39032.37
39439.23
39949.56
40358.89
40733.19
41233.5
41579.78
41859.79
42289.4
42996.5
43369.85
43949.62
44503.04
45211.77
45976.26
46446.32
47317.48
38000
40000
42000
44000
46000
Main Channel Distance (ft)


Segment 3, Final Proposed Conditions
SRH-1Dexport reach
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1080
1060
1040
1020
1000
980
960
940
24821.14
25130.27
25588.79
25984.73
27155.89
28351.8
29302.28
29930.48
30503.1
31247.17
32154.43
32890.18
33520.73
33827.33
34490.92
35138.66
35717.66
26000
28000
30000
32000
34000
Main Channel Distance (ft)



Segment 4, Final Proposed Conditions
SRH-1Dexport reach
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1020
1000
980
960
940
16807.43
17862.15
18421.27
19208.88
19948.57
20605.78
21331.28
22106.94
22851.85
23567.1
24299.42
24821.14
25130.27
18000
20000
22000
24000
Main Channel Distance (ft)



Segment 5, Final Proposed Conditions
SRH-1Dexport reach
Legend
WS PF 1
Ground
Left Levee
Right Levee
Elevation (ft)
1000
980
960
940
920
827.6368
1470.783
2179.908
2620.777
3925.888
5052.798
5584.117
6270.404
7135.791
7822.545
9292.372
10370.31
11231.14
12405.31
14167.71
15643.42
0
2000
4000
6000
8000
10000
12000
14000
16000
Main Channel Distance (ft)

14 APPENDIX E

Bed Material

			WEIGHT (LB) RETAINED																		
Key	**River Mile**	**Layer**	**362mm**	**256.00**	**181.02**	**128.00**	**90.51**	**64.00**	**45.25**	**37.50**	**32.00**	**19.00**	**9.50**	**4.75**	**2.36**	**1.18**	**0.60**	**0.30**	**0.15**	**0.075**	**Pan**	**Sum**
YAK Surface	109.5	Surface	0.00	0.00	0.00	0.00	42.00	70.00	50.50		33.00	22.15	4.96	0.04	0.08	0.07	0.11	0.10	0.09	0.05	0.07	223.22
YAK Sub-Surface	109.5	Sub-Surface	0.00	0.00	0.00	17.50	41.00	46.00	32.00		34.50	41.14	26.00	2.01	1.75	0.40	2.98	9.12	4.33	1.01	1.01	260.75
YAK combined	109.5	combined	0.00	0.00	0.00	17.50	83.00	116.00	82.50	0.00	67.50	63.29	30.96	2.05	1.83	0.47	3.09	9.22	4.42	1.06	1.08	483.97
YAK Surface	110.5	Surface	0.00	0.00	0.00	24.00	83.00	60.00	26.50		19.00	11.95	2.89	0.26	0.56	0.31	0.34	0.16	0.06	0.03	0.05	229.11
YAK Sub-Surface	110.5	Sub-Surface	0.00	0.00	0.00	17.00	16.00	40.50	32.50		34.00	43.66	37.14	8.15	17.74	7.63	10.62	6.80	1.92	0.47	0.48	274.61
YAK combined	110.5	combined	0.00	0.00	0.00	41.00	99.00	100.50	59.00	0.00	53.00	55.61	40.03	8.41	18.30	7.94	10.96	6.96	1.98	0.50	0.53	503.72
YAK Surface	111.5	Surface				0.00	0.00	7.80	0.50		4.60	4.87	3.09	0.90	0.23						0.21	22.20
YAK Sub-Surface	111.5	Sub-Surface				0.00	0.00	7.30	8.10		5.30	5.11	5.48	4.30	2.15	1.46	1.96	1.56	0.50	0.10	0.05	43.37
YAK combined	111.5	combined				0.00	0.00	15.10	8.60	0.00	9.90	9.98	8.57	5.20	2.38	1.46	1.96	1.56	0.50	0.10	0.26	65.57
YAK Surface	113.3	Surface				0.00	65.80	45.90	32.90		10.50	2.80									0.00	157.90
YAK Sub-Surface	113.3	Sub-Surface			24.40	7.00	12.40	35.30	21.70		22.50	22.16	19.31	13.69	7.64	5.88	6.91	4.44	2.06	0.62	0.31	206.32
YAK combined	113.3	combined			24.40	7.00	78.20	81.20	54.60	0.00	33.00	24.96	19.31	13.69	7.64	5.88	6.91	4.44	2.06	0.62	0.31	364.22
YAK Surface	115	Surface	0.00	0.00	0.00	0.00	12.00	18.50	43.50		68.50	57.79	0.05	0.00	0.02	0.01	0.02	0.02	0.03	0.03	0.07	200.54
YAK Sub-Surface	115	Sub-Surface	0.00	0.00	0.00	0.00	2.50	26.00	45.00		47.00	36.18	0.80	0.03	0.14	0.16	0.48	0.73	0.50	0.28	0.32	160.12
YAK combined	115	combined	0.00	0.00	0.00	0.00	14.50	44.50	88.50	0.00	115.50	93.97	0.85	0.03	0.16	0.17	0.50	0.75	0.53	0.31	0.39	360.66
YAK Surface	116	Surface	0.00	0.00	20.40	149.00	76.00	43.00	49.50		26.00	4.93	0.00	0.00	0.07	0.08	0.07	0.07	0.08	0.08	0.18	369.46
YAK Sub-Surface	116	Sub-Surface	0.00	0.00	24.00	76.50	38.50	42.00	30.50		38.50	40.25	22.62	4.46	8.66	2.44	2.82	9.53	7.12	2.95	2.94	353.79
YAK combined	116	combined	0.00	0.00	44.40	225.50	114.50	85.00	80.00	0.00	64.50	45.18	22.62	4.46	8.73	2.52	2.89	9.60	7.20	3.03	3.12	723.25
YAK Surface	117.5	Surface			21.40	59.40	42.80	18.00	5.90		2.30	0.50									0.00	150.30
YAK Sub-Surface	117.5	Sub-Surface		65.30			23.10	18.20	17.00		17.90	19.06	13.87	7.91	4.58	3.34	5.68	7.35	5.35	1.50	0.84	210.99
YAK combined	117.5	combined	0.00	65.30	21.40	59.40	65.90	36.20	22.90	0.00	20.20	19.56	13.87	7.91	4.58	3.34	5.68	7.35	5.35	1.50	0.84	361.29
YAK Surface	118.5	Surface					6.40	12.10	14.70		5.90	2.80										41.90
YAK Sub-Surface	118.5	Sub-Surface				9.60	4.80	8.10	13.00		14.50	10.47	11.44	9.68	4.83	3.33	4.16	3.68	1.39	0.28	0.14	99.40
YAK1 combined	118.5	combined	0.00	0.00	0.00	9.60	11.20	20.20	27.70	0.00	20.40	13.27	11.44	9.68	4.83	3.33	4.16	3.68	1.39	0.28	0.14	141.30
NACH Surface	0.9	Surface				86.40	144.80	53.30		31.54		16.40	1.87	0.25	0.05						0.17	334.78
NACH Sub-Surface	0.9	Sub-Surface				25.80	34.50	21.20		30.26		32.37	25.00	17.98	10.35	5.64	6.05	7.73	3.52	0.82	0.64	221.87
NACH combined	0.9	combined	0.00	0.00	0.00	112.20	179.30	74.50	0.00	61.80	0.00	48.77	26.87	18.23	10.40	5.64	6.05	7.73	3.52	0.82	0.81	556.65

			PERCENT RETAINED																			
Key	**River Mile**	**Layer**	**362.04**	**256.00**	**181.02**	**128.00**	**90.51**	**64.00**	**45.25**	**37.50**	**32.00**	**19.00**	**9.50**	**4.75**	**2.36**	**1.18**	**0.60**	**0.30**	**0.15**	**0.075**	**Pan**	**Sum**
YAK Surface	109.5	Surface	0.00	0.00	0.00	0.00	0.19	0.31	0.23	0.00	0.15	0.10	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK Sub-Surface	109.5	Sub-Surface	0.00	0.00	0.00	0.07	0.16	0.18	0.12	0.00	0.13	0.16	0.10	0.01	0.01	0.00	0.01	0.03	0.02	0.00	0.00	1.00
YAK combined	109.5	combined	0.00	0.00	0.00	0.04	0.17	0.24	0.17	0.00	0.14	0.13	0.06	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.00	1.00
YAK Surface	110.5	Surface	0.00	0.00	0.00	0.10	0.36	0.26	0.12	0.00	0.08	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK Sub-Surface	110.5	Sub-Surface	0.00	0.00	0.00	0.06	0.06	0.15	0.12	0.00	0.12	0.16	0.14	0.03	0.06	0.03	0.04	0.02	0.01	0.00	0.00	1.00
YAK combined	110.5	combined	0.00	0.00	0.00	0.08	0.20	0.20	0.12	0.00	0.11	0.11	0.08	0.02	0.04	0.02	0.02	0.01	0.00	0.00	0.00	1.00
YAK Surface	111.5	Surface						0.35	0.02		0.21	0.22	0.14	0.04	0.01						0.01	1.00
YAK Sub-Surface	111.5	Sub-Surface						0.17	0.19		0.12	0.12	0.13	0.10	0.05	0.03	0.05	0.04	0.01	0.00	0.00	1.00
YAK combined	111.5	combined						0.23	0.13		0.15	0.15	0.13	0.08	0.04	0.02	0.03	0.02	0.01	0.00	0.00	1.00
YAK Surface	113.3	Surface					0.42	0.29	0.21		0.07											0.98
YAK Sub-Surface	113.3	Sub-Surface			0.12	0.03	0.06	0.17	0.11		0.11	0.11	0.09	0.07	0.04	0.03	0.03	0.02	0.01	0.00	0.00	1.00
YAK combined	113.3	combined			0.07	0.02	0.21	0.22	0.15	0.00	0.09	0.07	0.05	0.04	0.02	0.02	0.02	0.01	0.01	0.00	0.00	1.00
YAK Surface	115	Surface	0.00	0.00	0.00	0.00	0.06	0.09	0.22	0.00	0.34	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK Sub-Surface	115	Sub-Surface	0.00	0.00	0.00	0.00	0.02	0.16	0.28	0.00	0.29	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK combined	115	combined	0.00	0.00	0.00	0.00	0.04	0.12	0.25	0.00	0.32	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK Surface	116	Surface	0.00	0.00	0.06	0.40	0.21	0.12	0.13	0.00	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
YAK Sub-Surface	116	Sub-Surface	0.00	0.00	0.07	0.22	0.11	0.12	0.09	0.00	0.11	0.11	0.06	0.01	0.02	0.01	0.01	0.03	0.02	0.01	0.01	1.00
YAK combined	116	combined	0.00	0.00	0.06	0.31	0.16	0.12	0.11	0.00	0.09	0.06	0.03	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	1.00
YAK Surface	117.5	Surface			0.14	0.40	0.28	0.12	0.04		0.02											1.00
YAK Sub-Surface	117.5	Sub-Surface		0.31			0.11	0.09	0.08		0.08	0.09	0.07	0.04	0.02	0.02	0.03	0.03	0.03	0.01	0.00	1.00
YAK combined	117.5	combined		0.18	0.06	0.16	0.18	0.10	0.06	0.00	0.06	0.05	0.04	0.02	0.01	0.01	0.02	0.02	0.01	0.00	0.00	1.00
YAK Surface	118.5	Surface					0.15	0.29	0.35		0.14											0.93
YAK Sub-Surface	118.5	Sub-Surface				0.10	0.05	0.08	0.13		0.15	0.11	0.12	0.10	0.05	0.03	0.04	0.04	0.01	0.00	0.00	1.00
YAK1 combined	118.5	combined				0.07	0.08	0.14	0.20		0.14	0.09	0.08	0.07	0.03	0.02	0.03	0.03	0.01	0.00	0.00	1.00
NACH Surface	0.9	Surface				0.26	0.43	0.16	0.00	0.09		0.05	0.01	0.00	0.00						0.00	1.00
NACH Sub-Surface	0.9	Sub-Surface				0.12	0.16	0.10	0.00	0.14		0.15	0.11	0.08	0.05	0.03	0.03	0.03	0.02	0.00	0.00	1.00
NACH combined	0.9	combined				0.20	0.32	0.13	0.00	0.11		0.09	0.05	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	1.00

