Geomorphic Assessment of the Water Gaps in the Yakima Basin, Washington

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Executive Summary

Yakima County Services requested an investigation into the geomorphology of "water gaps" of the Yakima and Naches Rivers, Washington. Water gaps are geologic constrictions within a river valley. The study intent is to better understand the current state of knowledge regarding the influence of water gaps on river morphology and dynamics, particularly with regards to the relative impact of human modifications to the adjacent alluvial landscapes, e.g., road prisms, diversion dams and levees. The report explores the magnitude to which artificial structures have constrained the river relative to the natural effects of the gaps. A review of the existing literature resulted in a best available science summary. The majority of sources specifically address this region; studies from other regions were included for the additional context they provide. More detailed analysis regarding the hydraulics and sediment transport within and between the water gaps will be part of future work. An independent assessment and comparison of the physical characteristics of the four gaps and their adjacent reaches was undertaken for the following gaps: The City of Yakima Water Treatment Plant (WTP) Gap and Rambler's Park Gap at Nelson Dam on the Naches River and Selah Gap and Union Gap on the Yakima River. Each of the study reaches indicate general downcutting or incision of the river valleys over recent geologic time (the last two million years). This valley incision is reflected in a series of alluvial terraces within the study reaches.

The water gaps of the Yakima and Naches Rivers have significant effects on the geomorphology, surface water, and groundwater of their basins. The location of the water gaps is controlled by the regional geology and local tectonics. The gaps can restrict flow, and hence sediment flux. They can cause backwater effects during floods, leading to increased upstream sedimentation and floodplain dynamics. Gaps can also restrict bedload sediment transport downstream. Groundwater-surface water exchange is modified as hydrogeology changes in the vicinity of the gaps. They force down-valley groundwater flows to the surface where they join the river; this upwelling moderates annual temperature variation (cool in summer and warm in winter) and contributes to nutrient levels. The elevation of the river surface also controls to a large degree the elevation of the piezometric surface of the valley as a whole, and changes to the elevation of th

Gaps were obvious places for locating infrastructure such as dams and highways, and the floodplains on either side of the gaps were attractive areas for agricultural, residential and industrial development. Development between and within the gaps has altered the form and processes of the rivers directly and indirectly. Flow regulation has changed flood intensity, duration and timing which has altered ecological conditions to the detriment of native salmonids and riparian vegetation. These changes also can increase the erosive power of floods by extending their duration. The construction of levees, roads, and other structures has disconnected the floodplain from the river and changed the patterns of sediment flux through the system. The practice of mining alluvial gravel has reduced sediment availability and increased avulsion risks when floodwaters breach the floodplain pits. Where built environments enter the rivers' channel migration and flood zones, hazards to life, property, and the environment ensue.

Our analysis shows that although each of the project water gaps is unique in their history and response to natural and anthropogenic influences, some similarities exist. Channel stability is greater within the gaps than the sub-reaches adjacent. Channel migration tends to increase as the river approaches a gap from upstream and increase with distance away from the gap downstream. The WTP Gap Reach experiences approximately five times the channel migration of the Rambler's Park and the Selah to Union Gap Reaches. Higher average river slope and less levee confinement at the WTP Gap Reach likely drive this higher channel migration rate.

The greater the proximity of levees and revetments to the floodplain and bankfull channel of the river, the higher the degree of confinement. Such confinement typically results in straightened, sediment starved reaches with little to no habitat for fish and other wildlife. While the length of river armored by levees is comparable in the project reaches, the level of confinement varies. The WTP Gap Reach experiences the most confinement from levees within the gap itself; Rambler's Park Gap and the Selah to Union Gap Reaches experience greater confinement between the gaps. The degree of bankfull channel confinement is much greater at Rambler's Park Gap and the Selah to Union Gap Reaches compared to the WTP Gap Reach. Average floodplain confinement increases from the WTP Gap Reach to Rambler's Park Gap Reach, with Selah to Union Gap Reach exhibiting the greatest floodplain confinement.

Recommendations for a long-term strategy for managing structures, river hazards, and restoration actions within the project area include the following:

- Levee removal to promote mainstem, side channel, and floodplain habitat restoration and sediment storage

- Improve fish passage, channel stability, and floodplain connectivity in a manner that protects existing water diversions.

    - WTP diversion
    - Gleed diversion
    - Yakima Valley Canal intake
    - Nelson Dam (Rambler's Park)
    - Wapato Dam

- Identify and manage avulsion hazards

- Side channel formation and protection

- Woody debris reintroduction and management (particularly linked to side channels)

- Floodplain re-forestation

Several additional analyses are recommended to support restoration activities:

- A quantitative appraisal of the magnitude and rates of sediment flux through the Yakima and Naches systems is recommended to enhance our understanding of the effects of future development and river response. This analysis would compliment the planform analyses conducted (especially through the Union Gap) as well as provide information on the thresholds at which we can expect incision versus aggradation. While the BOR is providing a sediment transport model for the gap-to-gap reach in a number of areas, localized sediment transport and hydraulic studies will likely be needed for site-specific restoration efforts.

- A strategic management plan should be developed for set back levees in the cities of Yakima and Union Gap in order to improve flood capacity, fish habitat, and natural fluvial processes while reducing erosion and flood elevations.

- An economic evaluation of the levee set back program that includes ecologic assets as well as flood protection for infrastructure and property. This evaluation would identify and assess the specific cost, benefit, and approaches for each management action.

- Adaptation of current diversions and weirs to improve fish passage and habitat and sustain geomorphic processes. This is specifically recommended for areas with high risk of avulsions such as downstream of the Yakima WTP and at Rambler's Park.

- A detailed hazard assessment plan is recommended that identifies avulsion risks, risks to infrastructure, and opportunities for betterments. This includes economic, engineering, and geomorphic assessments that will allow Yakima County to acquire federal funding for betterments that provide more sustainable and long term solutions to flood and habitat protection.

- Reconnecting gravel mine pits and locating future mining sites outside the 100-year floodplain is recommended. Restoration designs should mimic side channels to facilitate reclamation, and should not interfere with hyporheic flow.

- Bioengineering techniques such as engineered log jams and revegetation are recommended over conventional engineering approaches to protect critical infrastructure and property in a manner that delivers cumulative benefits instead of cumulative impacts.

1. Introduction

Yakima County Public Works requested an investigation and report on the geomorphology of "water gaps" of the Yakima and Naches Rivers. A water or valley gap is where a river has cut a notch through ridges of uplifted bedrock. The belt of uplifted bedrock creates barrier across the river's alluvial plain and constricts flow through the water gap. Because water gaps are being actively eroded by the river, they can form geologic controls on the river's grade and conveyance capacity that directly influence channel dynamics of the adjacent alluvial plain. Historically, water gaps were logical locations for transportation routes and dams. Where these facilities further constrain the water gap they could impose additional controls on geomorphic processes influencing flooding and sediment transport. The study focus is flood and sediment routing, the development of adjacent alluvial landscapes, and differentiating the magnitude to which artificial structures (e.g., road prisms, diversion dams and weirs) influence the former.

The investigation includes three sections covering the following basic elements:

- Summary of the best available science on water gaps, including theoretical and applied studies that relate to the natural and artificial effects. Background information will not be limited in geographic scope, but focus on the Western United States. Topics include the following with respect to water gaps: groundwater, flood conveyance, and sediment conveyance and sedimentation.
- Detailed geomorphic descriptions using available topographic, geologic and hydrologic information, for the following water gaps:

  Naches River
  - City of Yakima Water Treatment Plant (WTP) Gap
  - Rambler's Park Gap at Nelson Dam

  Yakima River
  - Selah Gap
  - Union Gap

- Specific recommendations for habitat improvement at the water gap reaches and through the adjoining valley segments in collaboration with Yakima County. Includes a basic summary of elements needed to develop and implement recommendations.

The water gaps are located in Yakima County in south central Washington State (Figure 1) along the eastern side of the Cascade Mountains. Selah and Union Gaps are formed on the southerly flowing Yakima River near the towns of Yakima and Union Gap. The Yakima River is paralleled by Interstate (I) 82 through and between the gaps. The WTP and Rambler's Park Gaps are formed on the southeasterly flowing Naches River near the towns of Eschbach and Yakima. The Naches River is paralleled by State Route (SR) 12 through and between the gaps.

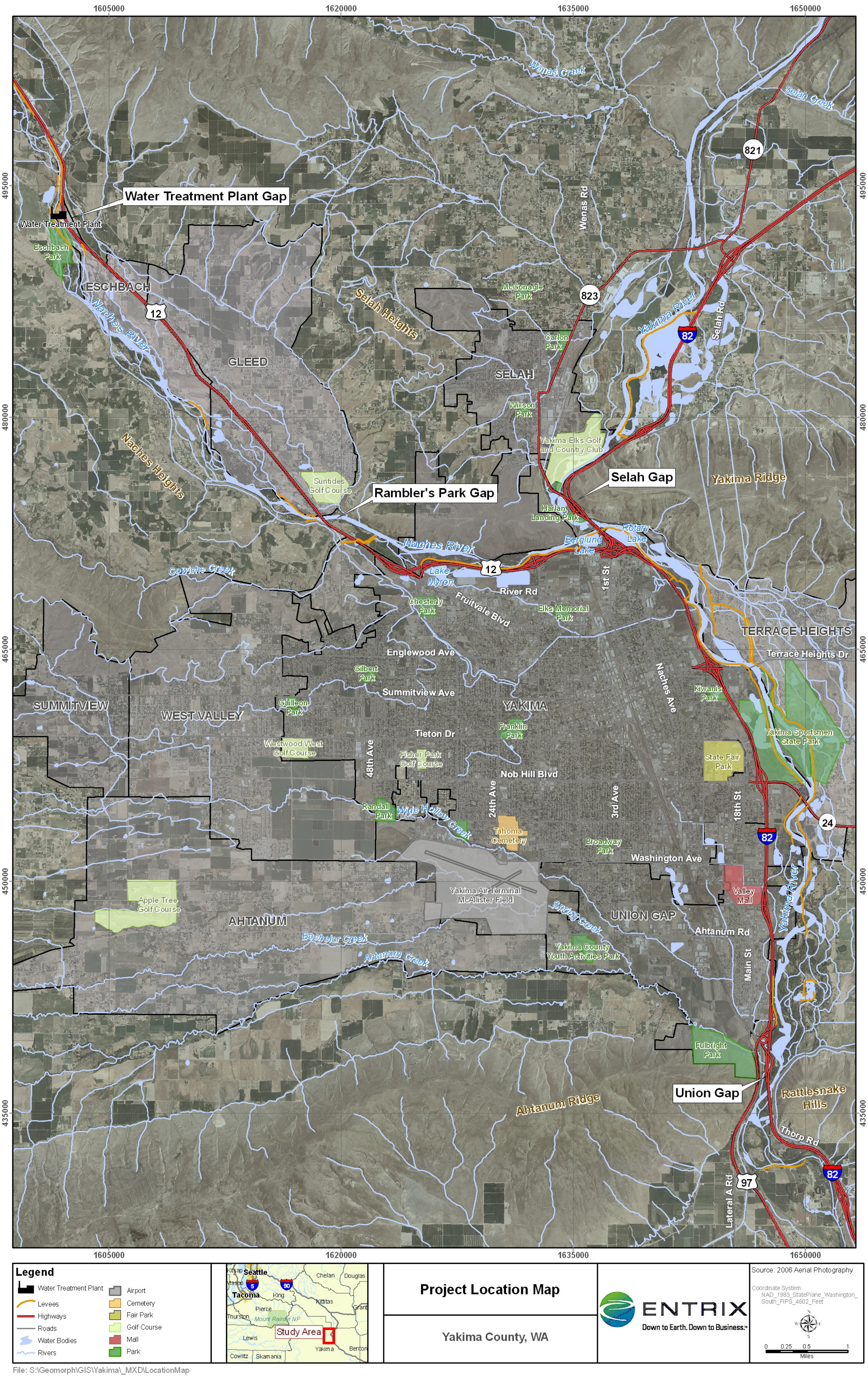


Figure 1 Location of the project water gaps and surrounding area.

2. Yakima Basin Water Gaps Best Available Science

This summary presents the best available science of the physical characteristics and infrastructure of the water gaps of the Yakima and Naches Rivers. The majority of sources for this report specifically address this region. Studies from other regions were included for the additional context and alternative perspectives they provide. These references range from river management plans to scientific investigations and extend from early seminal works to recent findings. The challenges facing these rivers and their human and ecological communities in the twenty-first century are considerable. Knowledge of the gaps and their influence on the river system can strengthen management decisions and inform long-term solutions to these challenges.

2.1. Regional Context

2.1.1. Geology

Basalt flows play a large role in the current geological conditions in the region. The Columbia River Basalt Group (CRBG) inundated an extensive area of the Columbia River Basin with multiple flows from 17 to 6 million years ago. The Yakima River Basalt subgroup measures about 4,500 feet thick at the margin of the Columbia Plateau and thickens further towards the middle (Waters, 1965). The lowest portion of the Yakima Basalt is comprised of massive flows with a typical pattern of columnar jointing, while the top 1,500 feet also exhibits sedimentary beds and lenses of clay, silt and sandstone and occasional conglomerate beds. The latter are exposed in many the water gaps (Bingham and Grolier, 1966).

Another key geological unit in the region of the gaps is the Ellensburg Formation. It interfingers with the youngest part of the Yakima Basalt group and overlies it with a thickness of 2,000 feet in the type location. This formation is comprised of conglomerates, sand, silt and clay with beds of fine-grained ash; much of the sediment is volcanic in origin (Bingham and Grolier, 1966; Swanson *et al.*, 1989). The upper portions show evidence of folding, erosion and deposition (Waters, 1965). Crustal deformation created anticlinal ridges, along with the synclinal valleys between, producing the 16 million year old Yakima Fold Belt. Some of the gaps of the Yakima Basin run through such ridges, including Selah, Union, and Rambler's Park Gap (Waters, 1965).

In the Pleistocene, the Tieton Andesite filled the Tieton and Naches River Valleys, but was subsequently eroded away. It outcrops in the lower Naches above loose boulder alluvium from the ancestral Tieton and Naches (Kinnison and Sceva, 1963). At this time, the Palouse loess was deposited by wind over an area of approximately 3,860 square miles and to a maximum depth of about 250 feet. (Sweeney *et al*., 2002). Most of the loess originated as silt and sand deposited by Glacial Lake Missoula during a series of enormous glacial outburst floods 14,000 to 16,000 years ago (Sweeney *et al*., 2002). The valleys of the basin are filled with sediment that reaches up to 1,840 feet thick (Jones *et* *al*., 2006). The fill is comprised primarily of modern stream alluvium and Pleistocene glacial deposits. Modern Yakima River gravels are derived from Naches River sediment, landslides in the Horseheaven Hills, Spokane Flood deposits, and ancestral Yakima River gravels (Campbell, 1983).

2.1.2. Hydrology

The Yakima River is a tributary to the Columbia River and drains 6,155 square miles before the confluence at Richland, Washington. The Naches River is a major tributary of the Yakima; its basin is approximately 961 square miles (Molash and McGuire, 2008). The flow of the Yakima and Naches originates as snow and rainfall on the slopes of the Cascade Mountains in the winter (Vano *et al*., 2009). The mountainous portions of the Yakima Basin exceed 8,000 feet of elevation with an average of 140 inches of precipitation per year, while the confluence with the Columbia River is at 340 feet and averages 7 inches of precipitation (Yakima Subbasin Fish and Wildlife Planning Board [YSFWPB], 2004). In the mountains, the average summer temperature is 55º F and snowpack can range from 75 inches at 2,500 feet to over 500 inches at the summit. In the valleys, the rainy season runs from November through January and the average summer temperature is 82º F (YSFWPB, 2004). The drainage area above the WTP Gap is approximately 27 square miles and at Rambler's Park is approximately 1,104 square miles. The contributing area of drainage at Selah Gap is approximately 21 square miles and at Union Gap is approximately 1,537 square miles.

Before alteration by European-Americans in the mid-nineteenth century, the basin hydrology included complex floodplain channel systems and surface/groundwater interactions. This modulated peak flows and provided the topographic and temperature diversity needed to support multiple salmonid life histories. The water generated by precipitation and snowmelt in the winter and spring would accumulate in the sediment of the basins. The deep alluvial deposits in the synclines between ridges allows for significant groundwater flows down the valley. When these flows encounter the water gaps the subsurface flows come to the surface as streamflow (Kinnison and Sceva, 1963). Highest flows occur with rain-on-snow winter storms, but spring snowmelt floods can last much longer—10 or more weeks (Park, 2008).

2.1.3. Climate Change

The hazards facing the Yakima and Naches River reaches in the vicinity of the gaps are not likely to decrease as human populations grow and climate change alters hydrology. Recent predictions indicate that snowmelt will occur earlier in the year and summer flows will decrease (Vano *et al*., 2009). This will increase the number of years of water shortage, which historically has been 14 %, by the 2020s (Vano *et al*., 2009). This could reduce agricultural production of the basin by 5 to 16 % (Vano *et al*., 2009). One degree Celsius (1.8 °F) of warming in the Cascade Mountains would result in a 20 % decline in spring snowpack (Vano *et al*., 2009). As snow packs decrease with global climate change, the conflict over water allocation for irrigation and salmonid recovery is expected to worsen (Molash and McGuire, 2008).

The Yakima Basin runoff regime is considered to be the transient type, a combination of rain dominant and snow-melt dominant (Elsner *et al*., 2009). Such middle elevation watersheds typically have two streamflow peaks: in winter during maximum precipitation when some snow melts and in late spring when the snowpack completely melts (Elsner *et al*., 2009). Near-term projections indicate that peak streamflow in spring will not change considerably; however, streamflow in winter will increase (Elsner *et al*., 2009). By the end of the century, the peak flow will occur in winter and the basin will exhibit rain-dominated hydrology (Elsner *et al*., 2009).

2.2. Impacts of Human Development

The presence of human modification can intensify the geomorphic and hydrologic effects of the gaps or alter the system in other ways. In the last 150 years, the hydrology of the rivers has been modified drastically with irrigation dams, diversions, and return flows. The construction of levees, roads, and other structures has disconnected the floodplain from the river and changed the movement of sediment through the system. In some cases it may also place these structures directly in the path of migrating channels or potential avulsion sites. The practice of mining alluvial gravel has changed sediment availability and increased avulsion risks when floodwaters breach the floodplain pits. See Figure 2 for an example of floodplain development in the area of the WTP Gap.

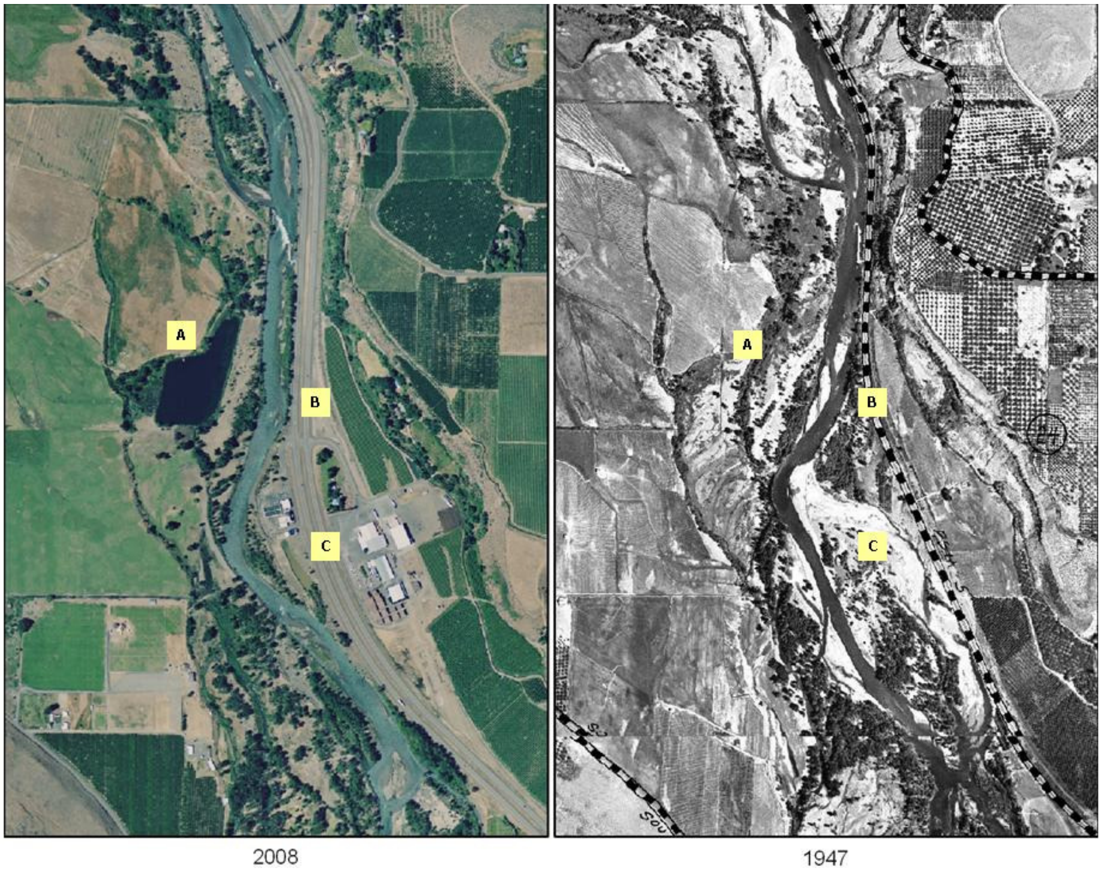


Figure 2 Aerial photographs of the WTP Gap Reach of the Naches River. Note the modification of the active floodplain: (A) gravel mine pit, (B) levees and straightening of the channel, and (C) roads and buildings.

Salmonids in the basin have not fared well. Middle Columbia steelhead/rainbow and bull trout are listed as threatened under the Endangered Species Act. Yakima summer steelhead are endangered, spring Chinook, fall Chinook, and Pacific lamprey populations have significantly diminished and sockeye and coho are extirpated from the basin (Molash and McGuire, 2008; YSFWPB, 2004; Yakima River Floodplain Mining Impact Study Team [YRFMIST], 2004). The western toad, western gray squirrel, White-headed Woodpecker, Lewis' Woodpecker, and Sage Grouse are all listed as species of concern or candidates for listing by the federal or state standards. The Sandhill Crane is considered endangered and the Sage Grouse and western gray squirrel are listed as threatened by the state (YSFWPB, 2004). Native cottonwoods are dependent on the patterns of pre-disturbance hydrology to support their growth cycles. Seedling recruitment requires spring peak flows to create and dampen new nursery beds. Falling flows then expose the seedlings while base flows maintain moisture during summer and autumn (Braatne and Jamieson, 2001). Native seedling recruitment is hindered by lack of seasonal flow variation and exotic invasive vegetation flourishes in proximity to highways, agriculture and urban areas (Braatne and Jamieson, 2001).

2.2.1. Irrigation

Today, six major reservoirs store water during high flows for use in irrigation during the summer low-flows (YSFWPB, 2004). Peak flows have diminished since the 1930s with the construction of the dams (Dunne *et al.,* 1976). Although built for irrigation, the dams also reduce flood size, frequency, and duration (YRFMIST, 2004). These smaller, longer-lasting floods pose a greater erosion hazard because they can attain flows beyond the entrainment threshold of the sediment for longer periods. This threshold is the flow rate at which the water can erode the bed and banks of the river: 7,500 cfs for the Yakima (Park, 2008).

A local irrigation management system called "flip-flop" has significantly altered the hydrology of the basin. Under flip-flop, the U.S. Bureau of Reclamation (BOR) releases water from dams on the Yakima for irrigation withdrawal in April through September. Then flow is reduced on the Yakima in September when spring Chinook are spawning. This causes the Chinook to spawn lower on the river, where flows will be sufficient to keep the redds under water. At that time, flows are released into the Naches for diversion into irrigation. These dam releases have a deleterious effect on Naches and Tieton steelhead. The torrent flushes out young fish along with critical elements of the ecosystem that supports them: insects and the seeds of cottonwood and other riparian vegetation (Molash and McGuire, 2008). Fish passage is also blocked by dams, diversions and pumps (YSFWPB, 2004).

These alterations have also damaged ecological conditions for native salmonids and riparian vegetation. Groundwater upwelling from alluvial aquifers contributes cool water; thermal regimes play a significant role in aquatic ecology by controlling dissolved oxygen, metabolic rates, bioenergetics, and biodiversity (Stanford *et al.*, 2002; Vaccaro, 2005). Today, the cool groundwater is replaced by irrigation returns that are warmer and possibly contaminated.

2.2.2. Floodplain development

The levees and the roads that act as revetments increase hazards by interrupting fluvial processes and by simply being in the path of flood waters. A network of levees was constructed after World War II; they were raised in the 1970s and 1980s (Otak, Inc. and KCM, Inc., 2007). The need for railways and roads prompted the building of bridges and revetments. The levees have also induced incision and disconnection from the floodplain (Hilldale, 2007a). The length of the mainstem river has been reduced by 43 % since 1884, and the active floodplain by 28 % from 1927 (Eitemiller *et al*., 2002). Lateral connectivity in the floodplain was also reduced and only 40 % of the Holocene floodplain retains surface connection to the river (Eitemiller *et al*., 2002). The floodplains also house gravel mines, recreational sites, sewage and water treatment plants, and hydroelectric facilities (Eitemiller *et al*., 2002). These floodplain uses increase water temperatures, alter sediment transport, and reduce groundwater-surface water interactions.

The presence of roads and levees in a dynamic floodplain has resulted in a number of hazards to infrastructure. For example, SR 12 is within the Naches River 100-year floodplain and has experienced at least two emergency repairs. As the channel attempts to migrate, it erodes the left bank and threatens the road and fiber optic cables (Molash, and McGuire, 2008). Any obstruction to flow can reduce the river's ability to transport sediment and result in channel filling and diversion (Dunne *et al.*, 1976). Sediment accumulation in the side channels is also a concern because of potential detrimental effects on salmon populations. Contaminants adhere to fine sediments and a fine substrate encourages excess growth of aquatic plants. Decay of excessive vegetation could lead to low dissolved oxygen levels when the channel is disconnected from the mainstem (Hilldale, 2007a).

Clearing of floodplain forests and wetlands for agriculture and development occurred in many places and levees were built to protect the structures (Eitemiller *et al.*, 2002). Disconnection of side-channels, dewatering for irrigation, chemical and thermal pollution, and gravel mining have reduced the capacity to support salmonid populations (Stanford *et al.*, 2002). The loss of floodplain habitat is a limiting factor for aquatic productivity, in overflow and disconnected channels and spring brooks (Stanford *et al.*, 2002; YSFWPB, 2004). At Union Gap, floodplain habitat has declined from 2,325 hectares before European-American settlement to 273 hectares in 2001 (Braatne and Jamieson, 2001). In the Naches, grazing and agriculture have given way to suburban development. Surface connection has been reduced to 43 % and 14 % of the 1927 floodplain has been lost (Eitemiller *et al.*, 2002).

2.2.3. Gravel Mines

Over the last century, and particularly since the 1950s, mines in the floodplain have produced aggregate for the region and the demand for this material is not likely to abate. There are roughly 140 active and abandoned gravel mines along the river (YRFMIST, 2004). The practice has caused serious disruption to river geomorphology and ecology. Abandoned gravel mines pose a danger to local communities by undermining floodplain stability (Dunne *et al.*, 1976). Erosion rates, sediment transport and channel location can change if the river captures a gravel pit (YRFMIST, 2004). For example, in 1971, a flood in Union Gap breached three pits in succession, moving the channel 2,000 to 3,000 feet to the west. The resulting channel is not as sinuous, long or gently-sloped as the abandoned channel. This will likely encourage bank erosion, channel migration and bar deposition as the channel adjusts (Dunne *et al.*, 1980).

Salmonids spawning in the river have specific substrate requirements that may conflict with mining. The removal of native riparian vegetation reduces shading and can allow invasive non-native species to flourish. The altered temperature regimes in the ponds favor exotic aquatic plants and fish, e.g. northern pike minnow. Without vegetation and soils, the riparian zone is also less able to filter contaminants (YRFMIST, 2004).

Active river channel bars could be considered renewable if the amount removed does not harm spawning or river processes (Dunne *et al.*, 1980). Some channel bars act as temporary storage of sediment in a dynamic equilibrium; removing too much will starve downstream bars. This would undermine banks and facilitate channel migration. Removal of a point bar could also straighten the flow path, increase water-slope and raise boundary shear stress against the bar, leading to scour and channel cut-off. Conversely, if the extraction of gravel prevents high velocity flows from exerting shear stress on the opposite bank, the migration toward the outer bank could be stopped (Dunne *et al.*, 1980).

2.3. Assessment of the Gaps

2.3.1. Water Gap Formation

Water gaps may form in a number of ways. They may occur through the action of ancestral streams on a changing landscape wherein streams maintain their original course as tectonic processes cause ridges to form, providing the river can incise into the ridges at the same rate as uplift. Faulting and folding of the rocks through which the gaps cross can lead to structural weakness and preferential erosion. Gap formation may include the process of stream capture. This process begins with headward erosion joining two streams on opposite sides of a ridge, forming a saddle. When the saddle cuts down to the base level of the valley, the streams merge, causing one stream to reverse flow direction and be captured by the second stream.

The sources used for this summary state that the Yakima Basin water gaps formed through an ancestral river downcutting into ridges as they uplift (Waters, 1965; Dunne *et* al., 1976). This interpretation states that the ancestral Yakima River originally flowed over flat Miocene basalt flows. Orogenic activity uplifted the lava into ridges, and the river downcut a series of gaps (Waters, 1965). This uplift continues today, with a slightly faster rate in the north (Dunne *et al.*, 1976). Today, the Yakima River between Selah and Union Gap flows through a wide floodplain of Quaternary alluvium and terraces, with Pleistocene alluvium, Palouse loess, and continental sedimentary deposits. The earthquake hypocenters in the region occur in high-angle planar clusters that reach the surface where the rivers cross the anticlines; one reason for this could be high-angle thrust faults and fault folds that continue to propagate (Finnegan and Montgomery, 2003). While more research would be required for confirmation of this occurring at the project gaps, the presence of such faults could indicate a tectonic driving force for the location of the Yakima gaps.

The Naches gaps likely formed under different conditions. The literature does not put forth any theories for these particular gaps; however, geologic maps of the region suggest a possible explanation. The ancestral Naches valley filled with Tieton Andesite flows in the Pleistocene. Currently, the Naches floodplain lies in a wide canyon with steep walls between the Tieton Andesite on the southwest side and the Ellensburg Formation and CRBG on the northeast side (Eitemiller *et al.*, 2002). The WTP Gap is located where an outcrop of the Columbia River Basalt has been mapped between the floodplain and the

Ellensburg Formation. Similarly, the Rambler's Park Gap is found in a section of the river between Tieton Andesite and Columbia River Basalt. Presumably, the gaps occur where the more resistant basalt outcrops have impeded the lateral movement of the river relative to where the Ellensburg Formation is found (Figure 3).

