Determining the Effects of Vegetation on Levee Structural Integrity on the Green River in King County, Washington

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Executive Summary

Conflicting mandates for riparian vegetation on levees has been a management challenge in King County and elsewhere along the West coast. US Army Corps of Engineers requirements to maintain eligibility for financial assistance required vegetation removal post hurricane Katrina, but that policy was modified mid-study. Current policy is that vegetation is still unacceptable, but does not affect eligibility for repair funding thus shifting liability for vegetation to the local sponsor. Endangered Species Act and Clean Water Act water provisions call for large woody vegetation to provide shade and other habitat functions. King County has been working to repair levees with bioengineering methods that provide both stability and habitat improvements but once the woody vegetation reaches a certain size the flood facility may become ineligible for repair funding unless the vegetation is removed.

No digital information was available on bioengineered levee projects on the Green River that could be used to develop a study plan. The first project task involved organizing files and documenting the institutional knowledge at King County on the levee projects along the Green River. Fifty-four bioengineered repairs on the Green River were visited and geo-referenced. This information is now in a GIS file maintained by the King County River and Floodplain Management Section. To complement the georeferenced file, an excel file was created that contains additional information on each repair. It is contained in the 'Master Green River Facility Repair Records' also maintained the King County River and Floodplain Management Section. Based on information gleaned from the data mining and mapping exercises, it became clear that comparisons of stability of bioengineered vs non-bioengineered levees with vegetation could not be made. In fact, there has been only one documented instance of damage to a bioengineered facility in King County. To directly address the issue of the role of vegetation in levee stability, a retrospective pilot study of 12 matched damaged and undamaged sites was undertaken to determine whether vegetation played a role in damages documented in flooding in November 2006. This is a case-control study where the cases are sites that are damaged and the controls are adjacent, geomorphically matched undamaged sites.

The paired differences between percent cover of trees, impervious, and bare ground were not statistically significantly different between damaged and control sites. T-tests indicate that the difference in percent tree cover at each pair was indistinguishable from zero. However of the paired sites where trees were present on both the case (damaged site) and the control, the control generally had more trees cover than the case. Shrub cover was statistically higher on damaged sites than on control sites but it was not possible to determine if shrub cover was native or non-native.

Post-hoc power analysis indicates that a much larger sample size of at least 54 matched cases and controls (damaged and undamaged sites) would be needed to determine a more scientifically defensible and statistically robust result for the effect the role of tree cover on levee damage The steps taken for the pilot study could be duplicated in any larger study. It is unlikely that all damages could be satisfactorily matched with bioengineered sites given the number of variables to be considering when matching. The following steps could be repeated for a larger study that examined damages. Barring extensive catastrophic flooding, it will be a challenge to find single flood events on single river levee systems that can provide a sufficient number of damages on the Green River with its upstream reservoir. Expanding to additional river systems and flood events as long as the matched pairs are from the same event and same system is one mechanism to increase sample size. Given the number of variables that affect levee stability, it is a challenge to isolate a single contributing factor.

Key words –bioengineering, levee, levee stability, levee vegetation, bank stability, riparian vegetation

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Introduction

River and floodplain management in the mid-1900s was based on an engineered approach involving levee and dam construction. This was the approach on the Green River in King County, Washington. Since these facilities were initially constructed, substantial maintenance has been needed, engineering practices have evolved, and environmental regulations have changed.

Beginning in the early 1990s, King County began using bioengineering methods in levee and revetment repair work. The bioengineering approach used by King County entailed the use of vegetation to not only provide bank stability but to also improve conditions for salmon. Methods are described in manuals produced by the State of Washington (Cramer et al. 2002) and King County (King County 1993).

Levee repair work, particularly on the Green River, is costly and risks from levee failure are unacceptable to local decision-makers as the surrounding floodplain is densely developed and populated. For these reasons, King County has many Green River levees enrolled in the US Army Corps of Engineers (USACE) cost-share program under Public Law 84-99 (PL 84-99). Under PL 84-99 the USACE is authorized to provide emergency assistance to construct levee repairs following a disaster event. Eligibility for this cost-sharing program requires that levee sponsors comply with the USACE Rehabilitation and Inspection Program, which requires the removal of vegetation greater than 2 inches in diameter from levees. For many years, King County operated under a de-facto regional modification of the national standard implemented by the Seattle District Engineer which required the removal of vegetation greater than 4 inches in diameter. A further modification of this regional allowance was formally adopted by the Seattle District in 2009, requiring vegetation in this size range to be limited to 4-foot diameter “clumps” spaced no closer than 35 feet apart on the levee slopes. The current interim policy is to not use vegetation to determine eligibility for federal financial assistance however vegetation is still relevant to maintenance and inspection.

This study was designed to examine the relationship between woody vegetation and the structural integrity of levees and revetments in King County, Washington. While an abundance of information has been gathered about the effects of native riparian vegetation on bank stability in natural riparian areas (e.g. Sidle et al., 1985, Gray and Megahan, 1989, Gyssels and Poesen, 2003, Wynn et al., 2004, Pollen and Simon, 2005, Pollen-Bankhead et al., 2009), less information is available on the role of vegetation in the structural integrity of levees and revetments, particularly those in the Puget Sound Basin.

This study seeks to identify these data gaps by defining terms, summarizing previous findings, providing results of a pilot study and recommending future study. By contributing to the body of knowledge about woody vegetation and levee integrity, resource managers will be better able to make informed decisions about ways to balance and integrate regional flood protection and environmental restoration goals.

King County entered into a sponsored research agreement with the University of Washington to determine whether levee vegetation makes levees and revetments more or less susceptible to flood damage. The goal was to see if the following hypothesis could be tested with existing information and if not, to develop a detailed study design with enough statistical power to determine whether vegetation affects levee stability.

> *Null hypothesis*: The structural integrity of flood facilities (levees and revetments) repaired using native woody vegetation in accordance with Washington State and King County bank stabilization guidelines does not differ from that of facilities without native woody vegetation.

If the hypothesis proved to be untestable given available data, then a study design that could test a similar hypothesis would be provided.

Levee Stability

Many levee attributes may have a greater influence on levee stability than vegetation. URS Corporation (Kabir and Bean 2011) systematically reviewed and summarized data obtained from engineering, construction, and maintenance records on levees in the Central Valley of California. Only 95 of the more than 10,000 records they reviewed (1.4 percent) mentioned vegetation in the performance record. Of those, only 11 records (0.1 percent) indicated that vegetation influenced levee performance. A similar study by Shields (1991) investigated woody vegetation and stability of riprap revetments along the Sacramento River following the flood of 1986. By mapping pre and post-flood vegetative cover using inspection records, Shields found that of the five revetment-armored levees enrolled in the PL 84-99 program that sustained damage during the 1986 flood, none of them supported woody vegetation before or after the flood. He also discovered that the damage rates for revetments with woody vegetation tended to be lower than for unvegetated revetments of the same age and material, located on banks of similar curvature. Using chi-squared statistics, the damage rates were greater for pre-1950 revetments and Shields concluded that vegetation did not appear to affect revetment durability. Gray, along with other researchers on the Independent Levee Investigation Team (ILIT), set out to determine the failure mechanisms of levees following Hurricane Katrina, including the role of woody vegetation in these failures (Gray 2007). In their final report they describe three failure mechanisms for levees, mass-stability failures, surficial erosion, and hydraulic forces.