			Percent Passing																	
Key	**River Mile**	**Layer**	**362.04**	**256.00**	**181.02**	**128.00**	**90.51**	**64.00**	**45.25**	**37.50**	**32.00**	**19.00**	**9.50**	**4.75**	**2.36**	**1.18**	**0.60**	**0.30**	**0.15**	**0.075**
YAK Surface	109.5	Surface	100.00	100.00	100.00	100.00	81.18	49.83	27.20	27.20	12.42	2.50	0.27	0.26	0.22	0.19	0.14	0.09	0.05	0.03
YAK Sub-Surface	109.5	Sub-Surface	100.00	100.00	100.00	93.29	77.56	59.92	47.65	47.65	34.42	18.64	8.67	7.90	7.23	7.08	5.93	2.44	0.77	0.39
YAK combined	109.5	combined	100.00	100.00	100.00	96.38	79.23	55.27	38.22	38.22	24.27	11.19	4.80	4.37	4.00	3.90	3.26	1.36	0.44	0.22
YAK Surface	110.5	Surface	100.00	100.00	100.00	89.52	53.30	27.11	15.54	15.54	7.25	2.03	0.77	0.66	0.41	0.28	0.13	0.06	0.03	0.02
YAK Sub-Surface	110.5	Sub-Surface	100.00	100.00	100.00	93.81	87.98	73.23	61.40	61.40	49.02	33.12	19.60	16.63	10.17	7.39	3.52	1.05	0.35	0.17
YAK combined	110.5	combined	100.00	100.00	100.00	91.86	72.21	52.26	40.54	40.54	30.02	18.98	11.03	9.36	5.73	4.16	1.98	0.60	0.20	0.11
YAK Surface	111.5	Surface	100.00	100.00	100.00	100.00	100.00	64.86	62.61	62.61	41.89	19.95	6.04	1.98	0.95	0.95	0.95	0.95	0.95	0.95
YAK Sub-Surface	111.5	Sub-Surface	100.00	100.00	100.00	100.00	100.00	83.17	64.49	64.49	52.27	40.49	27.85	17.94	12.98	9.62	5.10	1.51	0.35	0.12
YAK combined	111.5	combined	100.00	100.00	100.00	100.00	100.00	76.97	63.86	63.86	48.76	33.54	20.47	12.54	8.91	6.68	3.69	1.32	0.55	0.40
YAK Surface	113.3	Surface	100.00	100.00	100.00	100.00	58.33	29.26	8.42	8.42	1.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	113.3	Sub-Surface	100.00	100.00	88.17	84.78	78.77	61.66	51.14	51.14	40.24	29.50	20.14	13.50	9.80	6.95	3.60	1.45	0.45	0.15
YAK combined	113.3	combined	100.00	100.00	93.30	91.38	69.91	47.61	32.62	32.62	23.56	16.71	11.41	7.65	5.55	3.94	2.04	0.82	0.25	0.08
YAK Surface	115	Surface	100.00	100.00	100.00	100.00	94.02	84.79	63.10	63.10	28.94	0.12	0.10	0.10	0.09	0.08	0.07	0.06	0.05	0.03
YAK Sub-Surface	115	Sub-Surface	100.00	100.00	100.00	100.00	98.44	82.20	54.10	54.10	24.74	2.15	1.65	1.63	1.54	1.44	1.14	0.69	0.37	0.20
YAK combined	115	combined	100.00	100.00	100.00	100.00	95.98	83.64	59.10	59.10	27.08	1.02	0.79	0.78	0.73	0.69	0.55	0.34	0.19	0.11
YAK Surface	116	Surface	100.00	100.00	94.48	54.15	33.58	21.94	8.54	8.54	1.50	0.17	0.17	0.17	0.15	0.13	0.11	0.09	0.07	0.05
YAK Sub-Surface	116	Sub-Surface	100.00	100.00	93.22	71.59	60.71	48.84	40.22	40.22	29.34	17.96	11.57	10.31	7.86	7.17	6.37	3.68	1.66	0.83
YAK combined	116	combined	100.00	100.00	93.86	62.68	46.85	35.10	24.04	24.04	15.12	8.87	5.74	5.13	3.92	3.57	3.17	1.85	0.85	0.43
YAK Surface	117.5	Surface	100.00	100.00	85.76	46.24	17.76	5.79	1.86	1.86	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	117.5	Sub-Surface	100.00	69.05	69.05	69.05	58.10	49.48	41.42	41.42	32.94	23.90	17.33	13.58	11.41	9.82	7.13	3.64	1.11	0.40
YAK combined	117.5	combined	100.00	81.93	76.00	59.56	41.32	31.30	24.96	24.96	19.37	13.96	10.12	7.93	6.66	5.74	4.16	2.13	0.65	0.23
YAK Surface	118.5	Surface	100.00	100.00	100.00	100.00	84.73	55.85	20.76	20.76	6.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	118.5	Sub-Surface	100.00	100.00	100.00	90.34	85.51	77.36	64.29	64.29	49.70	39.16	27.66	17.92	13.06	9.71	5.52	1.82	0.42	0.14
YAK1 combined	118.5	combined	100.00	100.00	100.00	93.21	85.28	70.98	51.38	51.38	36.94	27.55	19.45	12.60	9.19	6.83	3.88	1.28	0.29	0.10
NACH Surface	0.9	Surface	100.00	100.00	100.00	74.19	30.94	15.02	15.02	5.60	5.60	0.70	0.14	0.07	0.05	0.05	0.05	0.05	0.05	0.05
NACH Sub-Surface	0.9	Sub-Surface	100.00	100.00	100.00	88.37	72.82	63.27	63.27	49.63	49.63	35.04	23.77	15.67	11.00	8.46	5.73	2.25	0.66	0.29
NACH combined	0.9	combined	100.00	100.00	100.00	79.84	47.63	34.25	34.25	23.15	23.15	14.39	9.56	6.28	4.42	3.40	2.31	0.93	0.29	0.14

			LOG INTERP PERCENT PASSING																				
Key	**River Mile**	**Layer**	**362mm**	**256.00**	**181.02**	**128.00**	**90.51**	**64.00**	**45.25**	**32.00**	**22.60**	**16.00**	**11.30**	**8.00**	**5.65**	**4.00**	**2.80**	**2.00**	**1.00**	**0.50**	**0.25**	**0.125**	**0.075**
YAK Surface	109.5	Surface	100.00	100.00	100.00	100.00	81.18	49.83	27.20	12.42	4.84	2.50	0.85	0.40	0.27	0.25	0.23	0.22	0.18	0.14	0.08	0.04	0.03
YAK Sub-Surface	109.5	Sub-Surface	100.00	100.00	100.00	93.29	77.56	59.92	47.65	34.42	24.01	18.64	12.87	9.92	8.35	7.72	7.42	7.23	6.78	6.04	1.66	0.61	0.39
YAK combined	109.5	combined	100.00	100.00	100.00	96.38	79.23	55.27	38.22	24.27	15.40	11.19	7.43	5.57	4.62	4.27	4.10	4.00	3.74	3.32	0.93	0.35	0.22
YAK Surface	110.5	Surface	100.00	100.00	100.00	89.52	53.30	27.11	15.54	7.25	3.44	2.03	1.27	0.92	0.72	0.58	0.48	0.41	0.23	0.14	0.05	0.03	0.02
YAK Sub-Surface	110.5	Sub-Surface	100.00	100.00	100.00	93.81	87.98	73.23	61.40	49.02	38.93	33.12	25.68	21.48	18.33	14.64	11.76	10.17	6.19	3.79	0.72	0.28	0.17
YAK combined	110.5	combined	100.00	100.00	100.00	91.86	72.21	52.26	40.54	30.02	22.93	18.98	14.59	12.13	10.32	8.25	6.63	5.73	3.48	2.13	0.42	0.16	0.11
YAK Surface	111.5	Surface	100.00	100.00	100.00	100.00	100.00	64.86	50.24	41.89	24.50	13.68	7.57	4.25	2.45	1.57	1.08	0.95	0.95	0.95	0.95	0.95	0.95
YAK Sub-Surface	111.5	Sub-Surface	100.00	100.00	100.00	100.00	100.00	83.17	63.40	52.27	43.46	35.98	29.90	24.24	19.50	16.21	13.78	11.85	7.90	3.40	0.92	0.24	0.12
YAK combined	111.5	combined	100.00	100.00	100.00	100.00	100.00	76.97	63.86	48.76	37.20	28.69	22.47	17.53	13.76	11.26	9.49	8.16	5.56	2.62	0.98	0.49	0.40
YAK Surface	113.3	Surface	100.00	100.00	100.00	100.00	58.33	29.26	5.69	1.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	113.3	Sub-Surface	100.00	100.00	88.17	84.78	78.77	61.66	48.05	40.24	32.15	26.15	21.65	17.75	14.57	12.21	10.40	8.82	5.67	2.66	0.98	0.31	0.15
YAK combined	113.3	combined	100.00	100.00	93.30	91.38	69.91	47.61	32.62	23.56	18.38	14.81	12.26	10.06	8.25	6.92	5.89	5.00	3.21	1.51	0.56	0.18	0.08
YAK Surface	115	Surface	100.00	100.00	100.00	100.00	94.02	84.79	63.10	28.94	1.18	0.12	0.11	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.06	0.04	0.03
YAK Sub-Surface	115	Sub-Surface	100.00	100.00	100.00	100.00	98.44	82.20	54.10	24.74	5.89	2.15	1.89	1.73	1.64	1.61	1.57	1.54	1.36	1.17	0.56	0.30	0.20
YAK combined	115	combined	100.00	100.00	100.00	100.00	95.98	83.64	59.10	27.08	3.95	1.02	0.90	0.82	0.78	0.77	0.75	0.73	0.65	0.56	0.28	0.16	0.11
YAK Surface	116	Surface	100.00	100.00	94.48	54.15	33.58	21.94	8.54	1.50	0.42	0.17	0.17	0.17	0.17	0.17	0.16	0.15	0.13	0.11	0.08	0.06	0.05
YAK Sub-Surface	116	Sub-Surface	100.00	100.00	93.22	71.59	60.71	48.84	40.22	29.34	21.99	17.96	14.51	12.49	11.04	9.61	8.52	7.86	6.97	6.45	2.82	1.32	0.83
YAK combined	116	combined	100.00	100.00	93.86	62.68	46.85	35.10	24.04	15.12	11.05	8.87	7.19	6.20	5.49	4.78	4.25	3.92	3.47	3.21	1.43	0.68	0.43
YAK Surface	117.5	Surface	100.00	100.00	85.76	46.24	17.76	5.79	1.09	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	117.5	Sub-Surface	100.00	69.05	69.05	69.05	58.10	49.48	39.00	32.94	26.12	21.59	18.42	16.04	14.22	12.86	11.78	10.90	8.89	5.70	2.45	0.79	0.40
YAK combined	117.5	combined	100.00	81.93	76.00	59.56	41.32	31.30	24.96	19.37	15.28	12.61	10.76	9.37	8.30	7.51	6.88	6.37	5.19	3.33	1.43	0.46	0.23
YAK Surface	118.5	Surface	100.00	100.00	100.00	100.00	84.73	55.85	16.15	6.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	118.5	Sub-Surface	100.00	100.00	100.00	90.34	85.51	77.36	59.73	49.70	41.84	35.09	29.54	24.11	19.45	16.22	13.84	11.93	8.14	3.81	1.11	0.29	0.14
YAK1 combined	118.5	combined	100.00	100.00	100.00	93.21	85.28	70.98	51.38	36.94	29.88	24.68	20.78	16.96	13.68	11.41	9.74	8.39	5.73	2.68	0.78	0.20	0.10
NACH Surface	0.9	Surface	100.00	100.00	100.00	74.19	30.94	15.02	7.48	5.60	1.05	0.42	0.19	0.11	0.08	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
NACH Sub-Surface	0.9	Sub-Surface	100.00	100.00	100.00	88.37	72.82	63.27	53.31	49.63	37.49	31.00	25.58	20.84	16.95	14.02	11.74	10.15	7.50	4.19	1.49	0.50	0.29
NACH combined	0.9	combined	100.00	100.00	100.00	79.84	47.63	34.25	25.98	23.15	15.78	12.64	10.33	8.37	6.80	5.63	4.71	4.08	3.02	1.71	0.63	0.23	0.14