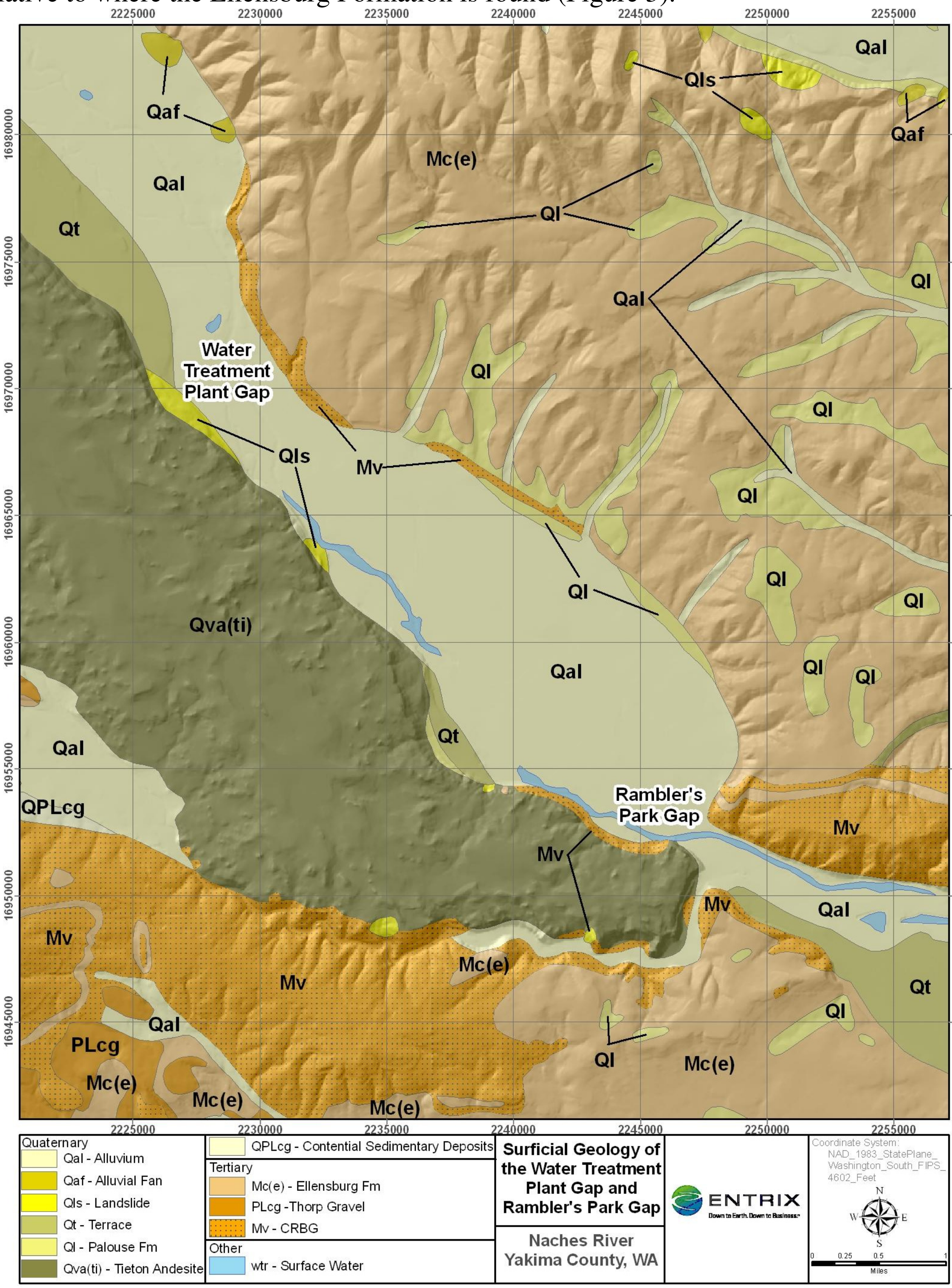
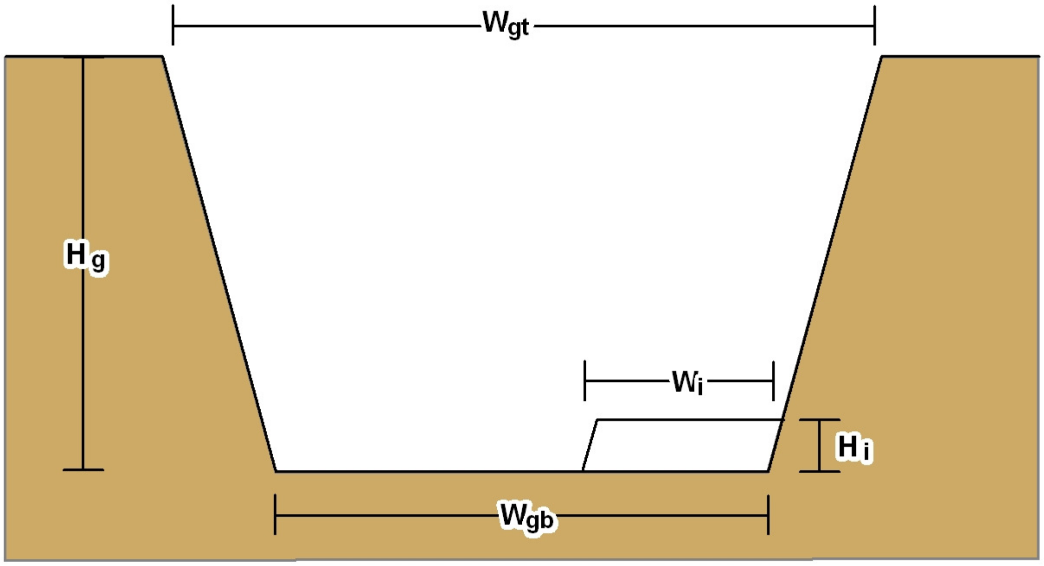


Figure 3 Surface Geology of the WTP Gap and Rambler's Park Gap on the Naches River. Note the outcrops of the CRBG (Mv) on the northeastern valley wall at both of the gaps. Geology data provided by Yakima County.

2.3.2. Water Gap Characteristics

A quantitative comparison of the project water gaps was performed to assess their similarities and the unique features of each gap. Both the gap geometry and its effect on river slope were used in the comparison. Figure 4 depicts the measurements obtained at each of the project water gaps for direct comparison and for computation of constriction ratios. Infrastructure placed within the gaps (roads, diversion canals, etc.) further decrease the natural bottom width of the gaps. Constriction ratios of both the natural and altered gap width (due to the presence of infrastructure) are used to compare the anthropogenic impact. Table 1 shows that each of the gaps is unique, however some aspects are similar between gaps. Both gaps on the Yakima River are similarly steep-sided, and the amount of reduced gap width due to infrastructure is of comparable magnitude. The influence of Selah and Union Gaps on the slope of the Yakima River is very similar, with the slope of the river reduced by approximately 50% within the gaps. The gaps on the Naches River are less similar than those on the Yakima River. In general there is less impact from infrastructure at the gaps on the Naches River, and the gaps are more steeply sided than those on the Yakima River. Comparing the degree of constriction from the upstream and downstream direction due to the gaps reveals that Selah and Rambler's Park Gaps have similar natural constriction ratios. However, when accounting for the reduced gap width due to the presence of infrastructure, they diverge. The WTP Gap is perhaps the most unique of the four gaps, due to its low constriction ratio and its effect on the river slope. Not only are the constriction ratios at the WTP Gap lower, but the upstream constriction ratio is less than the downstream constriction ratio. Additionally, the slope of the Naches River is highest within the gap. Both of these trends are opposite those of the other project water gaps.



W_{us} = width of the Qal upstream of the Gap
W_{ds} = width of the Qal downstream of the Gap
W_{gb} = bottom width of the gap
W_{gt} = top width of the gap
W_i = width of infrastructure
H_g = gap height
H_i = height of infrastructure

Figure 4 Geometric parameters measured to facilitate comparison between gaps

Table 1 Summary of parameters used to compare project water gaps

Parameter	Equation Used	Yakima River		Naches River	
		Selah Gap	Union Gap	Rambler's Park Gap	WTP Gap
Natural Upstream Constriction	W_{us}/W_{gb}	6.14	8.15	6.46	2.13
Natural Downstream Constriction	W_{ds}/W_{gb}	3.75	6	3.39	2.81
% Anthropogenic increase in constriction	$[(W_{gb}-W_i)/W_i] \times 100$	50	43.34	11.27	6.88
Altered Upstream Constriction	$W_{us}/(W_{gb}-W_i)$	12.27	14.39	7.28	2.28
Altered Downstream Constriction	$W_{ds}/(W_{gb}-W_i)$	7.50	10.58	3.82	3.01
Steepness of gap walls	W_{gb}/W_{gt}	0.37	0.26	0.59	0.93
Gap height	H_g	197 m	248 m	74.7 m	45.7 m
Infrastructure height	H_i	7.5 m	6.7 m	3 m	6.1 m
River slope upstream of gap		0.28%	0.25%	0.55%	0.36%
River slope within gap		0.13%	0.12%	0.45%	0.64%
River slope downstream of gap		0.3%	0.31%	0.52%	0.48%

2.3.3. Sediment Transport

Sediment supply is critical to create geomorphic forms such as bars and islands and to prevent incision. It allows the river to maintain the shifting habitat mosaic favored by salmonids and prevents disconnection of groundwater-surface water interactions. Water gaps may restrict the movement of sediment and the presence of infrastructure in the gap may intensify this effect. A quantitative appraisal of the amount and type of sediment flux through the Yakima and Naches systems will enhance our understanding of the effects of future development and river response.

A number of sediment transport studies have been conducted for the Yakima Basin to date. In the earliest study presented here, Dunne *et al.* (1976) examined the reach between the Selah and Union Gaps. Yakima River sediments are derived from mountains slopes, glacial sediments in the upper Yakima and Naches Basins, and valley floor alluvium dating from the Pliocene and Pleistocene Epochs. The river transports most of its sediment load as sand in suspension. The bedload of the river is comprised of coarse sand and gravel. The authors calculate sediment transport rates at 183,000 tons per year based on daily flows and suspended sediment recorded at Parker. The authors estimate bedload at 57,000 tons per year. Most of the total sediment transport occurs during the peak flows over the course of days, including the transport of clasts two to three feet in diameter. While total sediment load is not relatively high on the river (approximately 250,000 tons per year), the authors assert that obstruction of this process would result in channel filling and diversion.

Another study was conducted as part of the Reaches Project (Stanford *et al*., 2002), a collaboration between the Flathead Lake Biological Station of the University of Montana and the Central Washington University Department of Geography and Land Studies. The authors examined five reaches: Cle Elum, Kittitas, Wapato, Union Gap and Naches. The Union Gap Reach includes the gap and the river upstream about halfway to Selah Gap. The Naches reach includes the area from Rambler's Park Gap to the WTP. For the sediment transport portion of their study, the authors determined bed load flux rates for each reach. They began with calculating the quantities of sediment stored in the floodplain and in the channel bed and banks. They also estimated the amount of sediment available for transport in the bed and banks where there is high stream power. They then modeled sediment mobility based on particle size and bankfull discharge shear stress.

Sediment storage in the bed and banks of the river are important sources for geomorphic processes, even though it accounts for only 4 % of the total floodplain sediment on average. Bank erosion tends to account for roughly 40 year supply of sediment assuming bankfull discharge frequency of 1.5 years. While bank erosion is important on an annual time scale, it is less than one % of the total volume of sediment stored in the floodplain. Upstream sediment supplies are critical for channel complexity, groundwater interactions. They find that the reach between the Naches gaps and the Union Gap Reach of the Yakima have the lowest levels of sediment stored per kilometer of their study area. These reaches have a greater percentage of low relief para-fluvial (the scour zone between bankfull and low flow) zones rather than high terraces. However, these wide para-fluvial features provide a large mobile source of sediment that requires less bank erosion for movement than terraces. These reaches are more active as well; they have greater proportions of the historical floodplain that has been cut through to create contemporary channels. While the Kittitas and Cle Elum channels have not changed significantly from historical positions, the Union Gap and Naches reaches are in different locations. This may be a result of the availability of sediment. Where sediment supply is lower in the Cle Elum and Kittitas, the channels tend to incise. The Union Gap Reach alternates between segments of sediment transport and deposition. The reach between the Naches gaps primarily contains zones of sediment transport rather than supply or deposition. Its pattern of avulsion and scour of the para-fluvial zone requires a large sediment supply. In addition, many areas are highly mobile, providing sediment for the Union Gap Reach downstream.

Bed load transport is the main mechanism for volumetric flux and subsequent changes in channel morphology in gravel bed rivers. The authors examined bed load discharge during flood events where the geomorphic threshold for transport would be crossed, here estimated at 15,000 cfs for bankfull flow at Union Gap. Although the largest flood of record occurred in 1996, the greatest sediment transport occurred in 1971. Based on the 30-year record of the U.S. Geological Survey (USGS) flow gauge at Union Gap, most of the reaches have a bedload flux that represents about 30 % of the total available sediment, but at Union Gap it is 45 %. During long duration flood events above the threshold, the bed load flux will exceed the bank supply, leaving the reach dependent on upstream sediment supplies to maintain geomorphic surfaces. The volume of sediment moved by the larger flood may be underestimated because the model could not account for the increasing efficiency of transport and area of sediment source for larger floods. Stanford *et al*. estimate 555,361 cubic yards of daily bed load discharge for the 3 km study area. For the Naches reach, the reach flux is estimated at 29,862 cubic meters per day and 2,507 cubic meters per day per kilometer during bankfull discharge. In the Union Gap Reach, they estimate 151,763 cubic meters per day and 15,727 cubic meters per day per kilometer. The flux per river kilometer was greater in Union Gap than in any other reach studied because the para-fluvial zone is greater and the sediment mobility is high. They conclude that this reach exhibits the most fluvial activity.

In 2007, Hilldale proposed a BOR Technical Services Center sediment transport study of the reaches between Union and Selah Gaps and in the lower Naches River. This one-dimensional model would inform the plan to set back levees in the cities of Yakima and Union Gap in order to improve flood capacity, fish habitat, and natural fluvial processes while reducing erosion and flood elevations. The results would inform the positions and elevations of levees, the rehabilitation of gravel mine pits, and the location of City of Yakima's wastewater treatment plant outfall. The sediment transport model would produce data for the gap-to-gap reach in a number of areas: average annual sediment loads, comparison of the capacity to transport sediment in large and small floods, aggradation and degradation areas, areas of high erosion potential, and the type of floods that would exert high energy on the channel. Data requirements encompass information already collected by the BOR as well new data. Localized sediment transport and hydraulic studies will likely be needed for placement of the wastewater treatment outfall and numerous gravel mine pits.

The study would use existing data, such as aerial photographs from 2003; Light Detection and Ranging (LiDAR) from 2000, bathymetry for a portion of the Yakima reach, and bed material data from 2005. Additional data acquisition would extend the bathymetry survey further upstream and downstream on the Yakima and into the Naches. The model would require hydrology data for the USGS gage at Union Gap, the BOR's gage at Roza Dam, and additional hydrology data for the Naches. Additional bed material sample sites would need to be incorporated and sediment transport samples from USGS would need to be collected at the mouth of the Naches and at Selah Gap. Historical data can be used to calibrate and validate the model: bedload, suspended load, bed material, cross-sections, and a rating curve for downstream flow boundary condition.

In 2008, Mooney devised a sediment transport model as part of the Yakima River Basin Water Storage Feasibility Study for the BOR. The author analyzed a number of reaches of the Yakima and Naches Rivers for sediment loads; these figures are intended for use in the Ecosystems Diagnostic Treatment model and the USGS Decision Support System. Sediment loads were derived using the Sediment Impact Analysis Methods and were used to produce a number of parameters: gravel transport loads, redd scour, embeddedness, incipient motion threshold, flushing flow, and geomorphic work. Incipient motion estimates the flows required for bed material entrainment and geomorphic work summarizes the energy expended in mobilizing the sediment. The sediment transport calculation uses a daily flow record over a 20-year period along with bed material, and hydraulics. The models are run under a number of alternative flow release scenarios, the details of which are not included in the report. Sediment transport is averaged over the reach and can is used as a proxy for gravel motion. The author finds low rates of average annual sediment transport in most reaches of the Yakima River; periodic large flood events are responsible for most of the geomorphic work.

There are a number of limitations to this study. Absolute values from the model cannot be relied upon since they lack field calibration; results are to be used only for relative differences among scenarios and to a lesser degree, between reaches. The hydraulic model was not calibrated to the high flow water surface, so sediment loads may be underestimated. Uncertainty in inputs, particularly reference shear stress, creates load calculations which can vary by orders of magnitude. The 20-year record may not capture large events, e.g. those of a greater than 20-year recurrence interval. The study also fails to capture localized effects from spatial variability in bed material sizes and from channel form changes. The model is not able to assess the potential for aggradation and degradation, a key concept influencing the interaction between the gaps and infrastructure located therein.

3.0 Physical Description of Project Water Gap Reaches

Three project water gap reaches were identified to be included in a detailed geomorphic description of the four water gaps of interest. The project water gap reaches include the WTP Gap Reach, the Rambler's Park Gap Reach, and the Selah to Union Gap Reach (Figure 5). The boundaries of the river reaches for each gap were chosen based on the reach drainage divides and data extents used in their evaluation. The methodologies used to describe each reach are provided, followed by a description of each reach using the analyses performed.

3.1 Methods

Approaches used to describe the geomorphology of the three project water gap reaches are described here and are divided into several sections for each of the methods used. First, an overview of the data resources used for all of the analyses is provided. Second, the protocols for sub-reach delineation and cross-section location selection within each of the project water gap reaches are described. Third, a description is provided of the methods used to identify and delineate alluvial terraces formed within the Quaternary alluvium. And lastly, a description of the methods attempted and ultimately used to quantify geomorphic change associated with channel migration is presented.

3.1.1 Data Sources

Several data sources were utilized to complete detailed geomorphic descriptions of each project water gap reach. These sources included LiDAR topographic data, air photos, and digital vector datasets (Table 2).

Table 2 Data resources used in project water gaps descriptions

Raster datasets	Source	Date Acquired
LiDAR topography	Yakima County GIS	Oct 23, 2000
	Yakima County GIS	Aug 1-7 2008
Air Photos	Yakima County GIS	Oct & Nov 2000
	Yakima County GIS	June 27, 2008
Vector datasets	Source	
FEMA* flood boundary	Yakima County GIS	
Levee/Revetment Alignments	Yakima County GIS	
Surficial Geology	Wash. DNR	2005
Hydrology (Lines)	ENTRIX digitized	2008
Hydrology (Polygons)	ENTRIX digitized	2008
Transportation (roads, railroads)	WSDOT	

**Federal Emergency Management Agency*

All datasets were viewed and analyzed using ESRI ArcGIS 9.3 software with both Spatial and 3D Analyst extensions. All data were projected into Washington State Plane South coordinate system using the NAD 1983 datum (units of feet).

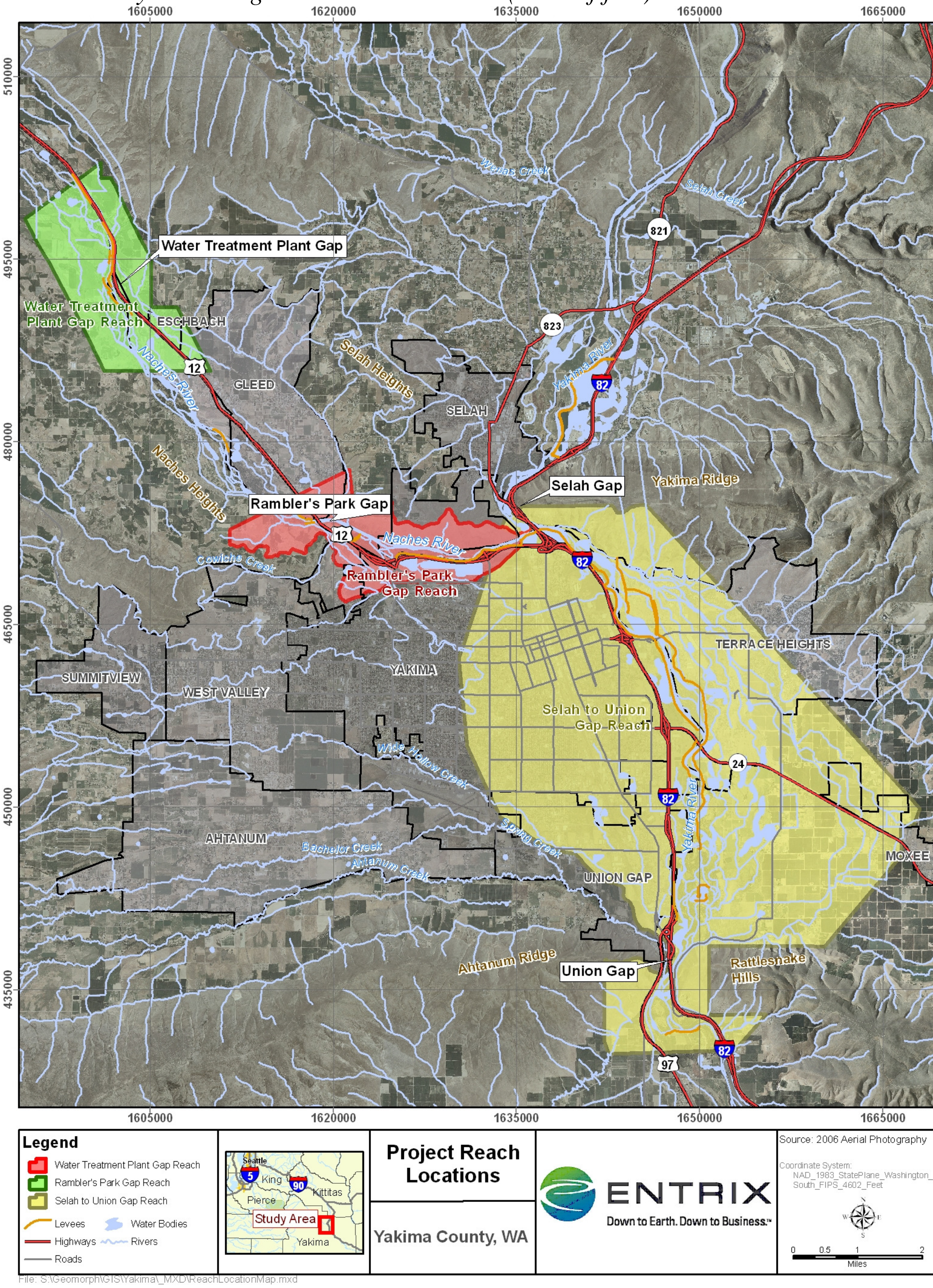


Figure 5 Locations of each project water gap reach.

3.1.2 Sub-Reach Delineation and Cross-Section Location Selection

Within each of the project water gap reaches, sub-reaches were delineated to divide the reaches into areas with similar hydrologic, hydraulic, geomorphic, and human impact regimes. Features used to delineate the sub-reach boundaries included the presence of tributary or diversion junctions, basin geometry (gaps), channel geometry (single vs. multi-channel), major road crossings, and the presence of levees/revetments. Similar length scales were used for each of the sub-reaches delineated to provide for more direct comparison.

Cross-sections were placed within each of the sub-reaches delineated to facilitate description and analysis for each of the sub-reaches. The locations of each cross-section were chosen to represent the range of conditions present within each of the project reaches and those which distinguish each sub-reach identified. Cross-sections were aligned to be perpendicular to the valley profile. A minimum of one cross-section was placed in each sub-reach, with a majority of sub-reaches having two or more cross-sections.

3.1.3 Alluvial Terrace Delineation

For each project water gap reach, terraces have formed in alluvial valley sediments by the migration and incision of the principal river (Naches or Yakima Rivers). The presence, number, distribution, and height of each terrace identified provides a useful tool to describe the geomorphology of each project reach. These parameters provide insight into the evolution of the river valley and the ability to project future change based on the observed trends. The impact of human alteration to the natural course of the river through forcing, using revetments and channelization, is highlighted and shows areas of induced instability.

The methods for terrace identification and delineation were adapted from Jones (2006) and are provided here. At each cross-section the boundary of the river water surface was located on the 2008 air photo. The nearest elevation point in the 2008 LiDAR dataset along the river water surface to the cross-section was selected and used as the river water surface elevation for the cross-section. This process was repeated for each of the cross-sections within the reach. The river water surface of each cross-section was added to the attributes of the cross-section GIS file and used to create a 3D GIS file with the river water surface as the "z" or elevation for each cross-section. The 3D GIS file was processed into a TIN and later a raster dataset that interpolated the river water surface elevation between the cross-sections. This resultant raster dataset of water surface elevation was subtracted from the 2008 LiDAR elevation dataset to create a new raster with values representing the height above the 2008 water surface (HAWS). A hillshade of the 2008 LiDAR dataset was produced to aid in identifying significant breaks in slope representing terrace boundaries. Manually placed cross-sections through these breaks in slope were generated to determine the range in HAWS values of each of the terraces present. These ranges were used to classify the HAWS raster by assigning unique color codes to each of the terraces identified.

3.1.4 Geomorphic Change Detection

Two methodologies were attempted in an effort to quantify the magnitude and distribution of topographic change as a result of channel migration and floodplain evolution within the project water gap reaches. One method attempted to utilize the two LiDAR topographic datasets (Table 2) to evaluate changes in topography. The other method used a digitized river water surface from each of the air photo datasets (Table 2) to infer topographic change. The limitations and assumptions of each method are provided to describe the ability of each in detecting change.

The first attempted method utilized the 2000 and 2008 LiDAR topographic datasets. These remotely sensed datasets provide highly accurate topography data for large areas, but have limitation to their use. These limitations include data density, relative accuracy between the datasets, and the inability of LiDAR to penetrate water surface (lack of bathymetric data). These limitations were evaluated at the WTP Gap Reach in an effort to determine the use of these datasets in detecting topographic change. A complete description of the evaluation performed is provided in Appendix 1. Briefly, it was found that interpolation errors between points related to data density, combined with the inconsistent relative accuracy between the datasets, resulted in spatially dependant error not readily correctable. In addition, the greatest amount of topographic change was found to be associated with channel migration, making quantification without bathymetric data limited.

Due to the limitations using the LiDAR datasets in detecting topographic change in this setting, a second approach was developed based on the observed river water surface from the 2000 and 2008 air photos. The river water surface was digitized for each of the project water gap reaches using the 2000 air photos, and again using the 2008 air photos. These two files were merged into a single file, and areas where water was present in both years were deleted. Areas where water was present in 2000 and not in 2008 were labeled "deposition". Areas where water was present in 2008 and not in 2000 were labeled "erosion". The governing assumption to this approach is that the discharge at the time the air photos were acquired is comparable, and that any increase or decrease in river water surface extent due to different discharges is minimal. The 2008 air photos were acquired June 27, 2008, and the Naches River gage near Naches, WA reported that day a daily average discharge of 2998 cubic feet per second (cfs). The Yakima River near Parker, WA reported a daily average discharge of 2103 cfs on June 27, 2008. The exact date of the 2000 air photos is unknown, but occurred during October and November 2000. The Naches River gage near Naches, WA reported daily average discharge values for October and November 2000 between 1811 and 88 cfs. The Yakima River gage near Parker, WA reported daily average discharge values for October and November 2000 between 2041 and 479 cfs. Observations comparing locations that remained topographically unchanged between 2000 and 2008 showed river water surface elevation was greater in 2008 than 2000. Much of where the increase in river water surface extent due to a higher discharge in 2008 occurred was limited to localized areas adjacent to the river water surface of low relief and some low-flow side channels. In addition to some locations returning a false erosion signal, others returned a false deposition signal. Abandoned channels due to upstream avulsion may return a false deposition signal because they would likely not be filled with sediment after the channel relocated. To the extent possible, these areas were omitted in the analysis.

3.2 Water Treatment Plant Gap Reach

The WTP Gap Reach on the Naches River (Figure 5) is approximately 3 miles long and stretches from 2 miles southeast of the town of Naches, WA to 1.5 miles northwest of Gleed, WA. SR 12 parallels the Naches River throughout the entire reach along the left bank of the river. The WTP is located within the natural constriction of the valley (WTP Gap) and is roughly in the middle of the WTP Gap Reach. A number of levees/revetments have been erected along the margins of the Naches River in several locations, primarily within the vicinity of the WTP and along SR 12. Adjacent to the river are cleared farm fields, pasture land, and to a lesser extent forested floodplain. A large inactive gravel pit exists immediately upstream and across the river from the WTP on the right bank floodplain of the Naches River.

The Naches River downstream from the confluence with the Tieton River occupies a northwest to southeast trending broad alluvial valley ranging from 1.75 mi to 0.75 mi across. The valley is at its widest approximately one mile southeast of the town of Naches, and at the town of Gleed. The valley narrows roughly halfway between Naches and Gleed, near the WTP on SR 12, to a minimum width of 0.75 mi. This natural constriction is the location of the WTP Gap. The southwestern valley wall is composed of the Pleistocene Tieton Andesite, with numerous landslide deposits present at the toe (DGER, 2005) (Figure 3). There are no major tributaries entering this part of the Naches valley from the southwest, and few minor ephemeral washes originating within the Tieton Andesite flow into the Naches valley. The northeastern valley wall is primarily composed of the Miocene Ellensburg Formation, with minor outcroppings of the Pomona member of the Miocene Saddle Mountains Basalt (a formation of the CRBG), and the Holocene-Pleistocene Palouse Formation. Several small alluvial fans are located along the base of the northeastern valley wall near the town of Naches. The northeastern valley wall is more dissected than the southwestern valley wall, with numerous small tributaries entering the valley. There are no major contributing tributaries from the northeastern valley wall. Very well defined discontinuous lateral terraces are present within the Quaternary alluvium on the valley floor representing historic floodplain elevations. As the Naches River has downcut through this alluvial fill over time, these remnants of previous floodplains are left abandoned along the valley margins (Figure 6).

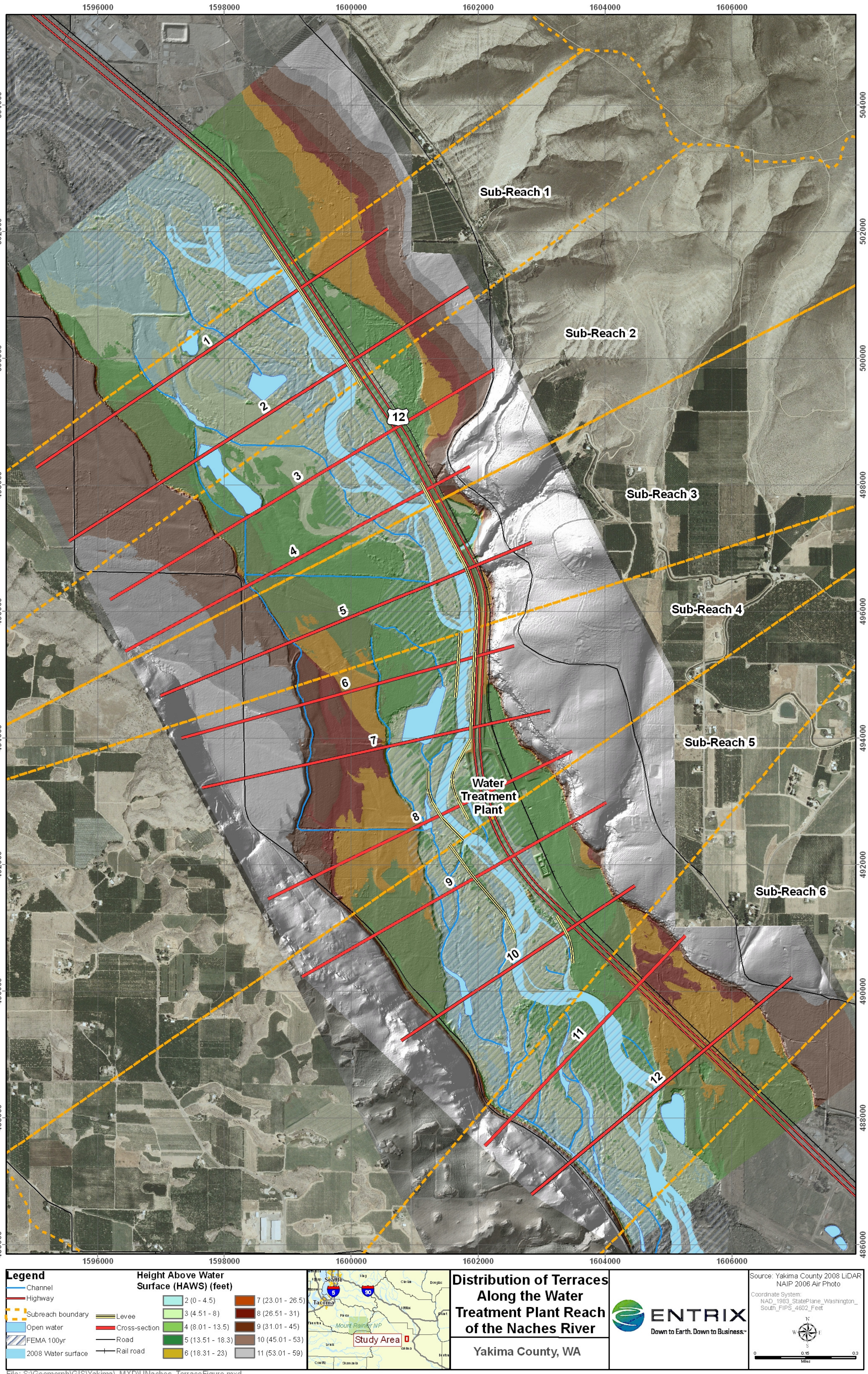


Figure 6 Distribution of Holocene alluvial terraces within the WTP Gap Reach on the Naches River.

3.2.1 Sub-Reach Delineation and Cross-Sections

A total of six sub-reaches were identified within the WTP Gap Reach. Sub-reach boundaries reflect the limits of influence from adjacent levees/revetments and locations of inlets/outlets of side channels (Figure 6). Twelve valley cross-sections were generated within the six sub-reaches, which represent the range of geomorphic, hydrologic, and anthropogenic influences present in each sub-reach. All of the valley cross-sections are presented in Appendix 2 of this report. Specific cross-sections are present in the subsequent discussions to facilitate description where applicable.

3.2.2 Alluvial Terrace Descriptions

Using the methods outlined in section 3.1.3 of this report, alluvial terraces were delineated within the WTP Gap Reach of the Naches River. Delineation was confined to the extent of the 2008 LiDAR dataset, which did extend to the non-alluvial margins of the valley except for within sub-reaches one and two. A total of ten different terraces were identified (Figure 6) and assigned a surface number ranging from two to eleven based on their vertical succession with the two surface (bankfull) the lowest elevation and eleven the highest terrace. The lowest surface (one) is represented by the water surface of the Naches River on June 27, 2008, the date of the air photos used to determine its extent. Table 3 presents a summary of the parameter defining each of the terraces identified. Terrace thicknesses ranged from 3.5 to 14 feet, and down-valley slopes ranged from 0.53 % (S_1, water surface) to 0.88% (S_{11}, the oldest and highest terrace). Surfaces 2 and 3 can be considered active floodplain based on historic channel locations and flood mapping.

