Memorandum

Northwest Hydraulic Consultants
16300 Christensen Road, Suite 350
Seattle, WA 98188
206.241.6000
206.439.2420 (fax)

DATE: December 10, 2012 NHC PROJECT: 0200051
TO: Erik Peters, P.E.
COMPANY/AGENCY: King County WLRD
FROM: Andrew Nelson, M.Sc., Derek Ray, M.Sc. P.Geo., Vaughn Collins, P.E.
SUBJECT: Reddington Setback Levee Project 65% Design Submittal: Geomorphologic Analysis

Introduction

King County has embarked on a long-term initiative to make system-wide improvements to the aging system of levees and revetments on the Lower Green River. Northwest Hydraulic Consultants (NHC) has been engaged to provide engineering design services for the Reddington Levee Setback Project between River Mile (RM) 28.25 and 29.5 near Auburn, Washington. A geomorphic analysis was performed to support the integrated erosion protection design for the setback project. This memorandum presents the results of work to evaluate and determine likely river response to the change in river hydraulics and channel confinement associated with the proposed levee setback.

Specifically, the main objectives of this analysis are to a) predict future channel pattern, b) predict where the river is most likely to encroach upon the new levee within a 10- to 50-year timeframe, and c) provide geomorphic context to guide engineering design of the erosion-protection system. A primary assumption in this analysis is that both the existing left bank levee as well as associated riprap armor will be removed as part of the proposed setback project.

In order to address these objectives, we have evaluated long-term historical changes to the factors controlling the geomorphic evolution of the Green River channel along the Auburn Reach between RM 26 and 31.5, and the channel response to those changes. Our approach is to place the project site in a basin, reach, and historical geomorphic context; evaluate processes causing channel migration and geomorphic change at the reach scale; and translate these reach-scale observations to local predictions of plausible channel migration.

Project Location and Basin Context

The project site is located between RM 28.25 and 29.5 (Figure 1, Figure 2) on an alluvial ridge of the Green River in the Duwamish Trough, a low gradient, relict glacial valley. The Duwamish trough was scoured by a subglacial stream to a depth on the order of 500 feet below modern sea level during the Pleistocene period of repeated glaciation and was subsequently filled to its present surface elevation with deltaic, alluvial, and lahar deposits (Dunne and Dietrich 1978, NWAA 2010, Collins and Montgomery 2011). The transition between the eroding Green River Valley and aggrading Duwamish

Trough lies just upstream of the project site (Collins and Montgomery 2011); and so the project site is located in a zone of transition of channel character, with downstream increase in water depth and reduction in water surface slope and boundary shear stress (Figure 3). The Green River Gorge lies upstream of the Green River Valley (Figure 1). Sandstone and mudstone eroding from the walls of the gorge contribute a large amount of sand and finer sediment (Dunne and Dietrich 1978), and landslides of glacial drift from the margins of the Green River Valley contribute significant gravel volumes (Perkins 1993). Additionally, the Army Corps of Engineers began a program of annually nourishing the river with approximately 10,000 tons of 13-254 mm gravel and cobbles (D_{50} ~100 mm) in 2002. It is unlikely this material is directly influencing the project reach, although a small fraction of the finer material may eventually reach that far downstream.

The Auburn Narrows reach of the Green River is located at the transition between the Green River Valley and Duwamish Trough. This reach is confined against the wall of the Duwamish Trough by the White River Alluvial Fan, which controls the slope of the Green River Valley upstream of RM 32. The abrupt reduction in channel slope upstream of Auburn Narrows creates a region of low shear stress (Figure 3) where a significant amount of sediment is deposited, resulting in persistent channel instability between RM 32 and 35 (Perkins 1993).

The river currently has an entrenched, single-thread meandering planform through the project reach (Figure 2). The right bank is armored with revetments of various types along almost the entire length; the left bank is mostly armored upstream of RM 29.75, and mostly unprotected downstream of RM 29.75. There are occasional bars associated with areas of active migration, which has mostly been suppressed by human intervention since the 1960s. Local water-surface gradients range from 0.0005 to 0.00125 (Figure 3). The mean ordinary high water channel width is 130 ft, and the mean low-flow wetted width is 110 ft (Anchor QEA, 2004). Pebble counts of gravel deposits show a downstream-fining trend between the Auburn Narrows and Horsehead Meander (Table 1). The banks are composed of 10-15 feet of fine sand and silt, which are interpreted to be Green and/or White River over-bank alluvial deposits, over up to 15 feet of sandy gravel, which are interpreted to be Green and/or White River channel deposits (NWAA 2010).

Table 1: River bed sediment grain size characteristics along Green River between the Auburn Narrows and Horsehead Meander (data from Anchor QEA, 2004).

RM	Location Description	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
31.75	Upper Auburn Narrows	32	85	181
30	Just below island	11	45	85
29	Center of project reach	13	41	75
27.5	Below 277th St	11	26	45
26.5	Horsehead Meander	3	27	60

Historical Context

Three main factors that strongly influence the geomorphology of the Green River in the project reach have changed dramatically during the historical period. These are the diversion of the White River in 1906, regulation of river flow by Howard Hanson Dam beginning in 1962, and construction of bank revetments and levees through the 20th century.

From the beginning of historic records through 1892, the White River typically flowed north across its alluvial fan to join the Green River near present-day Green River mile 31 (Figure 2). Below this confluence, the joined rivers were called the White River, which flowed in an alignment generally similar to that of the present-day Green River. The White River avulsed into the Stuck River and flowed south for several short periods between 1892 and 1900. A log jam diverted the flow of the White River again into the Stuck River in 1906, and engineering structures were put in place thereafter to permanently maintain this arrangement (Jones and Jones 1978). This diversion significantly altered the flow regime downstream of the former confluence, reducing peak flows by over 50%. It also dramatically reduced sediment transport into the project reach. Perkins (1993) suggests that this diversion reduced the sediment and water supply to the Green River below RM 31 by "more than half". To understand the relative magnitude of this and other historical changes to conditions governing the geomorphic function of the Green River in the project reach, a rough sediment transport model was constructed. This model applied the Wilcock and Crowe (2003) sediment transport function as implemented in BAGS (Stream Systems Technology Center 2009) to the location of local channel shear-stress minima at the head of Auburn Narrows using the upper Auburn Narrows grain size distribution reported in Anchor QEA (2004). A discharge-bed load transport rating curve was developed and applied to both pre- and post- dam flow duration curves to generate estimates of annual bedload transport volumes.

A recent study of sediment transport capacity and channel change on the White River (Czuba, Czuba, Magirl, & Voss, 2010) indicates that the White river presently transports 10,000 to 70,000 cubic yards of bedload annually. Assuming this volume is representative of historic conditions and comparing it to the sediment transport estimate for the Green River, indicates the present day Green River may transport an order of magnitude less bedload than when the two rivers were joined.

Secondly, the Howard Hanson Dam was completed in 1962, cutting off the sediment supply from 55% of the Green River's watershed above Auburn and altering the flow regime downstream. Flood peaks, which varied between 10,000 to 48,000 cfs under pre-dam conditions, are now regulated to a target of 12,000 cfs at the 1% annual probability flood peak flow (this is approximately the pre-dam 2-year flood). The regulation has resulted in the doubling in duration of flows between 2,000 and 10,000 cfs. The net effect of reduced peak floods and an increased duration of moderate flows on the overall sediment transport capacity of the river is not intuitively clear. Dunne and Dietrich (1978) speculated that the reduction in sediment supply and increase in duration of sediment transporting flows could lead to instability caused by an imbalance of reduced sediment supply and increased transport capacity. Pre-regulation flood flows, while much higher in magnitude, would have spilled over the left bank to Mill Creek and Mullen Slough, limiting the depths and shear stress in the channel. In addition, the channel had a wider, possibly shallower, cross sectional geometry prior to the White River diversion, and levees have been constructed concentrating flow in the current channel. The net result is that it is possible that the shear stress on the bed associated with a 12,000 cfs event today may be comparable to, or greater than, that of a pre-levee, pre-dam 20,000 cfs event. The bed load transport analysis described in the previous paragraph indicates that the post-regulation flow regime has increased the sediment transport capacity of the Green River by approximately 50%.

The White River diversion and the construction of Howard Hanson Dam have each reduced the influx of sediment into the project reach by a greater proportion than the change to the flow through the reach. Channel degradation and transition from a multiple-thread to single-thread channel are expected responses to these first two changes.

The third change in the macro-scale factors controlling the morphology of the Green River through the project reach has been the construction of bank revetments and levees. A few bank protection structures are shown on a 1907 Army Corps of Engineers map (Perkins 1993). Most existing revetments were constructed in the 1960s. Between RM 25 and 31, 75% or more of the bank length has some sort of revetment today. Revetments and levees have reduced channel migration and resulted in hydraulically smooth banks where less energy is dissipated relative to pre-development conditions, and which are less likely to accumulate logjams. This may have concentrated energy dissipation in unrevetted areas, increasing river migration potential in those areas, and increased shear stress along revetted banks, further exacerbating the effects of sediment starvation from the White River Diversion and flow regulation at Howard Hanson Dam.

Geomorphic Response to Historical Changes

Historical changes to the sediment supply and hydrologic regime, along with the construction of bank revetments, have caused pronounced changes to the Green River channel in the project reach. Historical maps and air photos show changes to the planform morphology of the stream, gage records from the USGS gage at Auburn (Figure 6) show changes in the bed elevation, and observation of modern topography shows the combined effect of these changes.

Transition from Wandering to Meandering Planform

Historic channel occupancy maps (Figure 4) show that the position of the Green River channel in the project reach has been much more stable over the past 39 years than it had been in the previous sixty-seven years. This change in overall lateral stability has accompanied an evolution in channel planform from a wandering (i.e. sinuous and occasionally braided) form to a meandering (i.e. sinuous single thread) form.

The channel trace from the 1906 map (Figure 5) shows a wandering planform with abundant islands, bars, and side channels. This planform is typically associated with relatively high rates of transport of bedload sediment, which is consistent with what is known about the sediment supply that would have come from the White River. Following the diversion of the White River, the Green River began to stabilize. In the 1936 air photo (Figure 5), secondary channels behind most islands had filled with sediment and the low flow channel wetted width had narrowed from ~300 feet in 1906 to 150-200 feet, but large unstable bars had persisted in some areas. By 1960, the channel had narrowed further to approximately 100 feet and all but one large gravel bar and two small islands (near RM 29) had disappeared. In the mid-1960s, construction of a levee and revetment cut off the left branch-channel around this island, and by 1978 the evolution to a single-thread meandering channel was complete. After 1978, changes in the channel position occurred through gradual lateral migration in isolated locations, but the general channel form remained stable.

Notwithstanding the reduction in sediment supply from the White River diversion, the sudden reduction in flood flows following completion of Howard Hanson Dam occurred at a time when there remained an abundant source of sediment within the channel in the form of bars and vegetated islands. The bedload

starvation caused by relative imbalance between channel transport capacity and sediment supply may have resulted in a brief period of increased channel instability.