Vegetation played little or no role in the failures and when growing on levees, the roots of woody vegetation reinforced the soil and increased the resistance to shallow, sloughing failures. Their observations in New Orleans showed that the presence or absence of trees on levees had little or no effect on hydraulic gradient-induced seepage failure. The main concern they documented for vegetation on levees was poor visibility and access that hindered proper inspection and flood-fighting capabilities.

In addition to the number of different variables or levee attributes that influence stability, differences in metrics, use of terminology and interpretation of damages were encountered. In the U.S., the method commonly used to locate levees, revetments and repair sites is the River Mile which is the distance of a given location, in miles, from the mouth of the river following the general flow of the river. Over time, the river channel migrates and when new maps are generated, the river miles at specific locations may change. Some of the data in King County are based on updated mapping data, and some are not. On numerous occasions it was found that terms were used differently between different data sets. In one example, a levee issue classified as having a slope stability problem in a USACE inspection report had a retaining wall exceeding a height limitation. A slope stability problem may be indicated in government records when in fact, there is no sign of failure on the site such as erosion, cracking or slumping. In addition, interpretation by different observers can play a large role in deciding the causes of levee erosion. One inspection might conclude that because of bank erosion, trees toppled while another concludes that because of trees toppling, erosion occurred.

Bioengineered Levees

The USACE has hypothesized that woody vegetation increases the risk for flood damage to levees by compromising the levee, and has required local governments to remove woody vegetation from levees and revetments to comply with national standards. In King County, 16 miles of lower Green River levees out of the County's inventory of flood facilities are enrolled in the program and are therefore, subject to the vegetation removal requirements. However, for over two decades, King County floodplain managers have been incorporating native woody vegetation into flood facility repair projects (Sims 2009). They have seen that such vegetation can actually increase the structural stability of the levee with proper design and construction (Sims 2009) and help meet the objectives of the Endangered Species Act and Clean Water Act. Figure 1 illustrates the general design of a standard USACE levee and a King County bioengineered levee.

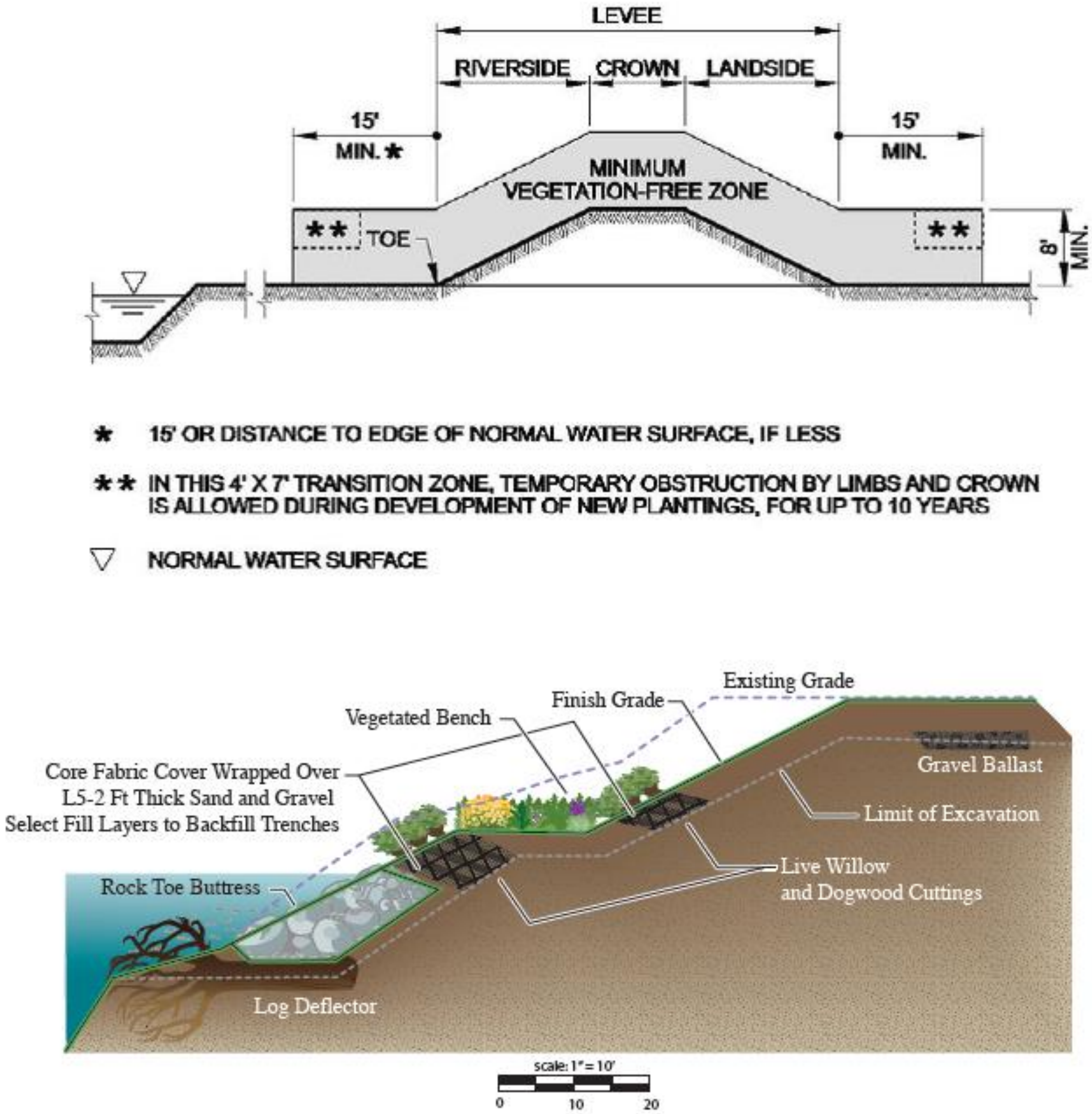

Figure 1. Schematics of a USACE Standard Levee Cross Section (top) and a King County bioengineered levee design (bottom)

Effects of Vegetation on Bank Stability

This is brief summary of select findings from the literature review report to King County of December 2013 (Adams 2013).