Table 3 WTP Gap Terrace Description

Surface	HAWS* (ft)		Height/ Thickness (ft)	Down-Valley Slope (%)
	Max	Min		
1 (WS**)	-	-	-	0.53
2	4.5	0	4.5	0.65
3	8	4.5	3.5	0.76
4	13.5	8	5.5	0.77
5	18.3	13.5	4.8	0.54
6	23	18.3	4.7	0.62
7	26.5	23	3.5	0.84
8	31	26.5	4.5	0.64
9	45	31	14	0.67
10	53	45	8	0.79
11	59	53	6	0.88

* Height Above Water Surface (HAWS)
**WS is the water surface of the Naches River (Daily Ave. Discharge of 2997 cfs on 6/27/2008)

A series of terraces of decreasing elevation toward the center of the valley does indicate that throughout the Quaternary, the Naches River was a degrading system. Episodes of aggradation are likely to have occurred throughout this time period, however the long-term trend of the river is incision. The spatial distribution of terraces within the WTP Gap Reach (Figure 6) shows the presence and location of each terrace is variable, and is related to its position relative to the WTP Gap. The highest and oldest terraces (S_{11} through S_8) are confined to the valley margins and are present on the southwestern side of the valley upstream of the gap, and confined to the northeastern side of the valley downstream of the gap. Terraces S_7 through S_4 are present on both sides of the valley except from cross-section 10 to the end of the WTP Gap Reach along the southwestern side of the valley. Terraces S_3 and S_2 are present throughout the entire reach, however their widths appear to be largely controlled by their proximity to the gap, where their widths decrease dramatically.

Plotting the slope of each terrace reveals an interesting pattern of decreasing slope over time punctuated by periodic sharp increases (Figure 7). This pattern can be interpreted either as large sediment pulses entering the valley from upstream, that increased the gradient of the river (and thus the associated floodplain terraces), followed by subsequent erosion through the sediment pulse with a gradual decrease in slope as the sediment was evacuated. Alternative tectonic hypotheses that could result in this pattern include changes to the downstream base level of the Naches River due to subsidence of the Yakima Basin, or localized uplift within the headwaters of the Naches River. This pattern of episodic increases in gradient is likely due to sediment pulses entering the Naches Valley from upstream due to low frequency, high magnitude discharge events and/or landslides. The magnitude of slope change is approximately 0.3% for each of trend in decreasing slope, thus gradual evacuation of a sediment pulse is likely the cause of the pattern observed. However, given the proximity of Mount Rainier and Mount Adams, two active volcanoes, to the Naches River basin, it is possible this pattern is related to large influxes of sediment during eruptive periods. Attainment of absolute ages for each of the terraces identified would make correlation to known eruptions possible.

The absolute ages of the terraces of the Naches and Yakima was not available from the papers used for the best available science analysis. In other regions, such ages have been derived from radiocarbon dating and cosmogenic nuclides such as ^{10}Be and ^{26}Al, with additional correlations from ground-penetrating radar, sediment cores, and profiles at river cut-banks (Repka *et al.*, 1997). For example, the terraces at the Delaware Water Gap are at least 11,500 years old and have experienced landscape stability for up to 400 years at times (Bitting *et al.*, 2006). From such absolute dates one can also estimate deposition rates for the sediments in the terrace and further define and predict the processes at work.

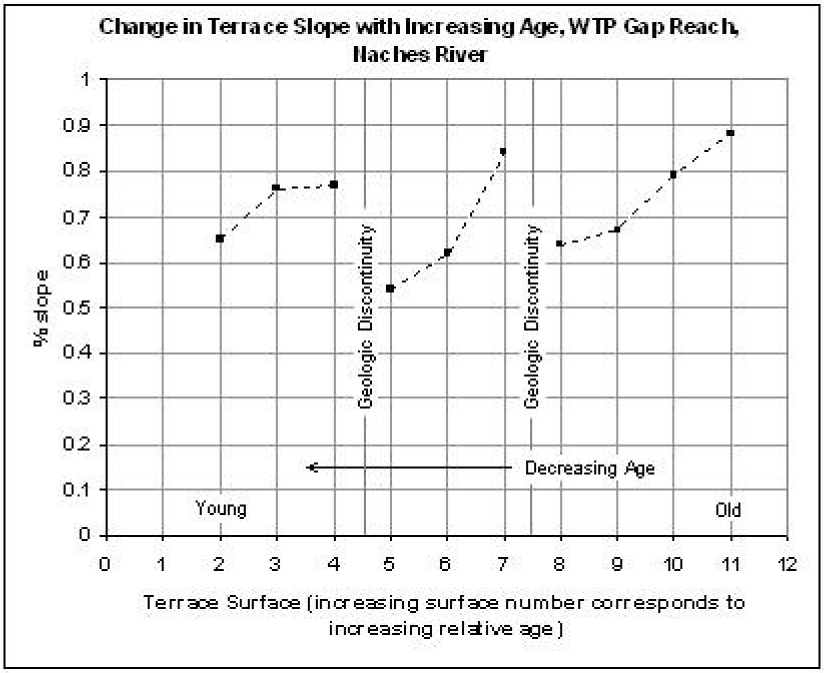


Figure 7 Patterns of changing terrace slope

The extent of the 100-year FEMA floodplain (hereafter referred to as the FEMA) does not correlate well with any of the terraces identified. Terraces S_2 through S_6 show at least partial inclusion within the FEMA, however it is largely confined to the S_2 and S_3 terraces. The FEMA extends beyond many of the levees/revetments identified within the Yakima County GIS dataset, primarily within the gap adjacent to the WTP.

3.2.3 Topographic Change Detection

Changes to the channel and floodplain geometry as a result of channel migration were evaluated by sub-reach using the methods outlined in section 3.1.4 of this report. Briefly, using the water surface extents from Oct-Nov 2000 and June 27, 2008, changes to channel location were evaluated. This was done assuming that locations where water was present in the 2000 air photo and not in the 2008 air photo experienced deposition, and locations where water was present in the 2008 air photo and not in the 2000 air photo experienced erosion. Care was taken to remove areas where the difference in surface water extent was the result of increased discharge. The erosion measured in this study is lateral erosion associated with channel migration; it should not be assumed that erosion equates to incision.

A table of the areas experiencing erosion and deposition, as well as the % slope of the Naches River by sub-reach is provided (Table 4). Sub-reach 4, where the WTP Gap is located, shows the least amount of geomorphic change. There is an increase in the amount of deposition from sub-reaches 1 to 3 leading up to the gap, and an increase in the amount of deposition from sub-reaches 5 to 6 moving downstream of the gap. A similar trend is present in the amount of erosion and net change, increasing from sub-reaches 1 to 3 and 5 to 6. These observations clearly indicate river channel dynamics are most pronounced immediately upstream from the gap and with increasing distance downstream from the gap. The long term storage of sediment immediately upstream of the gap is corroborated by the lower river slope and increase in depositional locations. However the current trend of the river is active removal of this wedge of sediment, which is reflected in the high amounts of erosion taking place in sub-reach 3. As the wedge of sediment upstream of the gap is removed and transported downstream, it appears to migrate through the gap readily and into reaches 5 and 6. The river slope within the gap sub-reach (4) is significantly higher than the surrounding sub-reaches (3 and 5). Typically gaps form in bedrock ridges with alluvial valleys on either side. The bedrock reach within the gap acts as a natural grade control on the river, thus one would expect the slope through the gap to be less than that up and downstream. This increase in slope through the gap is not expected, and is likely because the WTP Gap is formed in alluvium. In addition, the presence of levees/revetments on either side of the river through much of this reach likely contributes to the higher river slope through the gap. Long term storage of sediment appears to have taken place immediately downstream of the gap in sub-reach 5 due to its low river slope and diminished sediment transport capacity. However much like upstream of the gap, the current trend of the river is active removal of this wedge of sediment. These findings correlate with other studies in the area, which characterize the Naches River as dynamic and actively migrating across the floodplain (Stanford *et al*., 2002; Molash and McGuire, 2008; TetraTech/KCM, Inc., 2003; Park, 2008).

Table 4 Topographic change within the WTP reach of the Naches River

Sub-reach	River Slope (%)	Erosion		Deposition		Net Change	
		Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)
1	0.64	0.51	7.6	0.02	0.2	-0.50	-7.4
2	0.67	2.31	27.2	0.12	1.4	-2.19	-25.9
3	0.46	1.9	29.4	0.14	2.2	-1.76	-27.2
4 (Gap)	0.64	0.19	1.8	0.01	0.1	-0.18	-1.7
5	0.39	1.71	14.8	0.44	3.9	-1.27	-11
6	0.48	4.05	37.4	1.30	12	-2.75	-25.4
Total	0.53 (avg)	10.68	19.6	2.03	3.7	-8.64	-15.9 (avg)

3.2.4 Natural and Anthropogenic Confinement

Both natural and anthropogenic controls influence the geometry of the Naches River and its floodplain. Channel confinement (the ratio of valley width to active channel width) was used to demonstrate the contributing effects of both natural and anthropogenic controls on the Naches River system geometry. For each of the cross-sections generated within the reach, the bankfull width (S_2 surface), the width of the FEMA, and the width of surfaces S_1 (2008 water surface) through S_4 (S_1-S_4) were calculated. Two widths were calculated for the bankfull and S_1-S_4 surfaces, one accounting for the presence of levees, and one not. These values were used to calculate the confinement of the bankfull channel with respect to the FEMA, and with respect to the natural accessible floodplain (S_1-S_4) identified from the terrace delineation. Terrace surfaces S_1-S_4 were interpreted to have historically conveyed floodwaters of similar magnitude to a 100-year flood, and represent the potential extent of such flooding under completely natural conditions. Figure 8 shows the downstream trend of both the natural (N/N) and anthropogenic (L/L) confinement.

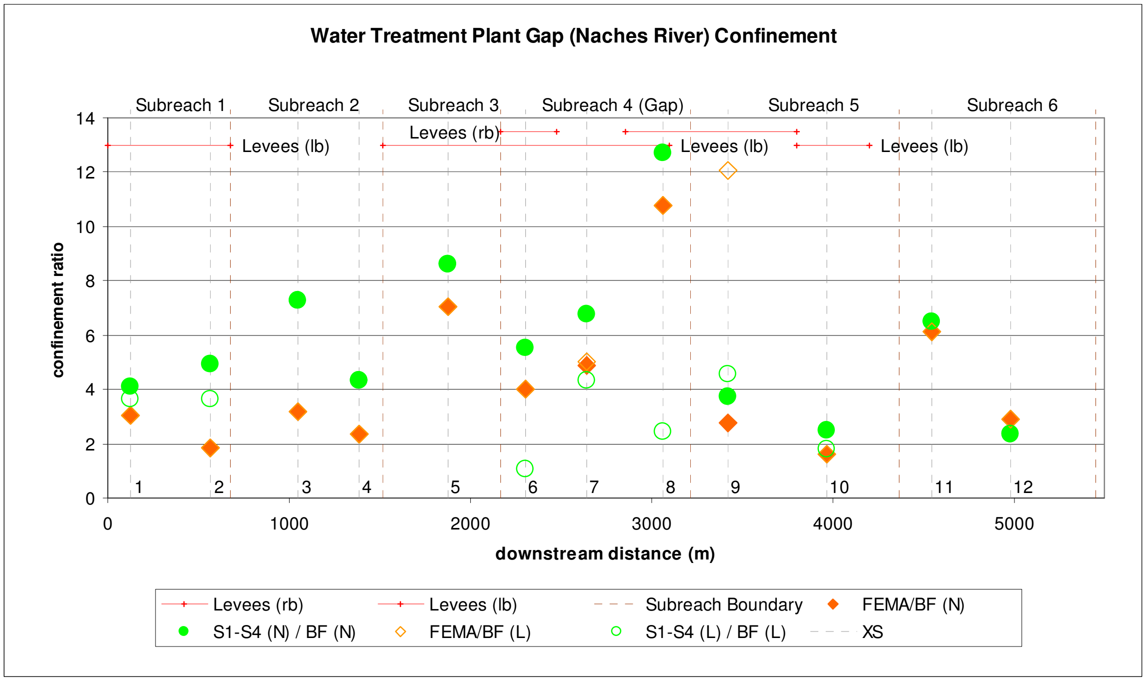


Figure 8 Confinement within the WTP Reach of the Naches River. (L represents the width accounting for the presence of levees, and N does not) BF represents the bankfull width. Cross-section numbers are above the X-axis of the chart (see Figure 6 for locations)

The gap, located in sub-reach 4, is not well defined by the confinement of the bankfull channel or either the FEMA or S_1-S_4 surfaces. The confinement defined by the S_1-S_4 surfaces is less than that defined by the FEMA for all but one of the cross-sections (12). The effect of increasing floodplain confinement due to the presence of levees is apparent for sub-reaches 1-4. The S_1-S_4 surfaces clearly show an increase in confinement due to the presence of levees in these sub-reaches. However the presence of levees does not impact the FEMA confinement within these sub-reaches. This indicates the bankfull channel width is not impacted by the levees within sub-reaches 1-4, but the floodplain is. There is a dramatic increase in confinement for both the S_1-S_4 surfaces and FEMA transitioning from sub-reach 4 to 5. This increase in confinement is driven largely by an increase in the bankfull width, and not a decrease in the floodplain width. At cross-section 9 the confinement is dramatically less when accounting for the levee located along the right bank of the river. This levee effectively isolates the river from the lowest part of the southwest valley floor, and forces it through the higher floodplain (Figures 6 and 5). The course of the river remains isolated from the lowest part of the valley floor downstream of the levee, and remains there through the remainder of the WTP Gap Reach. Figure 9 depicting cross-section 11 clearly shows the isolation of the contemporary channel from the lowest part of the valley floor due to the levee upstream. The isolation of this lowest part of the valley below the bankfull elevation is reflected in the decrease in confinement when the levees are accounted for at cross-section 9. The decrease in confinement is due to the reduction of bankfull width due to the levee.

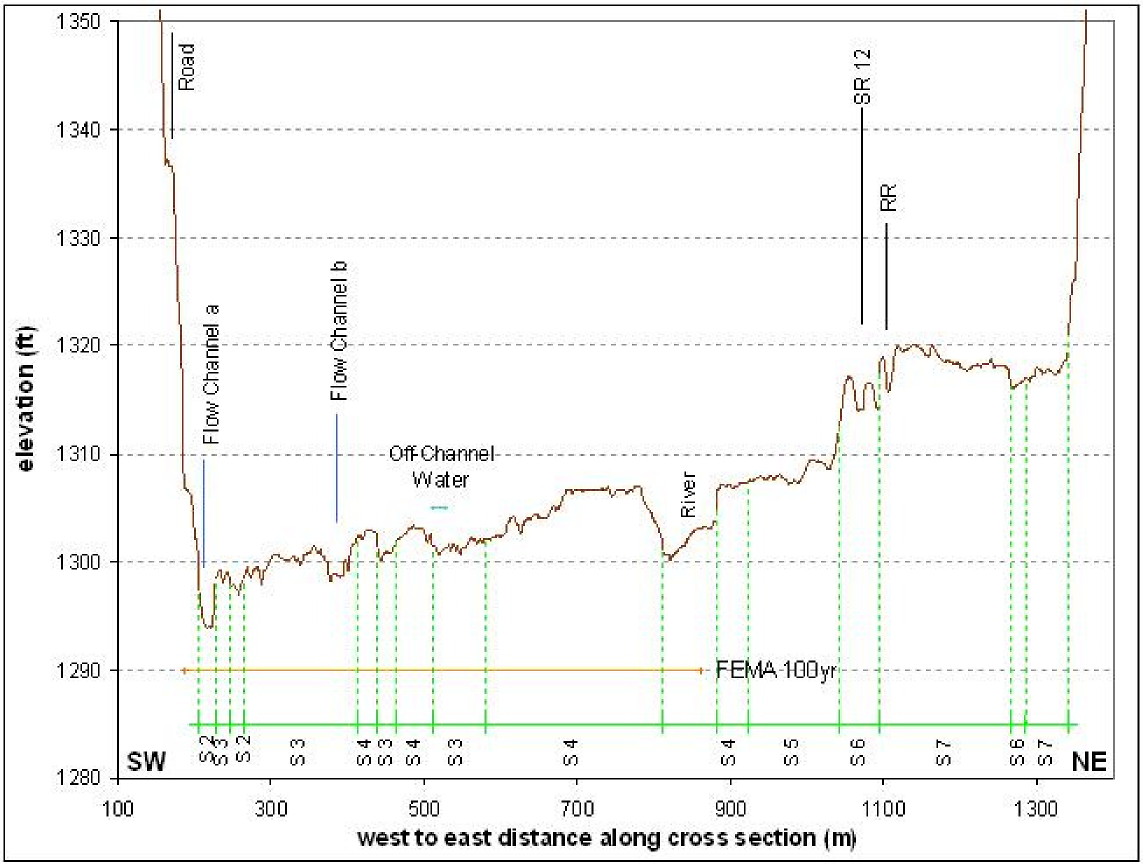


Figure 9 Cross-section 11 through sub-reach 6. Cross-section is looking upstream. The 2008 river channel is located in surface S_4 in the middle of the valley. Note the river is currently situated well above its floodplain to the southwest.

The ratio of the width of the S_1-S_4 surfaces accounting for the levees (L), to the width of the S_1-S_4 surfaces without the levees (N) are presented in Figure 10. The width of the bankfull channel accounting for the levees (L) to the bankfull channel width without the levees (N) is provided as well. A ratio of 1 means there is no levee present, or there is no impact to the width of the surface due to the presence of the levee. The degree to which the levees impact the natural widths of the S_1-S_4 surfaces and the bankfull channel is clearly illustrated (Figure 10), where the lower the ratio calculated the greater the impact. This figure clearly illustrates the impact of the levees to the S_1-S_4 surface width, especially in locations where both banks of the river have levees. The impact to the bankfull channel is shown to be less, except at cross-section 9 as described above. Both the S_1-S_4 surfaces and the bankfull channel are not impacted by the levee present at cross-section 5, where the mapped levee is at the toe of SR 12 outside of the floodplain.

Despite these effects, anthropogenic effects have not diminished channel length significantly and this floodplain is not as simplified or confined as other reaches in the central Yakima Basin (Eitemiller *et al*., 2002).

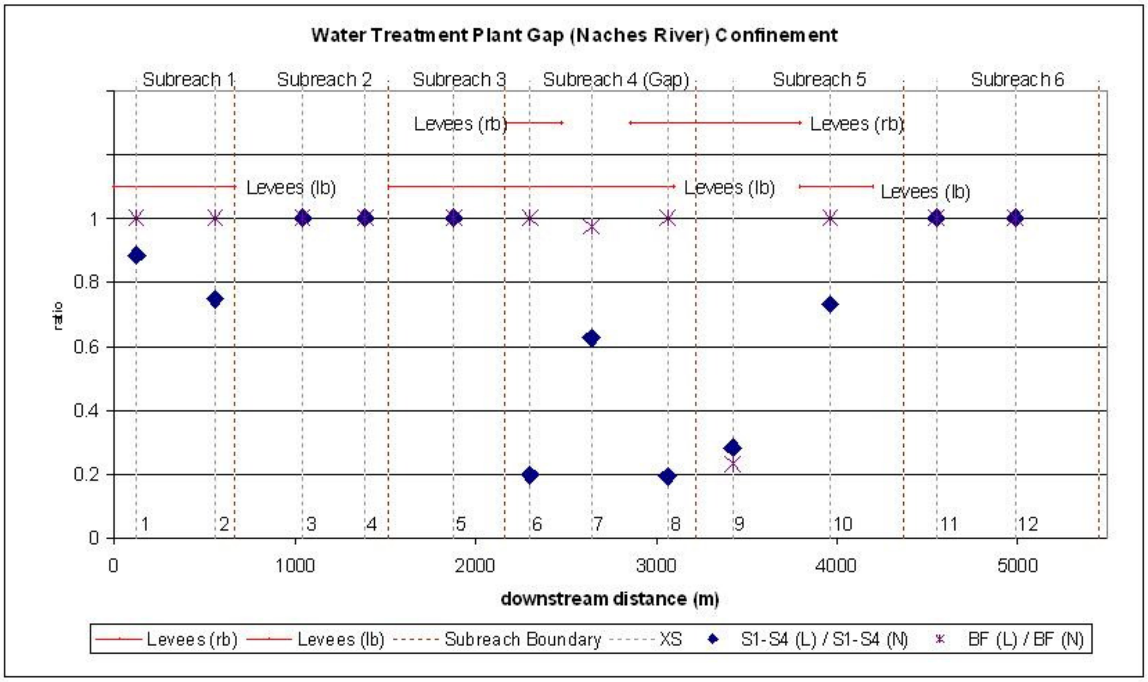


Figure 10 Impact of levees to the S_1-S_4 surface and bankfull channel (BF). (L represents the width accounting for the presence of levees, and N does not) Cross-section numbers are depicted above the x-axis.

3.3 Rambler's Park Gap Reach

The Rambler's Park Gap Reach on the Naches River (Figure 5) is approximately 4 miles long and stretches from the confluence with the Yakima River to the West Powerhouse Road exit on SR 12. SR 12 parallels the right bank of the Naches River throughout much of the reach, until is crosses the river on the upstream end of Rambler's Park Gap. A number of levees/revetments have been erected along the margins of the Naches River in several locations, primarily along the right bank of the river where it parallels SR 12, and on the left bank of the river upstream of Rambler's Park Gap. The levee has not been able to prevent flooding on several occasions, including a significant event in 1996 (TetraTech, 2003). Through the gap and downstream, the river is located between the base of the western end of Yakima Ridge and SR 12, in Fruitvale, WA. Upstream of the gap the reach extends into the Naches River Valley, where the river runs along the base of the southwestern valley wall.

Rambler's Park Gap is where the transition from the Naches River Valley to the Yakima River Valley occurs (Figure 11). The downstream end of the Naches River Valley immediately before Rambler's Park Gap, is filled with Quaternary sediments with a series of Holocene terraces along the valley margin. The southwestern valley wall is comprised of the Pleistocene Tieton Andesite, and the northeastern valley wall is comprised of the Miocene Ellensburg Formation. Through the gap the width of Quaternary alluvium decreases and the Holocene terraces are limited to the southwestern valley margin. The northeastern valley wall is comprised of the Miocene Frenchman Springs Member of the Wanapum Basalt and Grande Ronde Basalt. The Tieton Andesite forms the southwestern valley wall of the gap north of the Cowiche Creek, and the Miocene Ellensburg Formation overlies the Miocene Wanapum Basalt (a formation in the CRBG) south of Cowiche Creek. Downstream of the gap the Naches River enters the Yakima basin, where the southern boundary of the Naches River drainage basin is formed along a ridge of Pleistocene-Holocene terraces. The northern valley wall is formed by the Miocene Frenchman Springs Member of the Wanapum Basalt and Grande Ronde Basalt. Several small ephemeral drainages enter the Naches River from both valley walls, though are more abundant from the northern valley wall. Cowiche Creek (76,630 ac drainage area) represents a major tributary to the Naches River within this reach, and enters the river at Rambler's Park Gap.

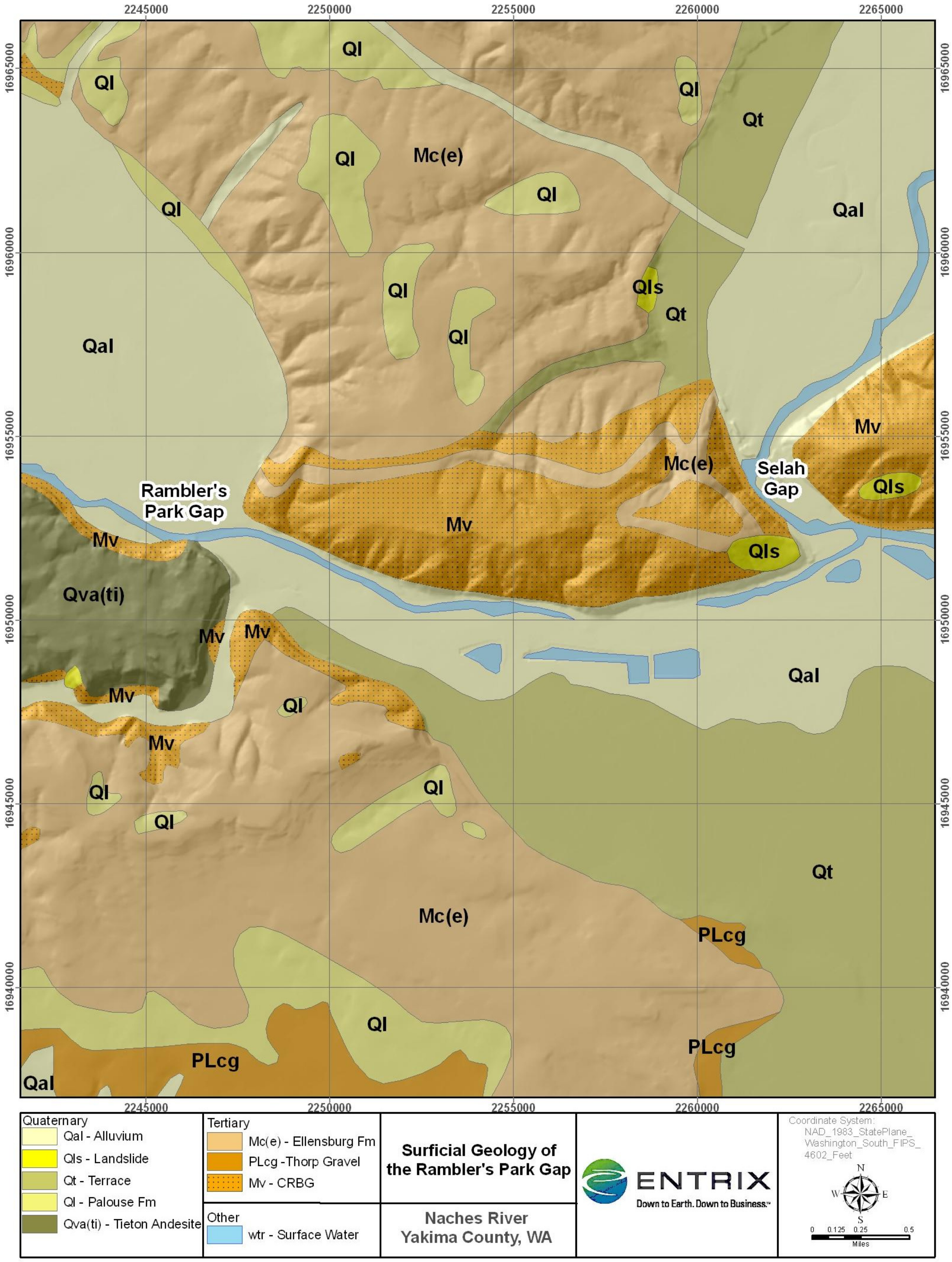


Figure 11 Surface Geology of the Rambler's Park Gap on the Naches River. Note the outcrops of the CRBG (Mv) on the north valley wall at the gap. Geology data provided by Yakima County.

3.3.1 Sub-Reach Delineation and Cross-Sections

A total of six sub-reaches were identified within the Rambler's Park Gap Reach. Sub-reach boundaries reflect the limits of influence from adjacent levees/revetments and locations of inlets/outlets of side channels (Figure 12). Eleven valley cross-sections were generated within the six sub-reaches, which represent the range of geomorphic, hydrologic, and anthropogenic influences present in each sub-reach. All of the valley cross-sections are presented in Appendix 2 of this report. Specific cross-sections are present in the subsequent discussions to facilitate description where applicable.

3.3.2 Alluvial Terrace Descriptions

Using the methods outlined in section 3.1.3 of this report, alluvial terraces were delineated within the Rambler's Park Gap Reach of the Naches River. Delineation was confined to the extent of the 2008 LiDAR dataset, which did extend to the non-alluvial margins of the valley. A total of seven different terraces were identified (Figure 12) and assigned a surface number ranging from two to seven based on their vertical succession with the two surface (bankfull) the lowest elevation and seven the highest terrace. The lowest surface (one) is represented by the water surface of the Naches River on June 27th 2008, the date of the air photos used to determine its extent. Table 5 presents a summary of the parameter defining each of the terraces identified. Terrace thicknesses ranged from 3.5 to 7.5 feet, and down-valley slopes ranged from 0.41 % (S_7, the oldest and highest terrace) to 0.64% (S_2, the bankfull channel).

Table 5 Rambler's Park Gap Terrace Description

Surface	HAWS* (ft)		Height/ Thickness (ft)	Slope (%)
	Max	Min		
1 (WS**)	-	-	-	0.49
2	4	0	4	0.64
3	8	4	4	0.60
4	12	8	4	0.33
5	15.5	12	3.5	0.60
6	23	15.5	7.5	0.58
7	26	23	3	0.41

* Height Above Water Surface (HAWS)
**WS is the water surface of the Naches River (Daily Ave. Discharge of 2997 cfs on 6/27/2008)

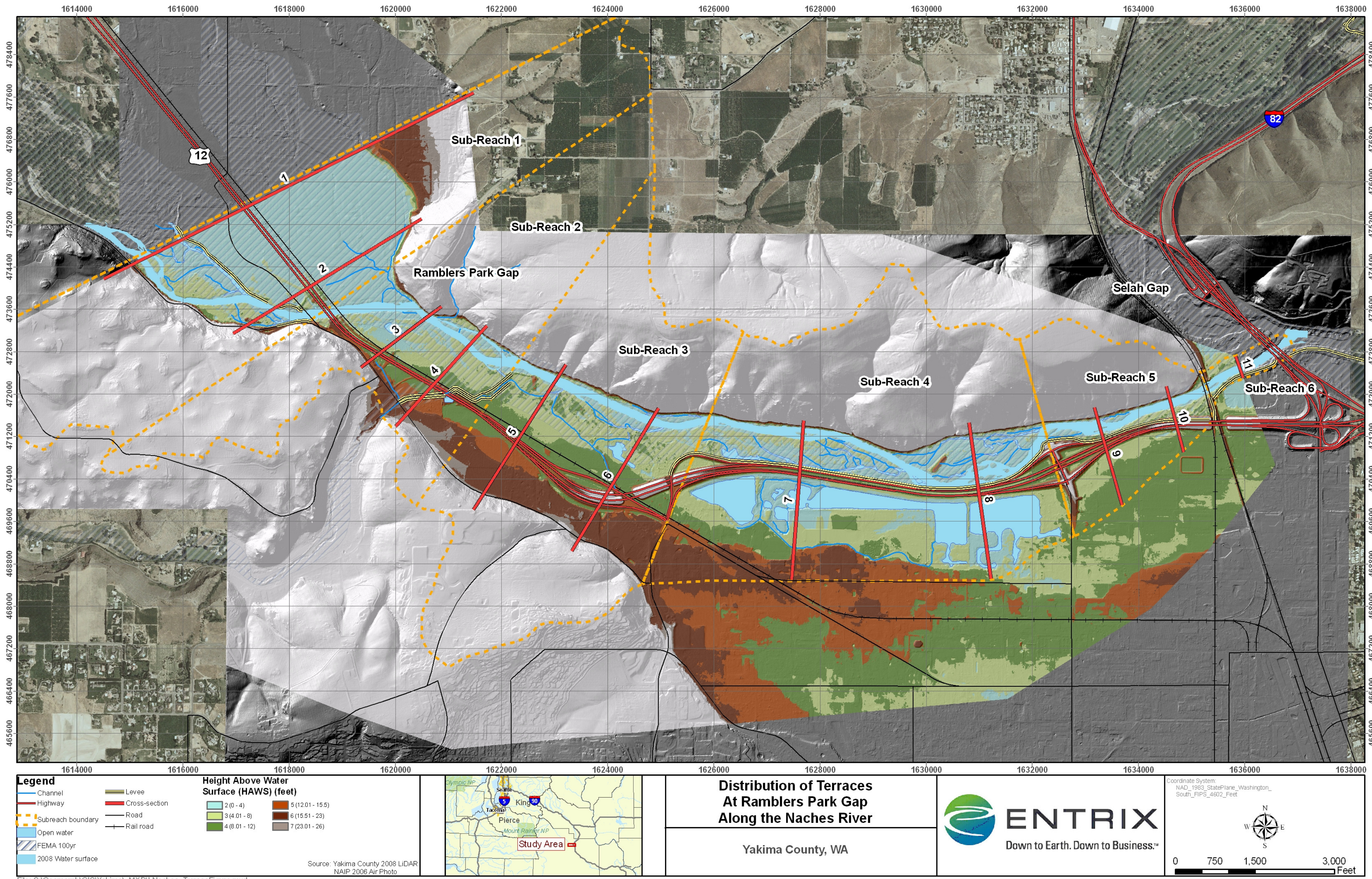


Figure 12 Distribution of Holocene alluvial terraces within the Rambler's Park Gap Reach on the Naches River.

A series of terraces of decreasing elevation toward the center of the valley does indicate that throughout the Quaternary, the Naches River was a degrading system through the Rambler's Park Gap Reach. Episodes of aggradation are likely to have occurred throughout this time period, however the long-term trend of the river is incision. The spatial distribution of terraces within the Rambler's Park Gap Reach (Figure 12) shows the presence and location of each terrace is variable, and is related to its position relative to Rambler's Park Gap. The highest and oldest terraces (S_7 through S_5) are confined to the valley margins and are present on the northeastern side of the valley upstream of the gap, and confined to the southern side of the valley downstream of the gap. Terraces S_4 and S_3 extend into the valley from terraces S_7 through S_5 and are present on the southwestern side of the valley upstream of Rambler's Park Gap, and form the southern watershed boundary of the Naches River downstream of the gap. Terraces S_3 and S_2 are present throughout the entire reach, however their widths appear to be largely controlled by their proximity to the gap. Upstream of the gap the S_2 (bankfull channel) occupies much of the valley bottom. Through the gap (sub-reaches 2 and 3) the S_2 width decreases dramatically while the S_3 width increases. At sub-reach 4 the S_2 width again increases, occupying much of the active channel between the right bank levee and the toe of the Yakima Ridge. The active channel is further confined in sub-reaches 5 and 6 before the junction of the Naches River with the Yakima River.