Evolution from a wandering planform to a single-thread meandering planform is consistent with a reduction in bedload and general increase in stability (Schumm 1985). The relative stability of the channel planform from 1960 to the present indicates that any changes to the channel planform that are a consequence of regulation and sediment trapping at Howard Hanson Dam are small compared to the adjustment to the White River's diversion.

Changes in Bed Elevation: Degradation

The transition from a wandering to single-thread meandering planform has been accompanied by significant degradation of the river bed. USGS stream gage records from the Auburn gage (station 12113000), just upstream of the historical White River confluence, show that the bed elevation dropped by approximately 2.5 feet between 1936 and 1988, and that the bed elevation has been generally stable or slightly aggrading from 1988 to the present (Figure 6). It is likely that significant degradation also occurred in the period between 1906 and 1936, given the pronounced planform adjustment that was occurring during that period. Based on the change in floodplain elevations that is described in the following section, it is possible that total channel degradation since 1906 has been on the order of 10 ft.

The gage height record from upstream is consistent with a comparison of repeat cross sections from 1985, 2006, and 2010 along the project reach (presented in full in Tetra Tech 2011). Two of the ten cross sections along two miles of the river show slight (1.2 to 1.4 feet) degradation while the remaining eight show zero to 1.4 feet of aggradation. In addition, comparison of the 1962 constructed channel at the project site with 2010 cross sections show that the bed has remained generally stable since then. Two of the cross sections show about 1 foot of thalweg degradation, but this is accompanied by slight channel narrowing and formation of bars, so that the average channel elevation at these locations has remained fairly stable over this 50 year period.

Modern Topography and the Interaction of Planform and Bed Elevation Changes

Several locations along the project reach show areas where recent (post 1960) migration has resulted in the formation of a new floodplain surface that lies significantly below the pre- White River diversion floodplain (e.g., at RM 26.8, 27.25, 27.5, 28, 28.5, 29.25, and 31 (see Figure 2 and Figure 4). The formation of this new floodplain is a consequence of the evolution from a wandering to meandering planform and downcutting of the channel bed. As the new, lower channel has migrated where not fully confined by revetments, it has eroded into the relict higher floodplain (now a terrace) and deposited sediment on the inside of meander bends at a lower elevation. This has formed an "inset" floodplain where modern flood flows are confined within the banks of the relict channel. The newly formed inset floodplain is typically vegetated, and lies 1-5 feet below the 2-year flood (8700 cfs) water surface.

Survey and LiDAR data were used to evaluate the elevations of the modern day inset floodplain and relict floodplain (terrace) elevations. Elevations were determined from cross sections cut across locations where inset floodplain surfaces had developed between RM 26 and 32. These elevations are plotted in Figure 7. Regression of the floodplain elevations versus river mile shows that, between RM 26 and 31, the slope of newly formed floodplain surfaces is approximately 0.00086. This is slightly steeper than the slope of the relict terrace surface (0.00064) (Figure 7). As a result, the difference in height between the pre-1906 floodplain and the newly forming floodplain ranges from 6-12 feet, and generally

increases downstream. Figure 8 shows a cross section at RM 27.4 showing the surface of the pre-1906 floodplain gently sloping away from the top of the channel bank, and the modern inset floodplain 10 feet below that surface.

The development of a thick layer of turf grass on the modern inset floodplain could be having a profound effect on the low- to medium-flow channel shape. Grasses that form a turf layer on the lower-elevation inset floodplain are very resistant to erosion and at the same time trap fine overbank sediments. The result appears to be a near-vertical bank margin, particularly on the insides of bends, rather than the sloping surface that is more typical of inside bend depositional bars. Once these sediments are protected by turf, higher flows cannot re-mobilize them, leading to further channel narrowing.

Modern Channel Migration

Recent Behavior

Observation of historical maps and air photos and the USGS specific gage height record suggests that the river has undergone a change in geomorphic regime in response to the diversion of the White River. It appears that this regime change occurred mostly in the first half of the 20th century, and that the geomorphic response to flow regulation and sediment trapping at Howard Hanson Dam has been comparatively smaller. Historical channel migration in nearby unrevetted areas over the past 60 years provides the best guide to possible future behavior in response to revetment and/or levee setback. The best analog areas occur at three sites just downstream of the project location between RM 26.5 and 28.25 (Figure 9). This is an area of slight downstream reduction in the water surface slope, while the project reach is in the middle of an area of relatively constant water surface slope. This means that the rate of local sediment deposition and consequent channel migration may be slightly higher at the three analog sites in this reach than in the immediate project vicinity. At these sites, the pattern of this migration has been gradual meander migration caused by point bar sediment deposition. Migrating meanders are translating downstream with little meander amplification (see Figure 9 for definition of these terms).

Three actively eroding unrevetted meander bends between RM 26.5 and 28.25 have migrated at rates between 8 and 16 feet per year with an average rate of 11 feet per year (Figure 9). These rates are greater than the average rate of 3.8 feet per year for eroding, non-armored areas in the same vicinity in the period between 1960 and 1992 determined by Perkins (1993). The discrepancy is possibly due to different interpretations of “actively eroding”. Slight meander amplification has occurred at two of the three active sites, with rates of up to 4 feet per year. Perkins (1993) found an average rate of 1.2 feet per year for all unrevetted areas in the same vicinity.

Future Geomorphic Evolution

It appears that the Green River channel in the vicinity of the project site had mostly re-equilibrated to the modern day governing-condition regime by the late 1960s. The best forecast of future geomorphic evolution in response to levee setback in the project reach can be obtained by applying what is known of the pattern and rate of migration at nearby unrevetted analog sites. Using these analog sites as guides, it is possible to say that lateral migration at the outside of meander bends, primarily through downstream meander translation, is likely and could proceed at rates on the order of 10 feet per year.

This migration will be accompanied by the formation of a new, lower floodplain surface within the modern inset floodplain, approximately 10 feet below the existing relict floodplain surface.

The new, lower floodplain surface (which is proposed for construction in some locations and expected to develop naturally in others within the project reach) will allow flows greater than approximately a one-year event to locally spread out and consequently reduce shear stress on the channel bottom. Preliminary one-dimensional hydraulic modeling indicates reductions in bed shear stress by up to 50% (Figure 10), matching levels similar to those for wider areas downstream where active deposition and channel migration are occurring. Typical responses to reductions in shear stress include local bedload deposition, LWD accumulation, bar formation, and aggradation. It is possible to look at the analog locations of locally reduced shear stress downstream to qualitatively evaluate the likely response to possible reduced shear stress on the bed at the project site. Downstream analog locations are primarily areas where channel migration in the past several decades has occurred and resulted in formation of a locally wider inset floodplain (see RM 27.5 and 28 on the right panel of Figure 4). In these locations, the primary morphologic response to channel widening and reduced shear stress appears (on the basis of the air photo record and limited repeat cross section surveys) to be local sediment deposition causing growth of point bars and migration of the thalweg, not an increase in the thalweg bed elevation. Lateral channel migration rates similar to those that have occurred in the downstream areas are likely at the project site.

Principal Erosion Risks

Risk Zone Delineation

Potential channel migration risk zones were evaluated in order to guide design of erosion protection for the setback levee and Tacoma Water Pipeline. The following assumptions were made in this evaluation:

- All non-project revetments (on the right bank and up- and downstream of the project area) will remain in place.
- The 1960-2011 migration patterns and rates at the analog sites are reasonable predictors of future behavior.

Table 2 shows unconstrained migration buffer distances derived from applying observed migration rates at the analog sites to various time intervals. Migration buffer distances for the extreme, high, and moderate bands were defined by multiplying the average observed migration rate by the number of years represented by the band. For example, the average observed migration rate in the translation direction on the outside of meander bends is 11 ft/year; when multiplied by 5 years, this gives a migration buffer distance of 55 ft. For the low band, the buffer distance was defined by multiplying the maximum observed migration rate by 50 years.

Table 2: Criteria used in channel migration hazard assessment.

Geomorphic Location	Observed Migration Rate (R) (ft/yr)		Unconstrained Migration Buffer Distances (ft)			
	Average $\overline{R}$	Maximum R_{max}	Extreme: Likely within 5 years	High: Likely within 10 years	Moderate: Possible within 50 years	Low: Plausible within 50 years
Buffer Calculation Formula			$\overline{R} \times 5$	$\overline{R} \times 10$	$\overline{R} \times 50$	$R_{max} \times 50$
Outside of Meander Bend (translation)	11	15	55	110	550	750
Outside of meander bend (amplification)	2	4	10	20	100	200

Migration hazard zones were developed based on the above meander migration rates with additional adjustments. These adjustments were applied in order of precedence as follows:

- All inset floodplain areas, including those on straight reaches and the inside of bends, were given a High Ranking in order to account for local perturbations, such as large wood jams, causing channel migration within a 10-year timeframe.
- Areas within 50 feet of the existing channel on straight reaches were categorized as Moderate.
- Channel Migration was not allowed beyond the design limit.

Results for the case where the design channel migration limit is the setback levee are shown on Figure 11. Risk zones were also delineated assuming the proposed erosion protection design (NHC 2012) is put in place to limit channel migration in key areas (Figure 12).

The most likely future channel migration scenario involves predominately downstream translation of existing meander bends. Significant changes in the phase or waveform of meanders do not appear likely as most of the right bank length will remain revetted through the project reach.

Avulsion Risk

Review comments during the design process included questions regarding the possibility of avulsion in the project reach, particularly at the RME wetland. At this location, the 1962 river channel was cut off during revetment construction, resulting in an unnaturally low floodplain and old channel path that will be reconnected to the river. Both of these factors could be considered as increasing the probability of avulsion.

In a review paper, Slingerland and Smith (2004) summarize that avulsion is likely where there is rapid aggradation of the main channel, a wide unobstructed floodplain that is able to drain downstream, and frequently occurring floods of high magnitude. These conditions provide a setup for avulsion where the channel is superelevated above the floodplain and where the ratio of the crevasse (or floodplain water surface) slope to main channel slope becomes elevated. Slope ratios in the range from 3 to 5 (consistent with the theoretical predictions) are observed in naturally avulsing systems. When conditions are favorable a triggering event, such as formation of a log jam, can initiate the avulsion, which may result in

complete stream capture, partial stream capture, or a failed avulsion (where the newly eroded channel ultimately is refilled with sediment and flow remains in the existing channel). Jerolmack and Mohrig (2006) distinguish between systems dominated by avulsion from systems dominated by lateral migration by calculating a mobility number *M* equal to the ratio of the time required for the river to aggrade one channel-depth above the surrounding floodplain to the time required for the channel to migrate one channel width by progressive bank erosion. They compiled a dataset from thirty net depositional systems and found that where M>>1, rivers migrate through avulsions and exhibit multiple active channels while where M<<1, rivers have a single thread channel and migrate laterally.

In this case, the Green River in the project reach is not aggrading, the channel is not currently superelevated, and the water surface slope through the wetland will be essentially identical to that in the main channel (i.e. a slope ratio of 1). With the evidence showing lateral migration will occur, but little to no trend of channel aggradation, the mobility number M is much less than one. Therefore the setup conditions favorable for avulsion are not present here. As a result, perturbances such as formation of a log jam will not necessarily trigger an avulsion.