Natural streams

Vegetation provides root reinforcement and reduces soil moisture through interception and transpiration (Sidle et al. 1985, Gray and Megahan 1989). Large-scale

vegetation removal generally leads to an increase in slope failures (Gray 1995). Vegetation located at the interface between flowing water and the streambank modifies the hydraulic and mechanical properties of soils and can provide reinforcement (Koloski et al. 1989). Riparian vegetation stabilizes streambanks by reducing erosion and mass wasting and removal of this vegetation leads to an increase in streambank erosion (Gyssels and Poesen 2003, Wynn et al. 2004, Pollen and Simon 2005, Pollen-Bankhead et al. 2009).

Hershey et al. (1994) found that trees in the bottomland of rivers perform many functions such as stabilizing soil and controlling scour erosion; stands of trees absorb the energy from floodwaters and cause the deposition of water borne sediments, and they store the overbank floodwaters and improve water quality and aquatic life. Daar (1984) found that on levees that have been overbuilt or setback, riparian vegetation planted on the resulting berm can be effective in dissipating energy of flood flows and waves against the main levee. Beeson and Doyle (1995) assessed pre and post flood damage on river bends with and without vegetation. Bends without vegetation were nearly 5 times more likely to have suffered detectable erosion than bends with vegetation.

Levees

Numerous factors may affect levee stability and all variables should be looked at within a local geophysical context. The most important factors include the height of the levee embankment, proximity to the riverbank, levee fill material, underlying soils, inclination of the levee and river embankment slope(s), location of woody vegetation on the levee itself, where the vegetation is located along the river, vegetation type, size, root architecture, rooting depth and tensile strength, as well as hydrologic and hydraulic conditions, and the presence of burrowing animals. A brief summary of these factors is presented below. For more detail see the Literature Review report of Dec 2013. (Adams 2013).

Gray (1995) gives an overview on how vegetation influences interception, retardation, restraint and infiltration as it relates to vegetation and slope stability. The book describes the positive influences of vegetation such as root reinforcement, buttressing and arching, surcharge, and soil moisture depletion. On levees, Gray (1995) described the primary negative influence of vegetation as the external loading that can occur on trees, which in turn can lead to uprooting by high winds or currents. However, this external loading is likely more critical for large trees growing on relatively small dams or levees, and sometimes the main component of the overburden weight acts perpendicular to the failure surface and can actually increase stability. This is due to the fact that many levee embankment slopes are generally constructed at relatively shallow inclinations. Gray (1995) also noted that woody plants with their stronger and

deeper roots provide greater mechanical bank reinforcement and that some species are better than others. The USACE Engineering Research and Development Center found that species did not affect root pullout stress, but diameter of root and location were important (USACE 2010).

Shields and Gray (1992) investigated the influence of woody vegetation on the structural integrity of sandy levees along the Sacramento River, California. They collected field data including soil properties and botanical surveys, and applied appropriate parameter values to perform seepage and mass stability analyses. The results showed that plant roots did not clearly relate to any open voids in the soil and that roots reinforced the levee soil and increased shear resistance. Even low root concentrations increased the Factor of Safety (FOS) significantly, due to the small increases in soil shear strength caused by the roots. Shields and Gray concluded that woody shrubs and small trees on levees enhance its structural integrity. Another levee study found no significant voids left in the soil by decaying roots of 12-15 year-old walnut stump (SAFCA 2013).

Location along the levee can affect stability. Shields (1991) found that three of five revetments with woody vegetation on the Sacramento River that sustained damage during the 1986 flood were on convex banks with very sharp bends.

In a California Levee Vegetation Research Program study, mammal holes played a greater role in flow paths than vegetation (SAFCA 2013). Results showed that mammal holes provided a more direct flow path than decomposing vegetation and dominated flow paths in the complex system. They also found that the wetting front was delayed in the area of the eucalyptus stump/root mass or system and concluded that preferential fluid flow through roots was not observed during their flow test.

A field study from UC Berkeley (Shriro et al. 2014) examined the effects of roots (live and decaying) on levee seepage and slope stability. They found that flow patterns were dominated by flow through animal burrows in the levee and that the last location to saturate during the wetting test was the area behind the tree stump studied, where presumably there were the most roots. It is worth noting that studies on burrowing mammals on levees from UC Davis (Van Vuren and Ordeñana 2011) have found that trees and leaf litter are strongly negatively correlated with burrowing activity and that burrow sites are preferentially located in barren areas and low shrub cover, and pavement, leaf litter, trees, gravel and riprap are avoided.

Clearly a number of factors affect whether vegetation is a beneficial or adverse factor on levee stability, and vegetation cannot be looked at in isolation.

Study Site

King County, Washington lies in the Puget Sound Basin, which is bordered by the Cascade Mountains to the east and the Olympic Mountains to the west. This area experiences a Mediterranean climate consisting of wet winters and warm, dry summers. King County has a total land area of 2,307 square miles (5,975 square kilometers). This investigation is limited to the Green River, approximately from River Mile 11 to River Mile 32 (Figure 2) where most of the bioengineered levee repairs have been done in King County.

Howard Hanson Dam was constructed at river mile 64.5 and completed in 1962 to control flooding in the downstream floodplain. Dam operations are intended to limit peak flows in the Green River to 12,000 cubic feet per second at the Auburn gage. These two characteristics are strongly linked to design and performance of levees and revetments downstream. For these reasons and also to control for interbasin variability, this study was limited to an analysis of the performance of Green River levees.

Several species of Pacific salmon reside in the Green River. Puget Sound Chinook *(Oncorhynchus tschawytscha)* and Puget Sound steelhead *(O. mykiss)* were listed as threatened in accordance with provisions of the Endangered Species Act in 1999 and 2007 respectively. Bull trout (*Salvelinus confluentus*) are also in the river and listed as threatened. Critical habitat has been designated for Puget Sound Chinook and bull trout and has been formally proposed for steelhead in the study area. Bioengineered levee designs used by King County include in-channel large wood installation and riparian trees that provide shade, detritus and prey organisms to aquatic habitats (see Figure 1). Specific limits on water temperature have been adopted in Washington State water quality standards to allow for salmonid survival. A Green River temperature water quality improvement report calls for buffers of native vegetation 32 meters tall (Coffin and Lee 2011). The vegetation specified in the King County and Washington State bank stability guidelines is native vegetation. Historically, the most common trees in the Green River Valley were red alder (*Alnus rubra*), willow (*Salix* spp.), black cottonwood (*Populus trichocarpa*), bigleaf maple (*Acer macrophyllum*), and vine maple (*Acer circirnatum*) (Collins and Sheikh 2005), of which only the oldest and largest approach 32m.

Figure 2. Location map of section of Green River in this study

Methods

Data mining

It was necessary to determine what data and other resources were available from King County and other agencies to conduct a research study on the effects of woody vegetation on levees in King County. Specifically, it was necessary to find data on where and when damages occurred, as well as what vegetation was present on the levees prior to these damages. Additionally, reviews of previous research studies and interviews of people who have been conducting relevant research aided in the development of this study.