			LOG INTERP PERCENT RETAINED																					
Key	**River Mile**	**Layer**	**362.04**	**256.00**	**181.02**	**128.00**	**90.51**	**64.00**	**45.25**	**32.00**	**22.60**	**16.00**	**11.30**	**8.00**	**5.65**	**4.00**	**2.80**	**2.00**	**1.00**	**0.50**	**0.25**	**0.125**	**0.075**	**PAN**
YAK Surface	109.5	Surface	0.00	0.00	0.00	0.00	18.82	31.36	22.62	14.78	7.58	2.34	1.64	0.45	0.14	0.02	0.02	0.01	0.04	0.03	0.07	0.03	0.01	0.03
YAK Sub-Surface	109.5	Sub-Surface	0.00	0.00	0.00	6.71	15.72	17.64	12.27	13.23	10.41	5.37	5.78	2.95	1.57	0.63	0.30	0.19	0.44	0.75	4.38	1.05	0.23	0.39
YAK combined	109.5	combined	0.00	0.00	0.00	3.62	17.15	23.97	17.05	13.95	8.87	4.21	3.77	1.86	0.94	0.35	0.17	0.11	0.26	0.42	2.39	0.58	0.13	0.22
YAK Surface	110.5	Surface	0.00	0.00	0.00	10.48	36.23	26.19	11.57	8.29	3.81	1.40	0.76	0.36	0.19	0.14	0.11	0.06	0.18	0.09	0.09	0.02	0.01	0.02
YAK Sub-Surface	110.5	Sub-Surface	0.00	0.00	0.00	6.19	5.83	14.75	11.83	12.38	10.09	5.81	7.44	4.20	3.15	3.69	2.87	1.60	3.98	2.40	3.07	0.45	0.10	0.17
YAK combined	110.5	combined	0.00	0.00	0.00	8.14	19.65	19.95	11.71	10.52	7.09	3.95	4.39	2.46	1.81	2.08	1.62	0.90	2.25	1.35	1.71	0.25	0.06	0.11
YAK Surface	111.5	Surface	0.00	0.00	0.00	0.00	0.00	35.14	14.62	8.35	17.39	10.83	6.11	3.32	1.80	0.88	0.49	0.14	0.00	0.00	0.00	0.00	0.00	0.95
YAK Sub-Surface	111.5	Sub-Surface	0.00	0.00	0.00	0.00	0.00	16.83	19.77	11.13	8.81	7.48	6.08	5.66	4.74	3.29	2.43	1.93	3.95	4.50	2.47	0.68	0.13	0.12
YAK combined	111.5	combined	0.00	0.00	0.00	0.00	0.00	23.03	13.12	15.10	11.56	8.50	6.22	4.94	3.78	2.50	1.78	1.33	2.60	2.94	1.63	0.49	0.10	0.40
YAK Surface	113.3	Surface	0.00	0.00	0.00	0.00	41.67	29.07	23.57	3.91	1.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	113.3	Sub-Surface	0.00	0.00	11.83	3.39	6.01	17.11	13.61	7.81	8.09	6.00	4.50	3.90	3.18	2.35	1.82	1.57	3.16	3.01	1.68	0.67	0.16	0.15
YAK combined	113.3	combined	0.00	0.00	6.70	1.92	21.47	22.29	14.99	9.06	5.18	3.57	2.55	2.21	1.80	1.33	1.03	0.89	1.79	1.70	0.95	0.38	0.09	0.08
YAK Surface	115	Surface	0.00	0.00	0.00	0.00	5.98	9.23	21.69	34.16	27.76	1.05	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.01	0.03
YAK Sub-Surface	115	Sub-Surface	0.00	0.00	0.00	0.00	1.56	16.24	28.10	29.35	18.86	3.74	0.26	0.16	0.09	0.03	0.04	0.03	0.18	0.20	0.61	0.26	0.10	0.20
YAK combined	115	combined	0.00	0.00	0.00	0.00	4.02	12.34	24.54	32.02	23.13	2.93	0.12	0.08	0.04	0.02	0.02	0.01	0.08	0.09	0.28	0.12	0.05	0.11
YAK Surface	116	Surface	0.00	0.00	5.52	40.33	20.57	11.64	13.40	7.04	1.09	0.25	0.00	0.00	0.00	0.01	0.01	0.01	0.03	0.01	0.03	0.02	0.01	0.05
YAK Sub-Surface	116	Sub-Surface	0.00	0.00	6.78	21.62	10.88	11.87	8.62	10.88	7.35	4.03	3.45	2.02	1.46	1.43	1.09	0.66	0.89	0.52	3.62	1.50	0.49	0.83
YAK combined	116	combined	0.00	0.00	6.14	31.18	15.83	11.75	11.06	8.92	4.06	2.18	1.68	0.99	0.71	0.70	0.54	0.32	0.45	0.26	1.79	0.75	0.25	0.43
YAK Surface	117.5	Surface	0.00	0.00	14.24	39.52	28.48	11.98	4.70	0.76	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	117.5	Sub-Surface	0.00	30.95	0.00	0.00	10.95	8.63	10.47	6.07	6.81	4.53	3.18	2.37	1.82	1.36	1.08	0.88	2.01	3.19	3.25	1.66	0.39	0.40
YAK combined	117.5	combined	0.00	18.07	5.92	16.44	18.24	10.02	6.34	5.59	4.09	2.67	1.86	1.39	1.06	0.80	0.63	0.51	1.17	1.86	1.90	0.97	0.23	0.23
YAK Surface	118.5	Surface	0.00	0.00	0.00	0.00	15.27	28.88	39.70	9.47	6.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YAK Sub-Surface	118.5	Sub-Surface	0.00	0.00	0.00	9.66	4.83	8.15	17.63	10.04	7.86	6.75	5.55	5.43	4.66	3.23	2.38	1.91	3.78	4.34	2.70	0.82	0.15	0.14
YAK1 combined	118.5	combined	0.00	0.00	0.00	6.79	7.93	14.30	19.60	14.44	7.06	5.20	3.90	3.82	3.28	2.27	1.68	1.35	2.66	3.05	1.90	0.58	0.11	0.10
NACH Surface	0.9	Surface	0.00	0.00	0.00	25.81	43.25	15.92	7.53	1.89	4.55	0.63	0.23	0.08	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.05
NACH Sub-Surface	0.9	Sub-Surface	0.00	0.00	0.00	11.63	15.55	9.56	9.96	3.68	12.13	6.50	5.41	4.75	3.88	2.93	2.28	1.59	2.66	3.30	2.70	0.99	0.21	0.29
NACH combined	0.9	combined	0.00	0.00	0.00	20.16	32.21	13.38	8.27	2.83	7.37	3.14	2.32	1.96	1.57	1.18	0.91	0.63	1.06	1.31	1.07	0.40	0.09	0.14

Key	River Mile	Layer	d84(mm)	d50(mm)	d16(mm)	d50class
YAK Surface	109.5	Surface	95.33	64.12	34.80	sm cob
YAK Sub-Surface	109.5	Sub-Surface	104.30	48.36	13.65	vcg
YAK combined	109.5	combined	99.66	57.50	23.13	vcg
YAK Surface	110.5	Surface	121.41	86.64	45.88	sm cob
YAK Sub-Surface	110.5	Sub-Surface	82.42	32.89	4.54	vcg
YAK combined	110.5	combined	111.43	59.87	12.63	vcg
YAK Surface	111.5	Surface	77.30	44.81	17.23	vcg
YAK Sub-Surface	111.5	Sub-Surface	65.11	29.26	3.88	cg
YAK combined	111.5	combined	71.14	32.93	6.95	cg
YAK Surface	113.3	Surface	112.05	81.95	52.66	sm cob
YAK Sub-Surface	113.3	Sub-Surface	122.36	47.56	6.61	vcg
YAK combined	113.3	combined	113.63	66.42	17.95	sm cob
YAK Surface	115	Surface	63.20	39.62	27.21	vcg
YAK Sub-Surface	115	Sub-Surface	66.51	43.12	27.23	vcg
YAK combined	115	combined	64.65	41.01	27.09	vcg
YAK Surface	116	Surface	165.43	119.36	54.88	sm cob
YAK Sub-Surface	116	Sub-Surface	156.16	66.21	13.13	sm cob
YAK combined	116	combined	162.23	96.97	33.11	sm cob
YAK Surface	117.5	Surface	178.24	132.29	86.00	lg cob
YAK Sub-Surface	117.5	Sub-Surface	302.65	65.36	8.00	sm cob
YAK combined	117.5	combined	266.39	106.74	24.02	sm cob
YAK Surface	118.5	Surface	89.72	60.81	45.01	vcg
YAK Sub-Surface	118.5	Sub-Surface	84.87	32.34	3.87	vcg
YAK1 combined	118.5	combined	87.75	44.16	7.22	vcg
NACH Surface	0.9	Surface	146.02	105.44	65.38	sm cob
NACH Sub-Surface	0.9	Sub-Surface	116.12	33.14	5.05	vcg
NACH combined	0.9	combined	137.48	92.84	22.83	sm cob

15 APPENDIX F

USGS Sediment Measurements

Water-Data Report 2008

12487010 YAKIMA RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA

Yakima Basin
Upper Yakima Subbasin

LOCATION.--Lat 46°37′53″, long 120°31′00″ referenced to North American Datum of 1927, in SW ¼ NE ¼ sec.12, T.13 N., R.18 E., Yakima County, WA, Hydrologic Unit 17030001.

DRAINAGE AREA.--2,138 mi^2.

SURFACE-WATER RECORDS

PERIOD OF RECORD.--May 2008 (discharge measurements and sediment data).

DISCHARGE MEASUREMENTS WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Date	Discharge, in ft^3/s
May 17, 2008	6,710
May 18, 2008	6,170
May 20, 2008	6,130

12487010 YAKIMA RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA—Continued

WATER-QUALITY RECORDS

PERIOD OF RECORD.--
SEDIMENT DATA: May 2008.

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Date	Time	Instantaneous discharge, cfs (00061)	Drainage area, mi2 (81024)	Suspnd. sediment, sieve diameter percent <.063mm (70331)	Suspnd. sediment, sieve diameter percent <.125mm (70332)	Suspnd. sediment, sieve diameter percent <.25mm (70333)	Suspnd. sediment, sieve diameter percent <.5 mm (70334)	Suspnd. sediment, sieve diameter percent <1 mm (70335)	Suspnd. sediment, sieve diameter percent <2 mm (70336)	Suspended sediment concentration mg/L (80154)	Suspended sediment discharge, tons/d (80155)
May											
17...	1645	6,710	2,138	84	90	96	100	100	100	228	4,120
18...	1030	6,170	2,138	85	93	97	100	100	100	201	3,350
20...	1200	6,130	2,138	88	94	97	99	100	100	86	1,430

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008
Part 1 of 2

Date	Time	Instantaneous discharge, cfs (00061)	Drainage area, mi2 (81024)	Bedload sediment discharge, tons/d (80225)	Bedload sediment, sieve diameter percent <.063mm (80226)	Bedload sediment, sieve diameter percent <.125mm (80227)	Bedload sediment, sieve diameter percent <.25mm (80228)	Bedload sediment, sieve diameter percent <.5 mm (80229)	Bedload sediment, sieve diameter percent <1 mm (80230)	Bedload sediment, sieve diameter percent <2 mm (80231)	Bedload sediment, sieve diameter percent <4 mm (80232)	Bedload sediment, sieve diameter percent <8 mm (80233)
May												
17...	1730	6,710	2,138	72	.0	1	2	18	67	75	79	82
18...	1000	6,170	2,138	81	.0	1	2	17	66	74	77	80
20...	0930	6,130	2,138	162	.0	.0	.0	11	53	64	67	71

12487010 YAKIMA RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA—Continued

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Part 2 of 2

Date	Bedload sediment, sieve diameter percent <16 mm (80234)	Bedload sediment, sieve diameter percent <32 mm (80235)	Bedload sediment, sieve diameter percent <64 mm (80236)	Bedload sediment, sieve diameter percent <128 mm (80238)
May				
17...	87	94	100	100
18...	84	94	100	100
20...	78	91	100	100

Water-Data Report 2008

12499010 NACHES RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA

Yakima Basin
Naches Subbasin

LOCATION.--Lat 46°37′47″, long 120°30′52″ referenced to North American Datum of 1927, in SW ¼ NE ¼ sec.12, T.13 N., R.18 E., Yakima County, WA, Hydrologic Unit 17030002.

DRAINAGE AREA.--1,106 mi².

SURFACE-WATER RECORDS

PERIOD OF RECORD.--May 2008 (discharge measurements and sediment data).

DISCHARGE MEASUREMENTS WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Date	Discharge, in ft³/s
May 17, 2008	8,250
May 18, 2008	9,300
May 20, 2008	8,290

12499010 NACHES RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA—Continued

WATER-QUALITY RECORDS

PERIOD OF RECORD.--
SEDIMENT DATA: May 2008.