Plotting the % slope of each terrace reveals a pattern of increasing slope over time punctuated by periodic sharp decreases (Figure 13). Two sequences of increasing slope are present, from S_7 to S_5 and from S_4 to S_2. From S_7 to S_5 the slope increases approximately 0.2 % and the slope increases approximately 0.3% from S_4 to S_2. The contemporary Naches River slope is 0.13% less than the S_2 (bankfull) surface. The transition between these two sequences of increasing slope occurs between S_5 and S_4. This same transition, from S_5 to S_4, at the WTP Gap (Figure 7) reach marks the break in sequences of decreasing slope from S_7 to S_5, and from S_4 to S_1.

It is important to note that the terrace slopes for the Rambler's Park Gap Reach were calculated on terraces within and downstream of the gap. This is significant when interpreting the sequences of increasing slope. The hypothesis posited for the WTP Gap Reach was a series of sediment pulses entering the system from upstream, resulting in punctuated increases in slope, followed by a steady decrease as the sediment is eroded. Due to the natural constriction of the river valley through Rambler's Park Gap, large volumes of sediment are likely to have been stored upstream of the gap as the sediment pulse was eroded at the WTP Gap Reach. This storage of sediment upstream of the gap would result in an increase in slope of the river through and downstream of the gap. The reduction in sediment supply due to storage upstream of the gap would result in increased sediment transport capacity downstream of the gap, resulting in incision and increasing slopes. The decrease in slope during the transition from S_5 to S_4 would need to be of sufficient duration that the wedge of sediment stored upstream of the gap could be evacuated.

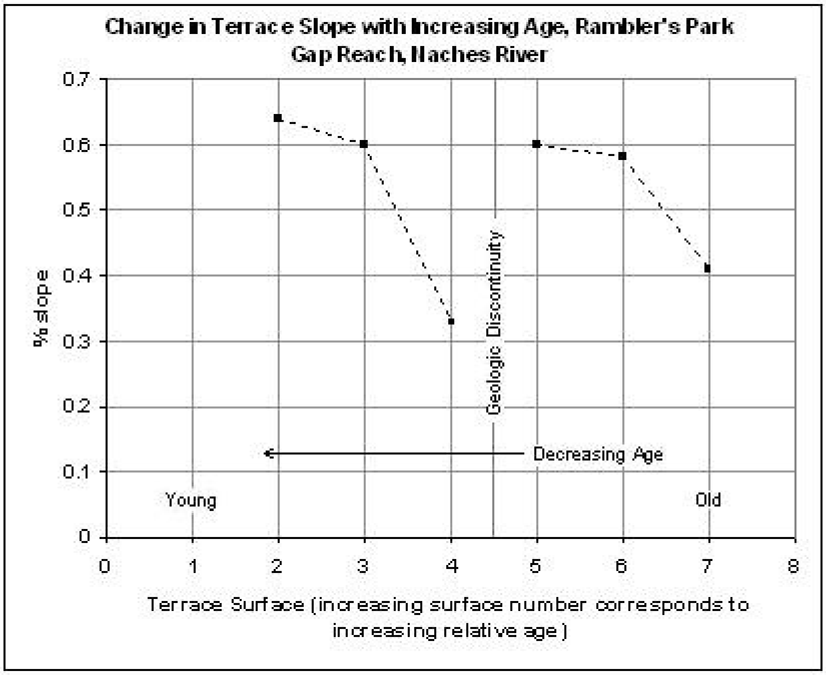


Figure 13 Patterns of changing terrace slope

The extent of the FEMA does not correlate well with any of the terraces identified. Terraces S_2 through S_6 show at least partial inclusion within the FEMA, however it is largely confined to the S_2 and S_3 terraces. The FEMA extends beyond the levees/revetment identified within the Yakima County GIS dataset along the left bank of the Naches River upstream of Rambler's Park Gap. Downstream of the gap the FEMA is largely confined by the Yakima Ridge to the north, and levees/revetments to the south. Where levees are not present the FEMA boundary is more closely aligned with the extent of the S_3 surface.

3.3.3 Topographic Change Detection

Changes to the channel and floodplain geometry as a result of channel migration were evaluated by sub-reach using the methods outlined in section 3.1.4 of this report. Briefly, using the water surface extents from Oct-Nov 2000 and June 27, 2008, changes to channel location were evaluated. This was done assuming that locations where water was present in the 2000 air photo and not in the 2008 air photo experienced deposition, and locations where water was present in the 2008 air photo and not in the 2000 air photo experienced erosion. Care was taken to remove areas where the difference in surface water extent was the result of increased discharge. The erosion measured in this study is lateral erosion associated with channel migration, it should not be assumed that erosion equates to incision.

A table of the areas experiencing erosion and deposition, as well as the % slope of the Naches River by sub-reach is provided (Table 6). Sub-reaches 2 and 3, where Rambler's Park Gap is located, and sub-reach 6, immediately upstream of the confluence with the Yakima River, show the least amount of geomorphic change. Sub-reaches 1 and 4, immediately upstream and downstream of the gap respectively, are the most dynamic sub-reaches within Rambler's Park Gap Reach. These sub-reaches account for 83% of the total erosion and 85% of the total deposition throughout the entire reach. Sub-reaches 5 and 6 show very little to no change, even less than through the gap, and is likely due to the high level of confinement from levees, which have effectively fixed the channel in-place. The slope of the Naches River decreases 0.1% as it enters Rambler's Park Gap from sub-reach 1, remains constant through the gap, increases approximately 0.05% through sub-reaches 4 and 5, and decreases 0.25% from sub-reach 5 to 6 immediately upstream of the confluence with the Yakima River.

Table 6 Topographic change within the Rambler's Park Gap Reach of the Naches River

Sub-reach	River Slope (%)	Erosion		Deposition		Net Change	
		Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)
1	0.55	1.87	15.2	0.77	6.2	-1.10	-9
2 (Gap)	0.45	0.45	3.6	0.18	1.4	-0.27	-2.2
3 (Gap)	0.46	0.15	1.3	0.00	0.0	-0.15	-1.3
4	0.50	2.41	11.2	1.29	6	-1.12	-5.2
5	0.52	0.29	2.9	0.19	1.9	-0.10	-1
6	0.27	0.00	0.0	0.00	0.0	0.00	0.0
Total	0.49 (avg)	5.17	7	2.43	3.3	-2.75	-3.7

3.3.4 Natural and Anthropogenic Confinement

Both natural and anthropogenic controls influence the geometry of the Naches River and its floodplain. Channel confinement (the ratio of valley width to active channel width) was used to demonstrate the contributing effects of both natural and anthropogenic controls on the Naches River system geometry. For each of the cross-sections generated within the reach, the bankfull width (S_2 surface), the width of the FEMA, and the width of surfaces S_1 (2008 water surface) through S_3 (S_1-S_3) were calculated. Two widths were calculated for the bankfull and S_1-S_3 surfaces, one accounting for the presence of levees, and one not. These values were used to calculate the confinement of the bankfull channel with respect to the FEMA, and with respect to the natural accessible floodplain (S_1-S_3) identified from the terrace delineation. Terrace surfaces S_1-S_3 were interpreted to have historically conveyed floodwaters of similar magnitude to a 100-year flood, and represent the potential extent of such flooding under completely natural conditions. Figure 14 shows the downstream trend of both the natural (N/N) and anthropogenic (L/L) confinement.

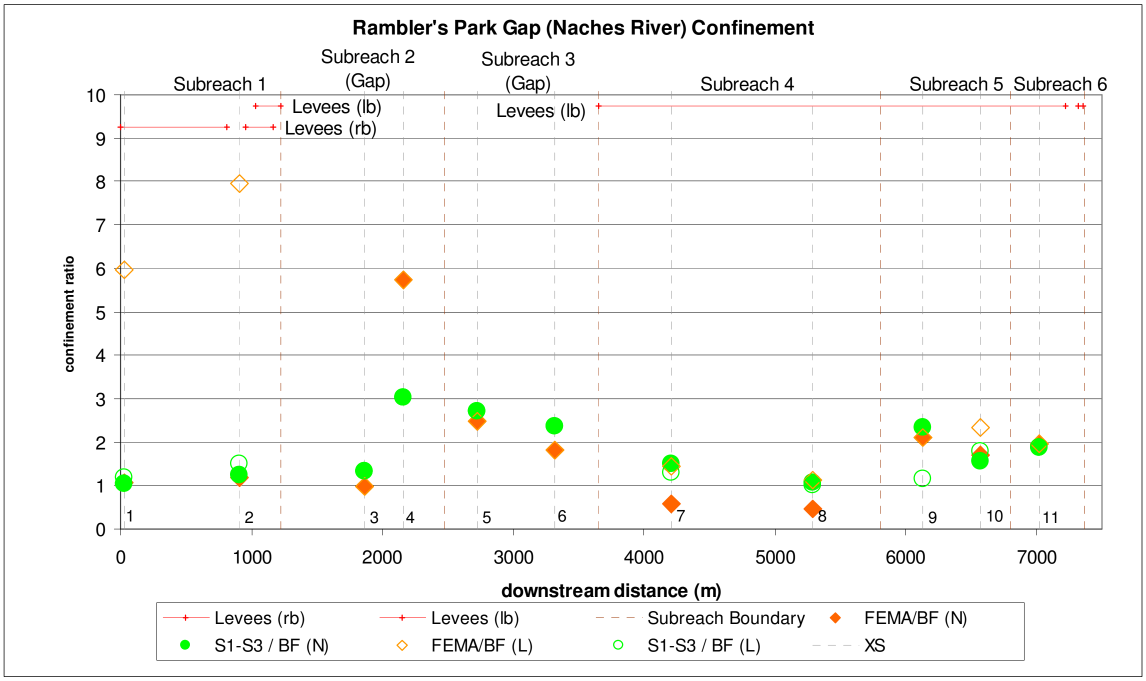


Figure 14 Confinement within the Rambler's Park Gap Reach of the Naches River. (L represents the width accounting for the presence of levees, and N does not) BF represents the bankfull width.

The gap, located in sub-reaches 2 and 3, is not well defined by the confinement of the bankfull channel or either the FEMA or S_1-S_4 surfaces. The confinement defined by the S_1-S_3 surfaces is less than that defined by the FEMA for all cross-sections except 4. At cross-section 4 the FEMA occupies much of the S4 surface, resulting in less confinement. The effect of increasing floodplain confinement due to the presence of levees is not apparent except at cross-section 9. The S_1-S_3 surfaces clearly show an increase in confinement due to the presence of levees at cross-section 9. The effect of the levees decreases the confinement of the FEMA at all cross-section except for at cross-sections 9 and 11. This indicates that the bankfull channel is partially isolated due to the presence of levees at most locations where levees are present. The greater the decrease in the confinement ratio of the FEMA/BF (L) versus the FEMA/BF (N), the greater the amount of bankfull channel isolation.

The ratio of the width of the S_1-S_3 surfaces accounting for the levees (L), to the width of the S_1-S_3 surfaces without the levees (N) are presented in Figure 15. The width of the bankfull channel accounting for the levees (L) to the bankfull channel width without the levees (N) is provided as well. A ratio of 1 means there is no levee present, or there is no impact to the width of the surface due to the presence of the levee. The degree to which the levees impact the natural widths of the S_1-S_3 surfaces and the bankfull channel is clearly illustrated in Figure 15, where the lower the ratio calculated the greater the impact. The greatest impact to both the S_1-S_3 surfaces and the bankfull channel are within sub-reaches 1 and 4, the same sub-reaches found to be the most active in section 3.3.3. The impact of the levees to the S_1-S_3 surfaces decreases downstream in sub-reaches 5 and 6, and is 1 at cross-section 6. This is likely due to the narrowing of the watershed boundary as the river traverses the Yakima River floodplain (Figure 12).

Under natural conditions the Naches River would have a hydrologic connection to the Yakima River floodplain here. This connection was significantly reduced in the twentieth century by the infrastructure built to support the construction of the dams in the Naches Basin and later by the expansion of SR 12 (Eitemiller, *et al*., 2002).

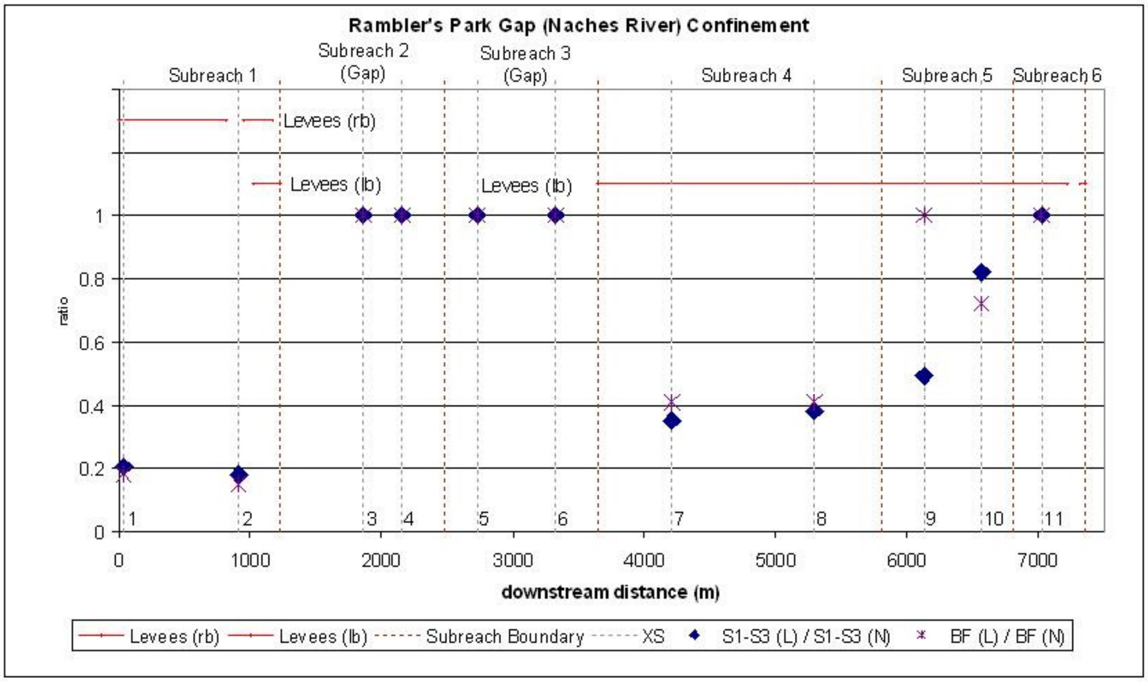


Figure 15 Impact of levees to the S_1-S_3 surface and bankfull channel (BF). (L represents the width accounting for the presence of levees, and N does not)

3.4 Selah Gap to Union Gap Reach

The Selah Gap to Union Gap Reach on the Yakima River (Figure 5) is approximately 11 miles long and stretches from the upstream end of Selah Gap to Parker Bridge Road, south of Union Gap. I 82 parallels the Yakima River along the entire reach on the right bank between the gaps, and on the left bank through the gaps and downstream of Union Gap. A number of levees/revetments have been erected along both banks of the Yakima River, primarily between the gaps in the towns of Yakima and Union Gap, WA. The Yakima River enters Selah Gap, formed within the Yakima Ridge, and enters the Yakima Valley near the intersection of SR 12 and I 82. The river flows southeasterly through the northern half of the Yakima Valley, and southerly through the southern half of the valley. Immediately south of the intersection of I82 and US 97 the Yakima River enters Union Gap, which is bounded by the Rattlesnake Hills to the east and Ahtanum Ridge to the west. Wapato Dam is located on the Yakima River at the downstream end of Union Gap. The river flows to the east downstream of the dam until it reaches I 82, where it flows south-southeast.

Selah Gap forms the transition between the Selah and Yakima Valleys (Figure 16). The gap is formed in the Yakima Ridge, which is comprised primarily of Miocene basalts.

Quaternary sediments make up the floor of the gap between the basalt walls of the Yakima Ridge. The Yakima Valley is comprised of Quaternary alluvium adjacent to the Yakima River. The width of this alluvium increases to the south from approximately 0.5 miles across downstream of Selah Gap, to approximately 1.5 miles across upstream of Union Gap. Within this Quaternary alluvium are a series of Holocene terraces. A series of older Pleistocene-Holocene terraces bound the Quaternary alluvium on either side of the Yakima River. The Miocene Ellensburg Formation, Pliocene Thorp Gravel, and Holocene-Pleistocene Palouse Formation are present on the eastern side of the Yakima Valley between the Pleistocene-Holocene terraces and the basalt ridges. Union Gap forms the transition between the Yakima and Toppenish Valleys. The gap is formed in the ridge bounding the southern extent of the Yakima Valley. This ridge is called the Rattlesnake Hills east of the gap and Ahtanum Ridge west of the gap. Both the Rattlesnake Hills and Ahtanum Ridge are comprised primarily of Miocene basalts. Quaternary alluvium extends through the gap and into Toppenish Valley, forming much of the valley bottom immediately downstream of Union Gap. Holocene-Pleistocene landslides and terraces, and Holocene alluvial fans are adjacent to the Quaternary alluvium on the western side of Toppenish Valley immediately downstream of Union Gap. The Miocene Ellensburg Formation, Holocene-Pleistocene Palouse Formation and terraces are east of the Quaternary alluvium immediately downstream of Union Gap. Several small ephemeral drainages are present along the basalt ridges bounding the Yakima Valley from the north and south. Major drainages contributing to the Yakima River within the Yakima Valley include Ahtanum and Wide Hollow Creeks, both of which enter the Yakima River immediately upstream of Union Gap.

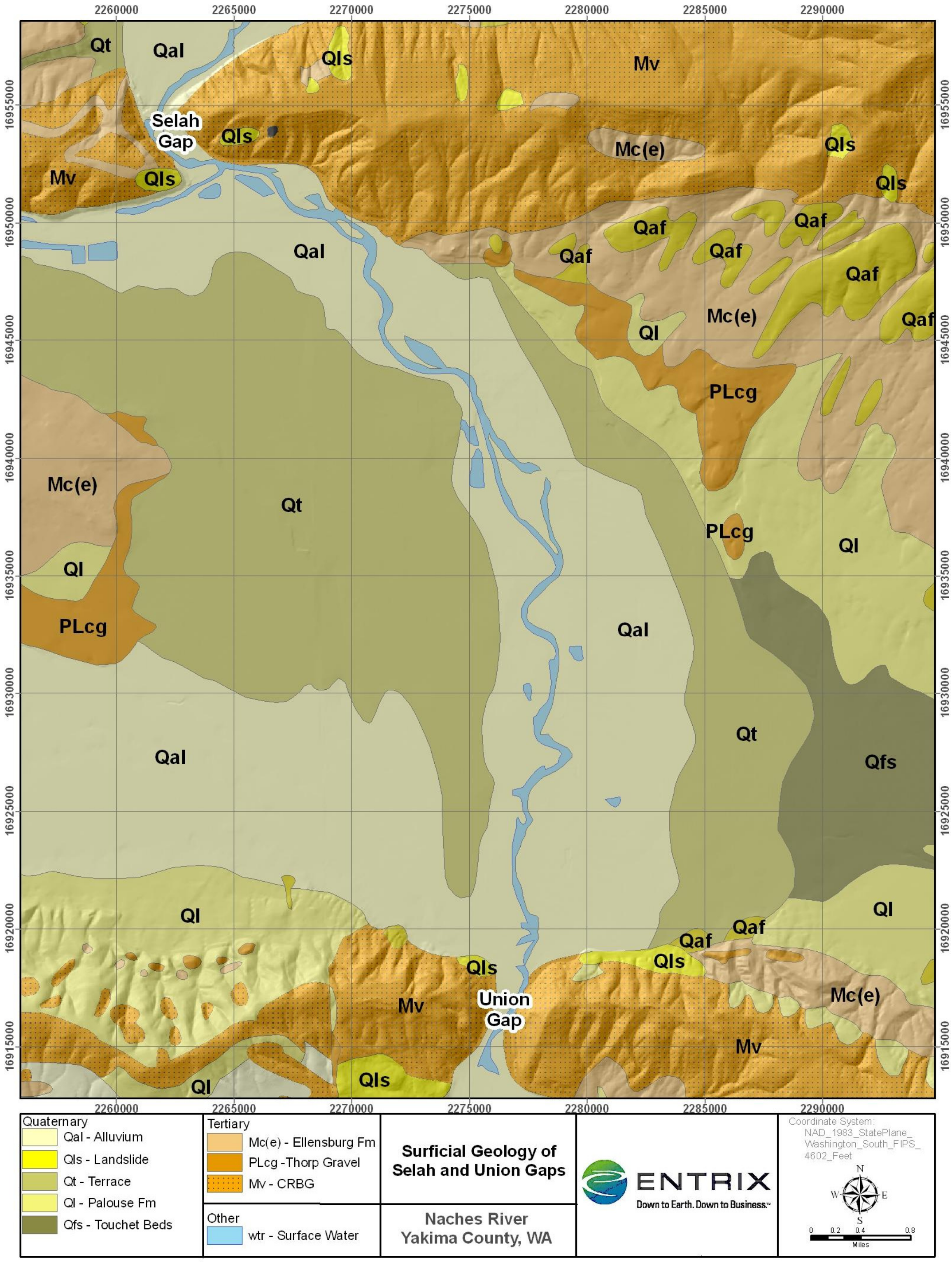


Figure 16 Surface Geology of the Selah to Union Gap Reach on the Yakima River. Note the outcrops of the CRBG (Mv) on both the east and west valley walls at the gaps. Geology data provided by Yakima County.

3.4.1 Sub-Reach Delineation and Cross-Sections

A total of eight sub-reaches were identified within the Selah Gap to Union Gap Reach. Sub-reach boundaries reflect the limits of influence from adjacent levees/revetments, locations of major road crossings, and the surrounding topography (Figure 17). Fourteen valley cross-sections were generated within the eight sub-reaches, which represent the range of geomorphic, hydrologic, and anthropogenic influences present in each sub-reach. All of the valley cross-sections are presented in Appendix 2 of this report. Specific cross-sections are present in the subsequent discussions to facilitate description where applicable.

3.4.2 Alluvial Terrace Descriptions

Using the methods outlined in section 3.1.3 of this report, alluvial terraces were delineated within the Selah Gap to Union Gap Reach of the Yakima River. Delineation was confined to the extent of the 2008 LiDAR dataset, which did extend through the Holocene-Pleistocene terraces within the Yakima Valley. A total of nine different terraces were identified (Figure 17) and assigned a surface number ranging from two to seven based on their vertical succession with the two surface (bankfull) the lowest elevation and seven the highest terrace. The lowest surface (one) is represented by the water surface of the Yakima River on June 27, 2008, the date of the air photos used to determine its extent. Table 7 presents a summary of the parameter defining each of the terraces identified. Terrace thicknesses ranged from 2 to 14 feet, and down-valley slopes ranged from 0.64 % (S_8, the second oldest and highest terrace) to 0.28 % (S_2, the bankfull channel) (the S_1 surface represents the water surface, and does not represent a terrace).

Table 7 Selah to Union Gap Terrace Description

Surface	HAWS* (ft)		Height/ Thickness (ft)	Slope (%)
	Max	Min		
1 (WS**)	-	-	-	0.26
2	4	0	4	0.28
3	6.3	4	2.3	0.31
4	14	6.3	7.7	0.43
5	18	14	4	0.31
6	21.5	18	3.5	0.32
7	29.8	21.5	8.3	0.29
8	44	29.8	14.2	0.64
9	57	44	13	0.56

* Height Above Water Surface (HAWS)
**WS is the water surface of the Yakima River (Daily Ave. Discharge of 2103 cfs on 6/27/2008)

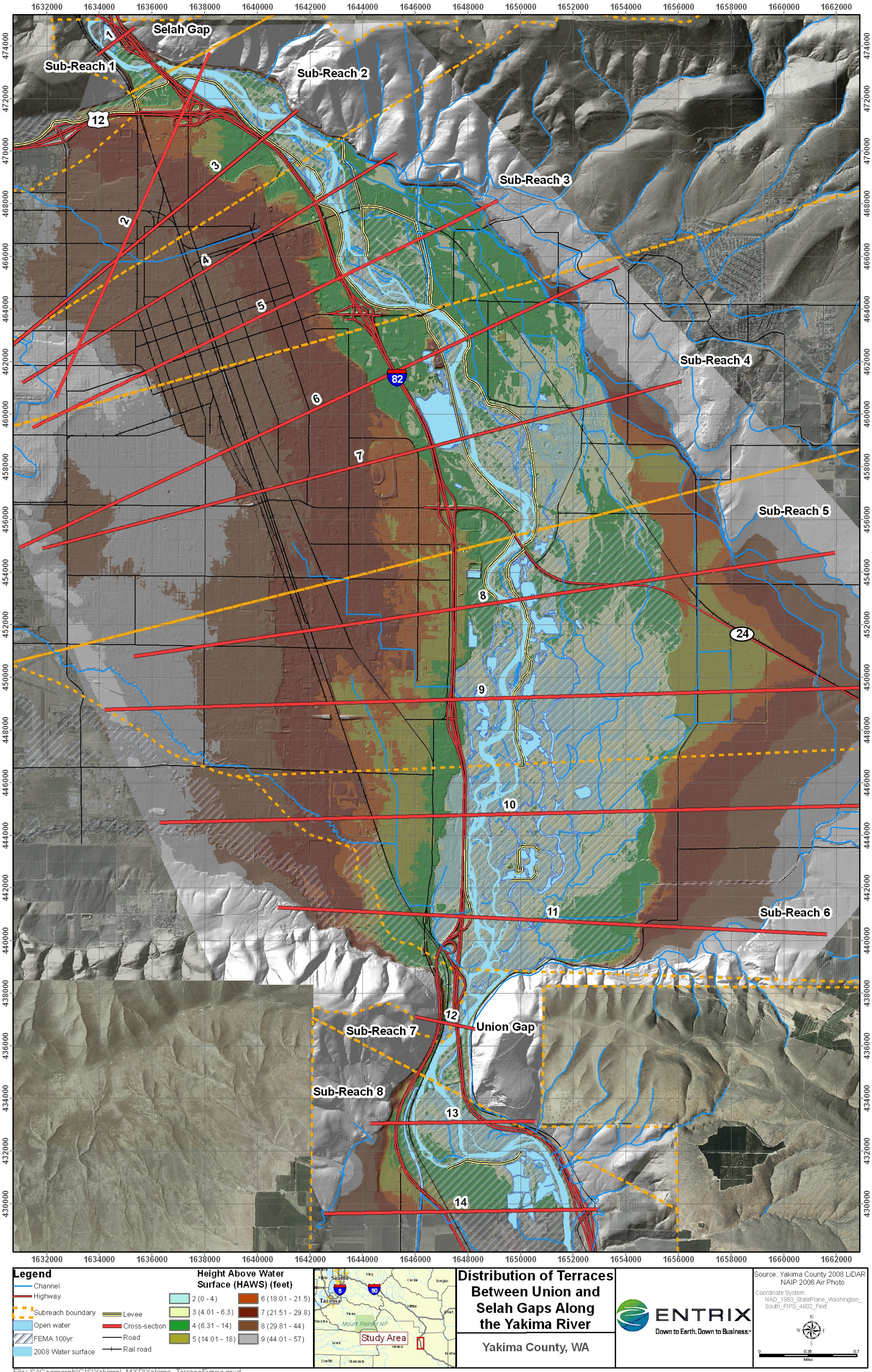


Figure 17 Distribution of Holocene alluvial terraces within the Selah to Union Gap Reach on the Yakima River.

A series of terraces of decreasing elevation toward the center of the valley does indicate that throughout the Quaternary, the Yakima River was a degrading system through the Selah to Union Gap Reach. Episodes of aggradation are likely to have occurred throughout this time period, however the long-term trend of the river is incision. The location of terraces within the Selah to Union Gap Reach (Figure 17) shows that the number and distribution of terraces is a function of their position within the Yakima Valley. The highest and oldest terraces (S_7 through S_9) are present along the entire western side of the Yakima Valley within the reach boundary. These same terraces are largely confined to the southern half of the eastern side of the Yakima Valley within the reach boundary. The widths of the S_2 (bankfull) and S_3 terraces appear to be largely controlled by their proximity to both gaps. Their widths remain relatively consistent downstream of Selah Gap, dramatically widen roughly half-way between the gaps, and remain wide until entering Union Gap, where they are dramatically reduced. Downstream of Union Gap the width of the S_2 (bankfull) and S_3 surfaces increase again and remain wide through the study reach.

Plotting the % slope of each terrace reveals a distinctly different pattern than those observed at the two project gap reaches along the Naches River (Figure 18). S_9 and S_8 slopes are nearly double those of S_1 through S_7. The slopes of S_1 through S_7 are relatively constant, ranging from 0.26 % to 0.32 %, except at S_4 where the slope is 0.43 %.

Because absolute ages of the terraces are lacking, direct correlation of terraces between the project gap reaches must rely on similar geometry and relative height within the terrace sequence. The S_4 surface along the Yakima River has a similar height above water surface and thickness to the S_4 surfaces at both project study reaches along the Naches River. The S_4 surface marked the beginning of the most recent trend of decreasing slope at the WTP Gap Reach, and increasing slope at Rambler's Park Gap Reach. Because the S_4 surface reflects a period when a shift in the channel equilibrium occurred at the other project gap reaches along the Naches River, it makes the increase in slope of the S_4 surface on the Yakima River more conspicuous. Three distinct periods are interpreted to have been recorded by the change in slope of the terraces. The oldest period, during formation of the S_9 and S_8 surfaces, the gradient of the river was much higher than subsequent periods. Some tectonic or stochastic sediment transport event changes the channel equilibrium between the formation of the S_8 and S_7 surfaces, decreasing the slope by 0.3%. The time during formation of the S_7 through S_5 surfaces the river gradient remained stable. A tectonic or stochastic sediment transport event changes the channel equilibrium between the formation of the S_5 and S_4 surfaces, increasing the slope by 0.1%. During formation of the S_4 surface to the present day (S_1) the river has gradually decreased in slope in response to the event that occurred between the formation of the S_5 and S_4 surfaces.

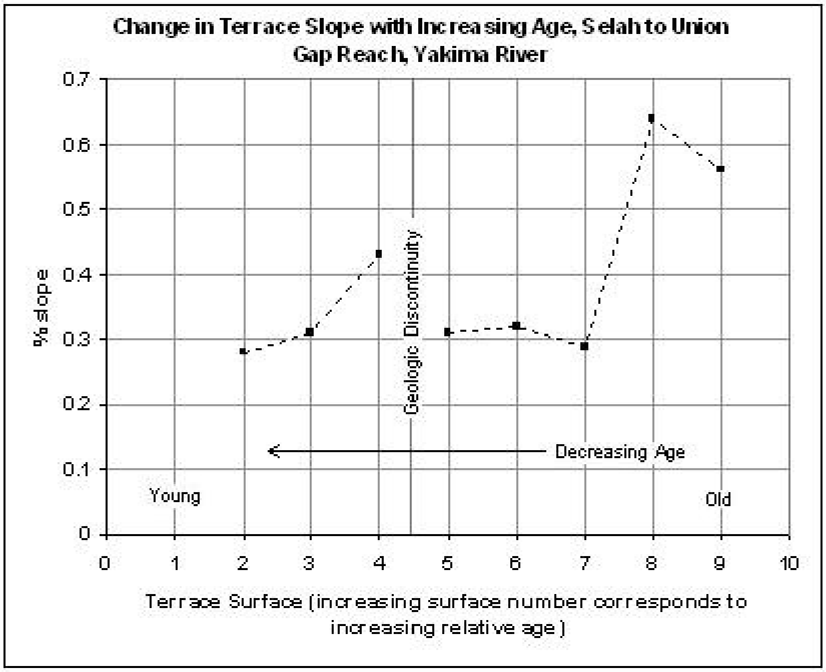


Figure 18 Patterns of changing terrace slope

3.4.3 Topographic Change Detection

Changes to the channel and floodplain geometry as a result of channel migration were evaluated by sub-reach using the methods outlined in section 3.1.4 of this report. Briefly, using the water surface extents from Oct-Nov 2000 and June 27, 2008, changes to channel location were evaluated. This was done assuming that locations where water was present in the 2000 air photo and not in the 2008 air photo experienced deposition, and locations where water was present in the 2008 air photo and not in the 2000 air photo experienced erosion. Care was taken to remove areas where the difference in surface water extent was the result of increased discharge. The erosion measured in this study is lateral erosion associated with channel migration, it should not be assumed that erosion equates to incision.