Most of the factors that may increase avulsion risk are expected to have an initially low probability of occurrence immediately after construction, possibly rising over time. For instance, channel aggradation due to less river confinement could lead to increasing avulsion risk over time. In summary, an avulsion is not likely to occur in the short term after project completion, and the project reach does not exhibit a form that lends itself to avulsion. Long-term avulsion risk may increase, but the RME area is expected to be dominated by lateral channel migration processes similar to the rest of the project each for the foreseeable future.

Design Recommendations

Based on recent relative stability in the long-term channel elevation trend and channel planform, as well as predictions of continued future stability or slight aggradation, calculations of local scour depths based on the current channel conditions would reasonably apply to future channel conditions that are expected to occur following levee setback. It will be necessary to incorporate protection against these scour depths in the engineering design for areas at the outside of bends or locations where outsides of bends will likely abut the levee. Because project objectives include more naturalized river processes, engineered erosion protection is not necessary to protect against immediate threats in straight reaches or on the inside of meander bends unless infrastructure is at risk. Ongoing monitoring, however, will be important to detect the development of local channel perturbations that may cause development of new meanders. The engineering approach based on these observations is described in the basis of design memo (NHC 2012.

Conclusion

The Green River at the project site has undergone dramatic morphologic changes in the past century, evolving from a wandering planform to a meandering single thread river, and downcutting on the order of 10 feet. These were responses to changes in the governing conditions that occurred starting in 1906 with the diversion of the White River. This was followed in 1962 with the completion of Howard Hanson Dam and construction of revetments, primarily in the 1960s. The overall channel morphology appears to have been generally stable since the late 1960s. Since then, the channel (where not constrained by revetments) has migrated laterally through the mechanism of downstream meander translation at rates of 8 to 15 feet per year. Degradation has resulted in abandonment of the pre-1906 floodplain surface

that has effectively become a terrace. Recent migration has resulted in the formation of a modern inset floodplain 6 to 12 feet below the abandoned terrace. The overall channel degradation trend stalled, and may have begun to slightly reverse in the late 1980s.

It is assumed that the geomorphic response to setback of the Reddington Levee is expected to include channel migration rates and patterns that are similar to those observed at unrevetted locations. This would include gradual meander migration and continued formation of a new, lowered floodplain surface. Continued widening of the inset floodplain may possibly result in reduced channel shear stress and some aggradation. Levee protection should be designed to account for possible scour and movement at the outside of meander bends; but the levee protection can be reduced in areas where constraints on channel migration due to planform, revetments, or setback distance are expected to result in little risk of attack on the setback levee or other infrastructure.

References

Anchor QEA, 2004. Final Lower Green River Baseline Habitat Survey Report. WRIA 9 Strategic Assessment.

Collins, Brian D., and David R. Montgomery. 2011 "The Legacy of Pleistocene Glaciation and the Organization of Lowland Alluvial Process Domains in the Puget Sound Region." *Geomorphology* 126, no. 1–2: 174–185.

Czuba, J. A., Czuba, C. R., Magirl, C. S., & Voss, F. D. (2010). Channel-Conveyence Capacity, Channel Change, and Sediment Transport in the Lower Puyallup, White, and Carbon Rivers, Western Washington. USGS Scientific Investigations Report 2010-5240.

Dunne, T, and Dietrich, W.E., 1978. Technical Appendix A in Jones and Jones, 1978. A River of Green: Hydrology, sedimentation, channel migration, and flood diking along the Green River: Seattle, Report to King County. P. A1-A33.

Jerolmack D,J., Mohrig, D., 2006, The conditions for avulsion-driven rivers, in Jerolmack, D., Modeling the Dynamics and Depositional Patterns of Sandy Rivers. Ph.D. Thesis MIT

Jones and Jones, 1978. A River of Green: Hydrology, sedimentation, channel migration, and flood diking along the Green River: Seattle, Report to King County.

NHC (Northwest Hydraulic Consultants), 2012 Reddington Setback Levee Project 30% Plan Submittal: Basis of Erosion Protection Design. For King County, WA.

NWAA (Northwest Archaeological Associates, Inc.) 2010. Cultural Resources Overview for the Reddington Levee Setback and Extension Project, King County, WA.

Perkins, S.J., 1993. Green River Channel Migration Study. King County Department of Public Works, Surface Water Management Division, Seattle, WA.

Schumm, S. A., 1985. "Patterns of Alluvial Rivers," *Annual Review of Earth and Planetary Sciences* 13: 5–27.

Slingerland, R., Smith N., 2004, River Avulsions and Their Deposits. Annual Reviews in Earth and Planetary Science v. 32 p. 257-285.

Stream Systems Technology Center, United States Forest Service, 2009. BAGS: Bedload Assessment in Gravel-bedded Streams. Software, Online. < http://www.stream.fs.fed.us/publications/bagsfaq.html>. Last Accessed April 2012.
Tetra Tech, 2011. Reddington Levee Setback and Extension Feasibility Report to King County Department of Natural Resources and Parks Water and Land Resources Division.

Wilcock, P.R. and Crowe, J.C. 2003. Surface-based Transport Model for Mixed-Sized Sediment. Journal of Hydraulic Engineering. Vo. 129:2 p 120-128.

List of Figures

Figure 1: Site location map

Figure 2: Reach overview map

Figure 3: Longitudinal pattern of channel shear stress, maximum depth, and energy gradient based on 2-year flood event simulation.

Figure 4: Green River historical channel occupancy map.

Figure 5: Air photos and channel traces showing evolution from wandering gravel bed planform to single-thread meandering planform.

Figure 6: Specific gage height record for the Green River near Auburn (USGS station 12113000), 1936-2012.

Figure 7: Inset floodplain elevations along middle Green River

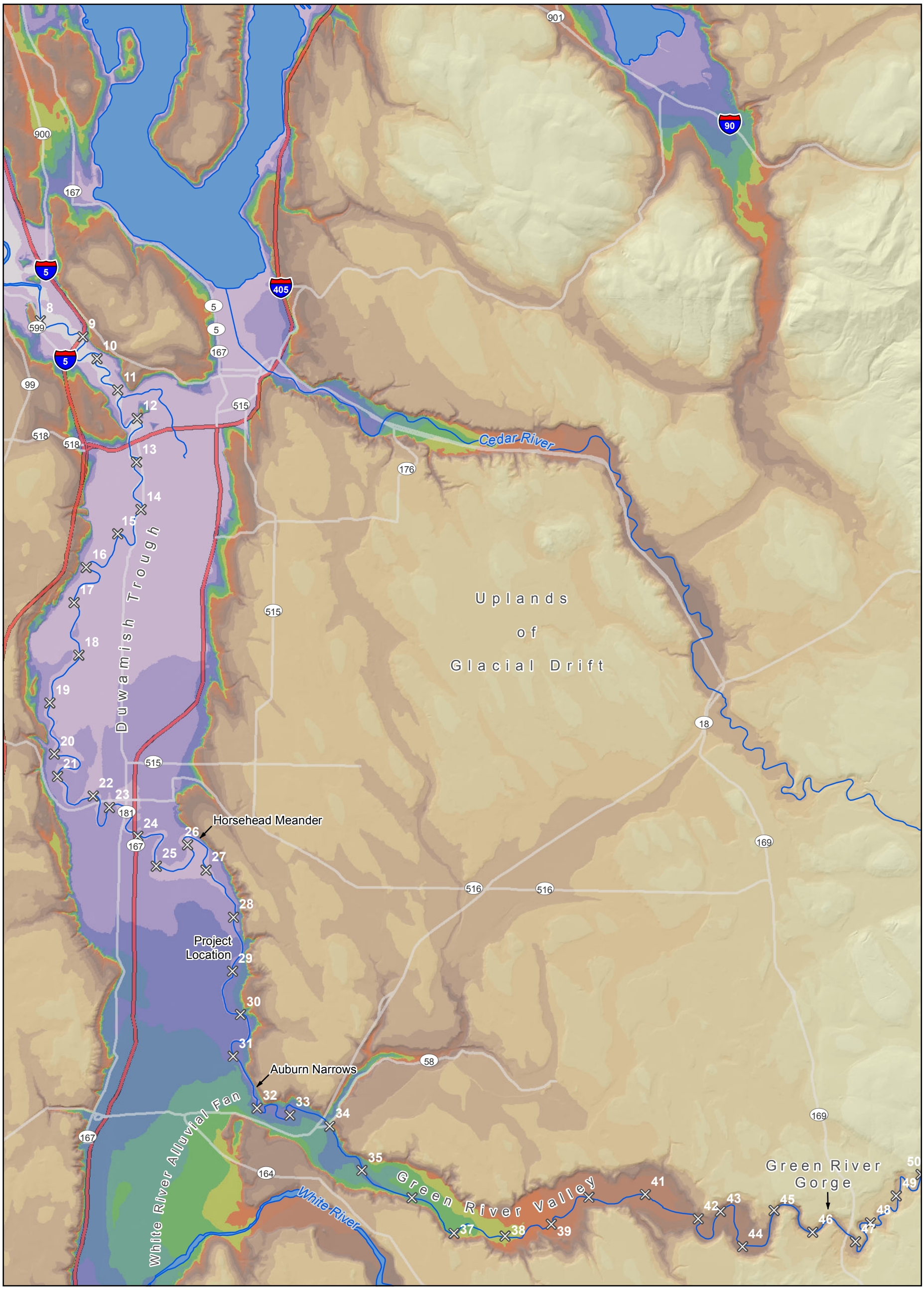
Figure 8: Formation of inset floodplain.

Figure 9: Migration rates at unrevetted outside meander bends.