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Date	Time	Instan-taneous dis-charge, cfs (00061)	Suspnd. sedi-ment, sieve diameter percent <.063mm (70331)	Suspnd. sedi-ment, sieve diameter percent <.125mm (70332)	Suspnd. sedi-ment, sieve diameter percent <.25mm (70333)	Suspnd. sedi-ment, sieve diameter percent <.5 mm (70334)	Suspnd. sedi-ment, sieve diameter percent <1 mm (70335)	Suspnd. sedi-ment, sieve diameter percent <2 mm (70336)	Sus-pended sedi-ment concen-tration mg/L (80154)	Sus-pended sedi-ment dis-charge, tons/d (80155)
May										
17...	1215	8,250	60	72	85	95	99	100	464	10,300
18...	1340	9,300	66	76	86	96	99	100	562	14,100
20...	1505	8,290	65	73	81	90	96	100	198	4,440

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008
Part 1 of 2

Date	Time	Instan-taneous dis-charge, cfs (00061)	Drain-age area, mi2 (81024)	Bedload sedi-ment dis-charge, tons/d (80225)	Bedload sedi-ment, sieve diameter percent <.063mm (80226)	Bedload sedi-ment, sieve diameter percent <.125mm (80227)	Bedload sedi-ment, sieve diameter percent <.25mm (80228)	Bedload sedi-ment, sieve diameter percent <.5 mm (80229)	Bedload sedi-ment, sieve diameter percent <1 mm (80230)	Bedload sedi-ment, sieve diameter percent <2 mm (80231)	Bedload sedi-ment, sieve diameter percent <4 mm (80232)	Bedload sedi-ment, sieve diameter percent <8 mm (80233)
May												
17...	1305	8,250	1,106	1,310	.0	.0	.0	7	32	40	45	48
18...	1315	9,300	1,106	1,430	.0	.0	1	8	34	40	43	47
20...	1325	8,290	1,106	772	.0	.0	.0	5	36	46	52	59

12499010 NACHES RIVER AT I-82 HWY BRIDGE NEAR YAKIMA, WA—Continued

WATER-QUALITY DATA
WATER YEAR OCTOBER 2007 TO SEPTEMBER 2008

Part 2 of 2

Date	Bedload sediment, sieve diameter percent <16 mm (80234)	Bedload sediment, sieve diameter percent <32 mm (80235)	Bedload sediment, sieve diameter percent <64 mm (80236)	Bedload sediment, sieve diameter percent <128 mm (80238)
May				
17...	52	67	85	100
18...	50	59	82	100
20...	65	72	87	100

16 APPENDIX G

Sediment Formula Information

(Excerpt from the SRH-1D user’s manual, Huang and Greimann (2009))

3.1.4.9 Parker's Method (1990)

Parker (1990) developed an empirical gravel transport function based on the equal mobility concept and field data:

$$\frac{q_{bi} g(s-1)}{p_i(\tau_b/\rho)^{1.5}} = 11.93 f(\phi_i) \quad (3.65)$$

where q_s = volumetric sediment transport rate per unit width; τ_b = total bed shear stress, d_{50} = the median diameter; g = acceleration of gravity; γ = specific weight of water; and s = relative specific density of sediment (ρ_s/ρ). The parameter ϕ_i is a measure of the shear stress relative to the reference shear stress:

$$\phi_i = \omega\theta_i/(\xi_i\theta_c) \quad (3.66)$$

where ω is a straining function as defined in Parker (1990) which typically is between 1.0 and 0.8; θ_c is the reference Shield's number; and θ_i = Shield's parameter of the sediment size class i computed as:

$$\theta_i = \tau_g/(\gamma(s-1)d_i) \quad (3.67)$$

where τ_g is the grain shear stress. The grain shear stress is computed based upon the velocity and representative grain diameter:

$$\frac{U}{\sqrt{\tau_g/\rho}} = 2.5\ln\left(\frac{12.27R'}{k_s}\right) \quad (3.68)$$

where U is the cross sectional average velocity, R' is the hydraulic radius due to grain shear stress ($\tau_g = \gamma R' S_f$). The parameter, k_s, is the grain roughness height computed as, $k_s = 2d_{90}$ as suggested by Parker (1990). Because this introduces another empirical parameter, the user also has the option of using the total shear stress in Eq (3.67). The parameter ξ_i is the exposure factor, which accounts for the reduction in the critical shear stress for relatively large particles and the increase in the critical shear stress for relatively small particles:

$$\xi_i = (d_i/d_{50})^{-\alpha} \quad (3.69)$$

where α = a constant. The function, $f(\phi_i)$, was fit to field data and is:

$$f(\phi) = \begin{cases} (1-0.853/\phi)^{4.5} & , \quad \phi > 1.59 \\ 0.000183\exp\left[14.2(\phi-1) - 9.28(\phi-1)^2\right] & , \quad 1 < \phi \le 1.59 \\ 0.000183\phi^{14.2} & , \quad \phi \le 1 \end{cases} \quad (3.70)$$

Two parameters can be defined by the user to use Parker's equation: θ_c and α. Ideally, these values should be fit to data of the stream being simulated. However, in the absence of data, several references provide guidance, such as Buffington and Montgomery (1997), Andrews (2000), and Mueller et al. (2005). Default values for θ_c and α are 0.0386 and 0.905 as recommended in Parker (1990).

3.1.4.10 Wilcock and Crowe (2003)

The Wilcock and Crowe formula is similar to the Parker (1990) in that it is a bedload formula and written in similar form:

$$\frac{q_{bi} g(s-1)}{p_i (\tau_b/\rho)^{1.5}} = 14 f(\phi_i) \tag{3.71}$$

where the variable definition is the same as in the Parker equation. The roughness height used to compute the grain shear stress is $k_s = 2d_{65}$. The function f is computed as:

$$f(\phi) = \begin{cases} \left(1 - 0.894/\sqrt{\phi}\right)^{4.5} & , \phi \geq 1.35 \\ 0.000143\phi^{7.5} & , \phi < 1.35 \end{cases} \tag{3.72}$$

The function has the behavior that as ϕ_i becomes large, $f(\phi_i)$ approaches 1. The parameter, f, is defined similar to the Parker equation:

$$\phi_i = \theta_i / (\xi_i \theta_c) \tag{3.73}$$

Wilcock and Crowe formulated an expression for the reference shear stress that was dependent upon the fraction of sand within the bed. Gaeuman et al. (2009) modified that expression so that it was dependent upon the geometric standard deviation of the sediment particle size distribution, σ_{sg}:

$$\theta_c = 0.021 + 0.015\left[1 + \exp\left(10.1\sigma_{sg} - 14.14\right)\right]^{-1} \tag{3.74}$$

The hiding function is:

$$\xi = (d_i / d_m)^{-\alpha} \tag{3.75}$$

where d_m is the geometric mean diameter. Notice that the geometric mean diameter is used in the above equation and not the median. The original paper mistakenly stated that the median should be used. The parameter α was specified as:

$$\alpha = 1 - 0.67\left[1 + \exp\left(1.5 - d_i / d_m\right)\right]^{-1} \tag{3.76}$$

where d_m is the mean particle diameter in the bed. The above equation has the behavior of approaching 0.33 for large d_i/d_m and approaching 0.88 for small d_i/d_m.

In SRH-1D, the following equations are used to compute θ_c and α:

$$\theta_c = \theta_{c0} + 0.015\left[1 + \exp\left(10.1\sigma_{sg} - 14.14\right)\right]^{-1}$$

$$\alpha = 1 - (1 - \alpha_0)\left[1 + \exp\left(1.5 - d_i / d_m\right)\right]^{-1} \tag{3.77}$$

where if $\theta_c = 0.021$ and $\alpha_0 = 0.33$, the Wilcock and Crowe (2003) relation is recovered. The user can specify the value of θ_{c0} and α_0.

3.1.4.13 Parker or Wilcock and Crowe combined with Engelund-Hansen

Bed load equations like Parker and Wilcock and Crowe ignore the suspended load transport and in systems where both suspended and bed load are a concern, they should be paired with an equation that would predict the suspended load. The Engelund-Hansen formula can be rewritten in the form:

$$\frac{q_{si}g(s-1)}{(\tau_b/\rho)^{1.5}} = p_i \frac{0.05V^2}{g(s-1)d_i} \tag{3.87}$$

which is similar in form to the Parker and Wilcock and Crowe formulas. The similar forms suggest that a transport equation for sand in a gravel system could be obtained by combining the Parker or Wilcock formulas with the Engelund-Hansen formula as follows:

$$\frac{q_{si}g(s-1)}{(\tau_b/\rho)^{1.5}} = p_i \max\left[C, \frac{0.05V^2}{g(s-1)d_i}\right] f(\phi_i) \tag{3.88}$$

with C = 11.93 or Parker and 14 for Wilcock and Crowe methods. The function *f* is (3.70) for Parker's method and (3.72) for Wilcock and Crowe's method. The above method is used to compute the sand load, while the standard methods for Parker, Wilcock and Crowe, and Gaeuman et al. are used for the gravel and larger sizes. There is some caution suggested in the application of this combination because its use has not been extensively applied or tested.

17 APPENDIX H

Sediment Model Sensitivity

Model Sensitivity

The Sediment model was tested for sensitivity to time step and the transport equation variables for reference shear stress and hiding factor. The time step sensitivity was tested by decreasing the time step value and evaluating the change in results. Because an improper value of the time step will most likely manifest itself in a local instability, the thalweg profile was used to evaluate time step sensitivity, with values ranging from 0.05 - 5 hours. Differences in the thalweg elevation for each cross section in the model were compared with the values resulting from the 0.05 hour results, looking for a significant deviation in mean bed elevation. This analysis indicated that a 0.5 hour time step was the most appropriate when balancing model error and run time efficiency.

Sensitivity to the reference shear stress and hiding factor was evaluated using results of mean bed elevation, changes to the final bed material composition, and average annual load. The mean bed elevation includes those bed elevations that are between the bank points, as configured in the HEC-RAS geometry. Two hydrologic scenarios were used to evaluate the sensitivity; a one year period that includes a flood with a magnitude of approximately 44,000 ft^3/s (water year 1996), and the previous 25-years (water years 1985 – 2009).

The one-year sensitivity runs indicate little change to the mean bed output, but some variability in values of bed composition and sediment load was observed. Large fluctuations and deviations from the initial bed composition are not expected and therefore these results were used to eliminate some values of reference shear stress and hiding factor. There is no reason to believe that significant change is anticipated in bed composition, based on the lack of a trend observed in the thalweg surveys from 1970 and 2005. If a significant trend in thalweg elevation was observed over that 35-year period, a change in bed composition may be expected. Therefore, preference was given to parameters that resulted in no significant change in bed composition. This analysis was made with consideration of the bed material composition trending over time toward measured values. As a result, reasonable values of the reference shear stress and the hiding factor were determined to be between 0.021 – 0.024 and 0.33 and 0.5, respectively. The combination of a reference shear stress of 0.021 and a hiding factor of 0.5 is preferred and was used for all predictive sediment analyses. These results are shown in Figures F1 through F-4.

Because model predictions will be reported over a 25-year period, sensitivity of reference shear stress and hiding factor mentioned above was tested over the period 1985 – 2005. The results of this sensitivity indicate that through a significant majority of the reach, the mean bed elevation is not highly sensitive to the parameters evaluated with respect to change in mean bed elevation (Figure F-5).

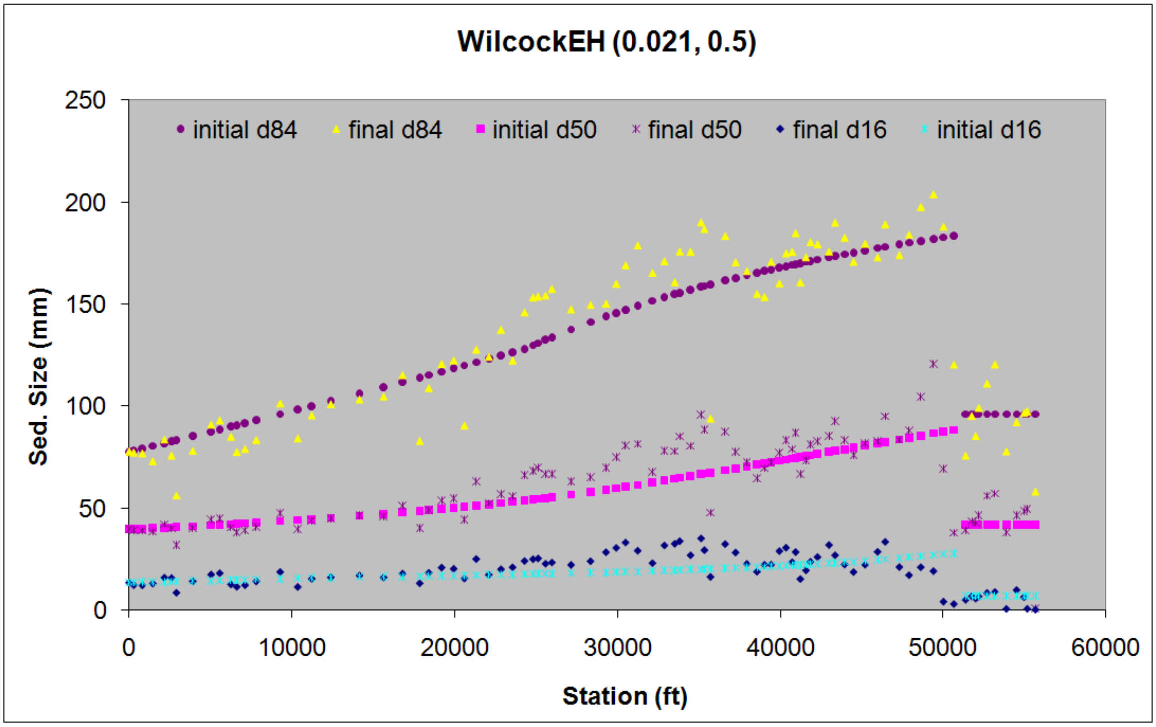


Figure F-1: Chart of initial and final bed composition resulting from the one year simulation for sensitivity. Sediment formula variables were set to 0.021 for reference shear stress and 0.5 for the hiding factor.