A table of the areas experiencing erosion and deposition, as well as the % slope of the Yakima River by sub-reach is provided (Table 8). Sub-reach 1 (Selah Gap) and 8 (Wapato Dam) show the least amount of geomorphic change. Union Gap (sub-reach 7) is more active than Selah Gap, with -1.58 m^2/river length (m) and -0.13 m^2/river length (m) net change respectively. The downstream trend of erosion is minimal erosion within Selah Gap, increasing dramatically immediately downstream of the gap (sub-reach 2), gradually increasing from sub-reaches 2-4, sharp increases from sub-reaches 4 to 5 and 5 to 6, a dramatic decrease from sub-reach 6 to 7 (Union Gap), and minimal erosion within sub-reaches 7 and 8. The gradual increase in erosion downstream of Selah Gap is likely due to the increased width and availability (within the levees) of the S_2 surface (bankfull). The sharp increases in the amount of erosion taking place from sub-reaches 4 to 5 is likely due to the termination of the right bank levee within sub-reach 5. The sharp increase in the amount of erosion taking place from sub-reaches 5 to 6 is likely due to the termination of the left bank levee at the boundary of the sub-reaches. Depositional site are largely restricted to sub-reaches 3 and 6, accounting for 76% of the total deposition measured within the reach. The slope of the Yakima River within both Selah and Union Gaps is more than half that found outside of the gaps. The slope of the Yakima River increases immediately downstream of Selah Gap, before reaching a maximum slope of 0.3% in sub-reach 3. Downstream of sub-reach 3 the slope of the river decreases gradually downstream to Union Gap, where the slope decreases dramatically within the gap. The slope of the Yakima River increases again sharply downstream of Union Gap. In previous studies, the Union Gap Reach exhibited high levels of fluvial activity relative to the rest of the Yakima basin (Stanford, *et al.*, 2002).

Table 8 Topographic change within the Selah to Union Gap Reach of the Yakima River

Sub-reach	River Slope (%)	Erosion		Deposition		Net Change	
		Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)	Hectares	M^2/River Length (m)
1 (Selah Gap)	0.13	0.07	0.5	0.06	0.4	-0.02	-0.1
2	0.27	0.71	3.3	0.15	0.7	-0.56	-2.6
3	0.30	1.47	5.4	1.72	6.3	0.26	0.9
4	0.29	1.91	6.1	0.36	1.2	-1.55	-4.9
5	0.24	3.61	10.8	1.41	4.2	-2.20	-6.6
6	0.25	7.36	27	4.36	16	-3.00	-11
7 (Union Gap)	0.12	0.26	1.6	0.00	0.0	-0.26	-1.6
8*	0.31	0.00	0.0	0.00	0.0	0.00	0.0
Total	0.26 (avg)	15.39	7.5	8.05	4	-7.34	-3.6

* Wapato Dam is located in sub-reach 8

3.4.4 Natural and Anthropogenic Confinement

Both natural and anthropogenic controls influence the geometry of the Yakima River and its floodplain. Channel confinement (the ratio of valley width to active channel width) was used to demonstrate the contributing effects of both natural and anthropogenic controls on the Yakima River system geometry. For each of the cross-sections generated within the reach, the bankfull width (S_2 surface), the width of the FEMA, and the width of surfaces S_1 (2008 water surface) through S_4 (S_1-S_4) were calculated. Two widths were calculated for the bankfull and S_1-S_4 surfaces, one accounting for the presence of levees, and one not. These values were used to calculate the confinement of the bankfull channel with respect to the FEMA, and with respect to the natural accessible floodplain (S_1-S_4) identified from the terrace delineation. Terrace surfaces S_1-S_4 were interpreted to have historically conveyed floodwaters of similar magnitude to a 100-year flood, and represent the potential extent of such flooding under completely natural conditions. Figure 19 shows the downstream trend of both the natural (N/N) and anthropogenic (L/L) confinement.

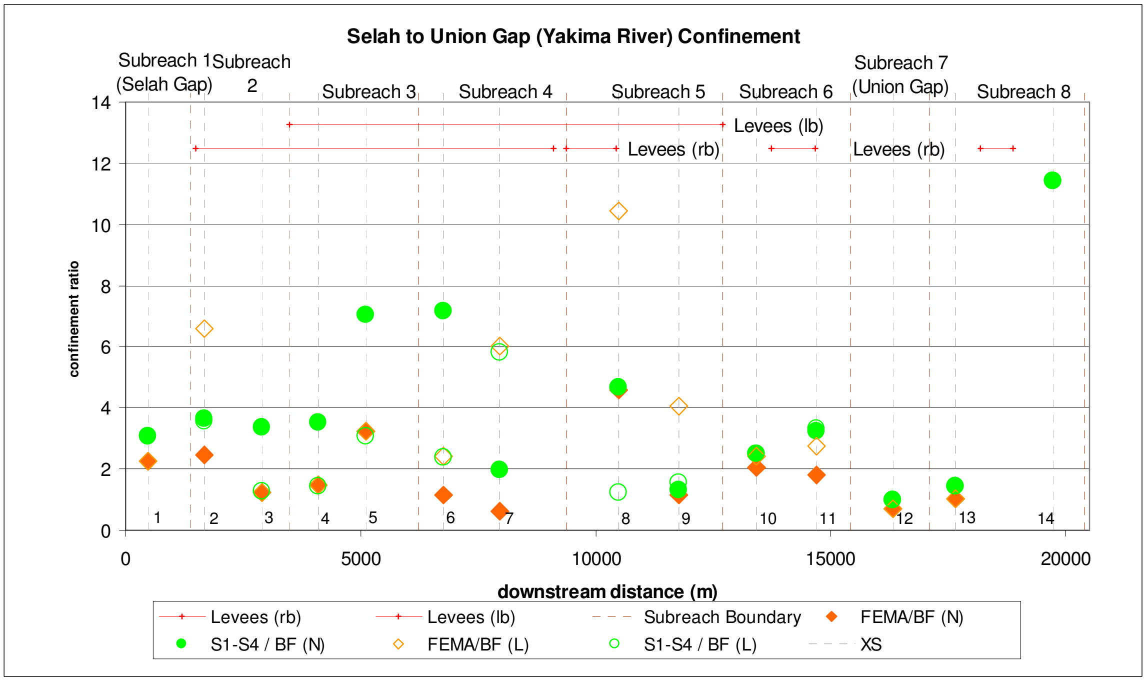


Figure 19 Confinement within the Selah to Union Gap Reach of the Yakima River. (L represents the width accounting for the presence of levees, and N does not) BF represents the bankfull width.

The highest measured confinement of the FEMA and S_1-S_4 surfaces is at Union Gap, however Selah Gap was not well defined by the level of confinement. The confinement defined by the S_1-S_4 surfaces is less than that defined by the FEMA for all cross-sections. The effect of increasing confinement of the S_1-S_4 surfaces due to the presence of levees is apparent from cross-sections 3 through 8, except at cross-section 7. At cross-section 7 much of the bankfull channel lies outside of the levees on either side of the contemporary river, thus when the levees are accounted for in calculating the confinement ratio it decreases. Isolation of the bankfull channel due to the presence of the levees is indicated by a decrease in confinement of the FEMA (N) relative to the FEMA (L). Cross-sections 2, 7, 8, 9, and 11 all show this isolation of the bankfull channel due to the levees. The greater the magnitude of decrease in the confinement ratio of the FEMA/BF (L) versus the FEMA/BF (N), the greater the amount of bankfull channel isolation.

The ratio of the width of the S_1-S_4 surfaces accounting for the levees (L), to the width of the S_1-S_4 surfaces without the levees (N) are presented in Figure 20. The width of the bankfull channel accounting for the levees (L) to the bankfull channel width without the levees (N) is provided as well. A ratio of 1 means there is no levee present, or there is no impact to the width of the surface due to the presence of the levee. The degree to which the levees impact the natural widths of the S_1-S_4 surfaces and the bankfull channel is clearly illustrated in Figure 20, where the lower the ratio calculated the greater the impact. The greatest impact to both the S_1-S_4 surfaces and the bankfull channel are within sub-reaches 4 and 5. The S_1-S_4 surfaces are impacted in sub-reaches 2 and 3, but not to the degree as in sub-reaches 4 and 5. The levees present in sub-reach 6 impact both the S_1-S_4 surfaces and the bankfull channel, however to a lesser magnitude when compared to sub-reaches 4 and 5. The greatest impact to both the S_1-S_4 surfaces and the bankfull channel from the presence of levees occurs within the same sub-reaches (5 and 6) found to be the most active in section 3.4.3.

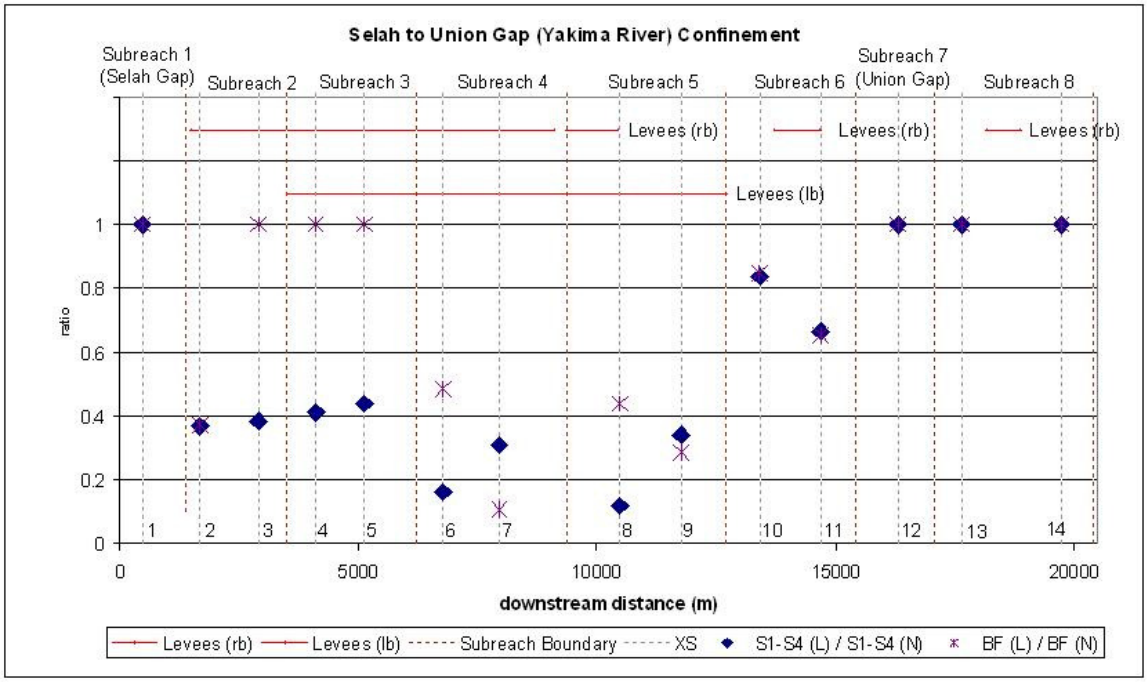


Figure 20 Impact of levees to the S_1-S_4 surface and bankfull channel (BF). (L represents the width accounting for the presence of levees, and N does not)

4. Conclusions

Geologic water gaps within the Yakima Basin have a fundamental role on the geomorphology of the Naches and Yakima Rivers and the channel dynamics between and within the gaps. They force down-valley groundwater flows to the surface where they join the river; this upwelling decreases temperatures and contributes to nutrient levels. They can cause backwater effects during large magnitude floods that result in sedimentation and increased rates of channel migration directly upstream of the gaps. Gaps can also restrict bedload sediment transport downstream. The presence of human modification within the gaps such as highways and flow control structures can intensify these effects or alter the system in other ways. The Yakima and Naches Rivers are dynamic, anabranching rivers that historically had complex floodplain and groundwater interactions. With European-American settlement in the last 150 years, many changes have been wrought. The hydrology of the rivers has been modified by dams, diversions, and return flows associated with irrigation projects. Subsequent changes to flood intensity, duration and timing have altered ecological conditions to the detriment of native salmonids and riparian vegetation. These changes also can increase the erosive power of floods by extending their duration. The construction of levees, roads, and other structures has disconnected the floodplain from the river and altered the movement of sediment through the system. Levees and revetments limit natural geomorphic process of channel migration and floodplain inundation. In some cases these structures can increase the risk of catastrophic channel changes by setting up major disequilibriums within the valley bottom. The practice of mining alluvial gravel has reduced sediment availability and increased avulsion risks when floodwaters breach the floodplain pits. Avulsions into gravel pits also result in changes that may take years for the river to adjust to and thus impose significant pressures on local ecology.

Our analysis shows that although each of the project water gaps is unique in their history and response to natural and anthropogenic influences, some similarities exist. For example, each of the project water gaps where found to be locations of channel stability. The degree of channel migration was much less within the gaps compared to sub-reaches outside of the gaps. In addition, there are distinct patterns of channel migration upstream and downstream of the gaps, with the magnitude and rate of migration increasing as the river approaches a gap and gradually increasing as the river moves away from the gap downstream. The WTP Gap Reach experiences approximately five times the channel migration of the Rambler's Park and Selah to Union Gap Reaches. Higher average river slope and less levee confinement at the WTP Gap Reach likely drives the higher channel migration rate.

The degree to which levee/revetment placement has confined the project gap reaches varies from reach to reach. The length of river with levees is similar at each gap, however their proximity to the floodplain and bankfull channel varies. The greater the proximity to the floodplain and bankfull channel, the higher the degree of confinement. Increased confinement creates river reaches that are typically straightened, sediment starved, and provide little to no habitat for fish and other wildlife. The WTP Gap Reach experiences the most confinement from levees within the gap, whereas Rambler's Park

Gap and Selah to Union Gap Reaches experience the most levee confinement between the gaps. The degree of bankfull channel confinement is much greater at Rambler's Park Gap (avg. 0.72) and Selah to Union Gap (avg. 0.73) Reaches compared to the WTP Gap Reach (avg. 0.93). Average floodplain confinement increases from the WTP Gap Reach (avg. 0.73), to Rambler's Park Gap Reach (avg. 0.68), to Selah to Union Gap Reach (avg. 0.57).

Although both Rambler's Park Gap and Selah to Union Gap Reaches have similar confinement attributes, the potential for restoration is greater for the Selah to Union Gap Reach. The most confinement occurs within the Rambler's Park Gap Reach (Figure 12) in sub-reaches 4 and 5, where the right bank levee is adjacent to and parallels SR 12. In order to decrease the confinement within these sub-reaches, SR 12 would need to be re-located. Alternatively, sub-reaches 4 and 5 in the Selah to Union Gap Reach (Figure 17) are highly confined by levees, however there is little infrastructure outside of the levees, especially along the left bank. Levee setbacks within these sub-reaches would dramatically increase side-channel habitat and the quality of mainstem habitat.

5. Recommendations

This report along with specific analysis conducted at the Yakima WTP (ENTRIX, 2008) provide information needed to develop recommendations to manage natural resource restoration as well as maintenance and planning for existing and future infrastructure within the study area.

While specific recommendations for the Yakima WTP have been provided to the County in a separate report (ENTRIX, 2008) this section of the report provides recommendations for a more long-term strategy for managing structures, river hazards, and restoration actions within the project area.

Areas to be considered a high priority for restoration consideration and/or action include:

- **Levee removal to promote mainstem, side channel, and floodplain habitat restoration and sediment storage**
- **Improve fish passage, channel stability, and floodplain connectivity in a manner that protects existing water diversions.**
    - **WTP diversion**
    - **Gleed diversion**
    - **Yakima Valley Canal intake**
- **Identify and manage avulsion hazards**
- **Side channel formation and protection**
- **Woody debris reintroduction and management (particularly linked to side channels)**
- **Floodplain re-forestation**

Several additional analyses are recommended to support restoration activities:

- A quantitative appraisal of the magnitude and rates of sediment flux through the Yakima and Naches systems is recommended to enhance our understanding of the effects of future development and river response. This analysis would compliment the planform analyses conducted (especially through the Union Gap) as well as provide information on the thresholds at which we can expect incision versus aggradation. While the BOR is providing a sediment transport model for the gap-to-gap reach in a number of areas, localized sediment transport and hydraulic studies will likely be needed for site-specific restoration efforts.

- A strategic management plan should be developed for set back levees in the cities of Yakima and Union Gap in order to improve flood capacity, fish habitat, and natural fluvial processes while reducing erosion and flood elevations.

- An economic evaluation of the levee set back program that includes ecologic assets as well as flood protection for infrastructure and property. This evaluation would identify and assess the specific cost, benefit, and approaches for each management action.

- Adaptation of current diversions and weirs to improve fish passage and habitat and sustain geomorphic processes. This is specifically recommended for areas with high risk of avulsions such as downstream of the Yakima WTP and at Rambler's Park.

- A detailed hazard assessment plan is recommended that identifies avulsion risks, risks to infrastructure, and opportunities for betterments. This includes economic, engineering, and geomorphic assessments that will allow Yakima County to acquire federal funding for betterments that provide more sustainable and long term solutions to flood and habitat protection.

- Reconnecting gravel mine pits and locating future mining sites outside the 100-year floodplain is recommended. Restoration designs should mimic side channels to facilitate reclamation, and should not interfere with hyporheic flow.

- Bioengineering techniques such as engineered log jams and revegetation are recommended over conventional engineering approaches to protect critical infrastructure and property in a manner that delivers cumulative benefits instead of cumulative impacts.

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Appendices

Appendix 1

Limitations to Using LiDAR Derived Topography in Detecting Geomorphic Change

LiDAR Limitations

Limitations to using airborne LiDAR topography data for change detection are discussed here in an effort to demonstrate the capability of this remotely sensed data. Briefly, LiDAR instruments are comprised of a laser altimeter pointed toward the ground surface from a fixed-wind aircraft. The beam is rotated in a circular pattern, creating a swath of land surface being measured as the aircraft passes over. The laser beam pulses, collecting elevation data as a series of points, with each point having multiple return values. These return values correlate to obstructions to the beam as is passes through vegetation until it reaches the ground, or the last return value. The width of the swath is a function of the rotation angle and altitude of the aircraft, and the data density is a function of the frequency of data acquisition (pulsed laser), swath overlap, and altitude and speed of the aircraft. Horizontal coordinates are measured real-time using onboard GPS equipment linked to a ground base station.

An evaluation of limitations in using two LiDAR datasets (acquired in 2000 and 2008) was performed within the channel migration zone of the Naches River in the Water Treatment Plant Gap reach to assess the ability to quantify the amount of topographic change as a result of channel migration (scour and fill), channel relocation (avulsion), and overbank deposition. The limitations evaluated include the relative accuracy between the datasets, and the difference in data density between datasets, resulting in interpolation error.

Metadata records for the 2000 LiDAR dataset report ± 0.4 m horizontal accuracy, ± 0.2 m vertical accuracy, and point spacing of 3.77m. Metadata records for the 2008 LiDAR dataset report 0.28 – 0.33 m horizontal accuracy, 0.07 – 0.14 m vertical accuracy, and point spacing of 1.59 m.

Relative Accuracy Evaluation

Relative accuracy between the 2000 and 2008 LiDAR datasets was evaluated to determine how well elevation values matched in areas where there is no expected change in elevation. Factors that would contribute a difference in elevation between the two datasets include the absolute accuracy of the data collected and any post-processing that may have been performed. To detect any difference between the two datasets, proximal point from each dataset need to be compared. To accomplish this, points from the 2000 dataset were selected that were within two feet from a point in the 2008 dataset. Next, points from the 2008 dataset were selected that were within two feet from a point in the 2000 dataset (Figure 1).

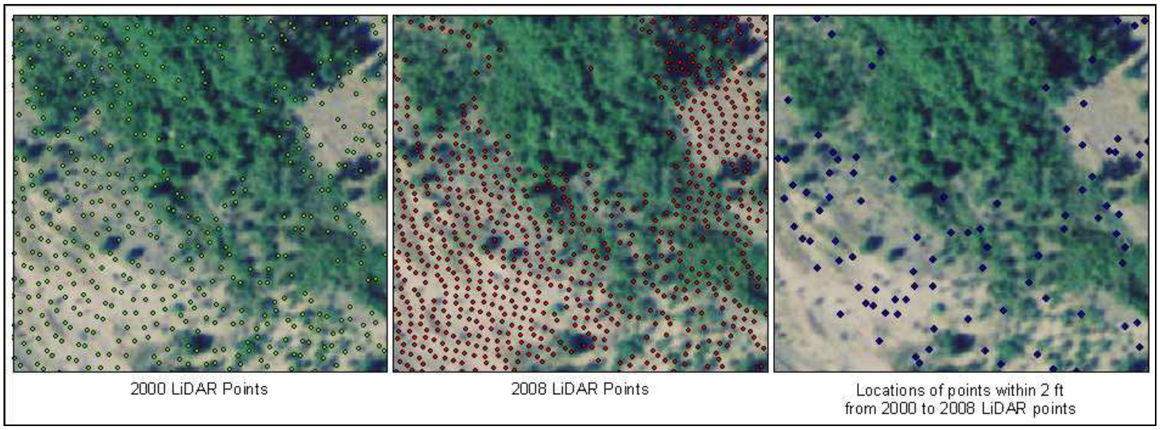


Figure 1. Distribution of 2000 & 2008 LiDAR points, and locations of points within two feet from each other from both datasets.

These files were joined together and the difference between the two points within two feet from each other (one from 2000 and one from 2008) was calculated. Points were selected in various landscape positions to determine if there was any effect from landuse/position effecting any elevation difference between the two datasets. Farm fields, paved surfaces, residential yards, and high floodplains were all examined to determine the distribution of elevation difference between the 2000 and 2008 datasets. Figure 2 depicts the locations used and the distribution of elevation difference between the datasets.

There is a distinct difference between the distribution of elevation difference by landuse/position, with median values ranging from -0.6 feet to 0.6 feet. Even within the same landuse type, the distribution of elevation difference varied. Omitting the paved surfaces (the elevations of which could have changed due to re-surfacing), a typical range of ± 1.3 ft (± 0.4 m) in elevation difference was observed. This range in vertical accuracy is higher than that reported for either dataset individually, due to the fact that when comparing two datasets the horizontal accuracy influences the alignment of vertical data values being compared. Without a systematic difference in elevation no attempt to correct for the difference is possible.

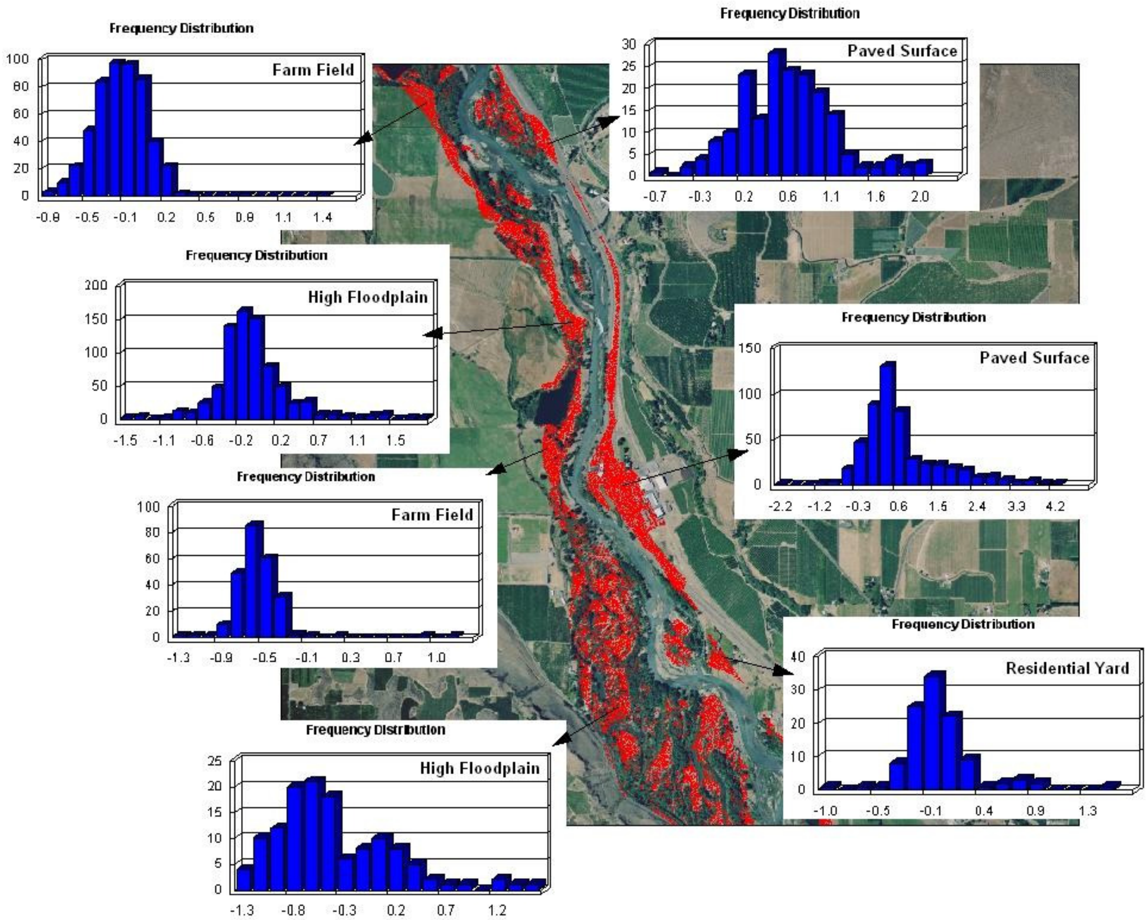


Figure 2. Locations of comparisons of offset and there distribution between the 2000 and 2008 LiDAR datasets.

Point Data Density and Interpolation Error Evaluation

Data density was determined for each of the two LiDAR datasets within the channel migration zone of the Naches River in the Water Treatment Plant Gap reach. The 2000 LiDAR dataset has an average density of 0.07 pts/m^2 and the 2008 LiDAR dataset has an average point density of 0.14 pts/m^2. These average density values are somewhat misleading in that all points within open water, including the Naches River, and in areas of dense vegetation where the last return value did not represent true ground elevation, were deleted from the dataset. In areas where point values have been retained, data density is much higher than the average. Point density within an area of good coverage for both datasets was 0.12 pts/m^2 for the 2000 dataset, and 0.25 pts/m^2 for the 2008 dataset.

The grid size of an interpolated DEM can be estimated by:

$$S = \sqrt{\frac{A}{n}}$$

where S is the grid cell size, A is the area covered in points, and n is the number of points (Hu, 2003). Using the average point density for the entire area of point returns, S values of 3.71 m^2 and 2.66 m^2 were calculated for the 2000 and 2008 datasets respectively. If DEM interpolation were limited to where there is sufficient data density, S values of 2.9 m^2 and 2.0 m^2 were calculated for the 2000 and 2008 dataset respectively. When comparing the two datasets the highest calculated S value from either dataset must be used when interpolating both datasets to DEM's.

Because LiDAR datasets have high sampling density, the IDW (Inverse Distance Weighted) interpolation algorithm is sufficient for DEM generation (Anderson 2005, Liu 2007). The IDW interpolation method determines DEM cell values using a linearly weighted combination of a set of sample points (Philip and Watson, 1982, Watson and Philip 1985). The weight is a function of inverse distance, thus points closes to the grid cell being determined are given greater weight in determining the interpolated value. Options are available to control the significance of known points on the interpolated values, based on their distance from the output location, and by limiting the number of points or search radius used in the interpolation.

Due to the nature of interpolation, care must be taken when comparing two datasets that have different data density and accuracy. The absolute accuracy of any interpolated DEM is variable, and the accuracy of any given grid cell is related to its distance from the data points used to generate it. This is especially important when comparing areas of low point data density where interpolation distances are greater. For example, when determining that amount of topographic change between two datasets, interpolated grid cells far from data points are evaluated in the same manner as grid cells proximal to data points.

When comparing interpolated DEMs from the 2000 and 2008 LiDAR datasets to determine the amount of topographic change over time, the problem of comparing areas of high data density and areas of low data density become apparent. Because the focus of change is linked to a water feature, the Naches River, there is no data where the river is located in either dataset. Where the river has migrated, data exists in one year but not in the other, thus any change is reflecting the results of comparing an area with high point density to an area with interpolated values with no proximal point data. Another challenge is the creation of inaccurate topography in areas with low point density. This is clearly shown when interpolating across the Naches River where there is a high bank on one side of the river and a low bank opposite (Figure 3). The high elevation values from the high bank are interpolated into the river (with zero point density) and low elevation values from the low bank are interpolated into the river until the two interpolations meet in the middle of the river, creating a false topographic feature. Although interpolated areas within the Naches River would not be used in a comparison of topographic change, it clearly illustrates the potential for interpolation to create false topography in areas with low data density.

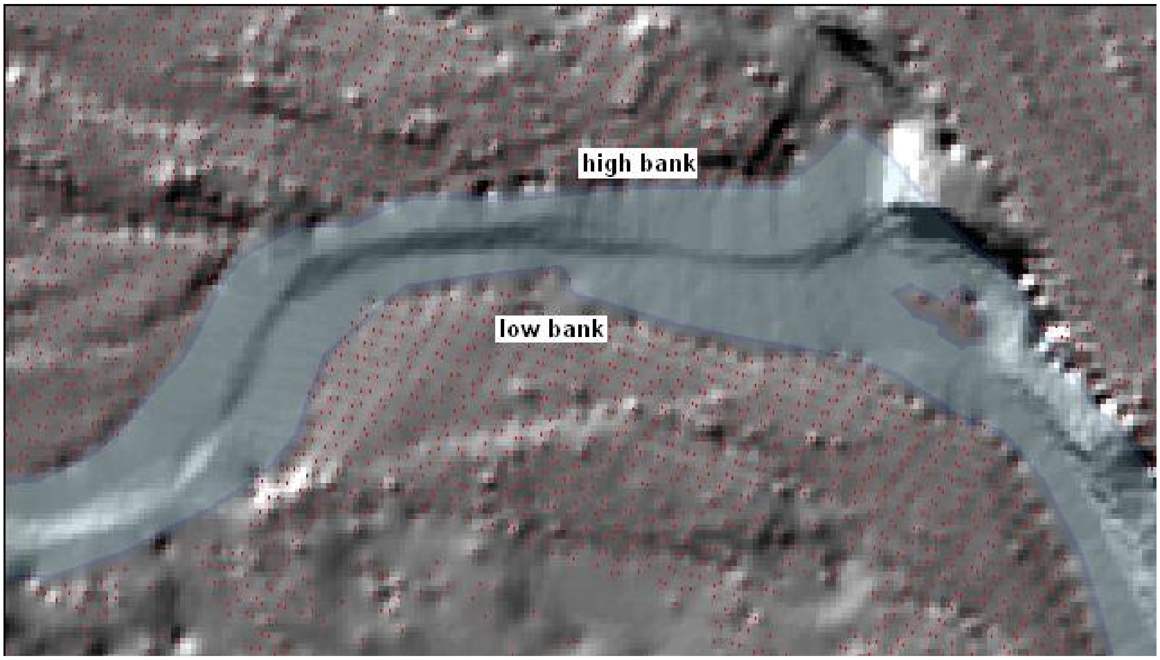


Figure 3. Creation of false topography during interpolation through areas of low data density. (red points are LiDAR data locations and blue polygon is the Naches River surface water extent)

References

Hu, Y. "Automated Extraction of Digital Terrain Models, Roads and Buildings Using Airborne LiDAR Data, (PhD Thesis), Department of Geomatics Engineering, The University of Calgary, Alberta, Canada, pp. 206.

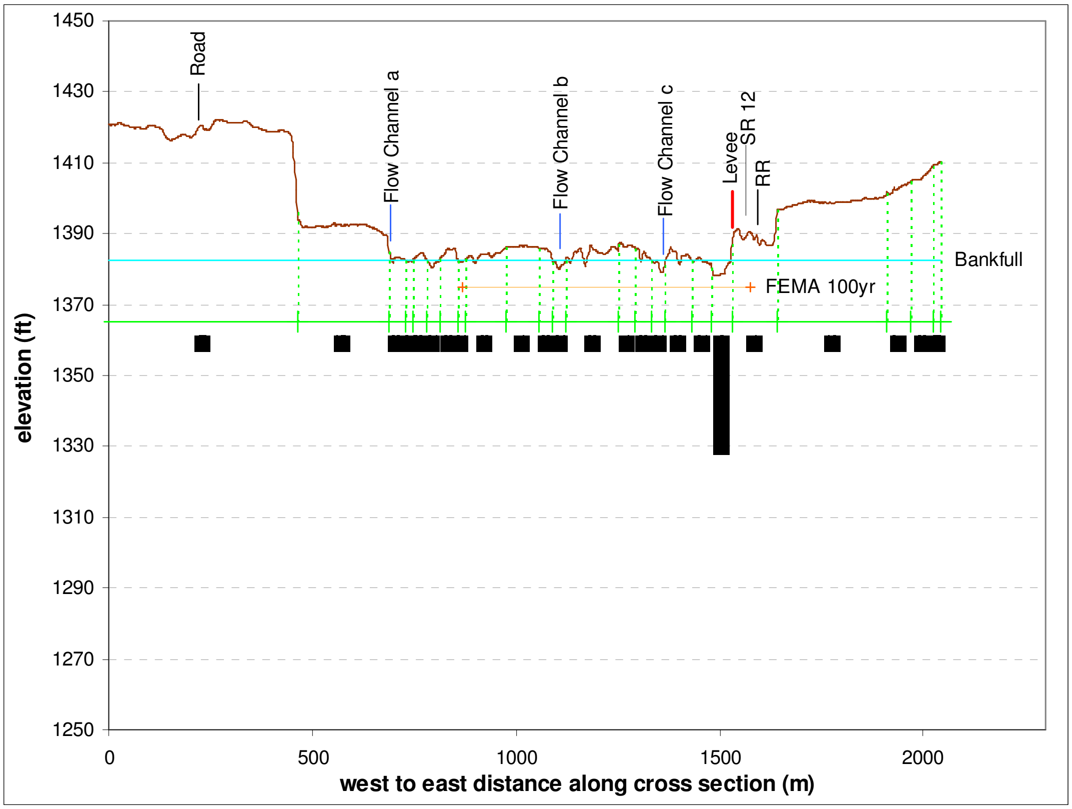
Philip, G.M., and D.F. Watson. "A Precise Method for Determining Contoured Surfaces". Australian Petroleum Exploration Association Journal 22: 205-212. 1982.