At the start of this study, King County had no single protocol in place for documenting, organizing or cataloguing information on levee construction, maintenance and damage reports. A substantial amount of time was spent organizing files and documenting the institutional knowledge at King County on the levee projects along the Green River. Repeated calls and requests were made to obtain inspection reports from the USACE. Interviews were conducted with King County engineers, ecologists, administrative specialists, program managers and supervisors to understand file organization systems, data availability and information needs. To better organize the data, information about the bioengineered levees was entered into a spreadsheet as it became available. In collaboration with King County ecologists and engineers, important information was included in the spreadsheet that describe more about the history of the river facilities, structural components of these levees, location along the river, etc. Often, original damage was not well documented nor whether vegetation was present on levees prior to these damages.

Levee mapping

No digital information was available on bioengineered levee projects on the Green River that could be used to develop a study plan. To fill this gap, a Trimble Global Positioning System (GPS) unit was used to map points at either end of bioengineered levee repair projects in the study area in January and February, 2013. A King County Senior Engineer (Andy Levesque) who had designed and worked on many of the projects helped identify project locations. Data were downloaded onto a desktop computer and used to create a data layer within the King County GIS with ArcMap 10.1. Fifty-four bioengineered repairs on the Green River were visited and geo-referenced. Eleven of the 54 sites were projects designed and constructed by the USACE with different standards than those used by King County. Figure 3 depicts a typical cross section of one of these repairs. Some differences are that wood was not anchored

directly into the levee structure, and that large volumes of rock were used to create "launchable toes" that are intended to slide into the river and thus prolong the life of the levee as channel incision progresses. Maps were generated with repair site locations, aerial photography acquired February 2006, tenths of River Miles and 2002 LiDAR.

Digital photographs were taken of each GPS point location as well as other locations along the repair to capture the type, cover and extent of vegetation present on the site. Notes were also taken about the site's damage, construction, and maintenance history, current structural condition and vegetation status.

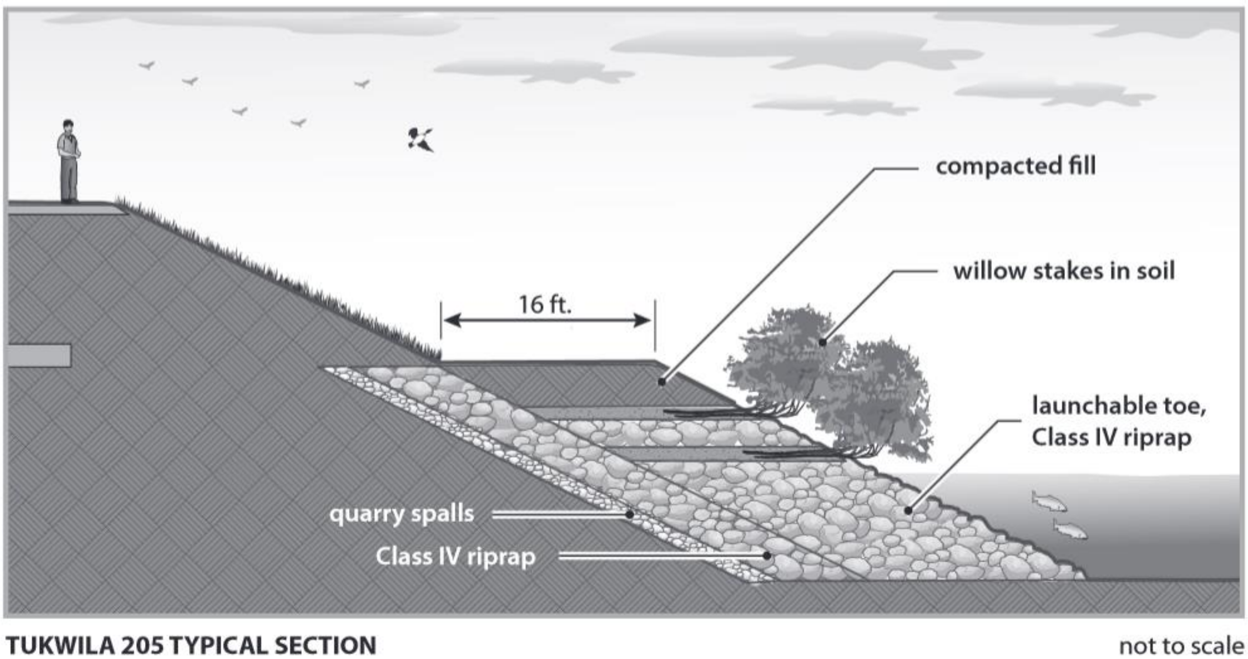

Figure 3. Schematic of a bioengineered levee repair with a launchable toe design in King County

Pilot Study

A retrospective pilot study was conducted that focused on levees damaged during flooding to determine what role vegetation may have played in damages. Pilot studies can determine the feasibility of a larger research project and can reveal deficiencies in the design of the proposed study, which can then be addressed prior to committing time and resources to a larger project. Ideally, the pilot study also provides sufficient data on estimating variability in outcomes and helps determine the minimum sample size for a large scale, statistically robust study.

For this pilot study, information on damages that occurred during the November 2006 flood, Federal Emergency Management Administration (FEMA) Disaster Declaration #1671 was used. The flood of November 2006 peaked with a flow of 8,060 cfs. The flood of record after construction of Howard Hanson Dam was 12,400 cfs at the

gage near Auburn in 1996. The flood of record prior to the dam was 28,100 cfs at the gage near Auburn in 1959. Howard Hanson dam controls discharge in the Green River and extreme floods are dampened by the available storage and the 2006 flood resulted in only 12 documented damaged levee sections.

Natural color aerial photographs taken on February 19, 2006 were digitized and orthorectified by King County prior to the start of this research project. Vegetation analysis was completed using this photo series at a scale of 1 inch equals 100 feet. In each study site, the upstream and downstream extent of the repair was measured to get the total length. A file was created by a King County GIS Specialist for the edge of water of the Green River and imported into the map layer. Then a polygon was created at each location using the edge of water as the riverside boundary and the length of the repair as the upper and lower boundaries. The fourth boundary of the polygon was placed on the middle of the crest of the levee determined through aerial photographic interpretation (see Figure 4).

Within each polygon, percent cover was calculated for each of five basic land cover categories selected for this study: trees, shrubs, grass, impervious surfaces, bare ground (Fig 4). Trees were differentiated from shrubs based on height, where trees were anything that appeared to be over five meters tall. In instances where it was difficult to distinguish height, first return LiDAR data acquired in 2002 was used to help with the land cover determination. Vegetation categories could not be broken down into native or non-native species due to the inability to distinguish this from aerial photographs. The impervious surfaces category included building footprint, roads, parking lots, and levee or revetment crown (if paved). The bare ground category consisted of bare exposed earth.