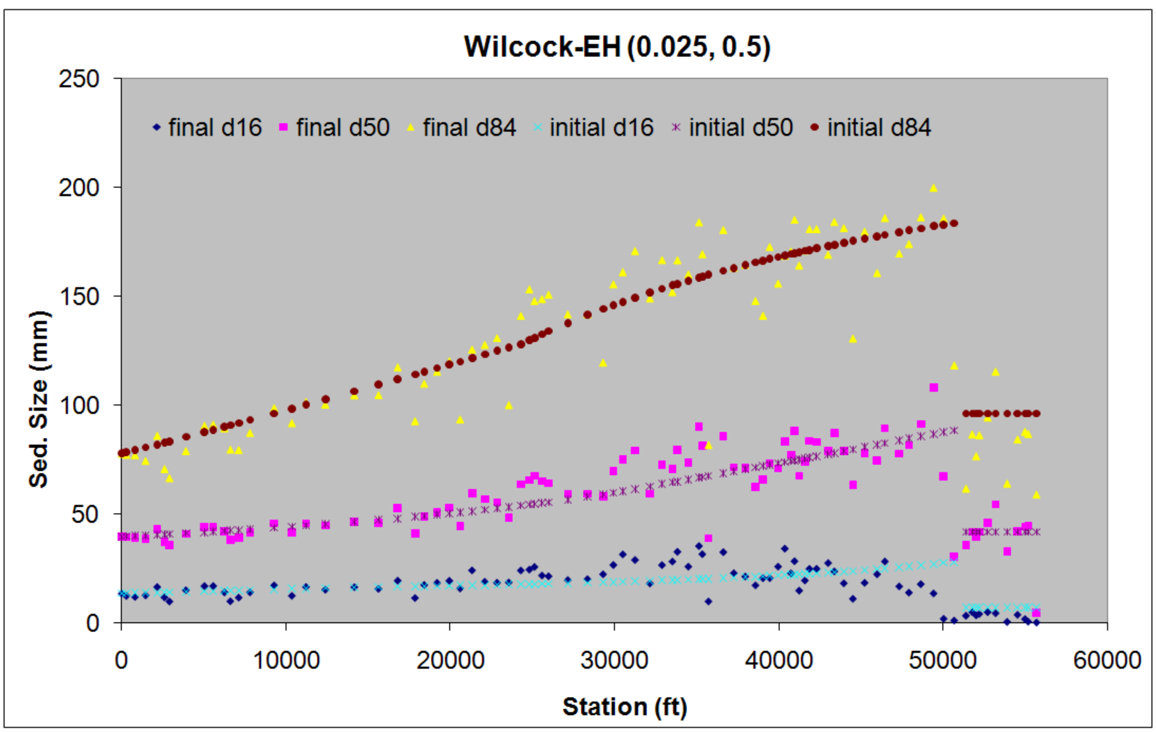


Figure F-2: Chart of initial and final bed composition resulting from the one year simulation for sensitivity. Sediment formula variables were set to 0.025 for reference shear stress and 0.5 for the hiding factor.

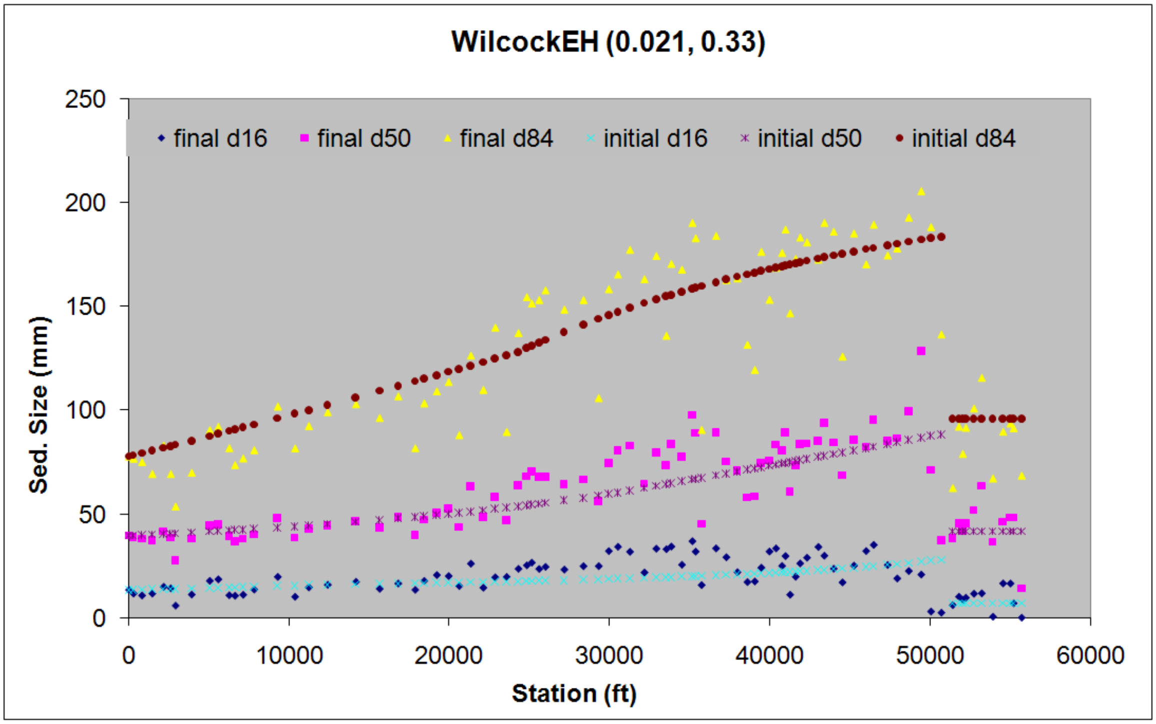


Figure F-3: Chart of initial and final bed composition resulting from the one year simulation for sensitivity. Sediment formula variables were set to 0.021 for reference shear stress and 0.33 for the hiding factor.

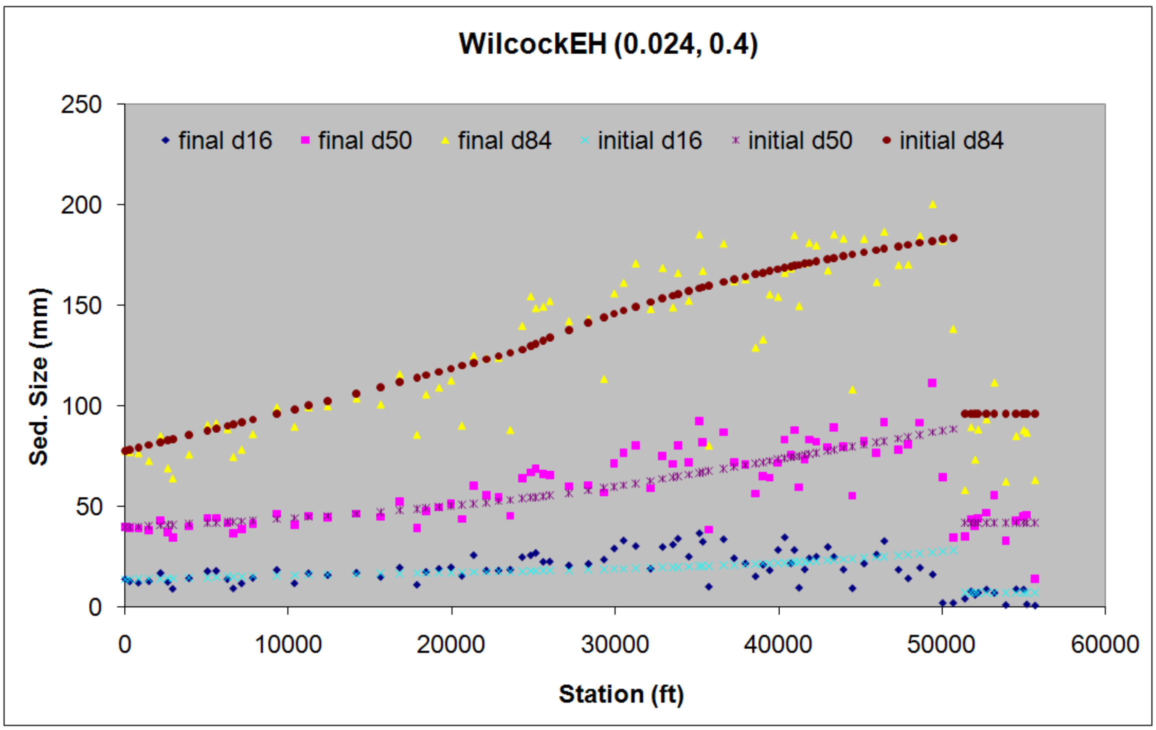


Figure F-4: Chart of initial and final bed composition resulting from the one year simulation for sensitivity. Sediment formula variables were set to 0.024 for reference shear stress and 0.4 for the hiding factor.

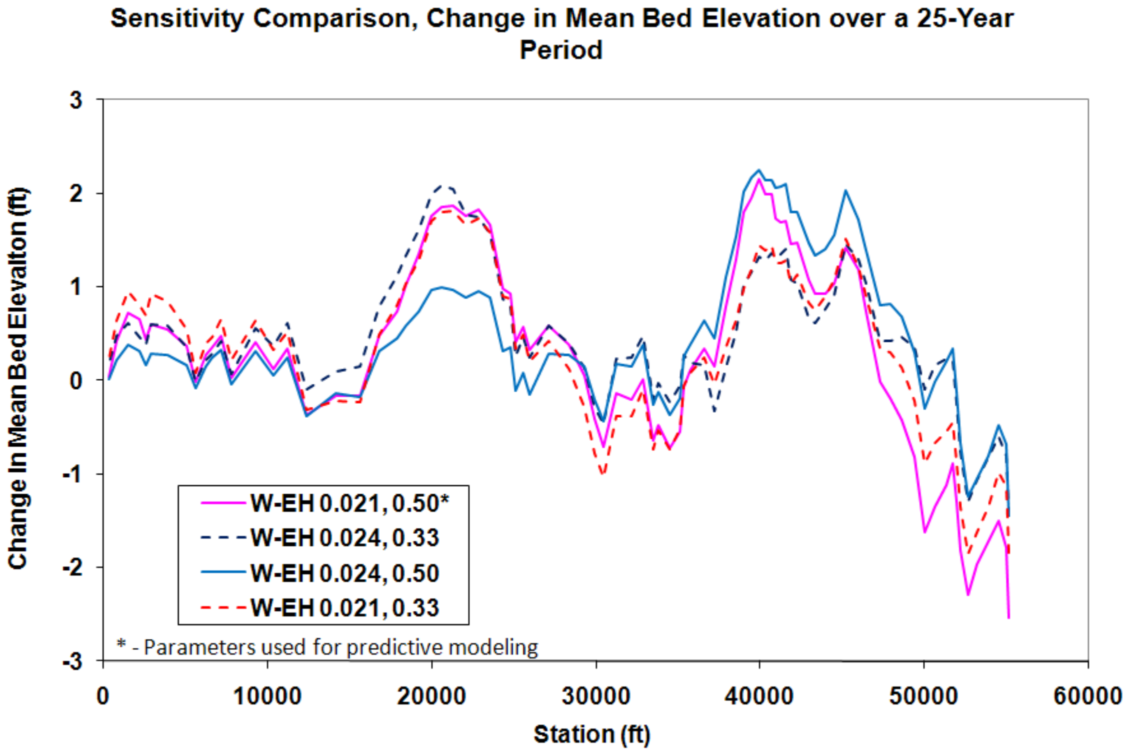


Figure F-5: Chart of final change in mean bed elevation composition resulting from the 25-year simulation for sensitivity. Sediment formula variables are indicated in the figure.

The variability in bed material load is shown in Table F-1. The values were taken from results obtained by running the model for a 25-year period (1985 – 2009) and are reach averaged, average annual values. The parameters used for modeling (0.024 and 0.5) indicate the smallest value in sediment load. The total variability is less than a fator of two.

Table 1: Table showing the sensitivity of bed material load to the variables in the sediment formula. Simulations for these variables were run for a 25-year period.