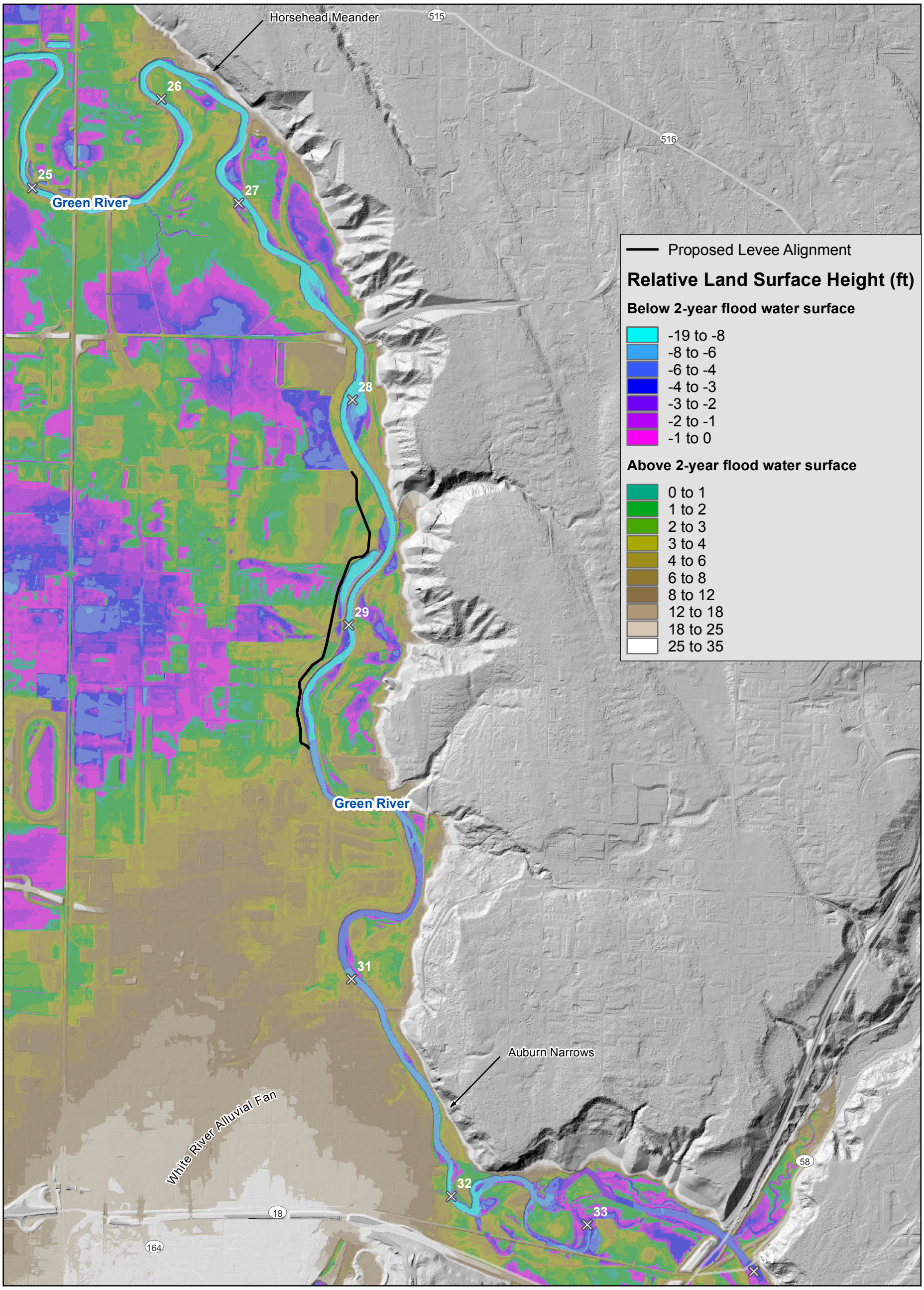
Figure 10: Longitudinal change in channel shear stress at a 2-year flood event resulting from removal of levee and formation or construction of a new “inset” floodplain at 50 foot elevation.

Figure 11: Migration hazard assessment Condition A

Figure 12: Migration hazard assessment Condition B

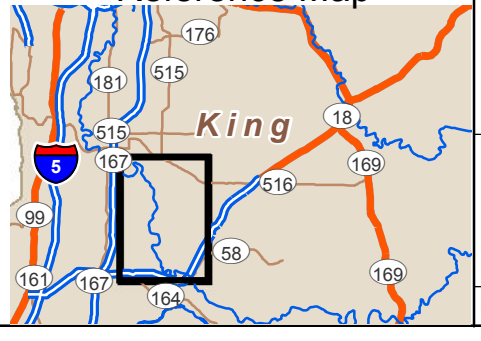


ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\vicinity_map.mxd



Note:
Height above water surface calculated from 2002 LiDAR and HEC-RAS simulated water surface elevations for calibrated 3-25-07 event (approx. 2-year event). HEC-RAS results extrapolated onto floodplain beyond cross-section extent.

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 2. Ground Elev. Relative to 2-Year Water Surface

Scale - 1:24,000

0 1,000 2,000 4,000 Feet

N

Northwest Hydraulic Consultants	project no. 200051	7/19/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\HAWS_reachy_overview.mxd

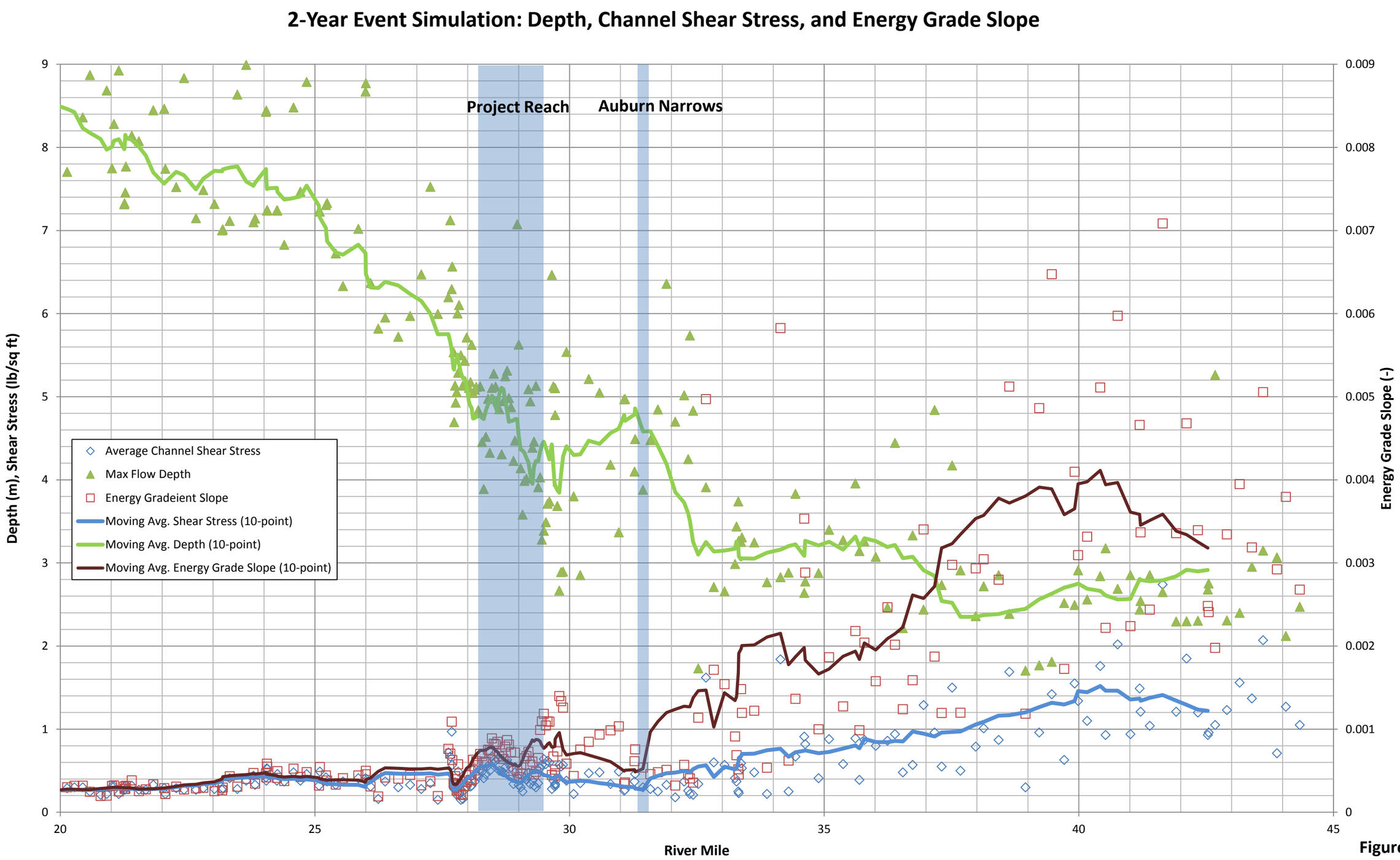
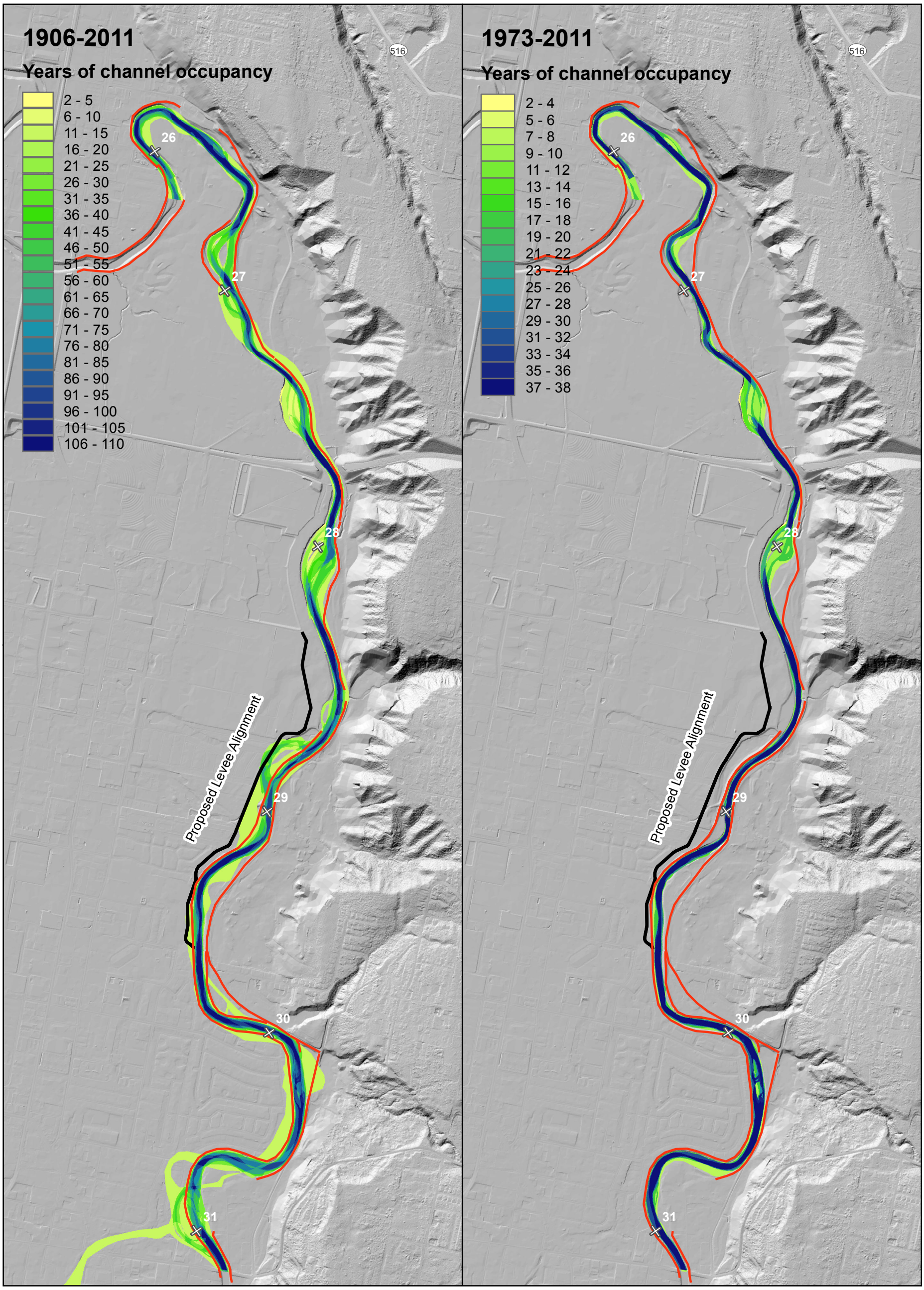