Pilot study analysis was performed using a statistical procedure called case control method (Keogh and Cox 2014). In this study, the “cases” were the 12 levee sites where damaged occurred during the 2006 flood. The “controls” were 12 additional sites that were selected to be as comparable (e.g. same facility and similar geomorphological position) as possible on a one-to-one basis with each of the damage sites. To the extent possible, the control was upstream of the case, on the same levee, with the same planform.

Once a control was chosen for each damage case, the steps for delineating land cover category were repeated within each polygon and percentages of each category were calculated for analysis. This method allows analysis of whether there is a correlation between percent cover of various categories between sections of damaged and undamaged levees.

Figure 4. Example of vegetation classification polygons

Statistical analyses were performed using IBM SPSS Statistics 19 for Windows. Paired t-tests were performed for each damage location and its corresponding control to test the null hypothesis, namely, that the mean difference in vegetation cover between paired case and control observations is zero. Using the resulting means and standard deviations from the paired t-tests, a power analysis was performed to determine sample size required to confidently detect a mean difference that is statistically significant from zero. This was performed using the online calculator, Simple Interactive Statistical Analysis (SISA) http://www.quantitativeskills.com/sisa/calculations/samsize.htm).

Results

Data Mining

Available information was organized on a spreadsheet and subsequently expanded by King County staff. This is referred to as the 'Master Green River Facility Repair Records' document and is maintained by the King County River and Floodplain Management Section.

Levee Mapping

During the field mapping, it was obvious that a number of additional variables were at play on these levees which made it challenging to group sites into discrete treatments. Although all of the repairs at the bioengineered sites had been completed using native vegetation, maintenance of these repairs varied significantly over the years. This resulted in many different vegetation regimes at the repair sites, from total native plant vegetation cover (Figure 5) to complete removal of the native vegetation and replacement with turf grass (Figure 6). At each site, GPS points were collected at the upstream and downstream extent of each bioengineered repair, the results of which are presented in the following section.

Figure 5 - Fenster levee 2004 Repair – photos taken January 7, 2013


Figure 6 - Dykstra levee repair 1995 – photos taken on January 7, 2013

Storm water facilities, notably a pump station near river mile 26, affect the location and shape of the levee and possibly the saturation of material within the levee. Construction materials in the levees vary as well as the bank slope, level of river confinement, erosive force, scour, and other variables. The collected georeferenced data were incorporated into a GIS file maintained by the King County River and Floodplain Management Section.

Pilot Study

Given the state of the data that were available and the lack of documented damage on bioengineered levees, King County requested that a pilot study be undertaken to assess the general role of vegetation on levee stability. For this pilot study, information on damages that occurred during the November 2006 flood, Federal Emergency Management Administration (FEMA) Disaster Declaration #1671 was used.

Only 12 sites had documented damage from the November 2006 flood event and all were included in the pilot study. None of these 12 sites were bioengineered. Pilot study analysis was performed using a statistical procedure called case control method (Keogh and Cox, 2014). In this study, the "cases" were the 12 levee sites where damaged occurred during the 2006 flood. The "controls" were 12 additional sites that were selected to be as comparable (e.g. same facility and similar geomorphological position) as possible on a one-to-one basis with each of the damage sites. To the extent

possible, the control was upstream of the case, on the same levee, with the same planform.

Locations and characteristics of the matched sites are shown in Table 1. In four locations, the best control was located on an adjacent but different facility. The length of the damage varied from site to site from 100 feet to over 1100 feet. Percent cover for each cover class was determined for each case (damaged) and control (undamaged). A King County data layer, not available at the time of control selection, revealed that six of the controls are sites that had been previously damaged but were repaired using bioengineered methods. Tables 2 and 3 shows percent covers for each case and control. Figure 7 shows the distribution and range of percent covers between cases (damages) and controls as box plots.

Tree cover ranged from 0-17% at the case (damage) sites and 0-43% at the control sites. Median tree cover was 5% for the case (damaged) sites and 5.5% for the control sites. Four cases and four controls had no tree cover, and three of these were matched pairs. Of sites with tree cover, the case (damage) sites had an average of 9.6% tree cover and the control sites averaged 15.9% tree cover. Shrubs were present on all sites except for one control site. Average shrub cover on the case sites was 61.5% and on the controls, 46.7%. Although native vs non-native species could not be identified via air photo analysis, recent field classification of the Lower Green River shrub layer revealed that overall at least 66% of the shrubs are non-native (personal communication, Sarah McCarthy).

Table 1 List of cases (damages) with corresponding matched control information. Planforms are inside (I), and outside bend (O) and straight reach (S). [1] Denotes revetment, not levee. If the control was partially or wholly on a bioengineered repair it is so noted.

Site name	Bank	Approx. Linear Feet	Control location up (u/s) or downstream (d/s) from damage?	Control on same facility as damage?	Name if control facility different	Date of bioengineer repair and approx. % of control if relevant	Case (damage) planform from d/s to u/s	Control planform from d/s to u/s
Tukwila 3 (U/S from S. 180th St.)	Left	1055	u/s	No	Tukwila 205 - Segale		S,I	I,S
Tukwila 5 (part of Segale)	Left	1055	u/s	Yes	-------------	1991 100% of control	I,S	S,I
Briscoe School Levee Repair	Left	525	u/s	Yes	------------		S	S
Kent Shops – Narita	Right	1600	d/s	No	Russell Road Upper	1998 15% of control	O,S,I,S,O	O,S,I,S,O
Myers's Golf	Right	1400	u/s	No	Signature Point	1997 30% of control	I,S	I,S
Horseshoe Bend Site 4	Right	1040	d/s	Yes	------------	1997 90% of control	I,S	S,I
Horseshoe Bend Site 3	Right	100	d/s	Yes	------------	1996 100% of control	S	S
Horseshoe Bend Site 2	Right	160	d/s	Yes	------------		S	S
Horseshoe Bend Site 5	Right	150	d/s	Yes	------------		O,S	S
Horseshoe Bend Site 1	Right	1140	u/s	Yes	------------		O	O
Galli's Section[1]	Left	1110	u/s	No	Dykstra		S,O	O,S
PL 87-99 Levee Rehabilitation, Dykstra	Left	375	u/s	Yes	------------	1994 75% of control	I,S	I,S

Table 2. Percent cover of each category for case (damaged) sites. (River miles taken from field measurements using GPS in 2013 and may be slightly different from maps produced later).