Reference Shear Stress	Hiding Factor	Bed Material Load (Tons)
0.024	0.4	52,170
0.021	0.33	74,337
0.021	0.5	70,065
0.025	0.5	44,886

18 APPENDIX I

Peer Review Comments and Responses by the Authors

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nhc
northwest hydraulic consultants

2010 May 10

Project No. 2-1587

Yakima County Public Services
Surface Water Management Division
128 North Second St.
Fourth Floor Courthouse
Yakima Washington
98901

Attention: Mr. Jeff Legg

Dear Mr. Legg:

Subject: Review of Draft Report: River Geomorphology and Sediment Transport Study Gap to Gap Reach, Yakima, WA

1. Introduction

Northwest Hydraulic Consultants (NHC) was retained by Yakima County Public Services to review ongoing hydraulic and geomorphic studies that are underway for the County. These studies are part of a comprehensive flood management plan to reconfigure levees and restore floodplain conveyance along portions of the Yakima River. The County's letter of March 4, 2009 identified three main tasks for NHC:

1. Review field data and model development and provide input for improving the data collection and model development and model validation. The analysis will identify limitations of the modeling with regard to the predictive response of the river to natural and infrastructure change;

2. Review the river/floodplain geomorphic analyses and assess whether these studies are consistent or disagree with the findings of the modeling investigations with regard to river response. Recommend means to resolve any conflicts if they exist;

3. Provide a technical memo summarizing Tasks 1 and 2 and identify the potential uses and applicability of the sediment models and geomorphic information in establishing the predictive response of the future design of levee reconfiguration, floodplain and habitat enhancement and improving or maintaining the function of existing infrastructure.

NHC staff (D. McLean and J. Johnson) met with County staff and conducted a field inspection along sections of the Yakima River at the initiation of the project in April 2009. NHC were subsequently provided the draft report:

> Yakima River Geomorphology and Sediment Transport Study: Gap to Gap Reach, Yakima WA dated March 2010, Bureau of Reclamation, US Department of the Interior, by Robert C. Hilldale and Jeanne E. Godaire.

Several other background reports and maps were provided at the same time to assist in the review. The additional reports that were consulted included:

- Entrix Inc. (2009): Annotated Bibliography of Water Gaps in the Yakima Basin, Washington
- Braatne, J., Jamieson, R., Gill, K. and S. Rood (2007): Instream flows and the Decline of Riparian Cottonwoods along the Yakima River, Washington, USA, River Research and Applications vol 23, pg 247-267.

- Braatne, J. and B. Jamieson,(2001): The Impacts of Flow Regulation on Riparian Cottonwood Forests of the Yakima River, Report to Bonneville Power Administration, Portland, Oregon.
- Washington State Department of Natural Resources (2004): Yakima River Floodplain Mining Impact Study
- Jones & Jones (1976): The Yakima River Regional Greenway –Hydrology prepared by Dr. Thomas Dunne
- Upper Yakima River Comprehensive Flood Hazard Management Plan, June 2007 Update from Yakima County Public Services web site.

Some initial discussion on the draft report was made by email with County staff (J. Freudenthal). However, this letter provides our first overall assessment of the entire report. These comments are mainly non-technical and are focused primarily on the method of approach, available data and interpretation of results. The overall purpose of the comments is to strengthen the conclusions that can be drawn on the longterm hydraulic and morphological response from the planned levee setbacks.

2. Overview of Draft Report

The report summarizes results of an integrated geomorphic-sediment modeling investigation of the Gap to Gap reach of the Yakima River and characterizes general hydraulic and bed material transport characteristics of the river at a reach-scale. The purpose of the study was to assess future channel conditions with regard to levee setback on the left bank in the vicinity and downstream of Highway 24 (DID #1 levee). The study also examines the effects of removing the Boise-Cascade levee along the right bank just downstream of the mouth of the Naches River.

The geomorphic investigations make use of previous geomorphic studies, particularly Clark (2003)[1] and other USBR work related to impacts of floodplain gravel mining. The study makes use of historic cross section comparisons (1969-2005) and radio-carbon dating of floodplain sediments.

A one-dimensional HEC-RAS hydraulic model was used to assess the initial effect of setting back the Cascade-Boise levee and the DID No. 1 levee. These simulations were made using a discharge of 44,000 cfs which corresponds to the peak of the 1996 flood (at Yakima River above Ahtanum Creek gage). The simulations showed that setting back the Boise-Cascade levee had only localized and relatively minor effect on the flood level. However, setting back the DID #1 levee reduced the flood level by up to 5 feet. Furthermore, the extent of the water level lowering was large (approximately 15,000 feet), reaching upstream of the SR24 Highway Bridge. The report concluded *under the proposed scenario, model results indicate that no levees are overtopped in this segment*.

The one-dimensional sediment model SRH-1D is used for characterizing sediment transport and for assessing the longterm impacts of levee set-backs on aggradation/degradation. The model used a 25 year time span (1989 to 2005) to simulate the most probable future hydrological conditions in the basin and also represented 25 year wet and dry year sequences. Four different flood events were also examined in detail, including the 1996 flood event. General results for the most probable 25 year flow simulation are shown in Table 1.

[1] Clark, K. (2003): Fluvial Response Related to Floodplain Gravel Mining: Yakima River Washington, USA. MS Thesis Central Washington University, Ellensburg, WA, 98p.

Table 1: Reach Average Changes-25 Year Simulation (Average Flow Conditions)

Segment	Reach	Without Levee Setback	With Levee Setback	Levee
1	Selah Gap to Triangular Gravel Pit	Degradation	Degradation (reduced)	
2	Triangular Gravel Pit to Oxford Hotel	Aggradation	Aggradation (increased)	Boise-Cascade
3	Oxford Hotel to SR24 Bridge	Approx. stable	Degradation	
4	SR 24 Bridge to Edler Ponds	Aggradation	Aggradation (reduced)	DID #1
5	Edler Ponds to Wapata Dam	Aggradation	Aggradation	

Segment 2 (which includes the Boise-Cascade levee) experienced the highest aggradation in the study reach. Setting back the DID #1 levee caused degradation in Segment 3 (upstream of SR 24 Highway Bridge) due to the reduction in water levels upstream of the bridge. However, setting back the levee resulted in net aggradation downstream of the SR 24 Bridge in Segment 4. It was indicated that the channel is expected to avulse into the Newland pond and adjacent gravel pits after the DID #1 levee is set back. The effect of this channel shift on water levels and sedimentation patterns was not assessed.

3. General Comments on Report

A more detailed assessment on the longterm effects of setting back the two levees on flood levels, aggradation /degradation and channel stability is warranted, considering its overall importance to the success of the project. The study needs to provide sufficient detailed analysis to verify that the two planned levee setbacks do not induce any adverse channel changes and that the flood level reduction due to the setback does not vanish over a short period of time due to future sedimentation. The assessment in the draft report specifically relating to this aspect is relatively brief and general.

The results from the HEC-RAS model (Figure 41) showing the immediate effect of setting back the two levees on the 1996 flood level. A similar plot should be produced after 10 years and 25 years of sediment model simulations to illustrate the effect of morphological changes on flood levels.

The report concludes that the river is likely to avulse and capture the Newland Pond #2 and adjacent gravel pits once the DID #1 levee is setback, but doesn’t describe the effect on channel stability, upstream degradation or future sedimentation patterns near the levee. It is important to forecast future channel conditions after this shift since it could induce adverse impacts (such as increased degradation upstream at the SR24 Bridge).

There should be a section in the report outlining the limitations of the study, particularly the data and 1D sediment modeling. In terms of the available data, measurements of sediment load are very limited (3 days at relatively low flows near the threshold of transport). The limitations of the 1D sediment transport model should be summarized and the approach used for overcoming these limitations should be outlined. It is widely recognized that the reliability of sediment transport model predictions depends to a large extent on the quality of the data available for calibration and verification. Ideally, a verification run would involve setting up the model using 1969 channel topography, simulating the period 1969-2005 and comparing the predicted bed levels with the recent surveys.

Some other specific limitations that affect the reliability of the model predictions are described below.

Sediment transport calculations are based on cross sectional average properties and parameters such as the mean channel velocity may not be representative in complex anabranched channels. Figure 45 in the report shows an example where the computed transport rate decreases with increasing discharge once the flow exceeds 15,000 cfs (Figure 45). The authors indicate this is not realistic and set the load to a constant value once flows exceeded 15,000 cfs. It is not understood why the load should be assumed constant at higher flows, nor is it clear whether this problem occurred at any other cross sections in the study reach.

1D sediment models can't represent lateral channel changes, bank erosion processes, meander migration or spatial variations in sediment transport and deposition associated with floodplain sedimentation. The extent of deposition and scour are specified initially on each cross section and the bed levels within this specified extent are raised or lowered on the basis of the computed volume of sediment deposition or erosion. The modeled scenarios assume the overall channel alignment remains unchanged over the 25 year simulation period. The simulations could not account for complicating factors such as a future channel shift and capture of a gravel pit. This makes the simulation of the DID #1 levee setback relatively artificial since it was indicated such a channel shift is expected to occur after the levee is removed.

These limitations are not unique to the present study by any means. Furthermore, it is not easy to overcome the limitations by simply using a more sophisticated 2D morphodynamic model such as MIKE21 or River2D-MOR. This is because the data requirements for calibrating and verifying 2D models are even greater than a 1D model. Often the best approach is to use other empirical or geomorphic-based methods to provide an independent check on the predictions from the sediment models. Some simple empirical based methods for assessing channel response are summarized in the US Army Corps of Engineers manual on channel stability assessment for flood control projects[2]. Some examples of using geomorphic-based methods to predict future conditions on the river are as follows:

- Checking sediment load predictions using morphologic-based estimates using channel surveys and air photos to compute sediment volume transfers[3];
- Assessing longterm vertical channel stability using specific gage plots from gaging stations;
- Using historic air photos to predict changes in planform, rates of bank erosion and response of channels following avulsions.
- Using historic surveys and air photos to document rates of floodplain deposition/accretion.

4. Geomorphic Analysis

The following comments describe some specific measures to strengthen the geomorphic analysis in the report.

- Make use of the relatively frequent recent air photography and prepare channel shift maps to update the earlier results by Dunne (1976). Provide projections of future channel conditions with and without levee setbacks;
- Relatively little use was made of the comparisons between the 1969 and 2005 cross section surveys. Comparisons on a reach by reach or site by site basis should be made incorporating the historic air photography data to assess the changes that occurred between the surveys. It should be possible to estimate volumes of erosion/deposition from historic river surveys and air photography and link the volumetric changes with the pattern of channel shifting. It also should be possible to document floodplain deposition rates or changes on the floodplain in response to channel shifting;
- Document the effect of extreme flood events (such as 1996) on channel morphology using available air photos;
- Characterize the bed and bank material composition in the reach (normally this type of material should be presented in the geomorphic section of the report rather than in the sediment modeling chapter). Grain size distribution curves for sub-surface, surface and bank materials should be presented in the main report (not just in

[2] US Army Corps of Engineers (1994): Channel Stability Assessment for Flood Control Projects, Engineering Manual EM 1110-2-1418.

[3] Neill, C. R. (1984): Bank Erosion Versus Bedload Transport in a Gravel River, in River Meandering: Proceedings of River's 83 Conference, New Orleans LA. October 24-26, 1983, Charles Elliott ed. American Society of Civil Engineers, New York, pp. 204-211.

tabular form in appendices). Fine grained wash load sediment is not found in appreciable quantities in the river bed. The D_{10} bed sediment size is often specified to define wash load[4] and its transport rate is generally supply limited, meaning that a plot of suspended sediment concentration versus discharge will show a very wide scatter. On gravel bed rivers, sediment considerably coarser than 0.063 mm may often behave as wash load. Results of bed material samples and suspended sediment concentration plots should be presented in the report to justify the wash load size that is adopted.

- Assess the reason for the reduction in grain size along the river in the Gap to Gap Reach. The downstream reduction in bed sediment size is often taken as an indicator of selective deposition or aggradation. Further assessment of the factors causing the selective deposition should be made. If the slope is not changing, are there accompanying changes to other hydraulic properties?
- Background information on sediment loads presented in Chapter 5 should be moved forward to the Geomorphic Section (Chapter 2). Sediment rating curves should be shown using all available sediment measurements on the Yakima River near the study reach, incorporating previous results from Dunne's analysis at the Parker gage as well as the data at Yakima River above Ahtanum Creek. Further effort to estimate the size fraction of the load from other sites or sampling is warranted to try to make full use of the available data. Estimates of annual suspended loads by size fraction should be presented. The sediment rating curve should be combined with flow-duration statistics to determine the dominant channel-forming discharge and to document the importance of extreme flows on long-terms sediment loads.

5. Sediment Transport Modeling

The following comments describe some methods to strengthen the sediment modeling component.