2-Year Event Simulation: Depth, Channel Shear Stress, and Energy Grade Slope
Project Reach
Auburn Narrows
Average Channel Shear Stress
Max Flow Depth
Energy Gradeient Slope
Moving Avg. Shear Stress (10-point)
Moving Avg. Depth (10-point)
Moving Avg. Energy Grade Slope (10-point)
Depth (m), Shear Stress (lb/sq ft)
Energy Grade Slope (-)
River Mile
0
1
2
3
4
5
6
7
8
9
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
20
25
30
35
40
45

Figure 3



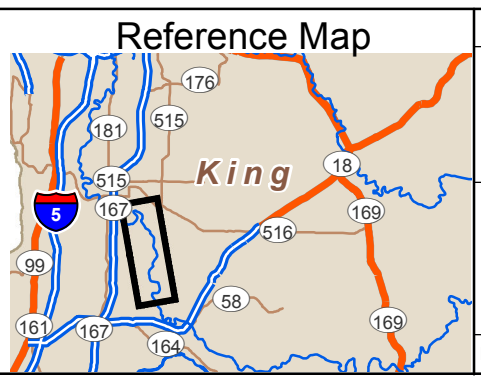
Existing Revetment (1993)

Proposed Levee Alignment

River Mile Marker

Historic Channel Occupancy Calculated from weighted 1906 map and 1936, 1942, 1960, 1973, 1978, 1990, 2006, and 2011 aerial photos.

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 4
Historic Channel Occupancy

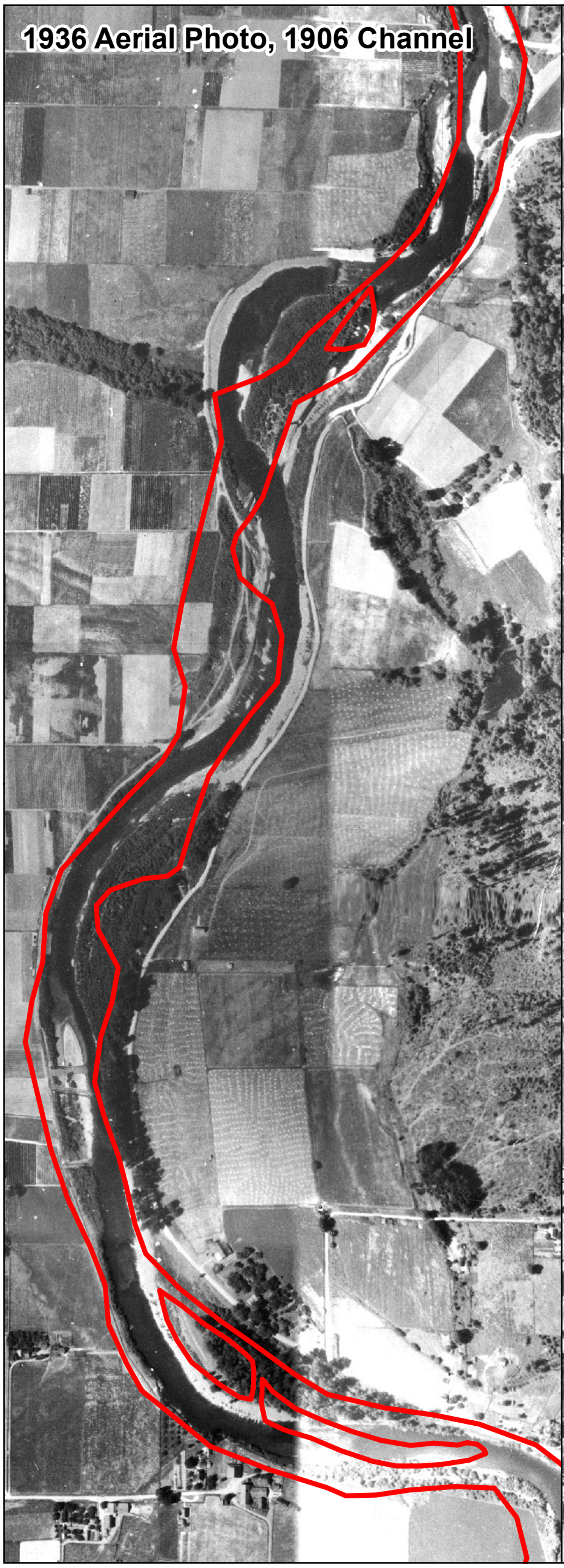
Scale - 1:20,000

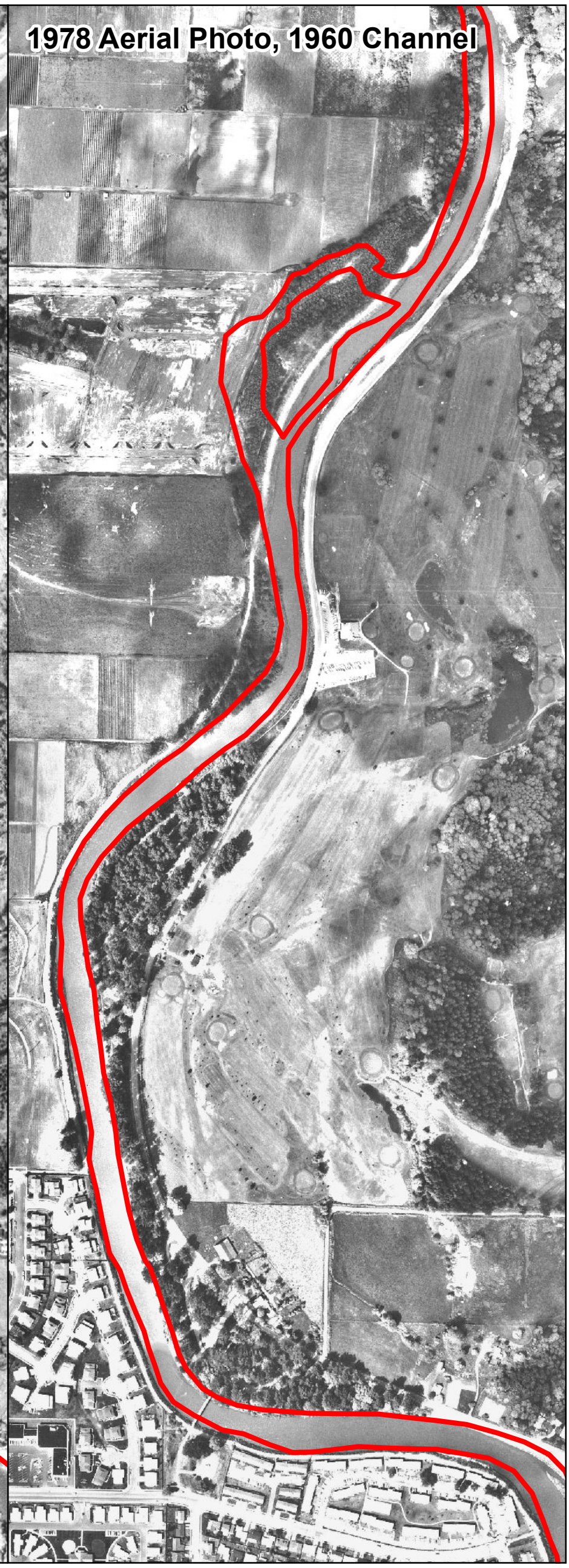
0 500 1,000 2,000 3,000 Feet

N

Northwest Hydraulic Consultants	project no. 200051	8/3/2012

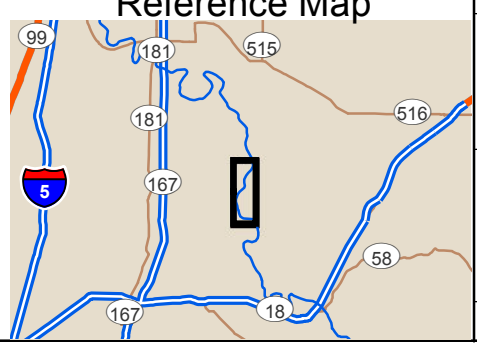
ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\HCO.mxd





Projection: State Plane Washington North

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 5
Channel Evolution - 1906 to 1978

Scale - 1:6,000

0 250 500 1,000 Feet

N

Northwest Hydraulic Consultants	project no. 200051	7/19/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\metamorphosis.mxd