Watson, D.F., and G.M. Philip. "A Refinement of Inverse Distance Weighted Interpolation:. Geoprocessing, 2:315-327. 1985.

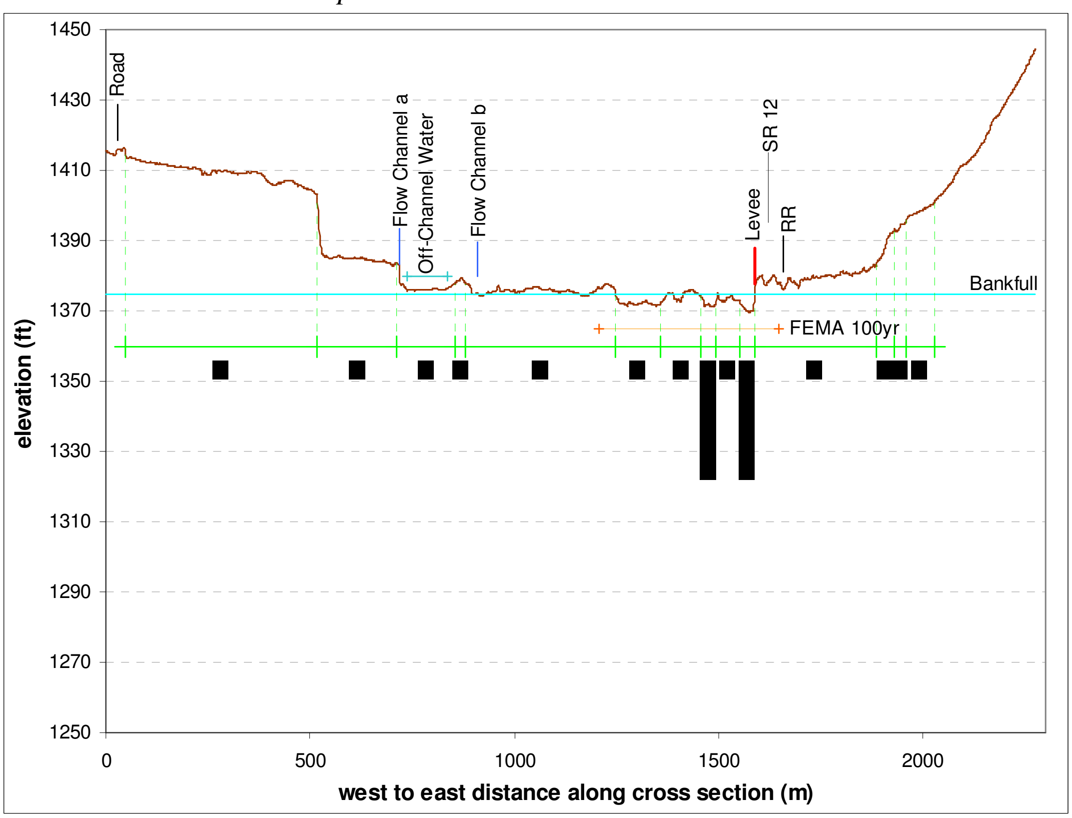
Appendix 2

Cross-Sections for Each of the Project Water Gap Reaches

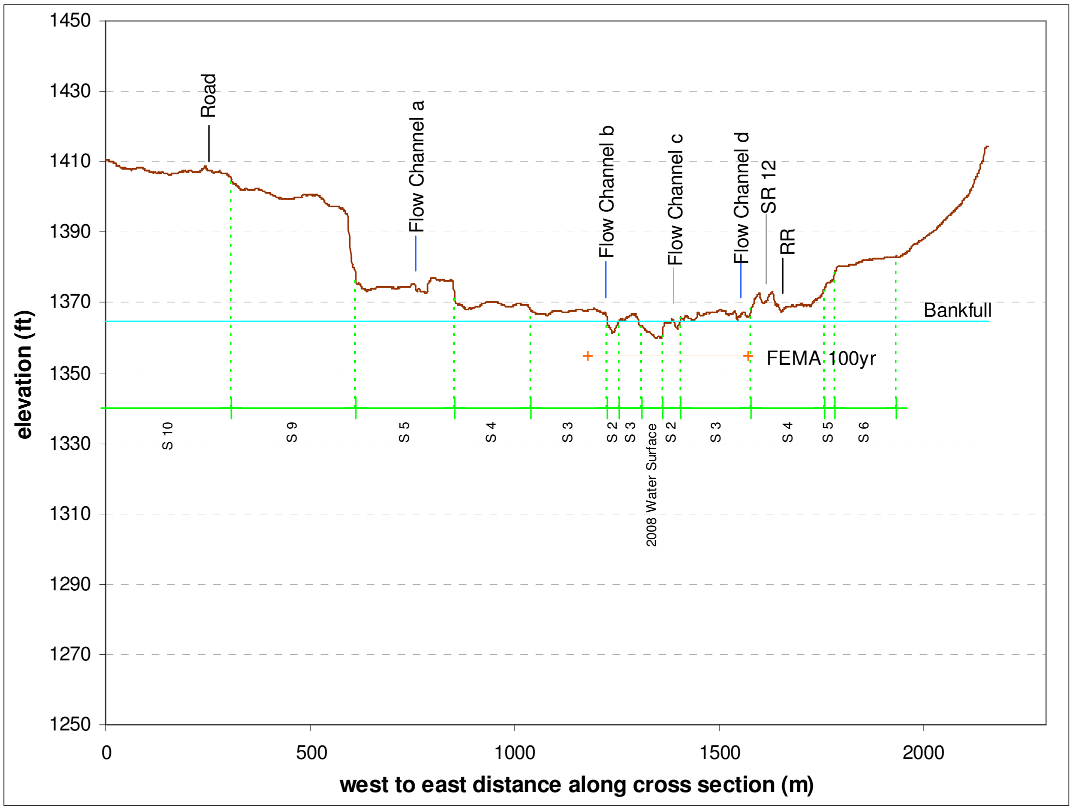
Water Treatment Plant Gap Reach XS 1



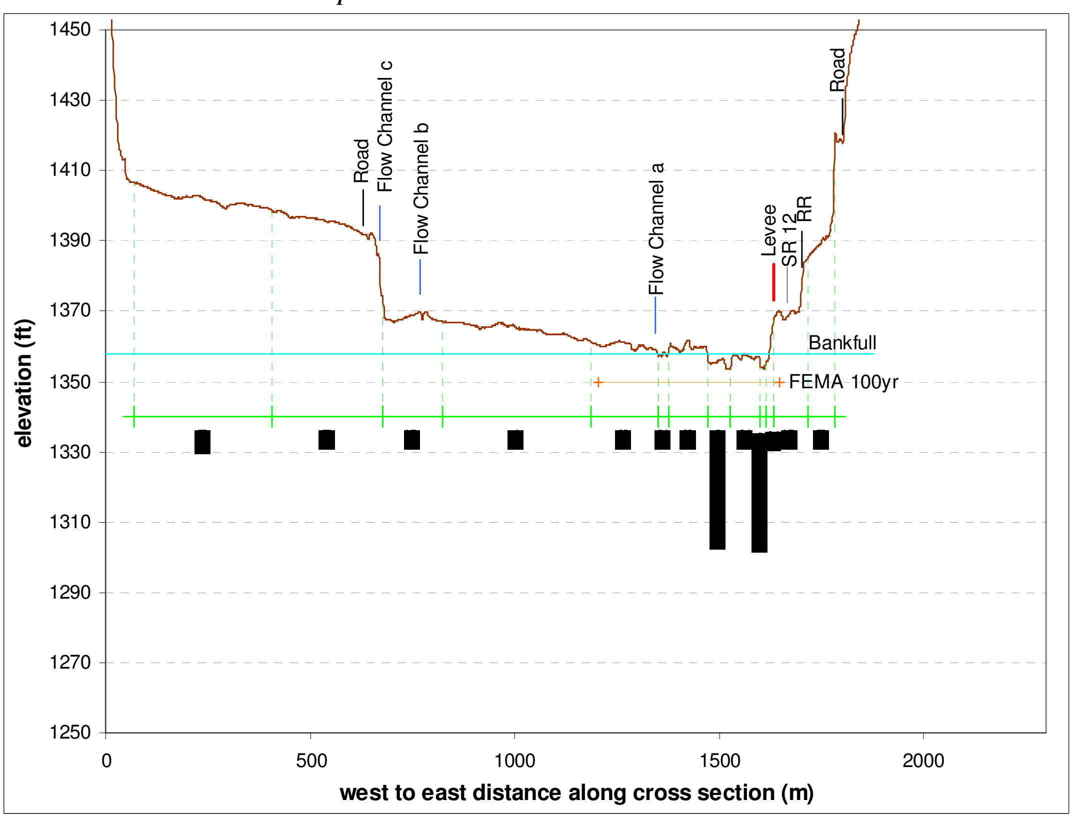
Water Treatment Plant Gap Reach XS 2



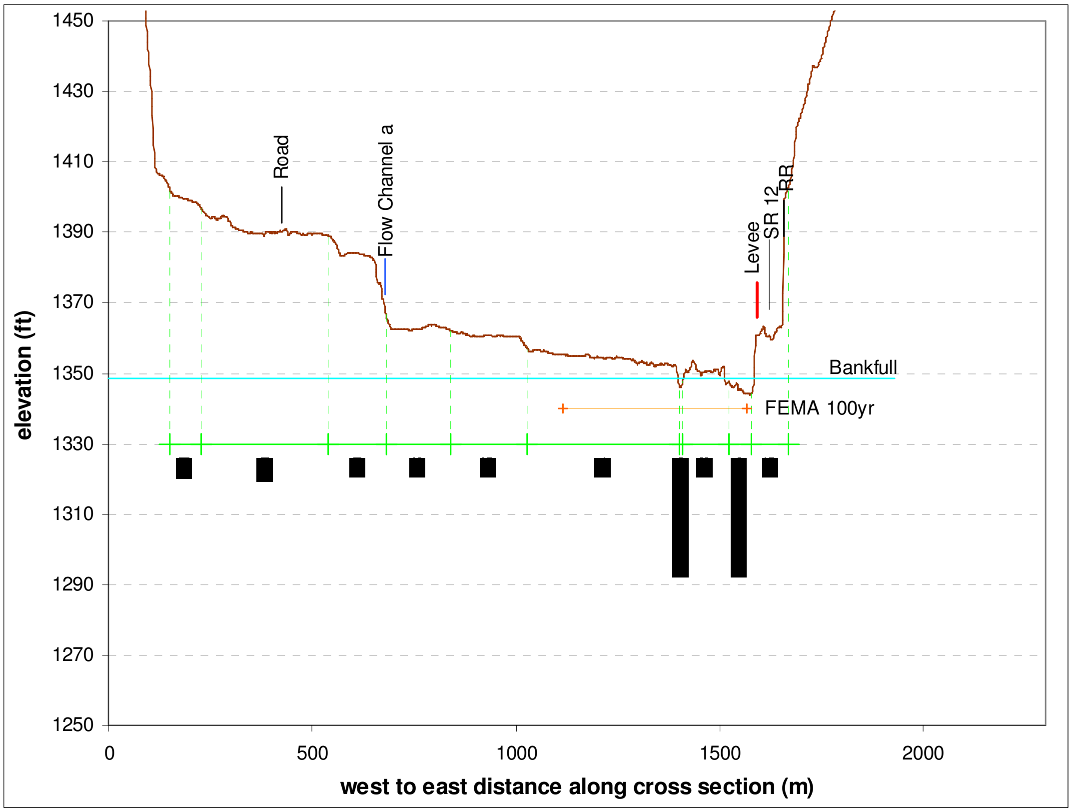
Water Treatment Plant Gap Reach XS 3



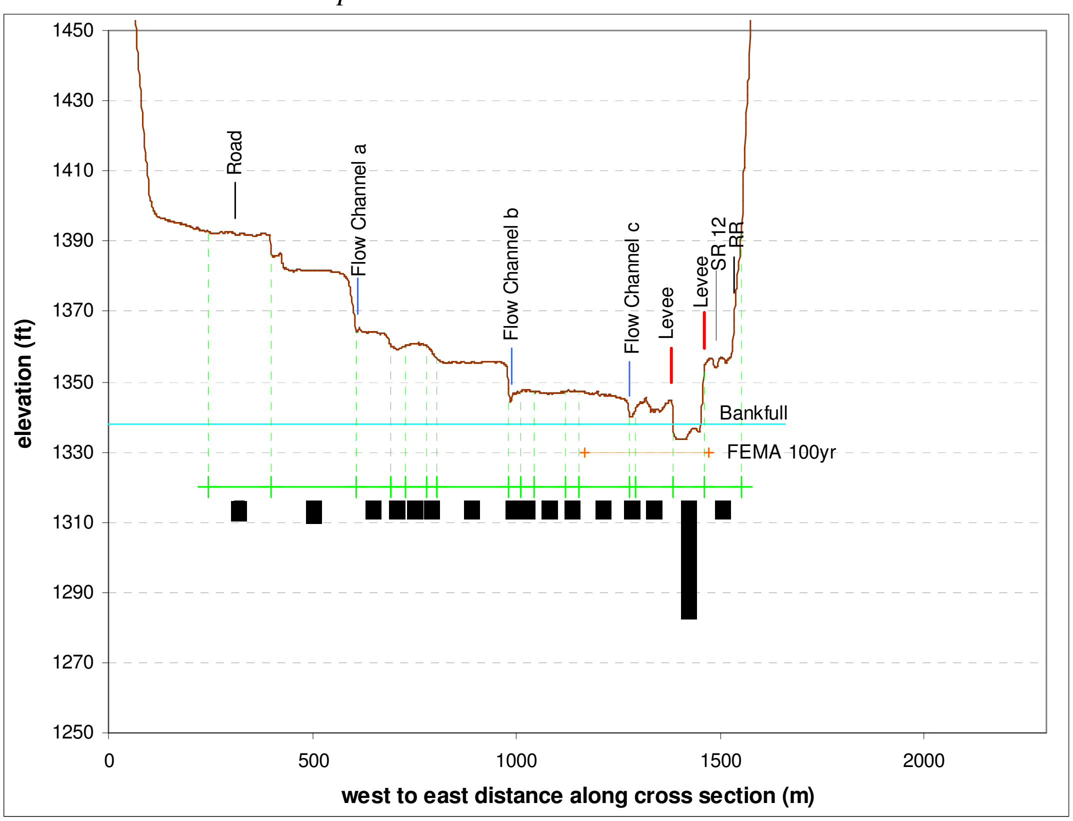
Water Treatment Plant Gap Reach XS 4



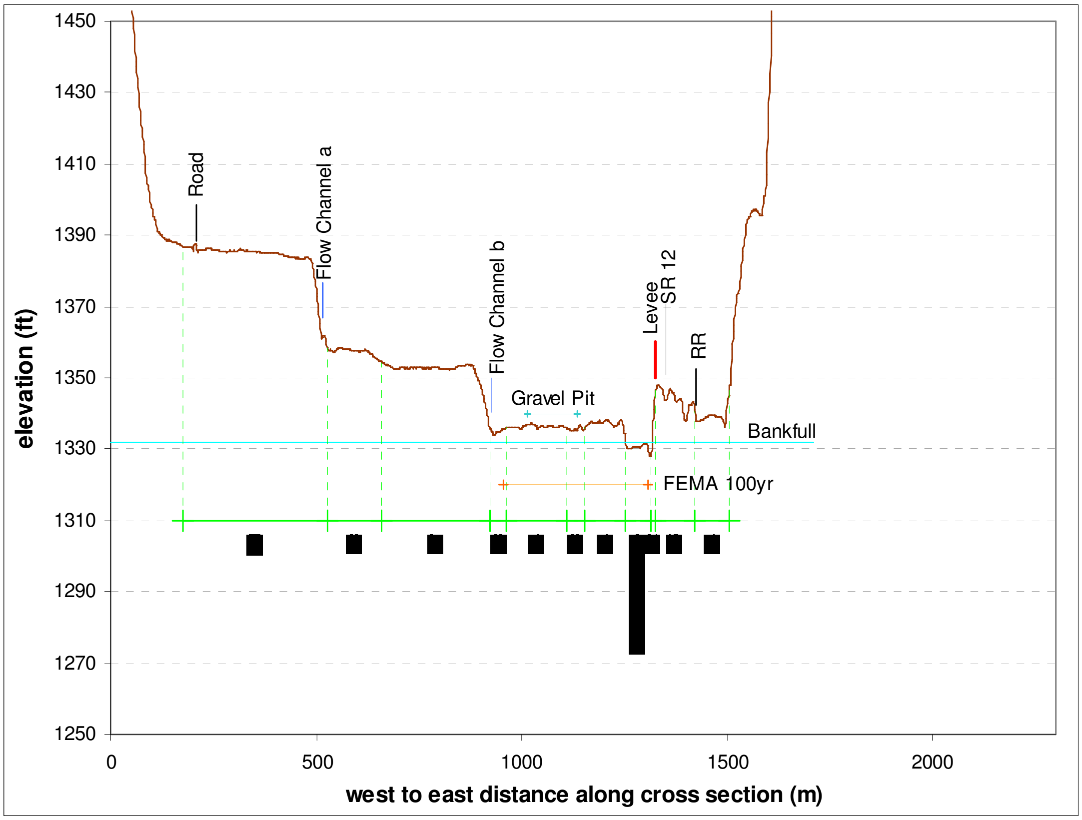
Water Treatment Plant Gap Reach XS 5



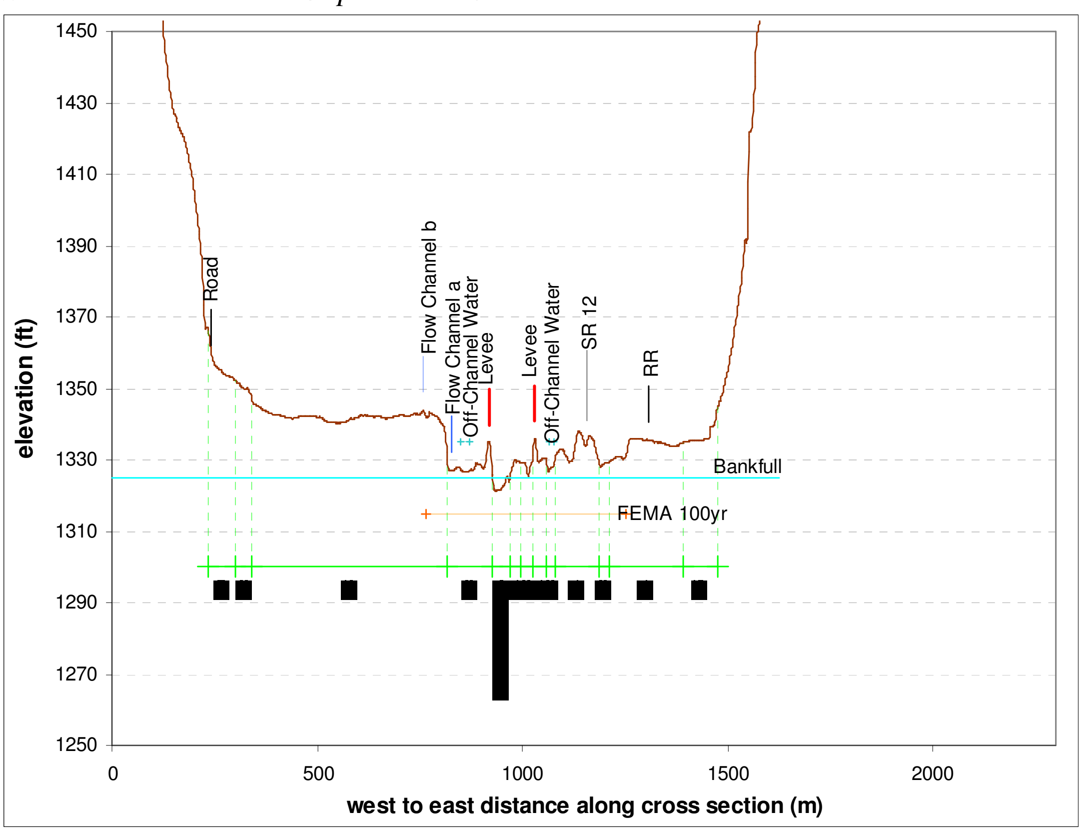
Water Treatment Plant Gap Reach XS 6



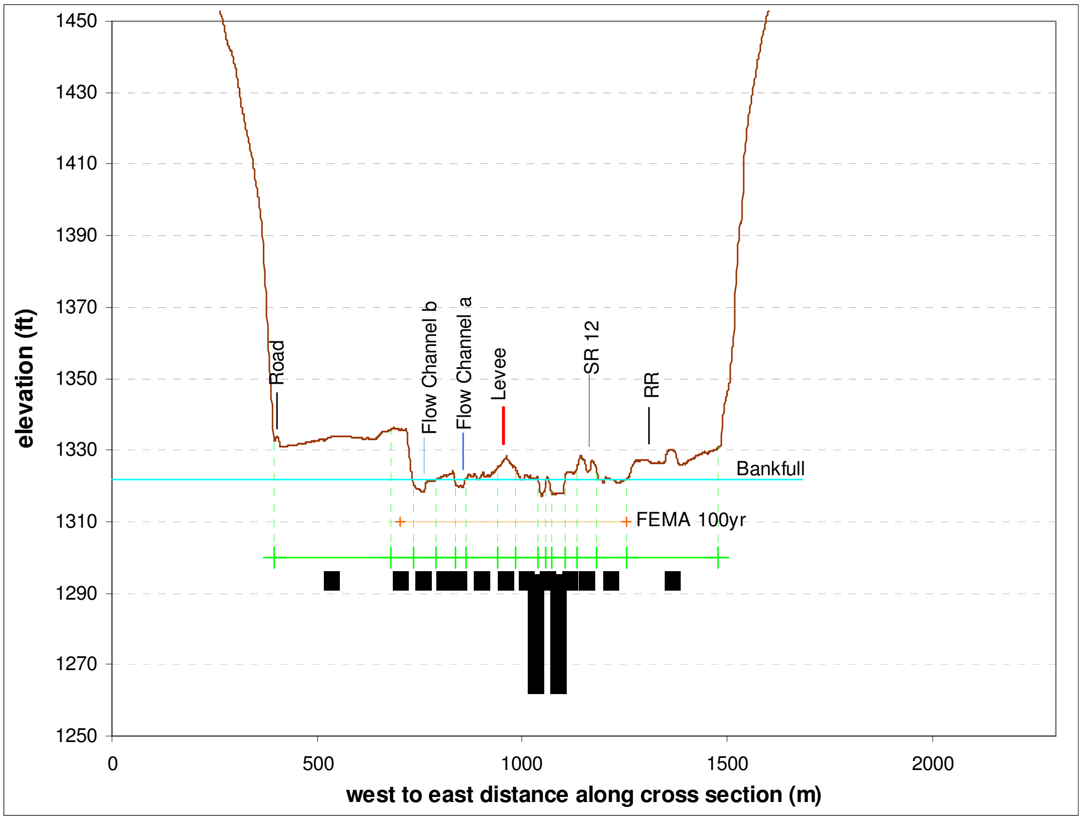
Water Treatment Plant Gap Reach XS 7



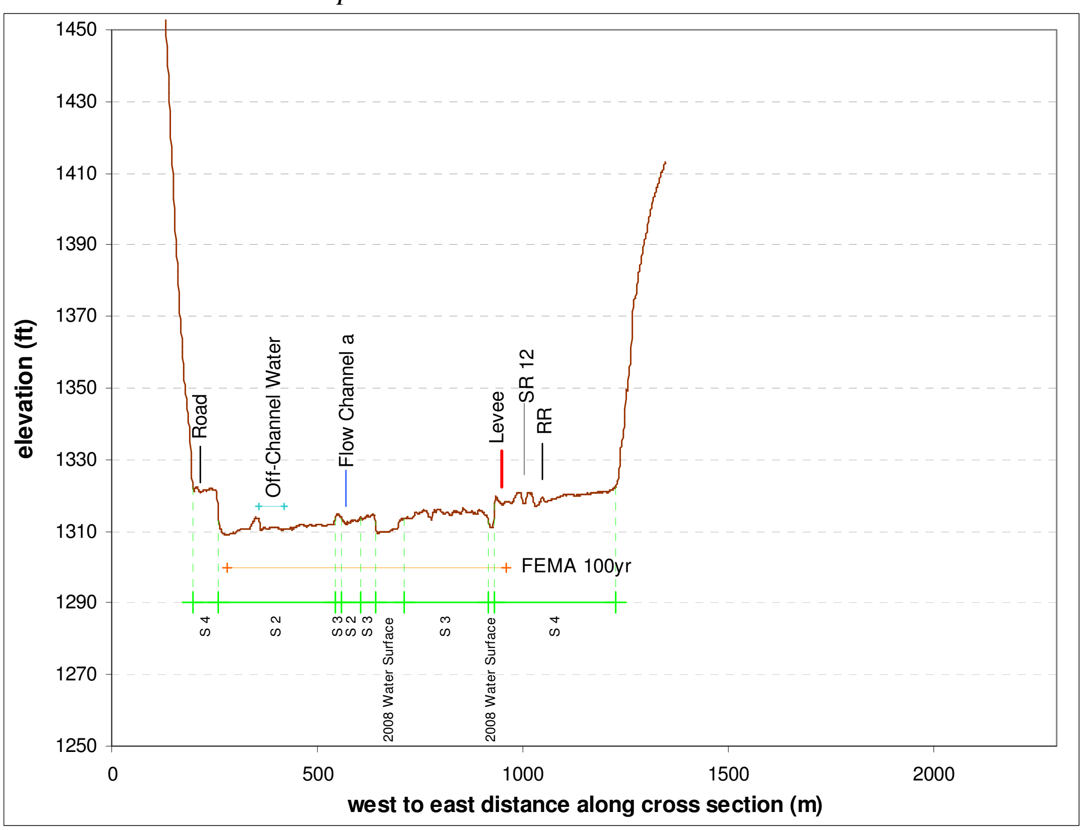
Water Treatment Plant Gap Reach XS 8



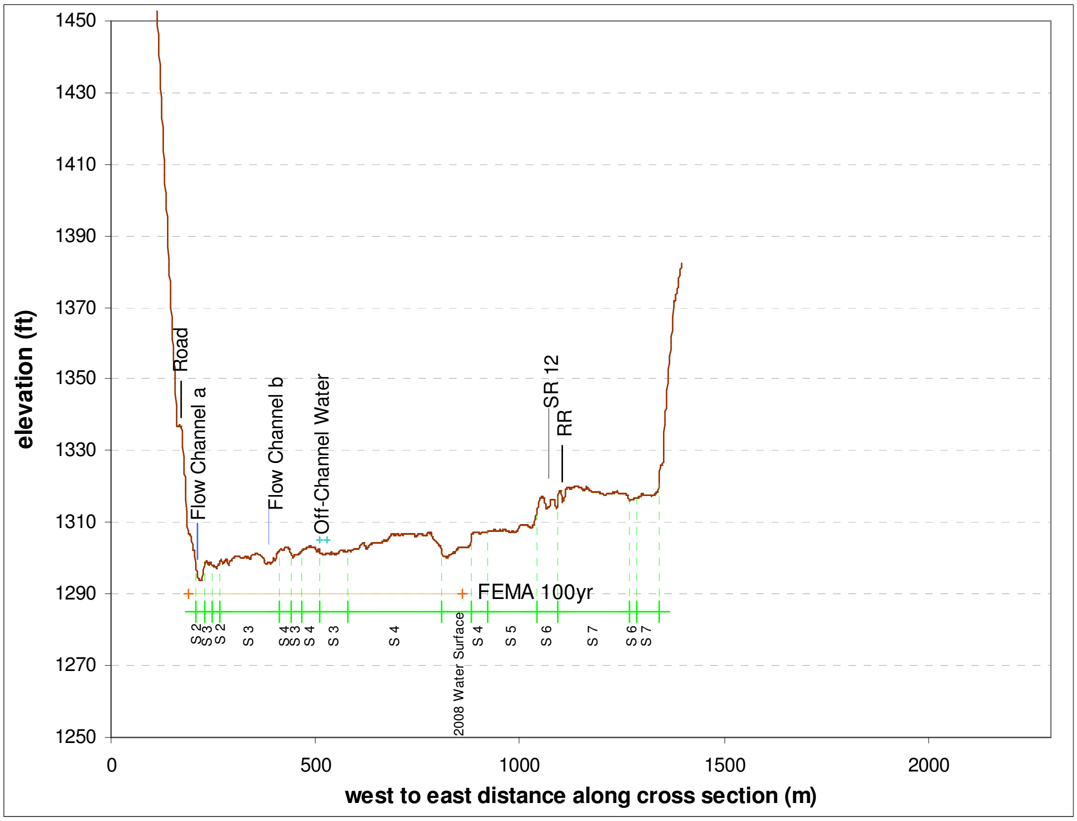
Water Treatment Plant Gap Reach XS 9



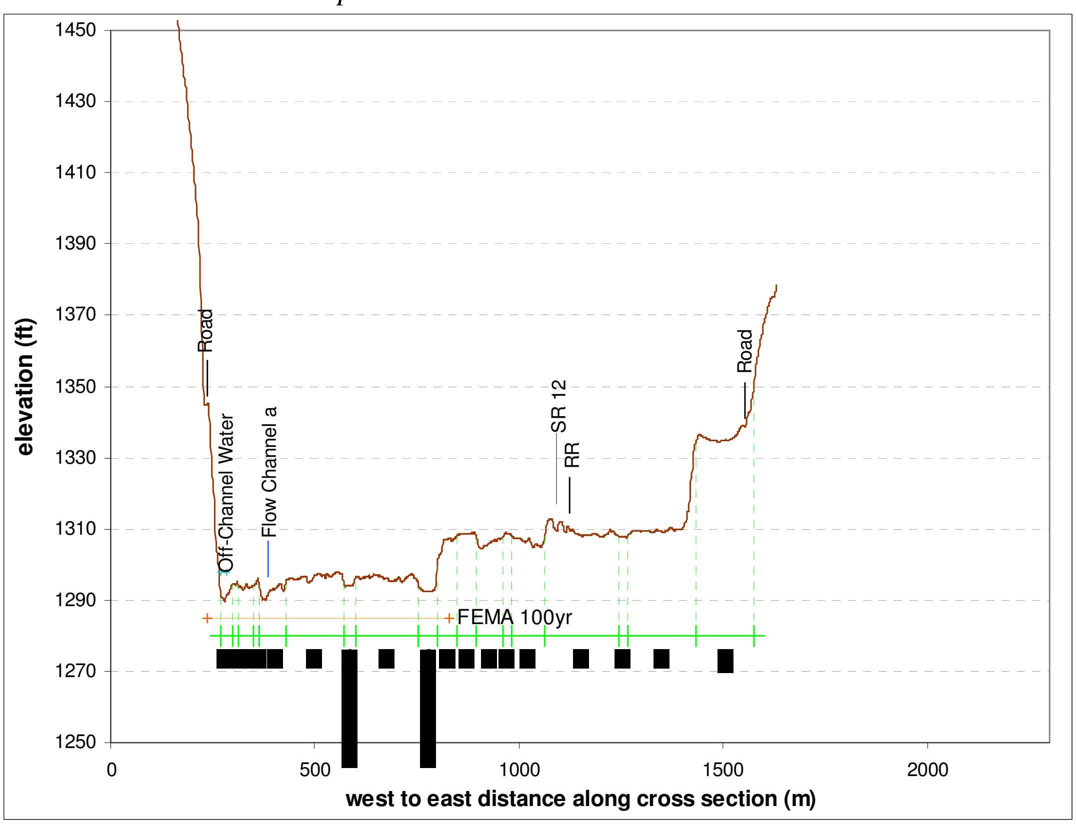
Water Treatment Plant Gap Reach XS 10