- Combining the Wilcock and Crowe gravel-sand sediment transport equation with the Engelund-Hansen sand transport equation is difficult to justify without other detailed supporting studies. The Engelund Hansen equation was developed for sand bed channels with dunes. To my knowledge it was never intended for use in gravel bed rivers. The Wilcock and Crowe equation is described as an equation "for mixed sand/gravel sediments[5]" so it is not clear why another sand transport equation should be combined with it. Since the approach of combining two independently derived transport equations has not been tried before and has not been verified with lab or field measurements, it makes it difficult to justify its use in the model. It would be useful to make the simulations using a more conventional and widely accepted sediment transport predictor such as the Ackers-White equation or Yang's equation (or simply use the Wilcock and Crowe equation alone) to check how sensitive the model predictions are to the method of calculating sediment transport.
- The modeling assumed that all sediment coarser than 0.063 mm is bed material load but never demonstrated that this was appropriate for the Yakima River. This assumption affects the verification of the model. Steps for characterizing the wash load were described previously.
- As described previously there is relatively little data available to calibrate and verify the 1D sediment model for making longterm predictions. More use of historic cross section data, specific gage analysis and geomorphic methods should be presented to increase the confidence of its results.
- It is stated that the model shows the river has reached dynamic equilibrium. However, since (1) relatively large reach-scale patterns of aggradation and degradation are predicted to occur over the next 25 year and (2) the sediment is being selectively deposited along the channel (since the grain size decreases in the downstream direction), the concept of dynamic equilibrium is probably not very useful in this situation.
- The time scale of the river channel response to levee setbacks should be described by showing bed level changes over time. Has the bed level changes reached equilibrium 25 years after the setbacks are implemented, or do impacts persist for a longer time span?

---

[4] Shen H. W. (1971): Wash Load and Bed Load Ch. 11 in River Mechanics, Fort Collins CO, USA.
[5] Wilcock, P. and J. Crowe (2003): Surface-based Transport Model for Mixed-Size Sediment, Journal of Hydraulic Engineering Vol. 129, No. 2, pp 120-128.

- The model shows only limited effects from levee setback, under the assumption that the overall channel alignment remains unchanged. As already mentioned, in the case of the DID #1 levee setback, site observations indicated the river will likely avulse after the setback and capture the existing gravel pits adjacent to Newland Pit No. 2. Since such a shift could significantly alter upstream degradation in Segment 3 near the SR 24 Bridge and sedimentation patterns in Segment 2, the effect of this shift should be quantified. One approach would be to develop an avulsion scenario using the historic information from other sites, develop a set of cross sections to represent the new channel path then model this scenario with SRH-1D to show the impact on the overall river system.

6. Future Work

The comments in this letter are primarily based on a review of the draft report and the other supporting background documents. It would be helpful if we could obtain a copy of the SRH-1D model to gain a better understanding of the model schematization and sensitivity of the model results to various input parameters. As an alternative, it would be possible to specify some sensitivity runs and then review the final results. Also, it would be useful to review some of the basic data such as the river cross section comparisons and historic air photos if these are available.

We would be pleased to arrange a meeting to discuss the status of the review and future direction of the work with the County. Please feel free to contact the undersigned any time.

Sincerely,

northwest hydraulic consultants

{*original sent by email*}

Dave McLean, Ph.D., P.Eng.
Principal

Comments from Dr. Dave McLean, Northwest Hydraulic Consultants and Responses by the Authors

.

The entire commentary from Northwest Hydraulic Consultants (NHC) has been included in this appendix in previous pages. Comments by NHC in chapters three through six have been copied onto these pages and pasted as plain text. The response by the authors is indented and written in italics.

3. General Comments on the Report

A more detailed assessment on the longterm effects of setting back the two levees on flood levels, aggradation/degradation and channel stability is warranted, considering its overall importance to the success of the project. The study needs to provide sufficient detailed analysis to verify that the two planned levee setbacks do not induce any adverse channel changes and that the flood level reduction due to the setback does not vanish over a short period of time due to future sedimentation. The assessment in the draft report specifically relating to this aspect is relatively brief and general.

> *The authors have expanded many discussions in the final report to include more detail, specifically the discussion regarding long term effects of levee setback and aggradation/degradation. A time series of sediment model results has been incorporated to enhance this discussion.*

The results from the HEC-RAS model (Figure 41) showing the immediate effect of setting back the two levees on the 1996 flood level. A similar plot should be produced after 10 years and 25 years of sediment model simulations to illustrate the effect of morphological changes on flood levels.

> *A plot similar to what the reviewer is describing has been incorporated in the report. Sediment model results showing aggradation/degradation have been shown for every 5 years throughout the simulation period, plotted for five segments so the resolution of the plot is capable of showing the detail.*

The report concludes that the river is likely to avulse and capture the Newland Pond #2 and adjacent gravel pits once the DID #1 levee is setback, but doesn't describe the effect on channel stability, upstream degradation or future sedimentation patterns near the levee. It is important to forecast future channel conditions after this shift since it could induce adverse impacts (such as increased degradation upstream at the SR24 Bridge).

The effects of levee setback regarding the capture of Newland Pond #2 and impacts at the SR24 Bridge are described in Chapter 7.3 and 7.4. The processes by which these areas may be adversely affected by the levee setback are described. Recommendations for actions prior to the levee setback are also made to address and mitigate these concerns prior to levee removal.

There should be a section in the report outlining the limitations of the study, particularly the data and 1D sediment modeling. In terms of the available data, measurements of sediment load are very limited (3 days at relatively low flows near the threshold of transport). The limitations of the 1D sediment transport model should be summarized and the approach used for overcoming these limitations should be outlined. It is widely recognized that the reliability of sediment transport model predictions depends to a large extent on the quality of the data available for calibration and verification. Ideally, a verification run would involve setting up the model using 1969 channel topography, simulating the period 1969-2005 and comparing the predicted bed levels with the recent surveys.

The authors have included a section in the final report that includes the limitations of the study. Regarding the number of sediment load measurements, it is acknowledged that more quality data is always better than less. Realizing the importance of measured data for calibrating this sediment model, these sediment measurements were requested specifically for this study at a significant cost to the project. These data were collected during the annual peak of the runoff. As sediment transport professionals we must work with the data available and must provide a favorable combination of accuracy and effort under typical circumstances (Wilcock, 2001). Collecting a small number of transport measurements at low transport rates is recommended by Wilcock (2001) for the estimation of sediment loads. Collecting sediment data at low transport rates provides some key advantages related to; logistical and safety issues, and longer duration samples that provide greater accuracy (Wilcock, 2001). Moreover, critical shear stress or the reference shear stress (as used in equations by Parker, 1990; Wu et al., 2000; and Wilcock and Crowe, 2003) is a parameter that can cause significant uncertainty in sediment transport modeling. Having sediment measurements near the threshold for motion allows for increased accuracy in calibrating the reference shear stress, thus significantly reducing the uncertainty of the calculations.

4. Comments on the Geomorphic Analysis

Make use of the relatively frequent recent air photography and prepare channel shift maps to update the earlier results by Dunne (1976). Provide projections of future channel conditions with and without levee setbacks;

Channel shift maps were prepared and are discussed in Chapter 7.3.These shift maps utilize geomorphic observations of recent changes within the last 5 years and historical aerial photography to define unstable areas, erosion areas, and potential avulsion points and paths. These data are overlaid with stream power computations to provide projections of future channel condition with the levee setback. The discussion also includes information regarding conditions without the levee setback.

Relatively little use was made of the comparisons between the 1969 and 2005 cross section surveys. Comparisons on a reach by reach or site by site basis should be made incorporating the historic air photography data to assess the changes that occurred between the surveys. It should be possible to estimate volumes of erosion/deposition from historic river surveys and air photography and link the volumetric changes with the pattern of channel shifting. It also should be possible to document floodplain deposition rates or changes on the floodplain in response to channel shifting;

During the review period, Yakima County performed an analysis of the vertical data in the 1969 cross sections after realizing that they were unreliable. Yakima County provided updated vertical values for the 1969 cross section data, which required a separate adjustment at each cross section. Such an adjustment brings into question the reliability of these data, however Reclamation believes that every effort was made to make a justifiable and appropriate adjustment. An analysis of all but one of the 1969 cross sections has been included in the report, including an area computation and mean channel and floodplain elevation comparison of the 1969 cross sections and 2005 cross sections. The alignment of the 1969 cross sections used in the final report was provided by Yakima County, based on locating them by eye from the USACE maps. No end point and inflection point coordinates are available for the 1969 cross sections, and as such, some cross section alignments are not exactly representative of the original alignment. This manifested itself in narrower or wider cross sections in the comparison, creating significant error in the change in area calculations that were performed. These cross sections are noted and an explanation is provided in the report.

Document the effect of extreme flood events (such as 1996) on channel morphology using available air photos;

The effects of the floods of the 1970's, 1996 and 2009 floods are documented in Chapter 2.5 and provide a description of the effect of extreme floods on channel morphology in the Gap to Gap reach. Types of changes include lateral migration, channel avulsion, bed *scour and bar formation and erosion. This topic also incorporated in Chapter 2.3 which discusses the role of extreme floods in gravel pit captures.*

Characterize the bed and bank material composition in the reach (normally this type of material should be presented in the geomorphic section of the report rather than in the sediment modeling chapter). Grain size distribution curves for sub-surface, surface and bank materials should be presented in the main report (not just in tabular form in appendices). Fine grained wash load sediment is not found in appreciable quantities in the river bed. The D10 bed sediment size is often specified to define wash load and its transport rate is generally supply limited, meaning that a plot of suspended sediment concentration versus discharge will show a very wide scatter.
On gravel bed rivers, sediment considerably coarser than 0.063 mm may often behave as wash load. Results of bed material samples and suspended sediment concentration plots should be presented in the report to justify the wash load size that is adopted.

The classification of sediment into wash load is a typological classification that does not generally improve our predictive capability. The sediment transport model calculates the sediment transport capacity of each size class independently. Relatively fine material will have a large transport capacity relative to the supply and the coarse material will have a transport capacity similar to the supply. The wash load classification is just a qualitative statement of the supply versus capacity relationship and this classification is not necessary once the supply and capacity have been quantified.
In this reach of the Yakima, the sand sized material and smaller (< 2 mm) would generally have a larger transport capacity than supply and would be classified as wash load. However, this is general classification and misses the fact that some portion of the sand-sized material is expected to be deposited in the flood plain at high flows.
The assumption of sediment smaller than the D10 comprising wash load does not apply to this reach of the Yakima River. Most of the bed material samples reveal a D10 in the gravel size range. Although it is acknowledged that some of the sand sized material (> 0.0625) may travel as wash load. Moreover, the data relating suspended sediment and river discharge lacks any size information with which to make the determination of the break between wash load and suspended load.
Sediment analysis is acknowledged to be of great significance, however these data remain in the appendices due to their size (number of pages), improving the readability of the report.

Assess the reason for the reduction in grain size along the river in the Gap to Gap Reach. The downstream reduction in bed sediment size is often taken as an indicator of selective deposition or aggradation. Further assessment of the factors causing the selective deposition should be made. If the slope is not changing, are there accompanying changes to other hydraulic properties?

> *The discussion in Chapter 5 has been expanded to include more details related to the reduction in grain size.*

Background information on sediment loads presented in Chapter 5 should be moved forward to the Geomorphic Section (Chapter 2). Sediment rating curves should be shown using all available sediment measurements on the Yakima River near the study reach, incorporating previous results from Dunne's analysis at the Parker gage as well as the data at Yakima River above Ahtanum Creek. Further effort to estimate the size fraction of the load from other sites or sampling is warranted to try to make full use of the available data. Estimates of annual suspended loads by size fraction should be presented. The sediment rating curve should be combined with flow-duration statistics to determine the dominant channel-forming discharge and to document the importance of extreme flows on long-terms sediment loads.

> *Following a discussion with Yakima County, it was decided to leave the presentation of the sediment data in Chapter 5. Although presenting the sediment data in Chapter 2 would make sense, Yakima County and the authors agree that our efforts are better spent elsewhere.*
>
> *All available, relevant gage data were used in this study. Data from the Parker gage contains very limited sediment data, all of which is TSS (total suspended solids) as opposed to SSC (suspended sediment concentration) data. "Using the TSS analytical method … to determine concentrations of suspended material in open channel-flow can result in unacceptably large errors and is fundamentally unreliable" (Glysson and Gray, 2003). The authors requested all available sediment data from the Parker gage, none of which contained SSC. The data Dunne used for his analysis was obtained from the Parker gage. The authors engaged in personal communication with Dunne regarding his report and analysis on the Yakima River and the sediment data used for his study. Dr. Dunne stated that if he found any sediment measurements other than what was contained in the Parker data set he would pass them along to the authors. The SSC data at the Yakima R. below Ahtanum Cr. Gage only includes concentrations. No breakdown of sediment sizes is available. This was verified through communication with the USGS field office in Pasco, WA. This is regrettable, as a more complete analysis of wash load versus suspended load could have been provided.*

5. Comments on Sediment Transport Modeling

Combining the Wilcock and Crowe gravel-sand sediment transport equation with the Engelund-Hansen sand transport equation is difficult to justify without other detailed supporting studies. The Engelund Hansen equation was developed for sand bed channels with dunes. To my knowledge it was never intended for use in gravel bed rivers. The Wilcock and Crowe equation is described as an equation “for mixed sand/gravel sediments[5]” so it is not clear why another sand transport equation should be combined with it. Since the approach of combining two independently derived transport equations has not been tried before and has not been verified with lab or field measurements, it makes it difficult to justify its use in the model. It would be useful to make the simulations using a more conventional and widely accepted sediment transport predictor such as the Ackers-White equation or Yang’s equation (or simply use the Wilcock and Crowe equation alone) to check how sensitive the model predictions are to the method of calculating sediment transport.