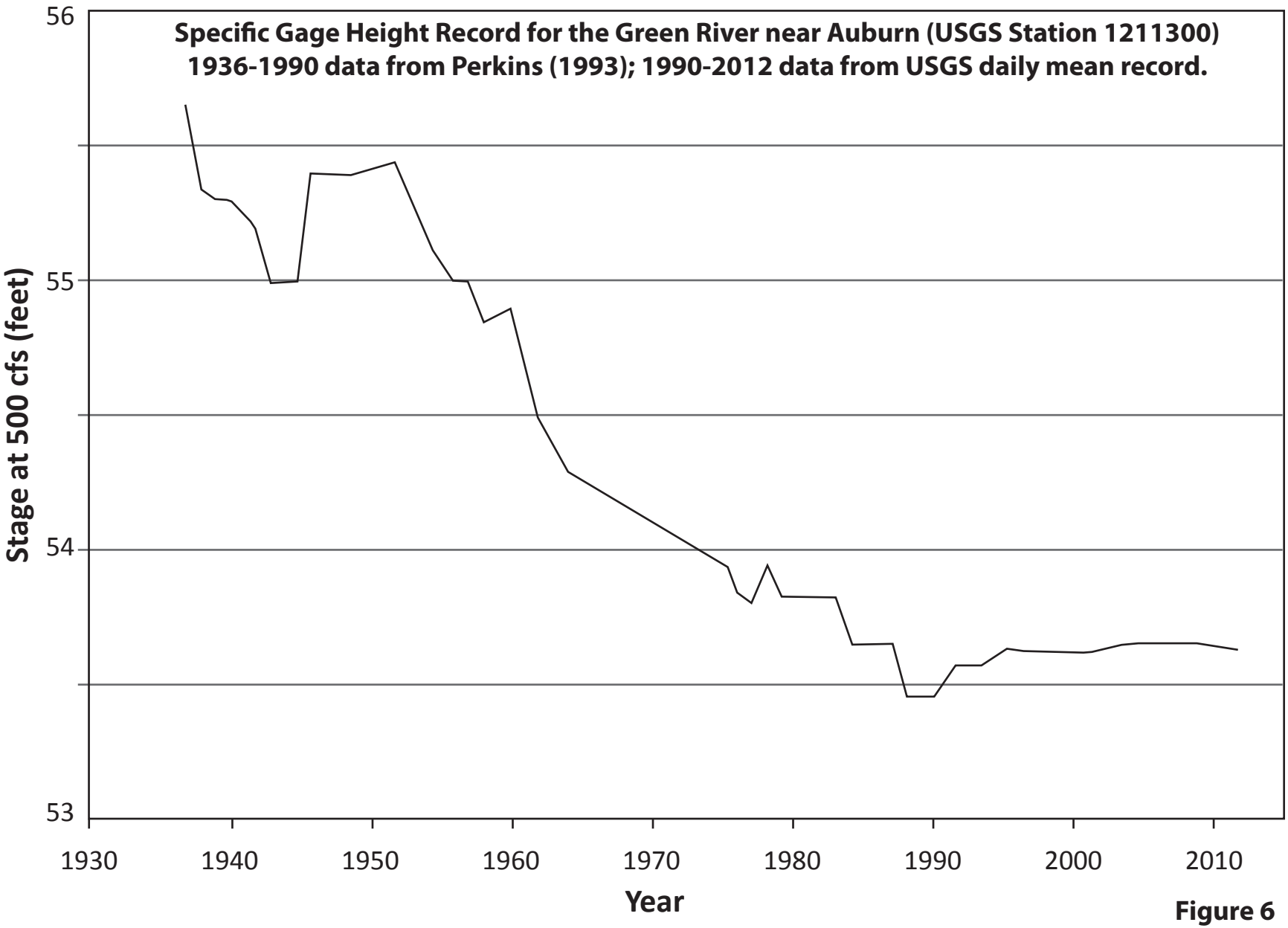

Specific Gage Height Record for the Green River near Auburn (USGS Station 1211300)
1936-1990 data from Perkins (1993); 1990-2012 data from USGS daily mean record.
Stage at 500 cfs (feet)
56
55
54
53
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

Figure 6

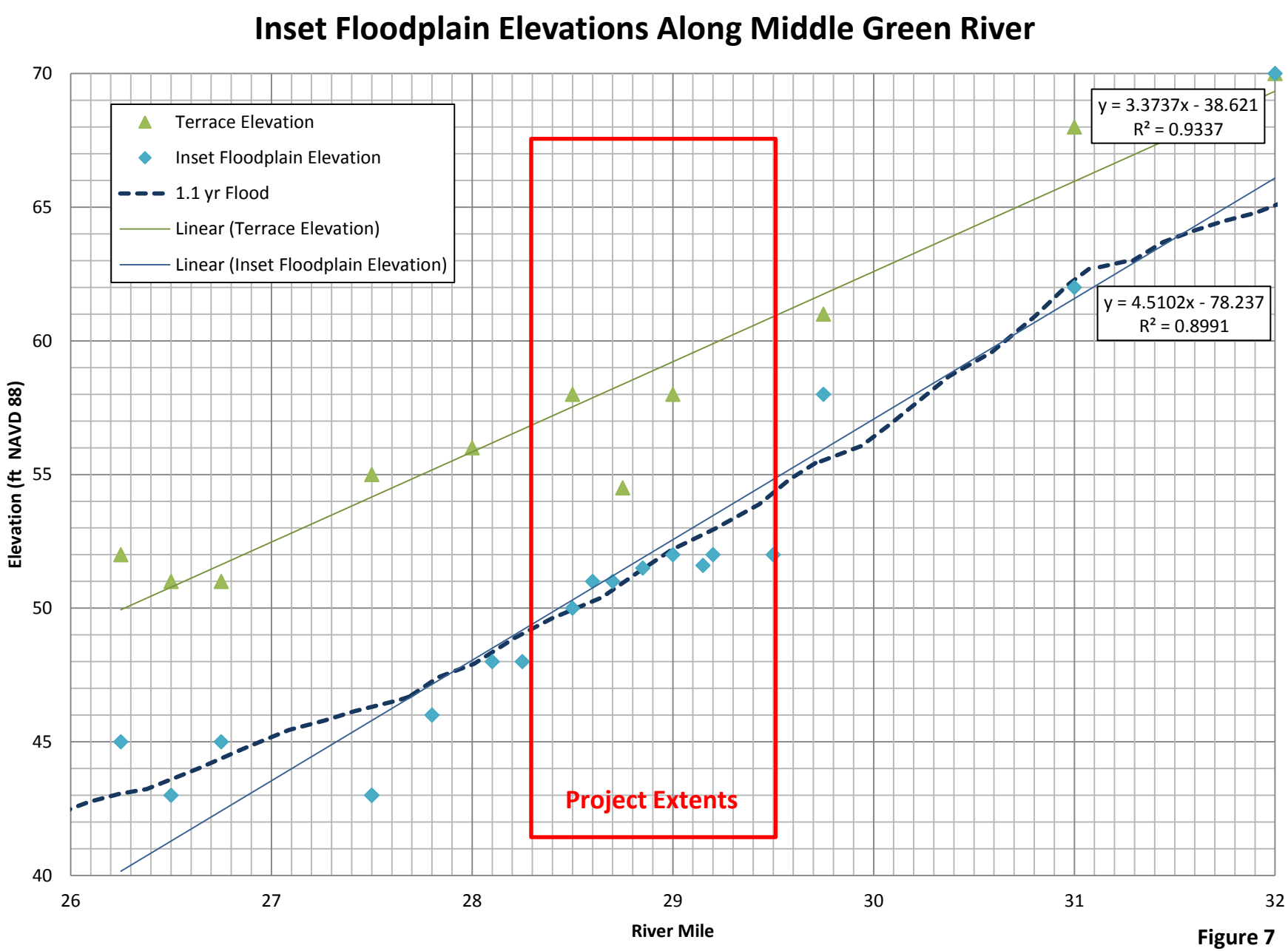
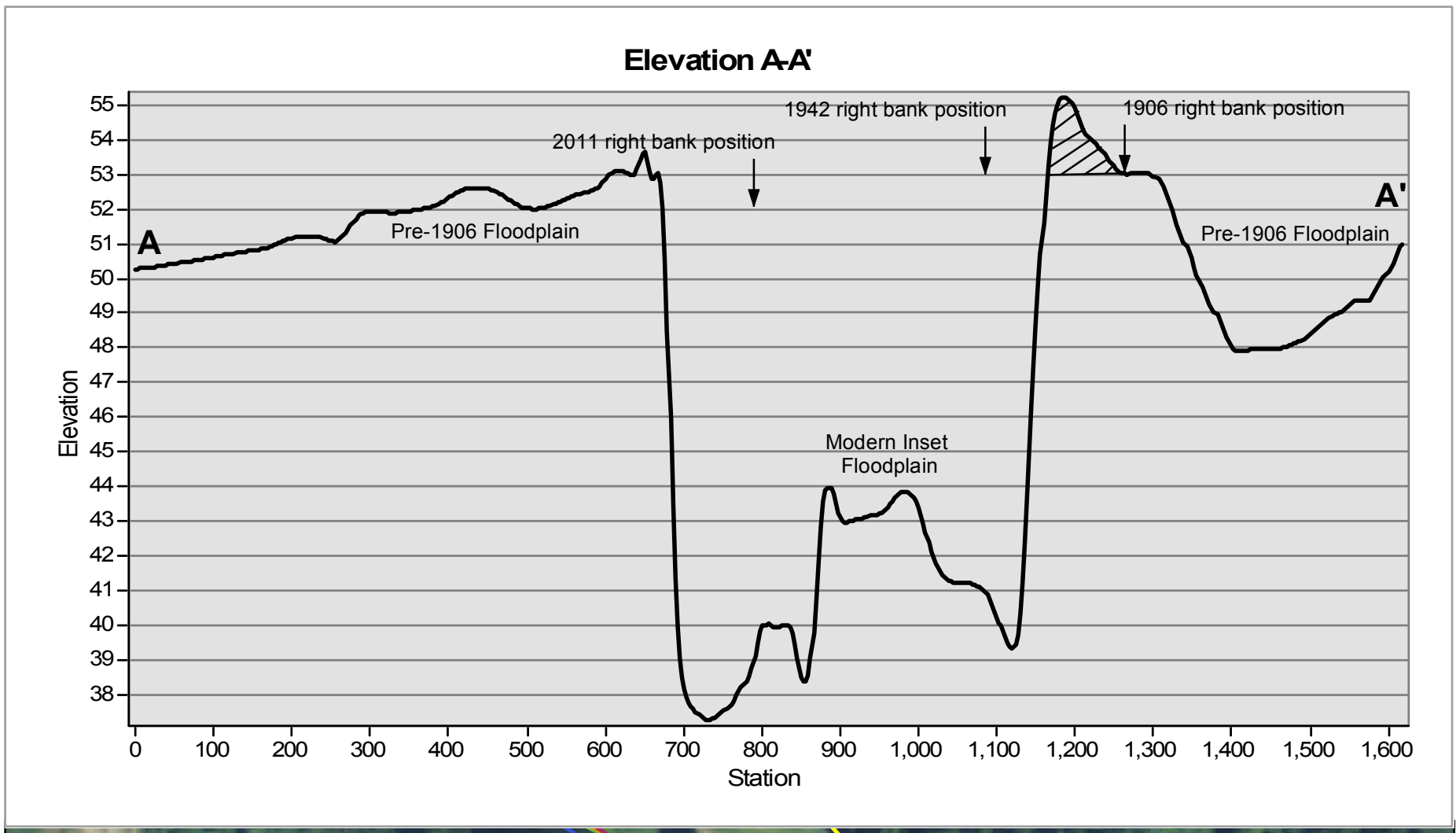
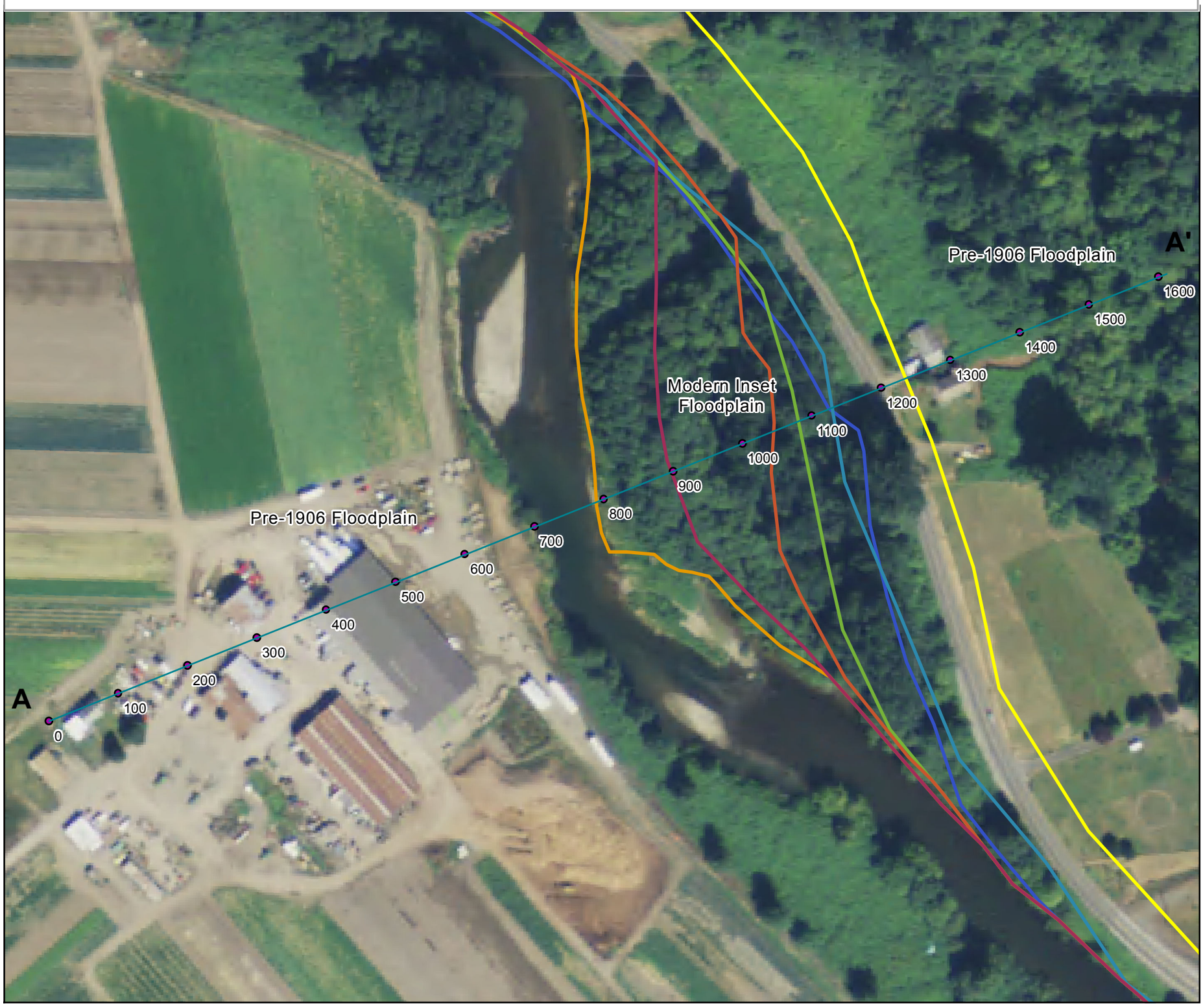