Repair Project Name (on Plan Drawings)	Bank	River Mile (downstream)	River Mile (upstream)	Damage, Total Area (sq ft)	% Trees	% Shrubs	% Grass	% Impervious	% Bare ground
Tukwila 3 (U/S from S. 180th St.)	Left	14.35	14.55	50,756	0	53	38	8	0
Tukwila 5 (part of Segale)	Left	14.90	15.09	56,129	0	81	19	0	0
Briscoe School Levee Repair	Left	16.34	16.44	30,641	0	75	17	0	8
Kent Shops -- Narita Levee	Right	20.38	21.07	191,956	2	57	32	9	0
Myer's Golf Levee	Right	21.52	21.84	97,945	1	73	16	10	0
Horseshoe Bend Site 4	Right	24.79	25.03	94,743	0	47	41	12	0
Horseshoe Bend Site 3	Right	25.20	25.22	3,590	17	15	58	9	0
Horseshoe Bend Site 2	Right	25.79	25.83	10,435	11	74	9	6	0
Horseshoe Bend Site 5	Right	25.83	25.93	23,353	11	64	11	9	4
Horseshoe Bend Site 1	Right	25.93	25.99	16,694	8	68	16	9	0
Galli's Section	Left	29.50	29.70	34,115	14	72	6	0	8
PL 87-99 Levee Rehabilitation, Dykstra	Left	30.02	30.14	13,905	13	59	20	0	8

Table 3 Percent cover of each category for control (undamaged) sites.

Project Name (on Plan Drawings)	Bank	River Mile (downstream)	River Mile (upstream)	Control, Total Area (sq ft)	%Trees	% Shrubs	% Grass	% Impervious	% Bare ground
Tukwila 3 (U/S from S. 180th St.)	Left	14.55	14.71	38,362	0	73	17	10	0
Tukwila 5 (part of Segale)	Left	15.09	15.30	59,530	0	63	30	7	0
Briscoe School Levee Repair	Left	16.63	16.73	27,093	0	62	29	10	0
Kent Shops -- Narita Levee	Right	19.69	20.36	229,653	4	39	48	10	0
Myer's Golf Levee	Right	22.57	22.88	122,864	6	63	24	8	0
Horseshoe Bend Site 4	Right	24.55	24.79	78,492	29	34	22	10	5
Horseshoe Bend Sit 3	Right	25.16	25.18	4,444	42	0	49	9	0
Horseshoe Bend Site 2	Right	25.45	24.49	1,1379	0	41	53	6	0
Horseshoe Bend Site 5	Right	25.49	25.59	27,511	22	23	48	7	0
Horseshoe Bend Site 1	Right	25.99	26.05	16,123	9	66	17	9	0
Galli's Section	Left	29.72	29.93	60,087	5	62	23	0	11
PL 87-99 Levee Rehabitilitation, Dykstra	Left	30.47	30.57	17,271	10	35	54	1	1

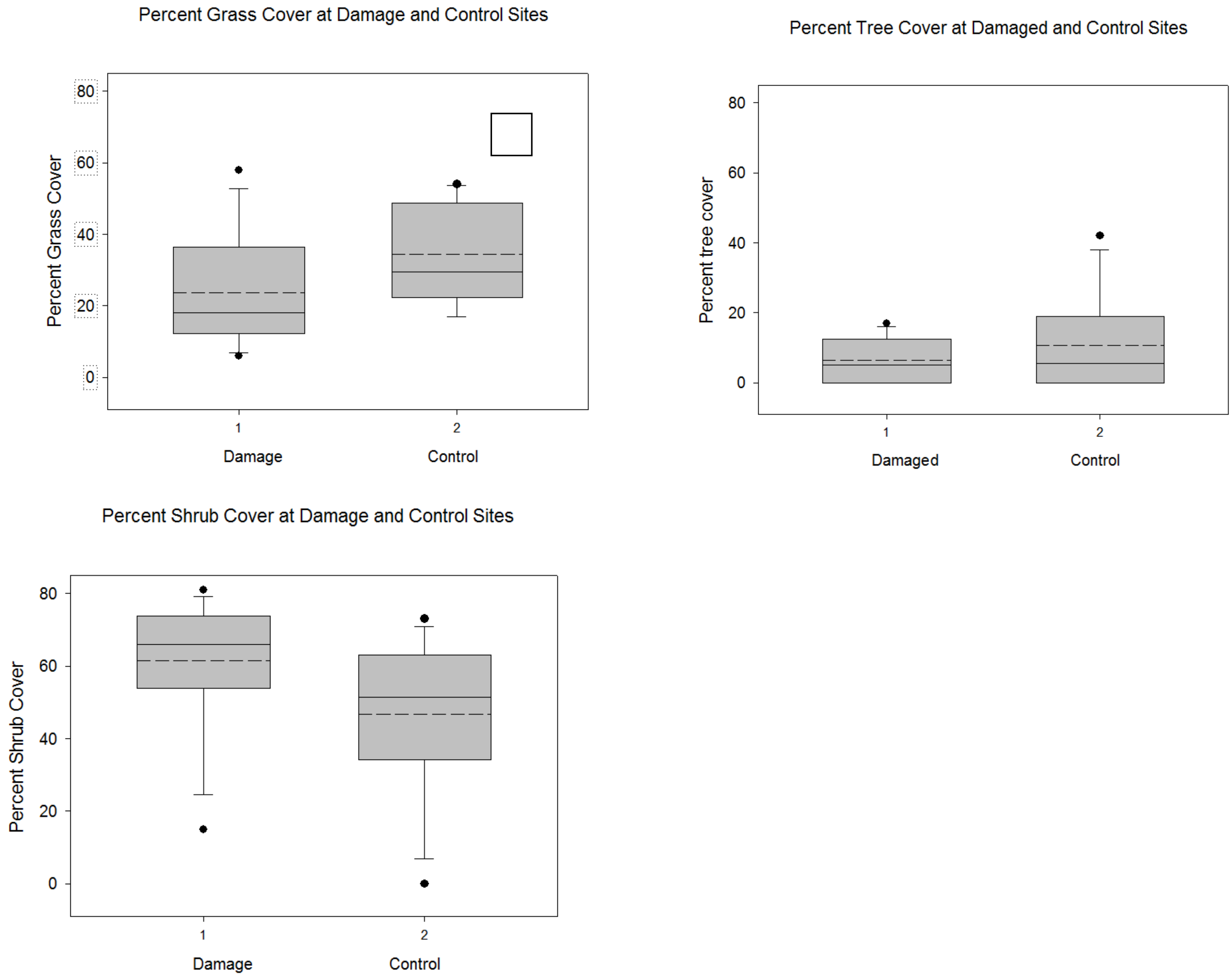

Figure 7. Box plots showing distribution of vegetation cover at sites prior to the November 2006 flood event. Solid line is median, dashed is average, box is 75th and 25th percentile, whiskers are 90th and 10th percentile. Dots are outliers.