> *The justification for combining the Wilcock-Crowe equation with the Engelund-Hansen equation to model sediment transport is that the Wilcock-Crowe equation accounts for bed load only. If Engelund-Hansen were not used in conjunction with Wilcock-Crowe, suspended sediment volumes would not be represented in the bed-material load computations. Although using a suspended load equation in conjunction with a bed load equation is not common in the literature, it is not unprecedented. Parker (1998) mentions the additional use of a formula such as Engelund-Hansen for calculating sand transport in a gravel bed river. Wu et al. (2000) uses a similar approach (separate equations for suspended load and bed load transport) to compute fractional sediment transport in mixed systems. Certainly a method is needed that accounts for both transport mechanisms, while also accounting for the hiding and exposure effects that are not addressed in equations such as Ackers and White or Yang. Using a combination of a bed load and suspended load equation accomplishes this.*

The modeling assumed that all sediment coarser than 0.063 mm is bed material load but never demonstrated that this was appropriate for the Yakima River. This assumption affects the verification of the model. Steps for characterizing the wash load were described previously.

> *The lack of detailed Q-Qs suspended sediment data has been explained previously. Although this could affect the calibration, no data exist that could be used in the manner you explain to change the calibration.*

As described previously there is relatively little data available to calibrate and verify the 1D sediment model for making longterm predictions. More use of historic cross section data, specific gage analysis and geomorphic methods should be presented to increase the confidence of its results.

> *The authors have expanded the discussion and inclusion of historic cross sections from 1969 and a thalweg survey from 1954. The 1969 cross sections had vertical a datum problem that has been resolved by Yakima County since the draft report was submitted. Additional data from 1954 were made available during the comment period. These data have been incorporated into the final report. With respect to more use of specific gage data, all available relevant gage data were used.*

It is stated that the model shows the river has reached dynamic equilibrium. However, since (1) relatively large reach-scale patterns of aggradation and degradation are predicted to occur over the next 25 year and (2) the sediment is being selectively deposited along the channel (since the grain size decreases in the downstream direction), the concept of dynamic equilibrium is probably not very useful in this situation.

> *The authors have removed the reference to dynamic equilibrium from the final report.*

The time scale of the river channel response to levee setbacks should be described by showing bed level changes over time. Has the bed level changes reached equilibrium 25 years after the setbacks are implemented, or do impacts persist for a longer time span?

> *This analysis has been included in the final report.*

The model shows only limited effects from levee setback, under the assumption that the overall channel alignment remains unchanged. As already mentioned, in the case of the DID #1 levee setback, site observations indicated the river will likely avulse after the setback and capture the existing gravel pits adjacent to Newland Pit No. 2. Since such a shift could significantly alter upstream degradation in Segment 3 near the SR 24 Bridge and sedimentation patterns in Segment 2, the effect of this shift should be quantified. One approach would be to develop an avulsion scenario using the historic information from other sites, develop a set of cross sections to represent the new channel path then model this scenario with SRH-1D to show the impact on the overall river system.

> *The authors agree that the river moving into Newland Pit #2 (or any other pit) would be a significant occurrence. However, the authors do not believe that assuming an avulsion scenario in a 1-D model intended to evaluate sediment conditions over a 10-mile reach is*

the best approach to analyze such an avulsion. Due to the significance of an avulsion into a gravel pit, it is felt that these scenarios should be evaluated outside of this study. At this time, there is no survey for Newland Pit #2 and the depth is not known. This is a significant parameter and should not be assumed. Additionally, evaluating a scenario such as a channel avulsion into a gravel pit has very limited feasibility in a 1D sediment transport model dedicated to a reach-scale sediment transport study. Lateral channel movement, changes in channel width, and floodplain interaction is likely and could not be feasibly approached within the existing sediment model or within the scope of the current study.

6. Comments on Future Work

The comments in this letter are primarily based on a review of the draft report and the other supporting background documents. It would be helpful if we could obtain a copy of the SRH-1D model to gain a better understanding of the model schematization and sensitivity of the model results to various input parameters. As an alternative, it would be possible to specify some sensitivity runs and then review the final results. Also, it would be useful to review some of the basic data such as the river cross section comparisons and historic air photos if these are vailable.

The authors sent the requested model and associated data to Yakima County following the receipt of review comments from NHC.

References cited:

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northwest hydraulic consultants

January 18, 2011

Project No. 2-1587

Yakima County Public Services
Surface Water Management Division
128 North Second St.
Fourth Floor Courthouse
Yakima Washington
98901

Attention: Mr. Jeff Legg

Dear Mr. Legg:

Subject: Review of River Geomorphology and Sediment Transport Study Gap to Gap Reach, Yakima, WA

1. Background

Northwest Hydraulic Consultants (NHC) was retained by Yakima County Public Services to review hydraulic and geomorphic studies being undertaken as part of a plan to reconfigure levees and restore floodplain conveyance along portions of the Yakima River. The County's letter of March 4, 2009 identified three main tasks for NHC:

1. Review field data and model development and provide input for improving the data collection and model development and model validation. The analysis will identify limitations of the modeling with regard to the predictive response of the river to natural and infrastructure change;
2. Review the river/floodplain geomorphic analyses and assess whether these studies are consistent or disagree with the findings of the modeling investigations with regard to river response. Recommend means to resolve any conflicts, if they exist;
3. Provide a technical memo summarizing Tasks 1 and 2 and identify the potential uses and applicability of the sediment models and geomorphic information in establishing the predictive response of the future design of levee reconfiguration, floodplain and habitat enhancement and improving or maintaining the function of existing infrastructure.

The draft report "*Yakima River Geomorphology and Sediment Transport Study: Gap to Gap Reach, Yakima WA*" dated March 2010, prepared by Robert C. Hilldale and Jeanne E. Godaire of the Bureau of Reclamation, US Department of the Interior was provided by the County for review. I subsequently discussed the findings with Joel Freudenthal and Karen Hodges of Yakima County, particularly sections related to the historical analysis of cross section surveys and geomorphic assessment. I submitted review comments on the draft report to the County in a letter report dated May 10, 2010. The review indicated several areas where the report could be strengthened. We subsequently received an updated version of the report on December 8, 2010, along with two sets of SRH-1D model runs. This letter report summarizes our comments on the updated report. I have also provided some recommendations on further hydraulic design studies that should be undertaken.

2. Review of Updated Report

The updated report has addressed most of the issues that were identified in the earlier review. Additions to the updated report include:

- More detailed assessment of historical channel trends, including a re-assessment of cross section survey comparisons, incorporating new information and analysis conducted by the County;
- An assessment of the upstream extent of influence of Wapato Dam;
- A description of sediment model limitations;
- Predictions of flood level changes due to levee set-backs for the simulated case 25 years in the future;
- Predictions of potential locations of future channel erosion and avulsion hazard using a stream-power assessment as well as geomorphic-based observations;
- More detailed comments and discussion on the potential impacts of levee set-backs on channel instability, sedimentation patterns, scour and upstream degradation;
- Recommendations on future studies and monitoring work.

No additional information was provided to justify combining the Engelund-Hansen and Wilcock sediment transport equations. To my knowledge this approach has not been verified extensively using field or laboratory data. However, I don't believe further model runs using different sediment transport equations or different assumptions about bed material loads would fundamentally change the main findings of the report. I believe the team has gone about as far as one can go with one-dimensional (1d) sediment modeling, given the limited data for calibration and verification. The main limitations of any 1d model for conditions on the Yakima River are:

- Can't represent the flow or sediment transport patterns in bends or complex flow spills onto the floodplain or breaches of levees into gravel pits;
- Can't represent different mechanisms for transporting or re-distributing the sand and gravel sediment from the main channel onto the floodplain;
- Can't represent bank erosion processes or avulsions.

Another site-specific limitation is that there is very little historic data available for verifying the 1D sediment model predictions. Although historic cross section data exists, at least five gravel pits excavated on the floodplain have been captured by the river during the period of the surveys. These limitations have been overcome as much as possible by supplementing the model predictions with other geomorphic-based methods or field observations.

The study provides useful information to assist in assessing the overall benefits of the proposed levee set-backs. For example, the study has shown that under existing conditions, the overall pattern of sediment deposition / degradation in the study reach will be relatively small in the future, provided no new re-alignment of the channel occurs due to an avulsion. The predicted average annual sediment loads along the river were relatively small, amounting to approximately 8,000 tons/year of gravel and around 9,000 tons/year of sand (17,000 tons/year of bed material). After setting back the DID No. 1 levee, the flood level was predicted to decrease by between 3 to 5 feet. This reduction in flood levels was shown to be nearly the same after 25 years of simulated flows and sediment transport. Degradation was predicted to occur upstream due to the reduced backwater effect, which could cause bed lowering at the SR24 Bridge and the Beech Street gravel pit.

One of the most important sections of the report deals with the effect of setting back DID No 1 levee on the river's stability. Much of this assessment has been based on previous experience and site observations rather than the model predictions. Following removal of DID No. 1 levee the main channel could avulse into the existing gravel pits on the left bank. This avulsion could cause additional headcutting and degradation upstream and could affect the integrity of the SR24 Bridge abutment and foundation. The report recommends that a plan should be in-place to prevent an avulsion into the gravel pit.

The report also refers to the case study by Norman (1998)[1] concerning the 1996 avulsion of the Yakima River into the gravel pits just upstream from the study area at Selah Gap. Some of the key findings by Norman were as follows:

- Large ice jams played an undefined but likely significant role;
- About 6 to 8 feet of incision occurred after the avulsion immediately upstream of the pits. There was local knickpoint migration as evidenced by a migrating standing wave and increased bank erosion as the river tried to re-establish its grade;
- At least 300,000 cubic yards (roughly 450,000 tons) of gravel was scoured from the river bed and deposited as 6 foot thick layer in the excavated pit;
- More than 100,000 cubic yards (150,000 tons) was moved from the river bed during the flood and deposited on gravel bars and private lands upstream of the pits.

The magnitude of these channel changes (both the bed level changes and quantities of gravel transport) are far greater than the computed bed level changes and sediment loads estimated by the sediment model over a 25 year simulation period. A single avulsion or channel shift may induce very large changes in the river's behaviour and may completely alter the pattern of sediment transport that occurs under stable channel configurations.

3. Conclusions and Recommendations

I believe the updated report is substantially complete and has fulfilled its main objectives. Some minor typo corrections were noted, which should be incorporated into the final document.

Additional hydraulic design investigations should be carried out to design appropriate river training measures to prevent an avulsion of the river into the existing gravel pits after the DID levee is set-back. The scope of the hydraulic design studies should include (1) design of measures to prevent an avulsion into the existing pits near the DID No. 1 levee, (2) mitigating potential scour or erosion at the SR24 Bridge and (3) mitigating upstream degradation to prevent an avulsion into the Beech Street gravel pit. The additional investigations should include gathering topographic surveys in the gravel pits and the adjacent floodplain and more detailed channel bathymetry. It would be useful to develop a 2 dimensional numerical model of the reach extending from upstream of the SR24 Bridge down past the DID No. 1 levee. The 2D model would be used to assist in designing river training / channel stabilization works and to verify that the anticipated flood level reduction due to setting back the levee can still be achieved.

[1] Norman, D., Cederholm, C. and W. Lingley Jr. (1998): Flood Plains, Salmon Habitat and Sand and Gravel Mining, Washington Geology, vol 26, no.2/3 September 1998.

Consideration should be given to using a mobile-bed physical hydraulic model to test the performance of the bank stabilization designs. This would significantly increase the confidence that the proposed measures will prevent an avulsion into the gravel pit and prevent any adverse impacts to the SR24 Bridge, while still achieving the desired reduction in flood levels.

If you have any questions on these comments or wish to discuss the scope of any further hydraulic investigations, please feel free to contact me by email at dmclean@nhc-van.com or by phone at 250-754-6425.

Sincerely,

northwest hydraulic consultants

{*original sent by email*}

Dave McLean, Ph.D., P.Eng.
Principal