Inset Floodplain Elevations Along Middle Green River
Terrace Elevation
Inset Floodplain Elevation
1.1 yr Flood
Linear (Terrace Elevation)
Linear (Inset Floodplain Elevation)
y = 3.3737x - 38.621
R² = 0.9337
y = 4.5102x - 78.237
R² = 0.8991
Project Extents
Elevation (ft NAVD 88)
River Mile
70
65
60
55
50
45
40
26
27
28
29
30
31
32

Figure 7



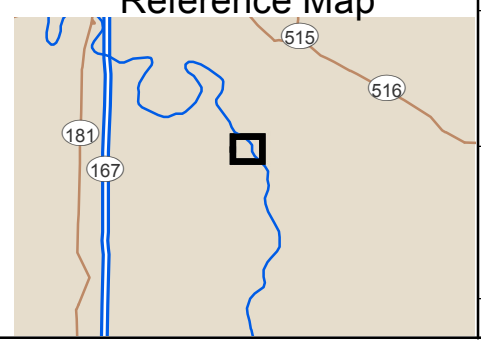


Right Bank Position

- 1906
- 1936
- 1942
- 1960
- 1978
- 1990
- 2006

Cross-Section Profile Derived from LiDAR & 2010 Bathymetry. 2011 NAIP Aerial Photo
Projection: State Plane Washington North

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 8
Formation of Inset Floodplain at RM 27.4

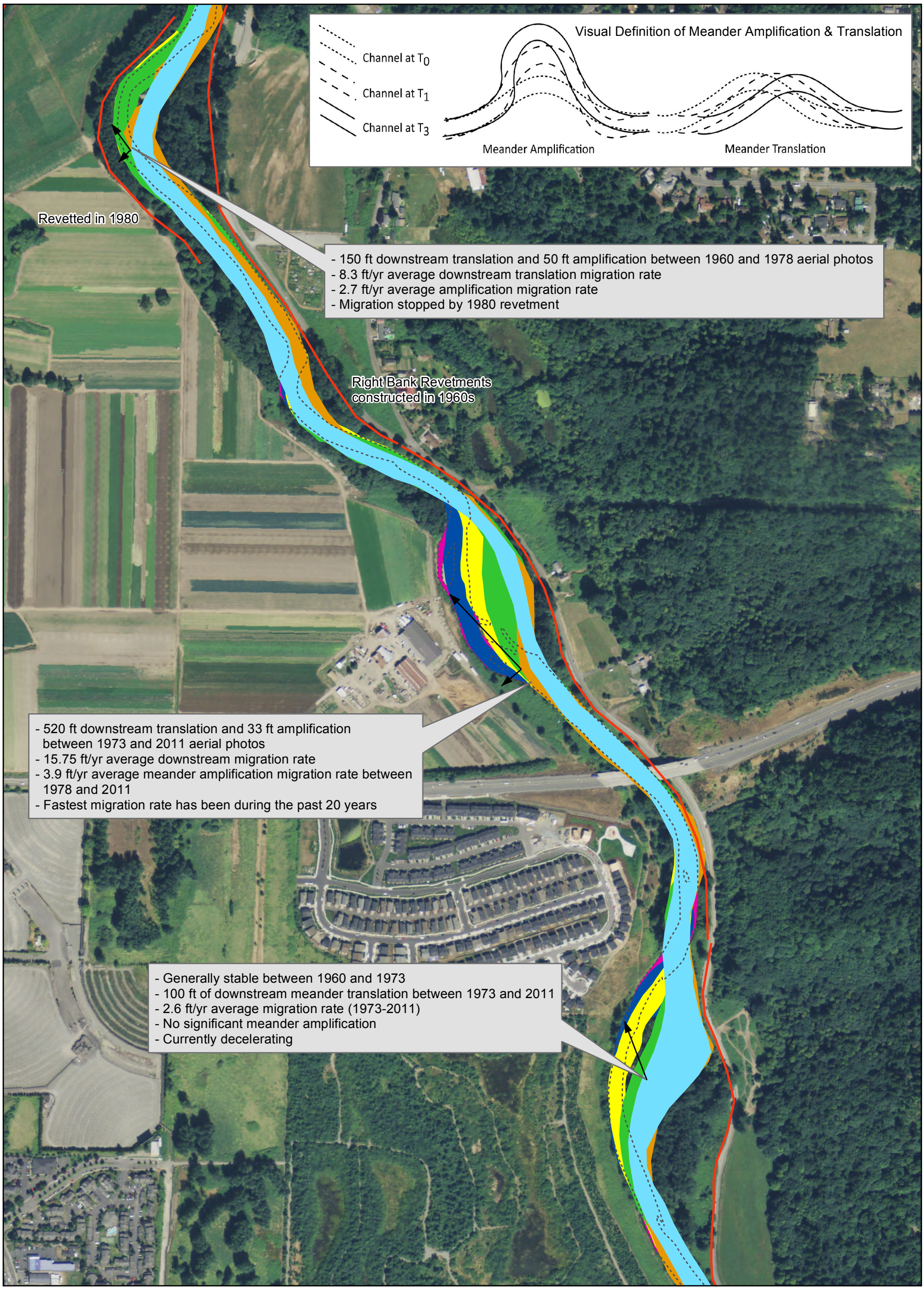
Scale - 1:2,000

0 75 150 300 Feet

N

Northwest Hydraulic Consultants	project no. 200051	8/3/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\inset_floodplainA.mxd



Existing Revetment (1993)

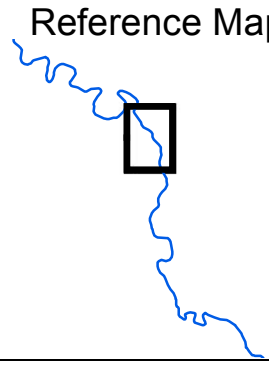
Channel Positions

1960
1973
1978
1990
2006
2011*

*Dashed line indicates full extent of 2011 channel.

Channel positions determined from 1960, 1973, 1978, 1990, 2006, and 2011 aerial photos.
Projection: State Plane Washington North

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 9
Unrevetted Outside Bend
Migration Rates - RM 26.5 to 28.25

Scale - 1:6,000

0 250 500 1,000 Feet

N

Northwest Hydraulic Consultants	project no. 200051	11/13/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\bend_migration60%.mxd