All sites had grass cover. Case (damage) sites had an average grass cover of 23.6% and controls had an average grass cover of 34.5%. On no site did impervious cover exceed 12% nor did bare ground exceed 11%.

Statistical analysis

In this case-control study, the important variable is not the total cover but rather the difference in cover at each paired site. Figure 8 shows the range of paired differences for each category of vegetation. Negative values mean that the case (damage) site had less cover than its paired control; positive values mean that the damage site had more cover than its paired control. The box plots show that overall, the control sites had more tree cover and less shrub cover than their paired case (damage) site. To test whether the paired differences were statistically significant a paired t-test was performed for each (Table 4).

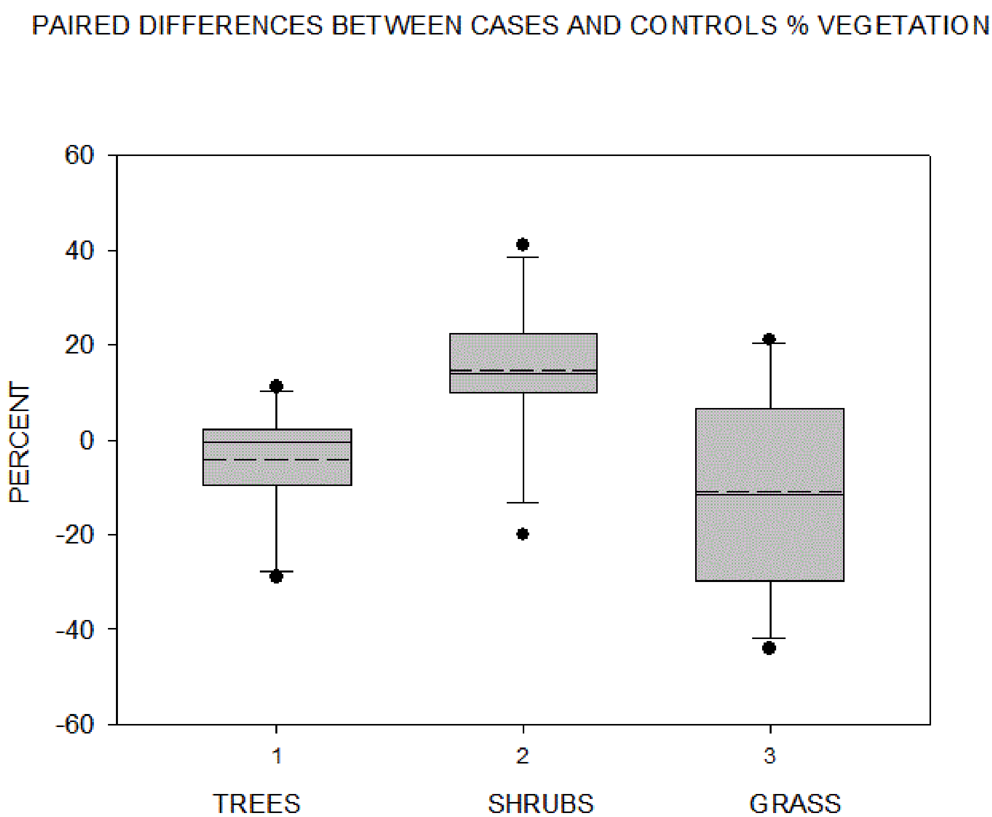

Figure 8. Box plots of paired differences in vegetation cover. Solid line is median, dashed is average, box is 75th and 25th percentile, whiskers are 90th and 10th percentile. Dots are outliers. Cases are damaged sites.

Table 4. Statistical results of paired t-test between cases (damage) and controls

Paired Samples t- Test		Paired Differences			t	df	p
		Mean	Std. Deviation	Std. Error Mean			
Pair 1	Trees_damaged - Trees_undamaged	-4.167	12.134	3.503	-1.189	11	0.259
Pair 2	Shrubs_damaged - Shrubs_undamaged	14.750	15.226	4.395	3.356	11	0.006
Pair 3	Grass_damaged - Grass_undamaged	-10.917	20.865	6.023	-1.812	11	0.097
Pair 4	Impervious_damaged - Impervious_undamaged	-0.500	4.719	1.362	-0.367	11	0.721
Pair 5	BareGround_damaged - BareGround_undamaged	0.917	3.728	1.076	0.852	11	0.413

Results show that the paired damaged and undamaged sites have a statistically significant difference ($p < 0.1$) between the mean differences for shrubs and grass cover. Damaged sites had on average, 14% higher shrub cover than their paired control. Grass cover was marginally statistically significant with control sites having about 11% more grass cover than their matched case. The paired differences between percent cover of trees, impervious, and bare ground were not statistically significantly different between damaged and control sites. The t-test indicates that the difference in percent tree cover at each pair was indistinguishable from zero. However of the paired sites where trees were present on both the case and the control, the control generally had more trees cover than the damaged site.

To check whether the non-significant results were due to an insufficiently large sample size, post hoc power analyses were performed using the resulting means and standard deviations from the paired t-tests with the online calculator Simple Interactive Statistical Analysis (SISA) http://www.quantitativeskills.com/sisa/calculations/samsize.htm). Power ($1 - \beta$) was set at 0.80 and $\alpha = 0.10$, two tailed. Results (Table 5) show that the sample size should be increased to at least 54 pairs of matched damage and control sites to have any level of confidence in determining if percent tree cover is related to damage. Even though the result for grass was close to 0.10, the power analysis indicates that a larger sample (double the size of this sample) would have more power to find a 'true' result. These results indicate that the pilot study was too small to draw any strongly defensible conclusions about vegetation cover and levee stability.

Table 5. Results of power analysis on sample size needed to test effects of various cover categories on levee stability

Variable	Mean Difference	Standard Deviation of Differences	Alpha	Sample size needed
Trees	-4.17	12.13	10	54
Shrubs	14.75	15.23	10	8
Grass	-10.92	20.87	10	24
Impervious	-0.5	4.72	10	553
Bare Ground	0.92	3.73	10	104

Discussion, Conclusions and Recommendations

No digital information was available on bioengineered levee projects on the Green River prior to this study. The first project task involved organizing files and documenting the institutional knowledge at King County on the levee projects along the Green River. Fifty-four bioengineered repairs on the Green River were visited and geo-referenced. This information is now in a GIS file maintained by the King County River and Floodplain Management Section. To complement the georeferenced file, an excel file was created that contains additional information on each repair. It is contained in the 'Master Green River Facility Repair Records' also maintained the King County River and Floodplain Management Section. A pilot study was conducted and has provided necessary preliminary information about the relationship between five different land cover classes (trees, shrubs, grass, impervious surface, and bare ground) and levee damages. Most importantly it allowed the computation of the necessary sample size to see statistically significant results.