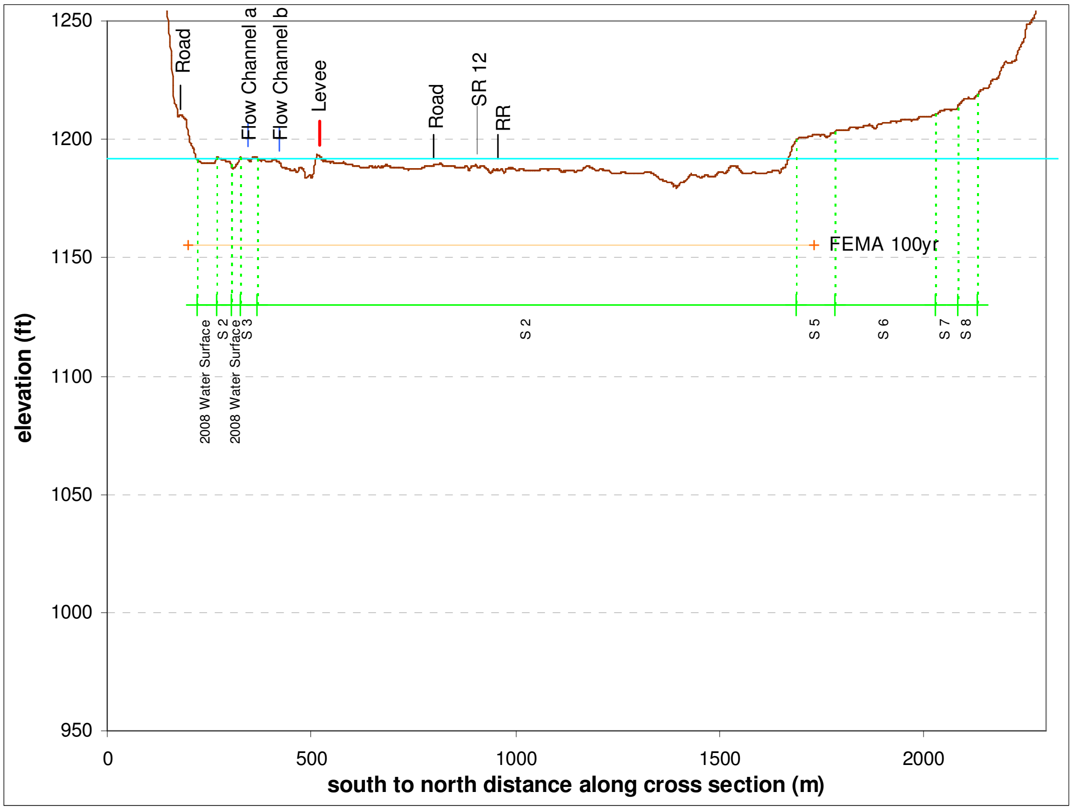
Water Treatment Plant Gap Reach XS 11



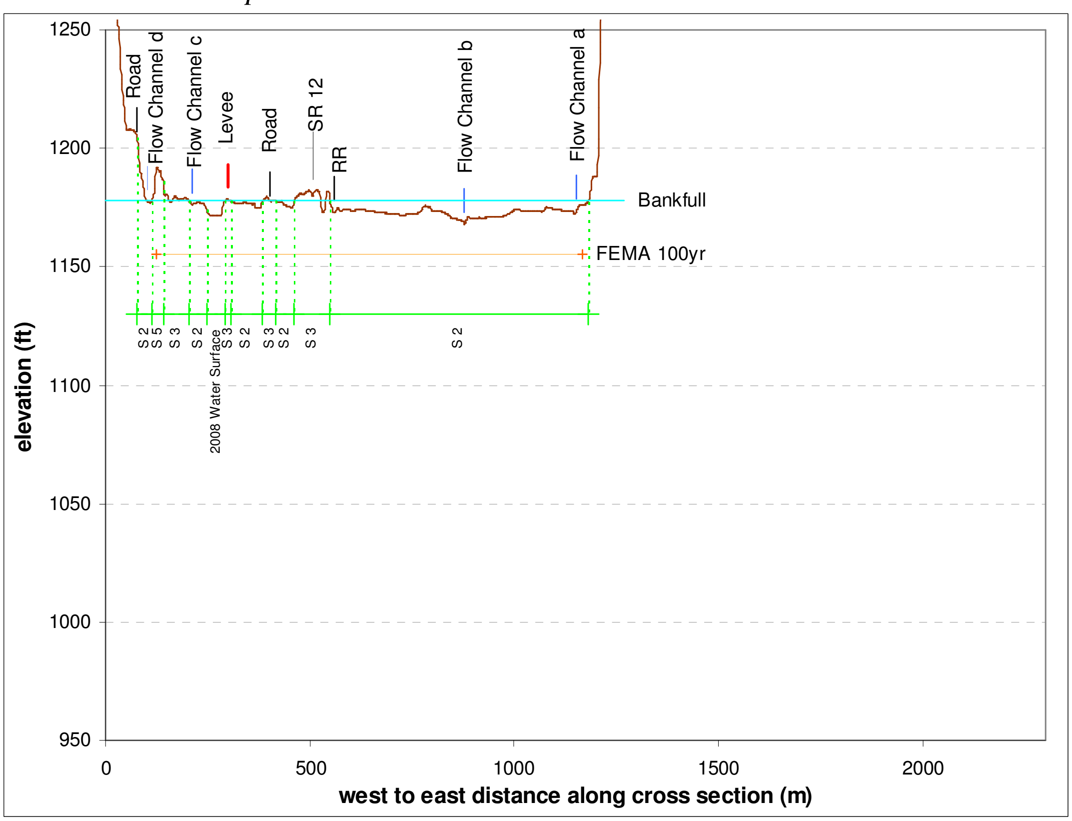
Water Treatment Plant Gap Reach XS 12



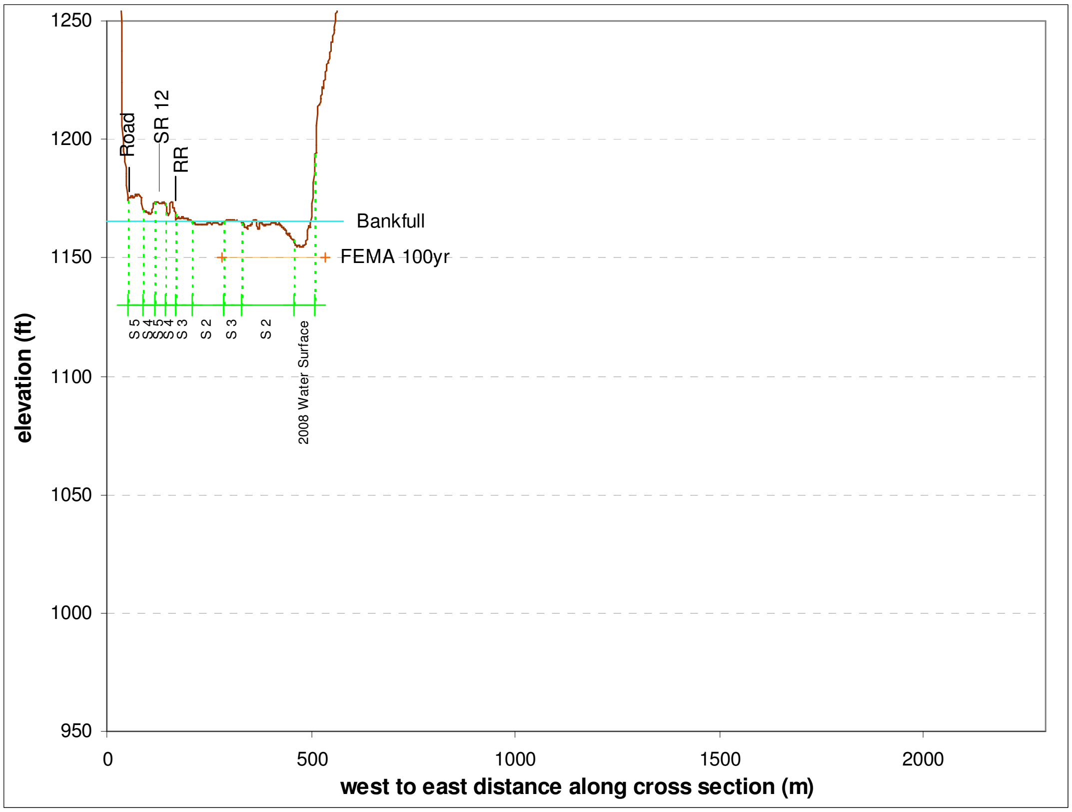
Rambler's Park Gap Reach XS 1



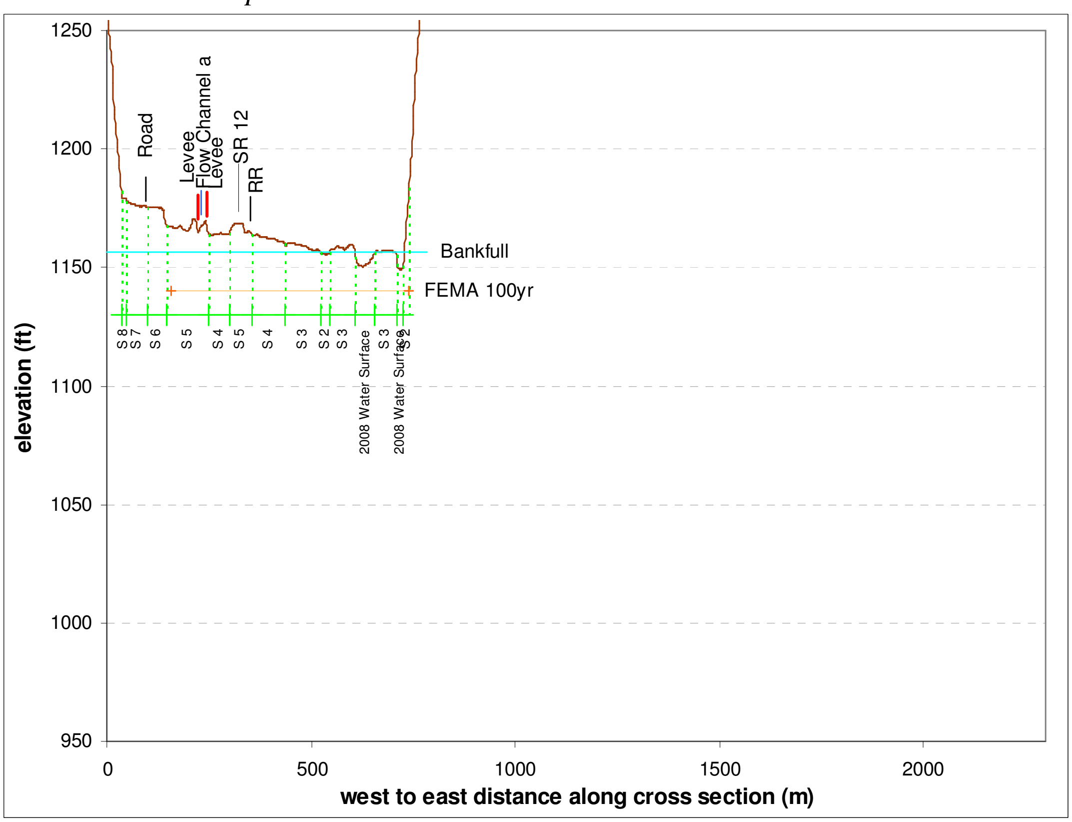
Rambler's Park Gap Reach XS 2



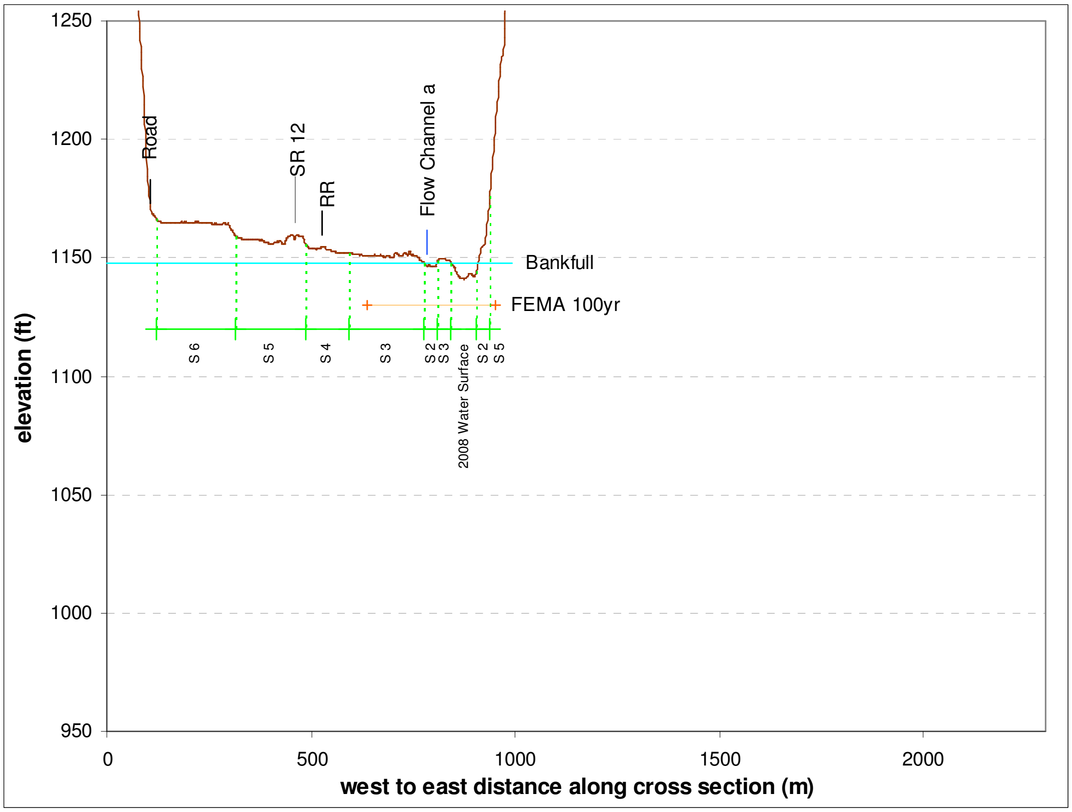
Rambler's Park Gap Reach XS 3



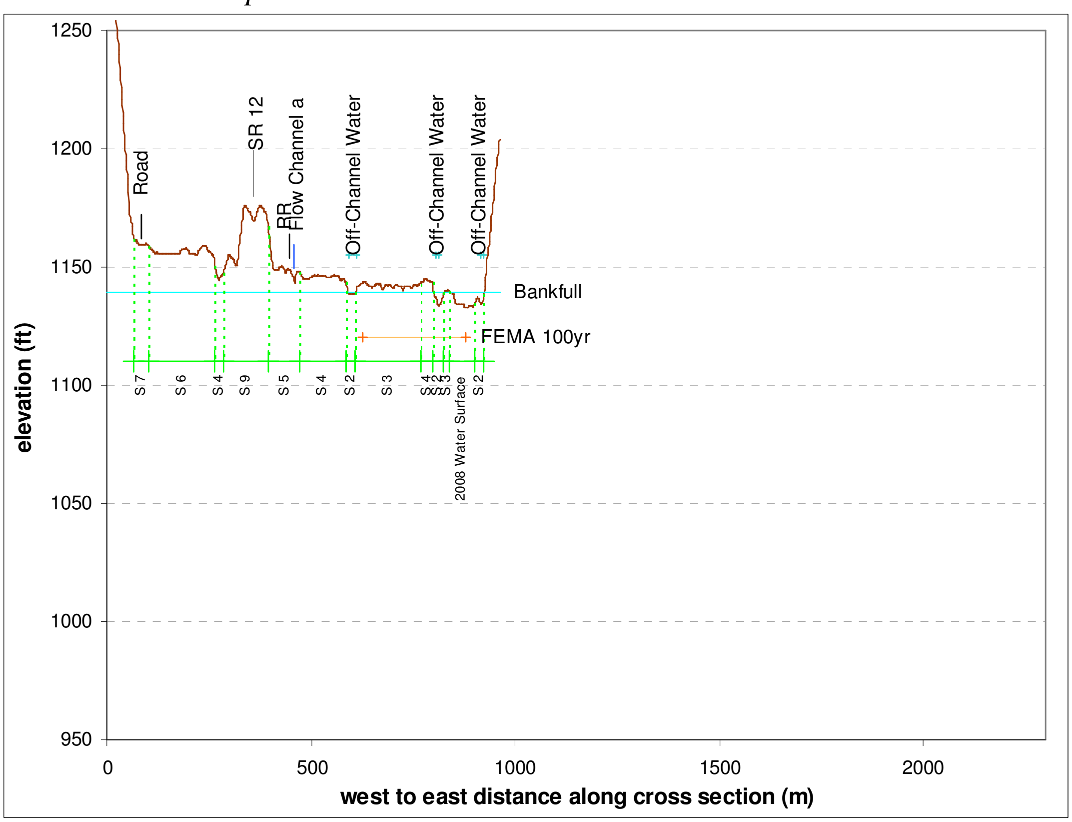
Rambler's Park Gap Reach XS 4



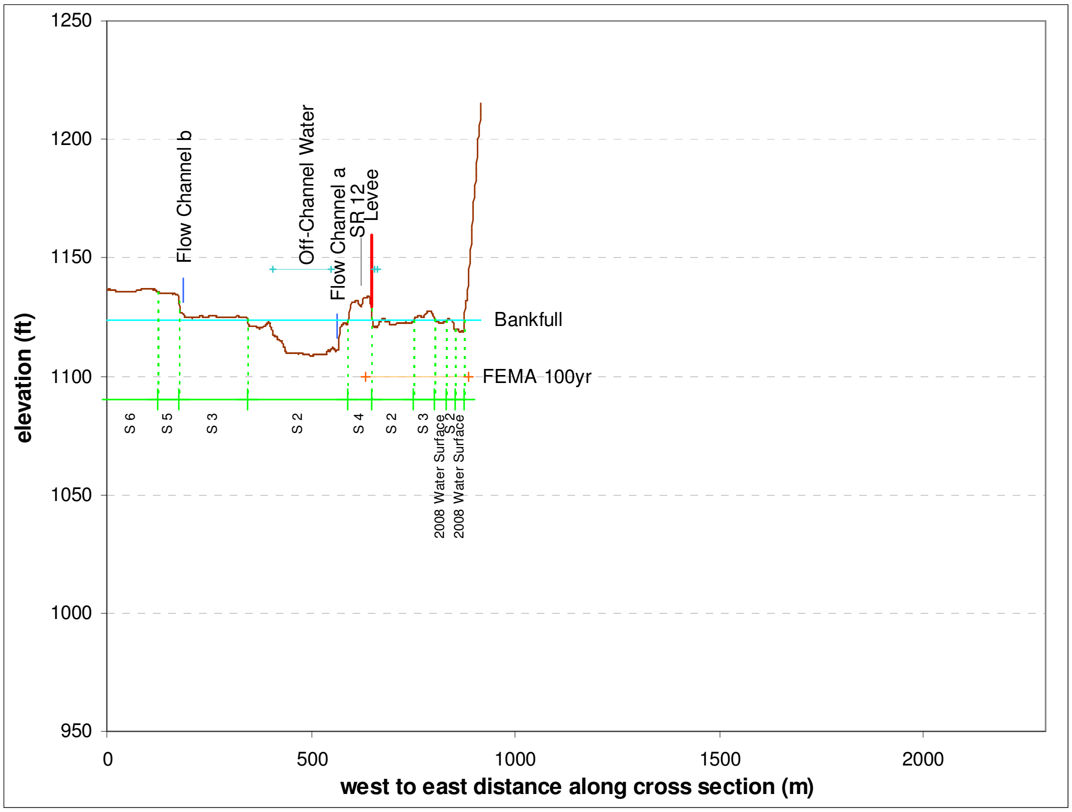
Rambler's Park Gap Reach XS 5



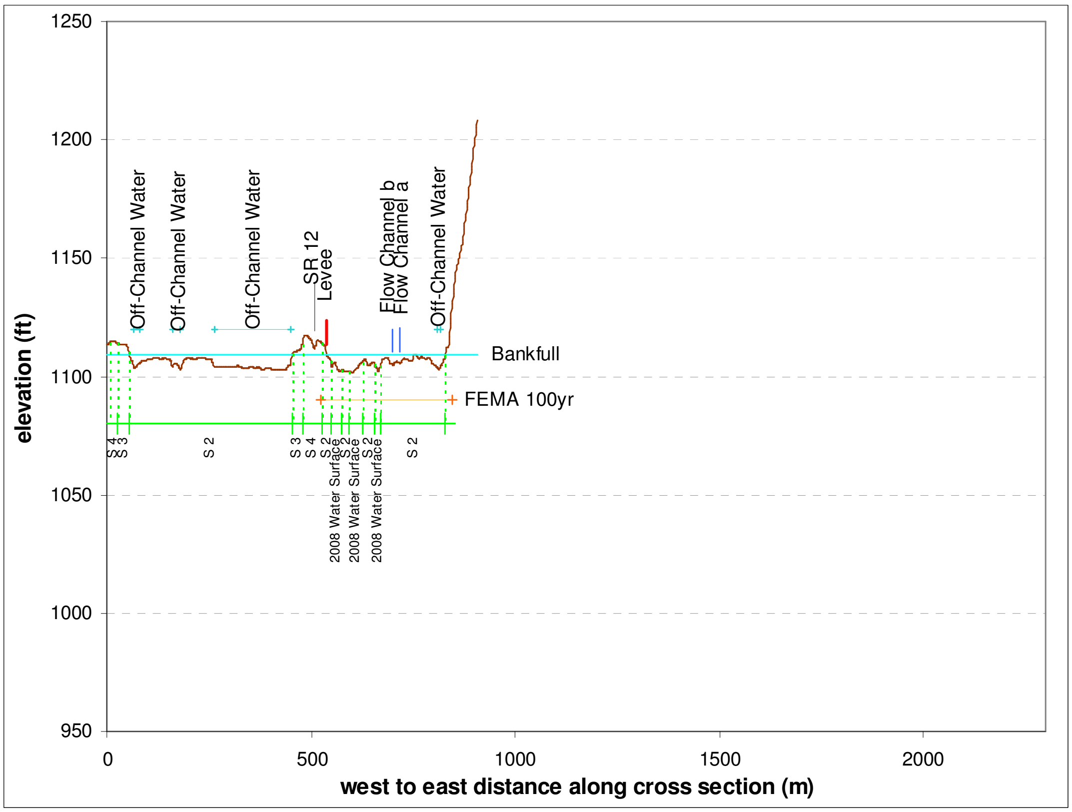
Rambler's Park Gap Reach XS 6



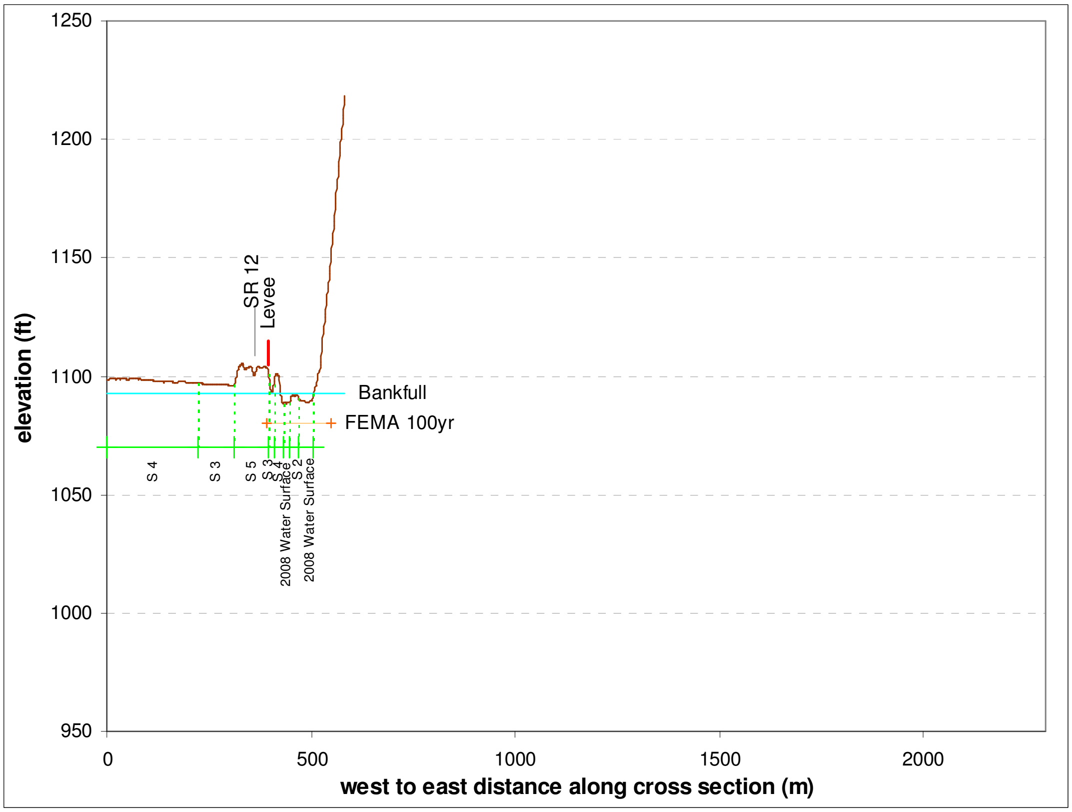
Rambler's Park Gap Reach XS 7



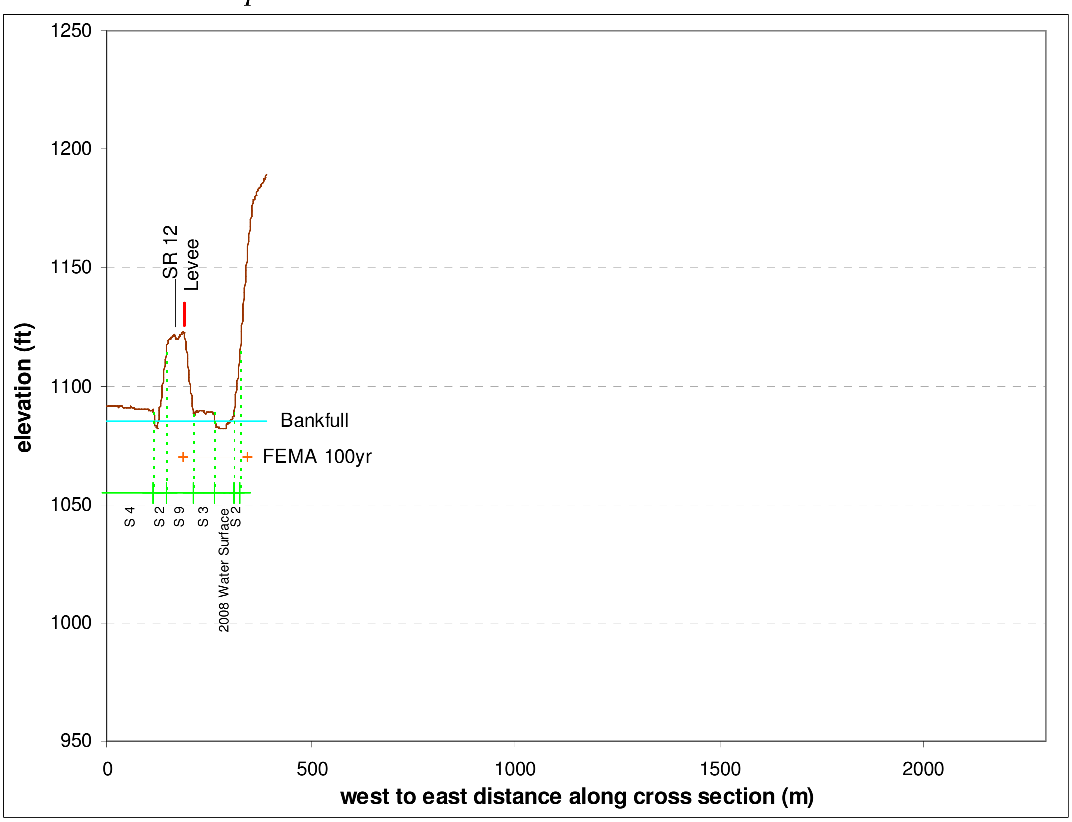
Rambler's Park Gap Reach XS 8



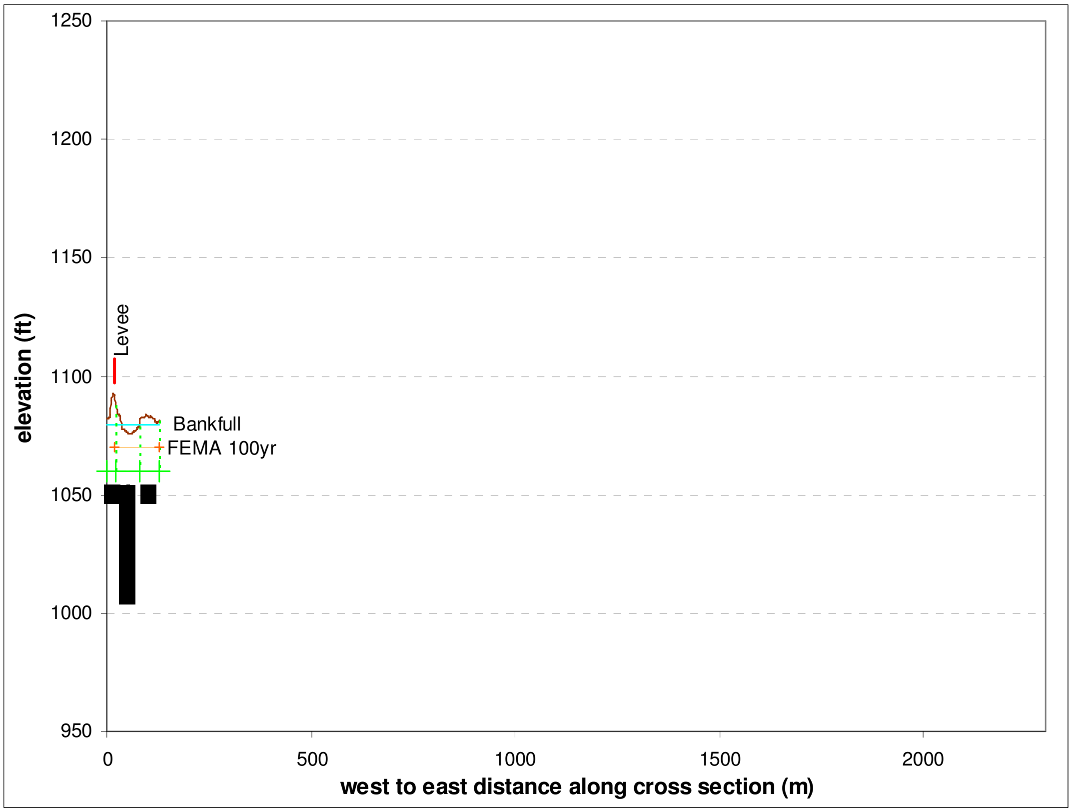
Rambler's Park Gap Reach XS 9



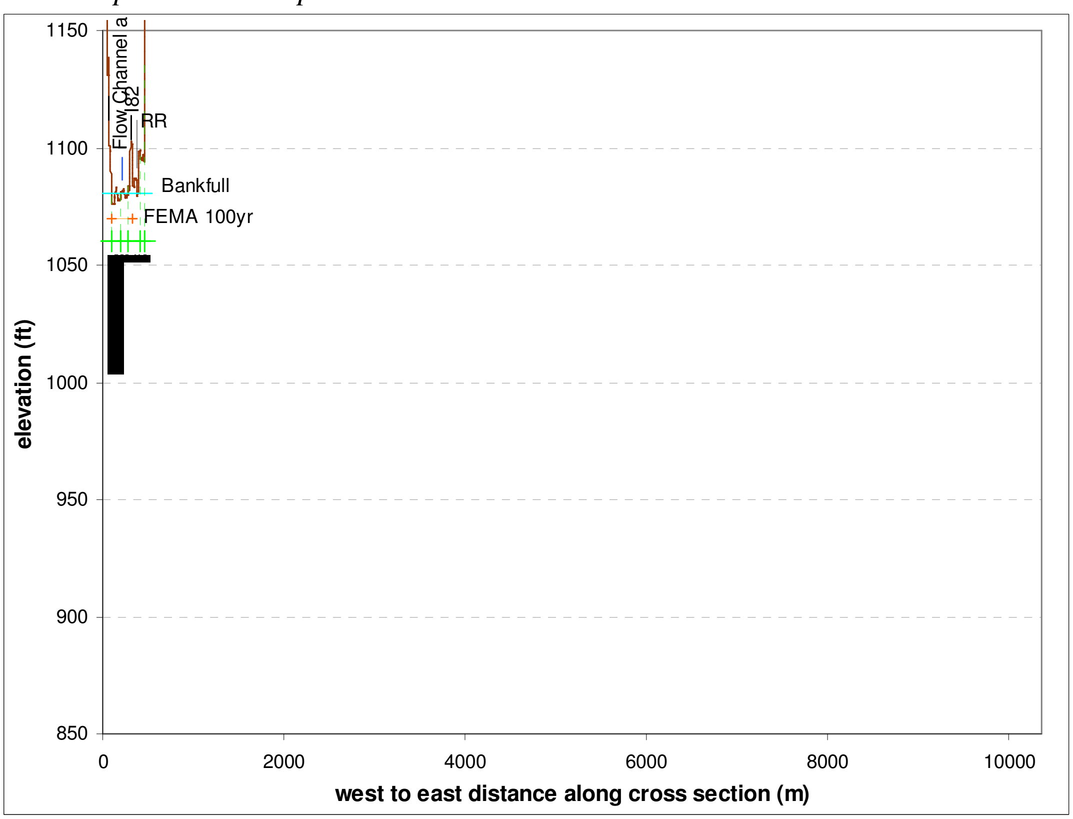
Rambler's Park Gap Reach XS 10



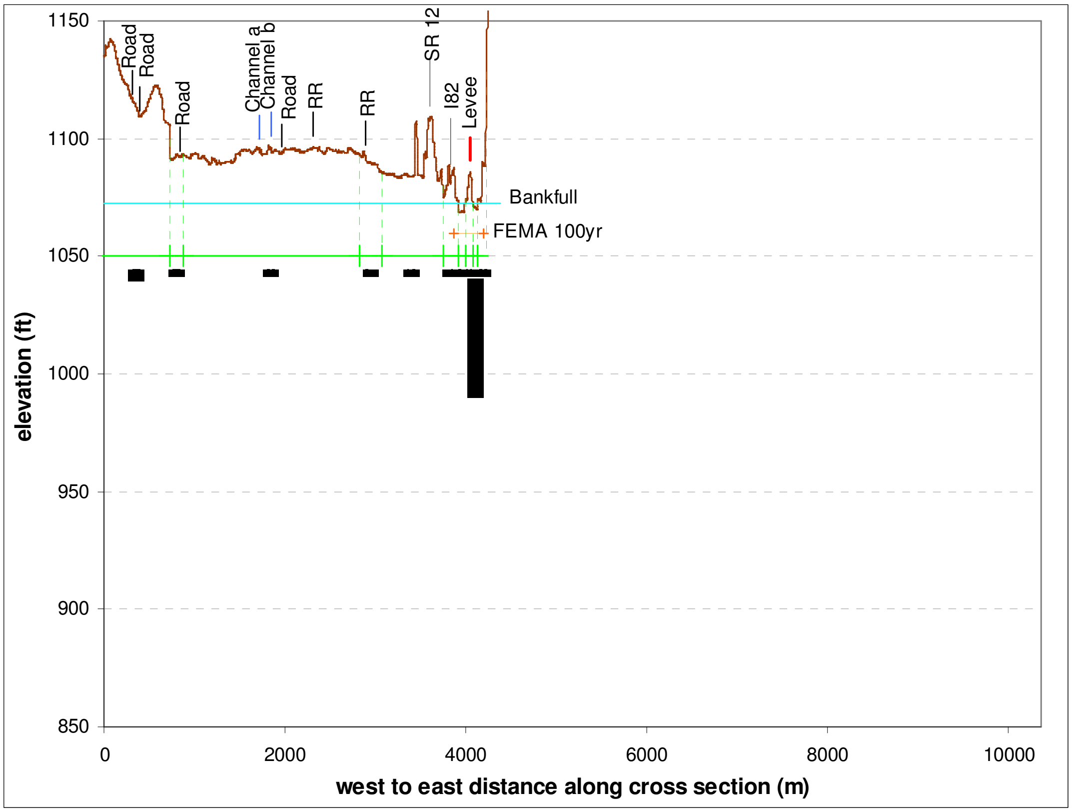
Rambler's Park Gap Reach XS 11



Selah Gap to Union Gap Reach XS 1



Selah Gap to Union Gap Reach XS 2