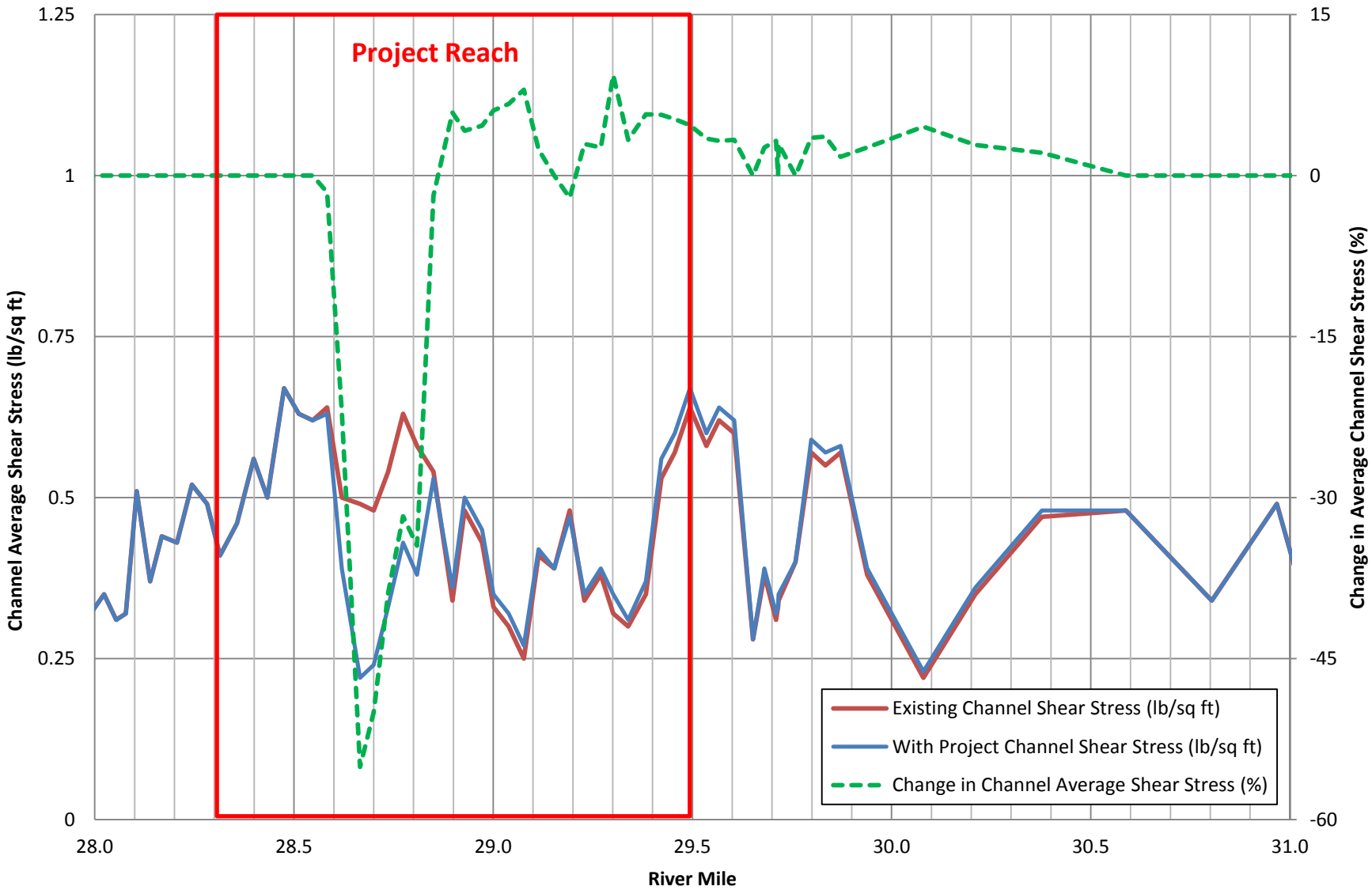
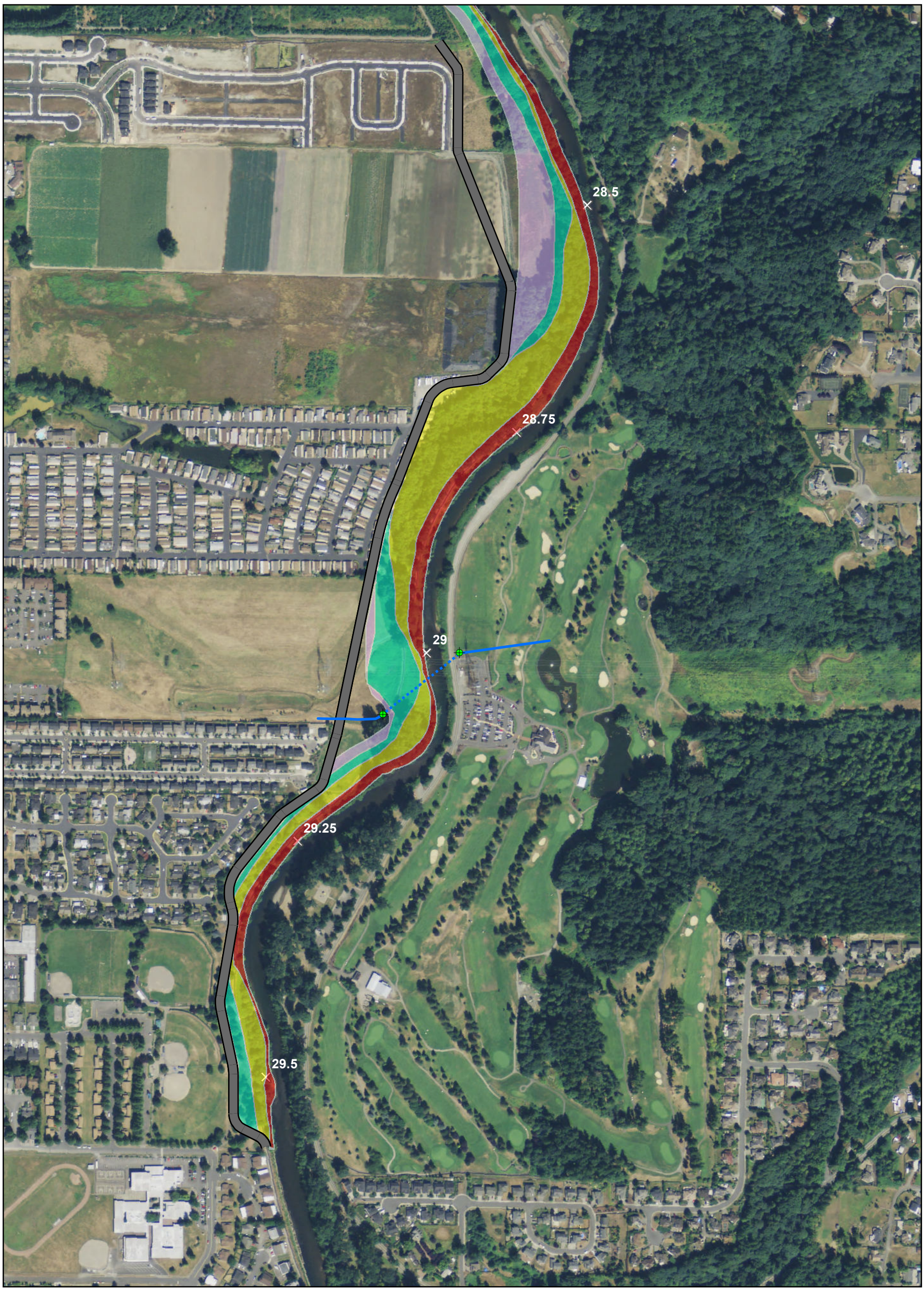


Figure 10: Comparison of 2 year flood channel shear stress for current and with-project conditions



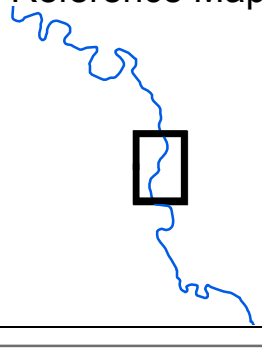
Migration Hazard Zones

- Extreme (occupation within 5 years likely)
- High (occupation within 10-20 years likely)
- Moderate (occupation within 50 years possible)
- Low (occupation within 50 years plausible)
- Proposed Levee Alignment
- River Mile Marker

Tacoma Water Line

- Deep
- Shallow

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 11
Migration Hazard Zones (Condition A)

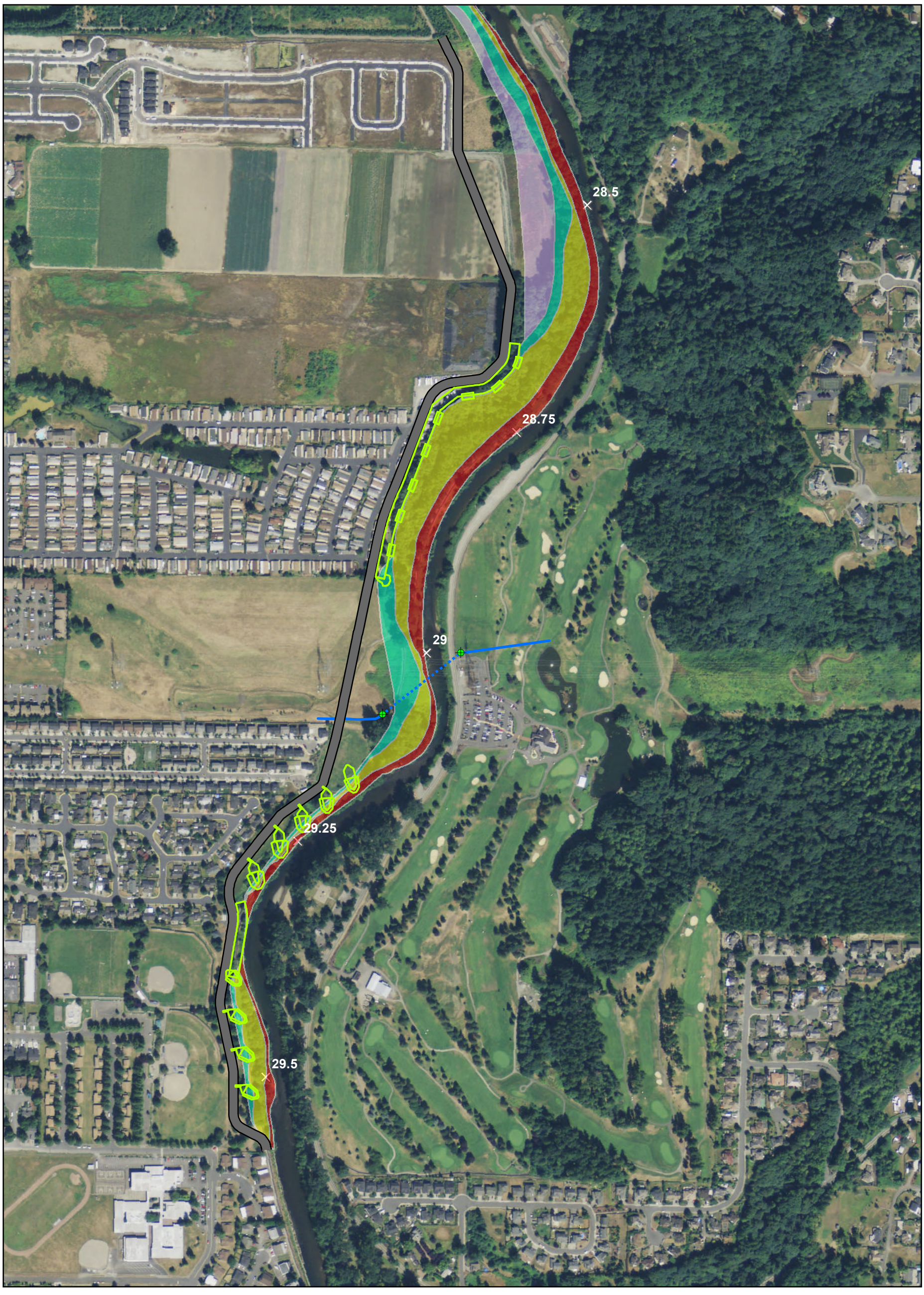
Scale - 1:6,000

0 100 200 400 600 800 1,000 Feet

N

Northwest Hydraulic Consultants	project no. 200051	12/17/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\migration_hazard_A 90%.mxd



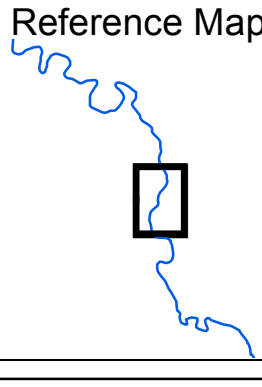
Migration Hazard Zones

- Extreme (occupation within 5 years likely)
- High (occupation within 10-20 years likely)
- Moderate (occupation within 50 years possible)
- Low (occupation within 50 years plausible)
- Proposed Rock Barbs & Revetments
- Proposed Levee Alignment

Tacoma Water Line

- Deep
- Shallow

Reference Map



Reddington Levee Protection Geomorphic Evaluation

Figure 12
Migration Hazard Zones (Condition B)

Scale - 1:6,000

0 100 200 400 600 Feet

N

Northwest Hydraulic Consultants	project no. 200051	12/17/2012

ADN, Q:_B\200051_Reddington_Levee_Design\GIS\figures\migration_hazard_B 90%.mxd