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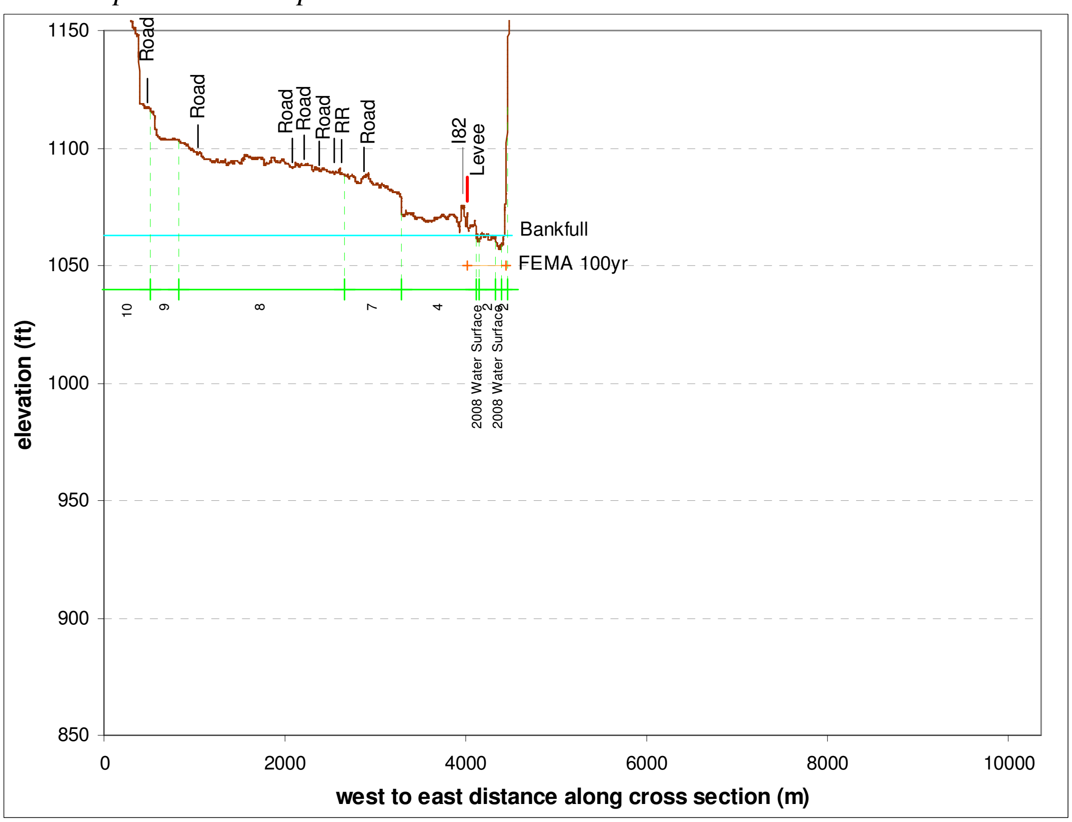

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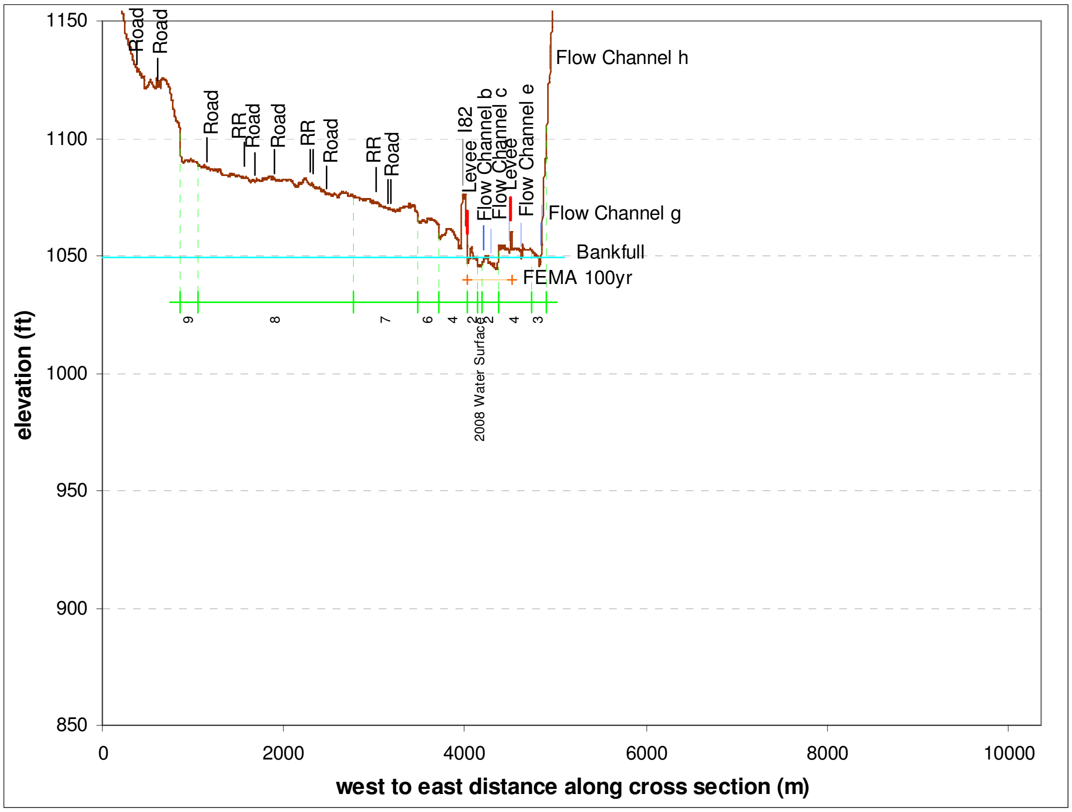

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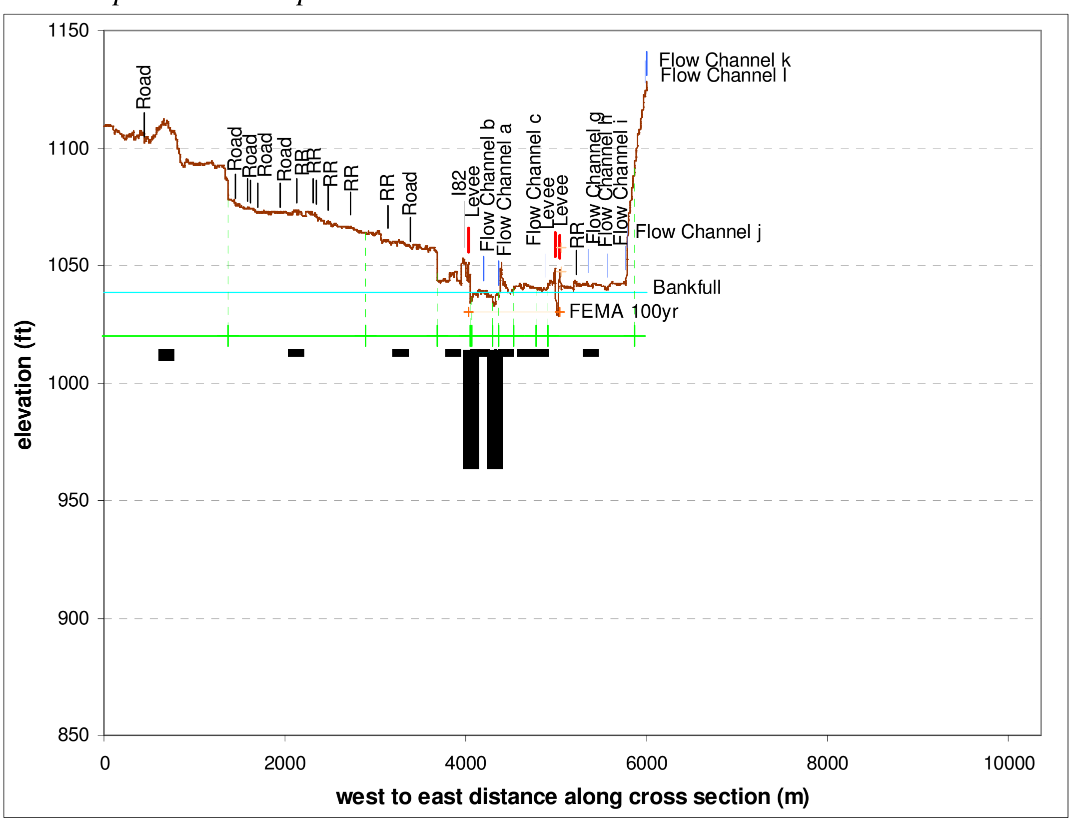

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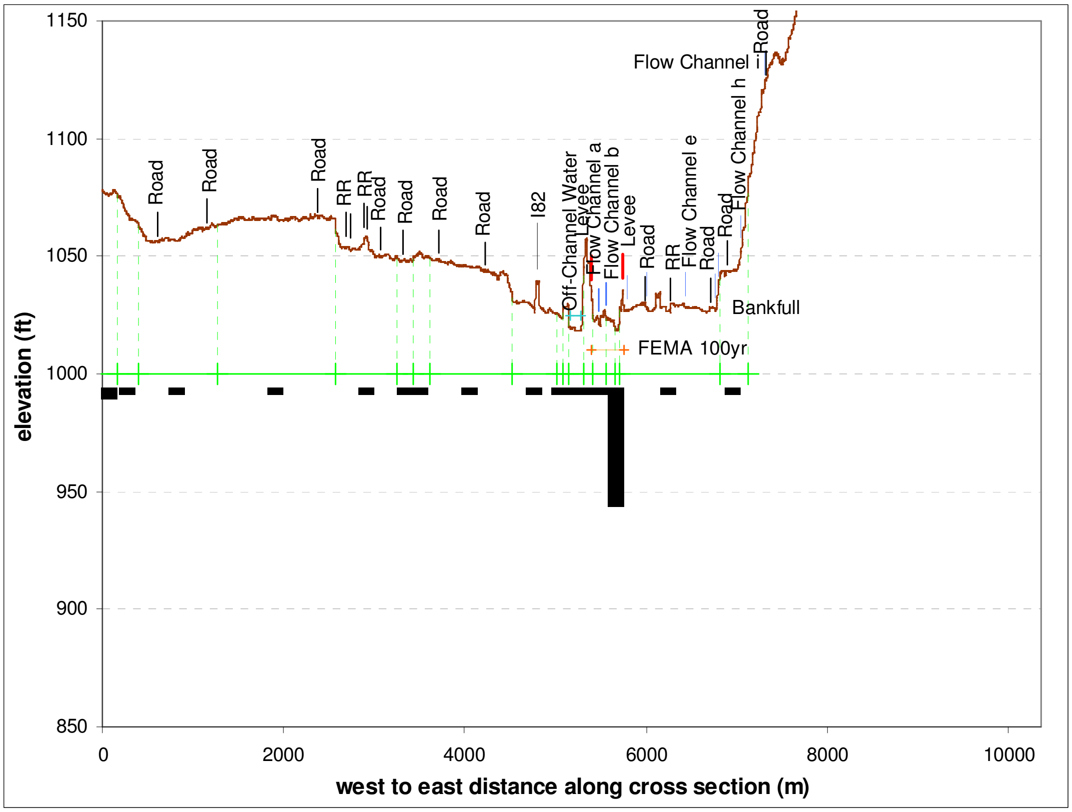

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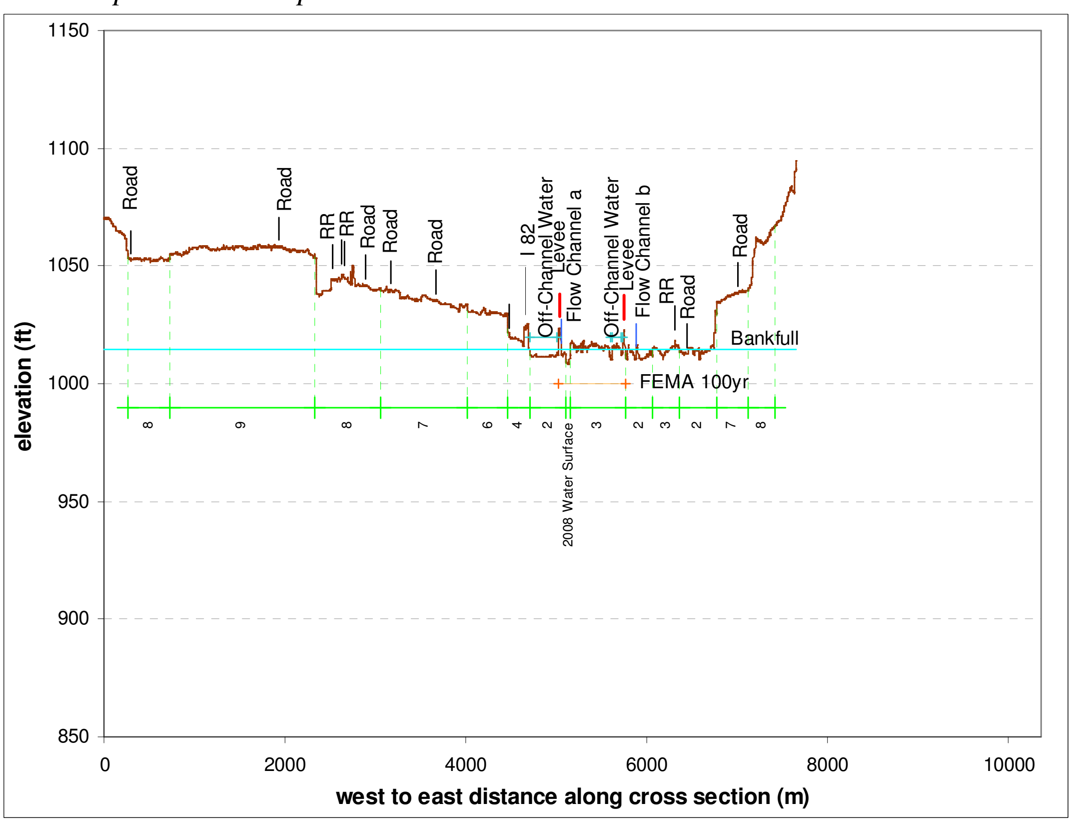

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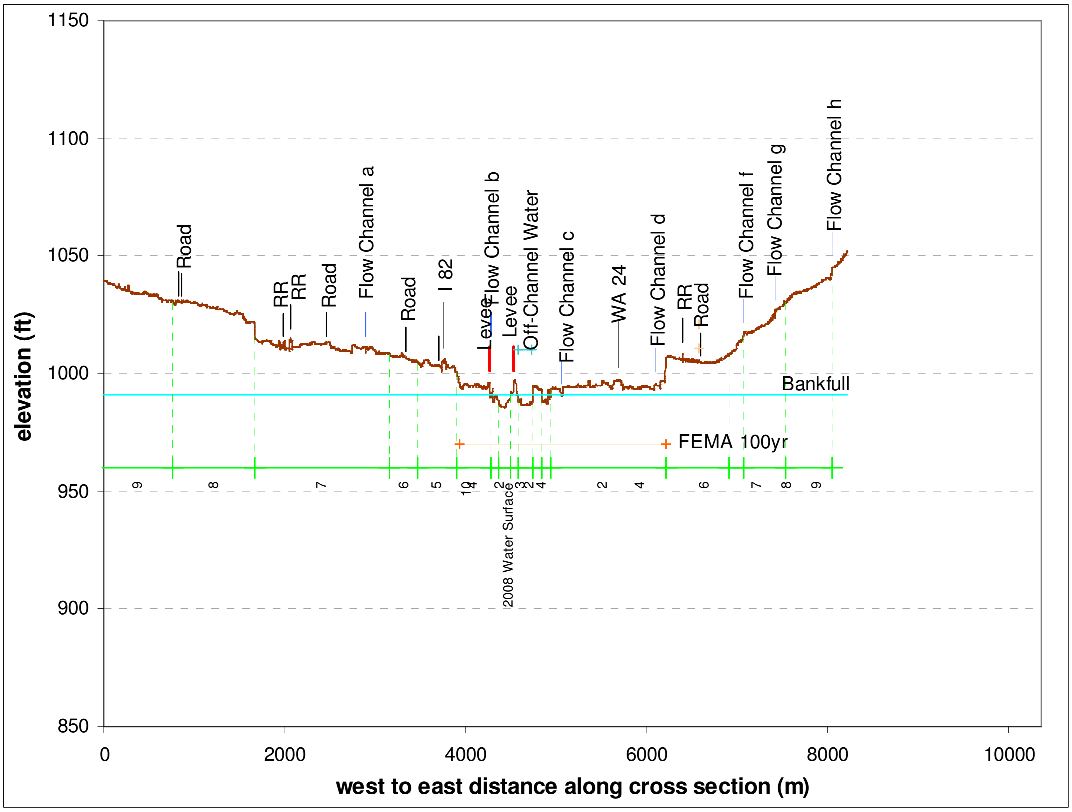

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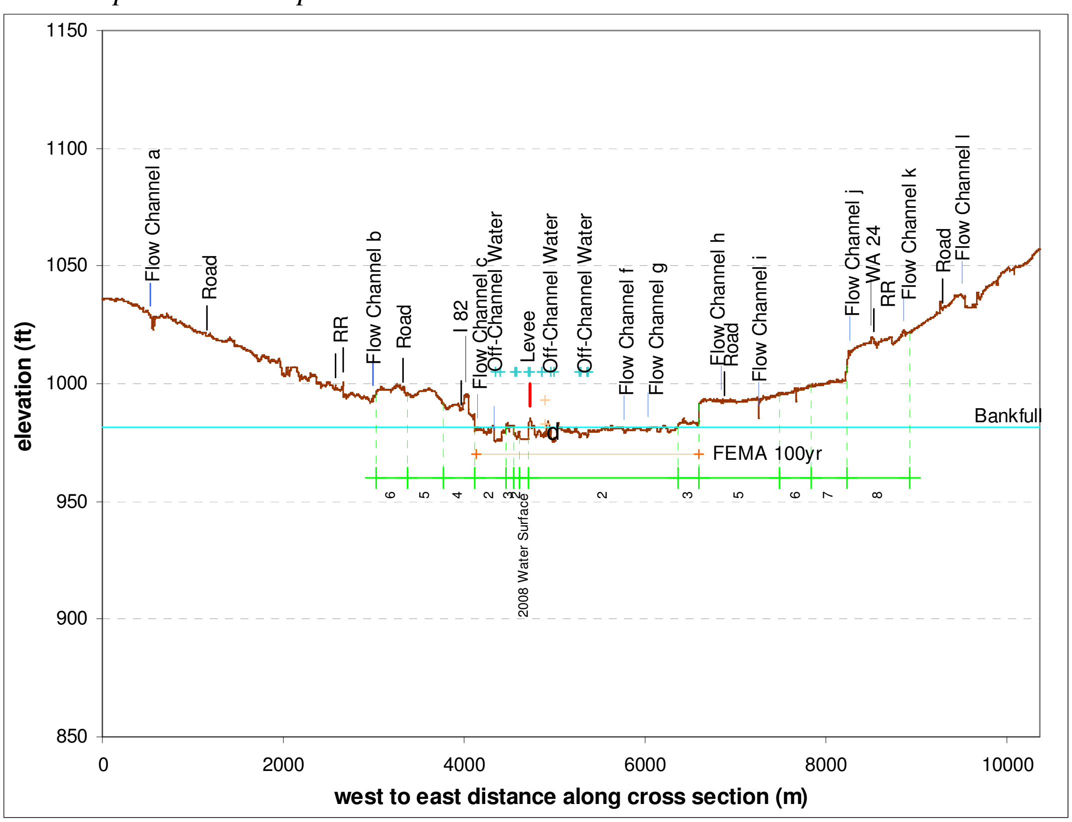

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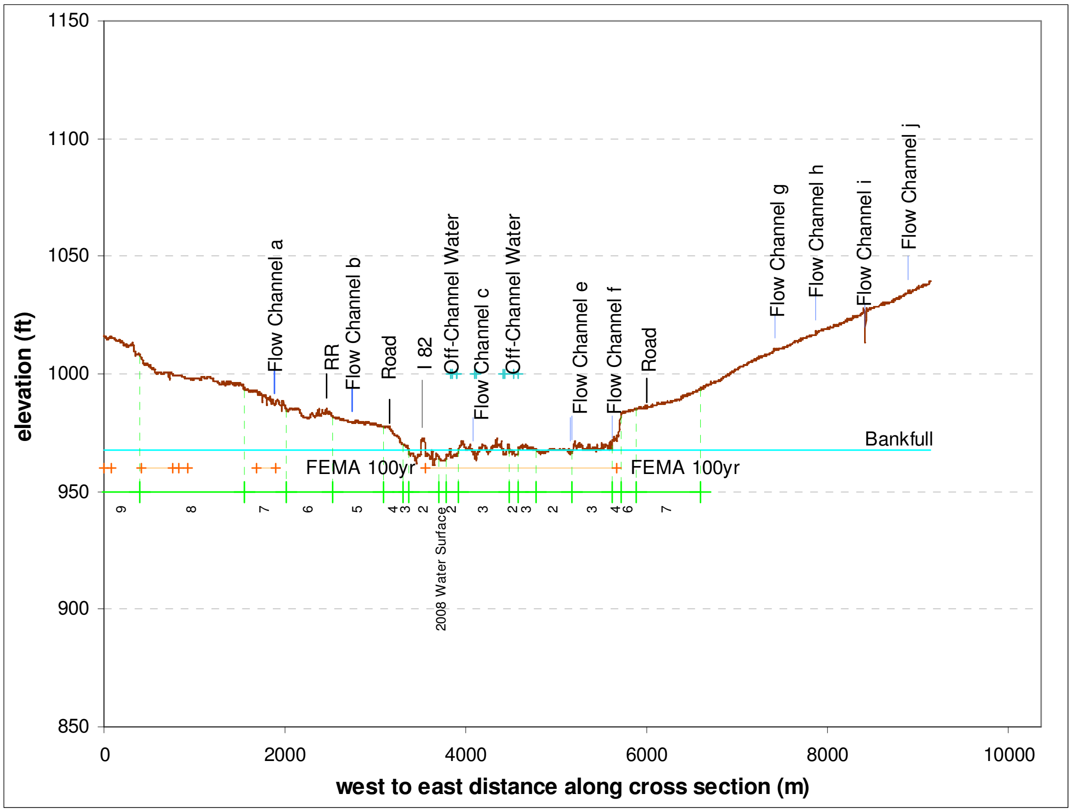

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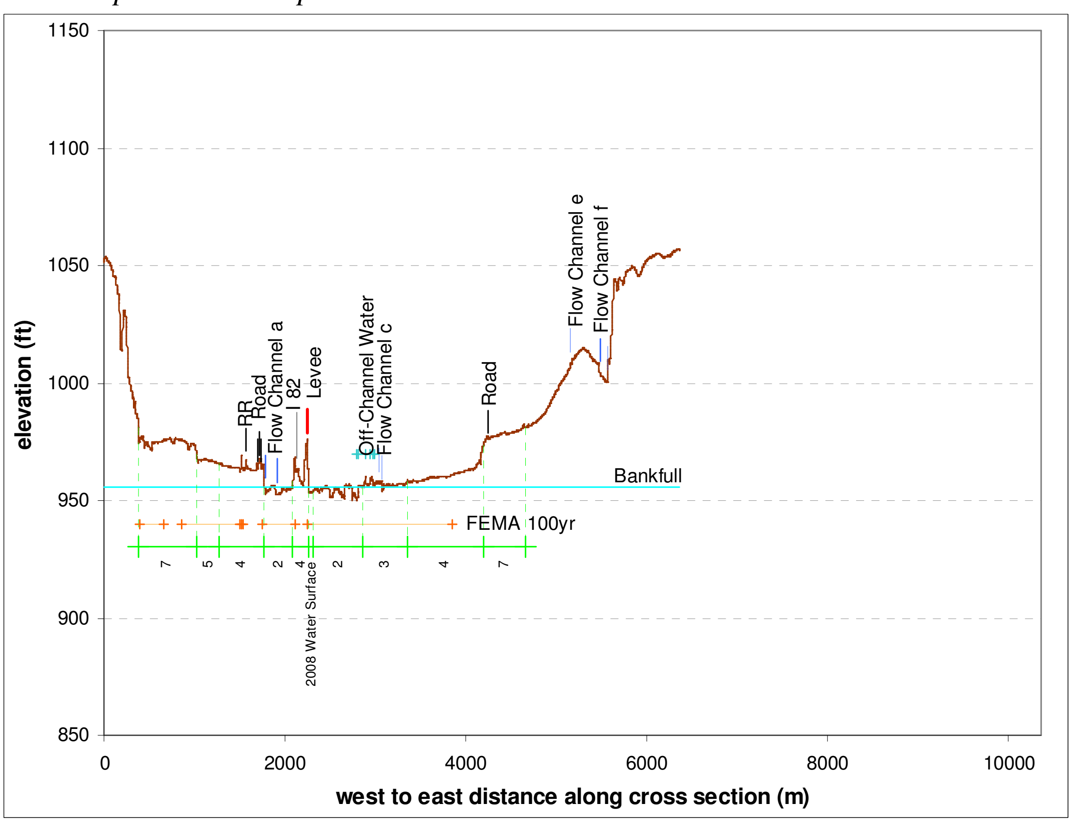
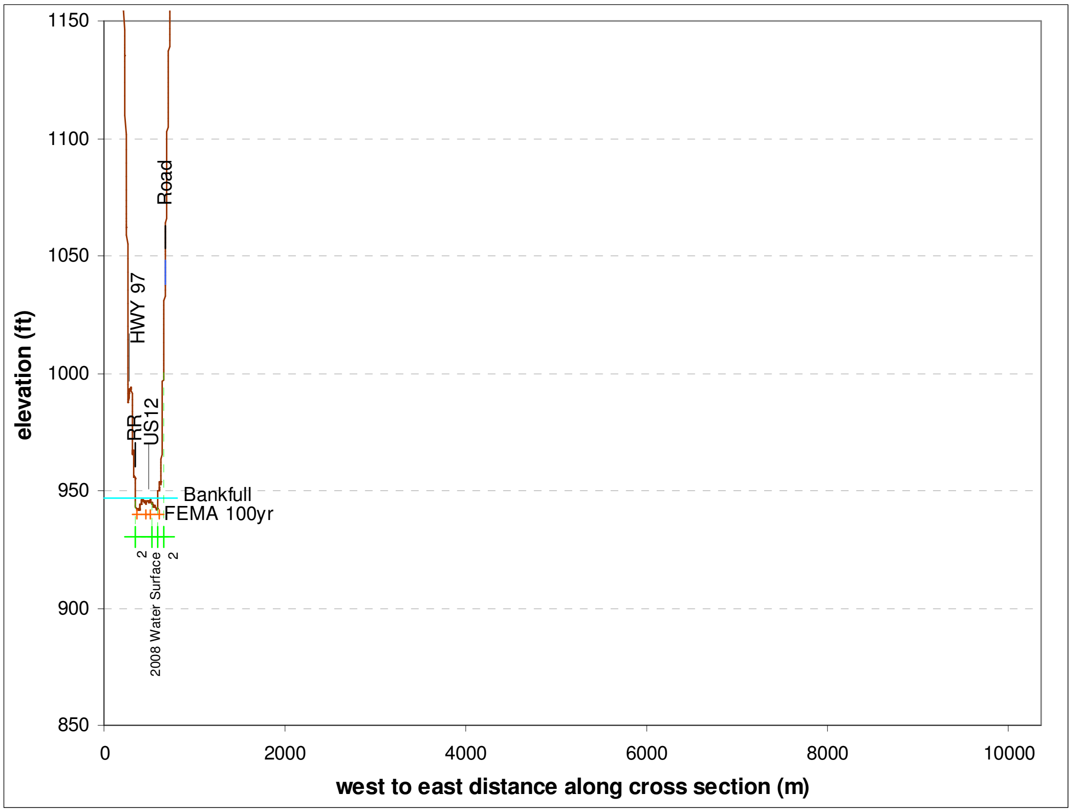


Selah Gap to Union Gap Reach XS 12



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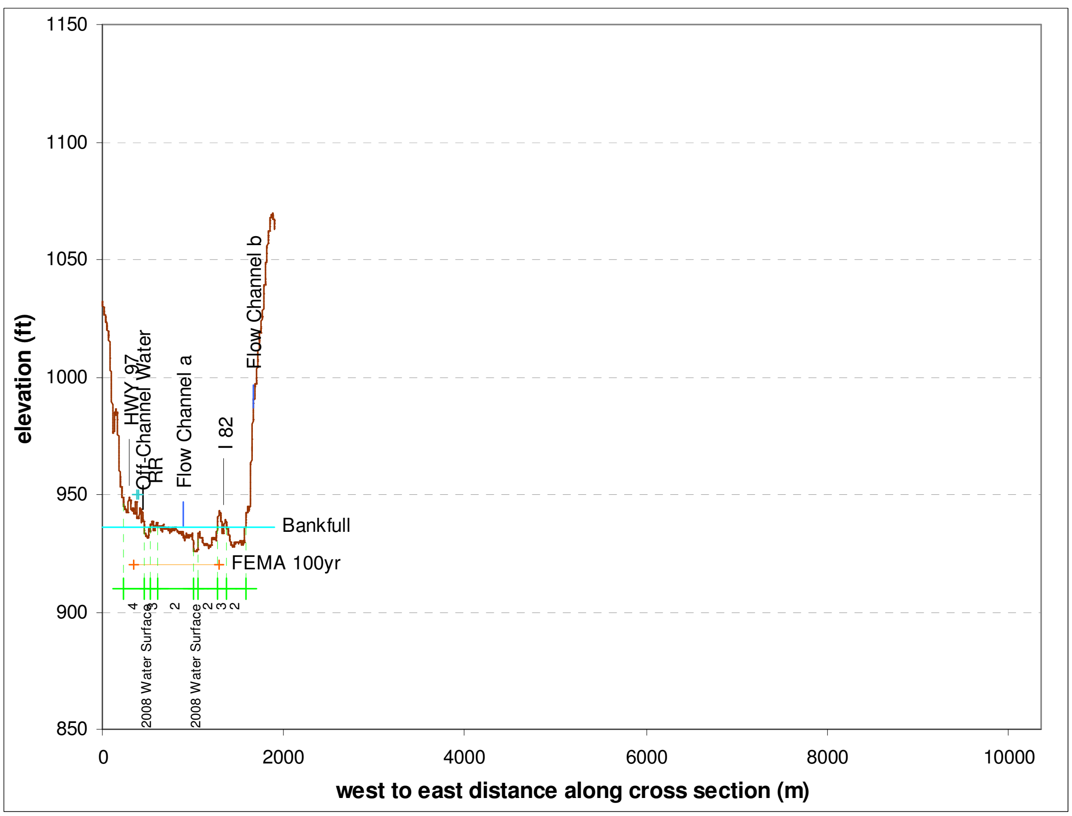

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