The pilot study was a matched case-control study and with matches chosen to control for as many of these physical parameters as possible given the available data. Hydrology was controlled for by placing all of the matches on the Green River which is regulated by the Howard Hanson Dam during the same flood event. The location of vegetation along the river was controlled for by choosing a matched control site with a similar planform, whether it was on an inside bend, outside bend, straight reach, or a combination of these (Table 2). One thing to note is that of the 12 cases where damaged occurred, three occurred on a straight reach, while the rest occurred on some combination of inside bends, outside bends and straight reaches. In the case of the Horseshoe Bend Sites 1, 2, 3, 4, and 5, the planform of some of the controls show it on a straight reach, but it's important to note that these sites are actually on a much larger meander in the river, and sometimes in sub-meander locations as well. This may have

an effect on the hydraulic conditions of the river and thus, the location of damages. Size of the levee or levee setback, fill material, and age of the levee were all controlled by choosing a control site on the same levee as the cases (damaged sites) when possible. When this was not possible, a site was chosen on the next closest levee with a similar planform (Table 2). Of the 12 matched controls, eight of them occur on the same levee, while the remaining four were placed on adjacent levees. Although the assumption is that levees in King County were built with similar construction methods and materials, this may not always be the case and this fact should be taken into consideration for any analysis. In fact, late in the study it was learned half of the controls were at least partly on bioengineered sites.

As indicated by the results above, a much larger sample size of matched cases and controls (damaged and undamaged sites) would be needed to produce a more scientifically defensible and statistically robust result. The steps taken for the pilot study could be duplicated in any larger study. It is unlikely that all damages could be satisfactorily matched with bioengineered sites given the number of variables to be considering when matching. The following steps could be repeated for a larger study that examined damages. Barring extensive catastrophic flooding, it will be a challenge to find single flood events on single river levee systems that can provide a sufficient number of damages on the Green River with its upstream reservoir. Expanding to additional river systems and flood events as long as the matched pairs are from the same event and same system is one mechanism to increase sample size.

Steps for a larger study

1. Identify locations of damages on a levee(s). Preferably the damages occurred during the same flood event on the same river to control for discharge, antecedent moisture conditions and seasonal vegetation characteristics

2. Identify suitable controls. Think about geomorphic position, similar levee construction, materials and planform, same river system, and available historical documentation (for damaged sites and control) such as air photos or LiDAR (documented pre-damage vegetation is necessary.

3. Need to have at least 54 matched pairs, the more the better.

4. Proceed with classification of vegetation at the paired, matched sites.

5. Do descriptive statistics of the differences in cover for each matched pair and plot the data; box plots are quite useful.

6. Conduct tests of normality and t-tests of differences in vegetation cover between matched pairs

7. Evaluate results

In addition to using King County sponsored levees in the recommended study, collaboration with other flood management agencies within King County or in the Puget Sound region (e.g. Snohomish and Pierce Counties) could increase the potential sample size of damages and repairs for this study. However, construction and repair methods may be different from agency to agency, and moving to different river systems will complicate the study with different hydrologic and hydraulic, sediment loading and transport regimes.

Alternative study option

The case control method used for the pilot study looked at types of cover differences between damaged and undamaged sites on levees. Trees were the main issue between King County and the USACE with respect to levee maintenance due to issues related to fish habitat. However, vegetation cover is but one aspect of bioengineered levees. To test the more holistic idea of bioengineered vs traditional levees a chi square test could be used similar to Shields (1991). Data needs would include accurate and up-to-date information on levee construction and history along a river system that has sustained damaged from a flood. One could identify characteristics of areas of damage such as construction type, year and geomorphic location (inside bend, outside bend, straight reach) and then [match] record the same characteristics from undamaged levee reaches. If one assumes equal probability of damage from a single flood, one could use chi square test to compare the distribution of the particular characteristic between damaged and undamaged areas.

Other considerations

Damage events along levees are influenced by a large number of variables of which vegetation is only one. Levee design, material and planform affect how hydraulic forces are directed and the effect of the forces on stability; climate is important to the extent that it determines the size of the flood and hence the velocity and turbulence of the flow and also the antecedent moisture condition of the levee, in other words to what extent were levee materials saturated prior to the flood event. Saturated soils have low shear strength and are easily eroded. As noted in the literature review, tree size is not the only variable that affects rooting depth and size of roots; tree species and levee and embankment material also play a role. Since vegetation is only one of many factors that

affect levee stability, it will be challenging to design a robust study that isolates the effect of vegetation. Many other variables will have to be controlled as much as possible.

In addition to the effect of vegetation on levees and revetments, there are other physical parameters that may contribute to structural stability problems of levees. These include hydrologic and hydraulic conditions, where the vegetation is located along the river, levee fill material, size of the levee or levee setback, width of the riparian corridor, bioperturbation, location of woody vegetation on the levee itself, and age of the levee.

This study was designed to explore the relationship between woody vegetation and the structural integrity of levees and revetments in King County, WA. The original goal was to evaluate levee repairs that had been completed using bioengineering methods incorporating native woody vegetation and compare them with those levees repaired without woody vegetation. However, this relationship could not be explored due to lack of data (few documented damages) that would provide adequate and comparable cases and controls for a robust statistical analysis. In fact, only one King County levee that was repaired using bioengineered methods has sustained damage due to flooding, which itself did not involve the actual vegetated levee embankment, but rather undercutting of the constructed rock toe below the waterline, likely attributable to channel incision resulting from long-term levee confinement of flows. (It is worth noting that none of the sites that failed in the 1996 floods and were repaired using bioengineering were damaged in the 2006 floods.) As such, a retrospective pilot study was conducted instead to look at vegetation prior to known levee damage and compare them with sections of levee that had not been damaged during the same time period. This was evaluated looking at aerial photographs prior to major flooding in November 2006.

This research has demonstrated the complexity of conducting an empirical, scientific study on the effect of woody vegetation on the structural integrity of levees and revetments. There are issues with policy, interpretation, terminology, and data gaps. The literature review and pilot study have revealed complications with trying to isolate vegetation as the sole cause of structural stability keeping all other factors constant.

A one-size-fits-all levee vegetation policy for floodplain management is clearly not a viable or desirable choice given the local concerns and circumstances, not to mention the dynamic and heterogeneous nature of our nation's rivers and weather. Blanket standards required of levee sponsors in King County for emergency funding under Public Law 84-99 are outdated and are being assessed by SWIF as of 2014. While public safety is the number one concern for levee management, environmental protection is also necessary. Future research should focus on site-specific investigations to take into account local differences in geology, hydraulic conditions, levee material, local flora and fauna, and weather patterns, as well as regional environmental and economic circumstances. The issue of woody vegetation and levee

stability remains controversial; however, continued research on the subject is helping pave the path to effective collaboration and management amongst levee sponsors, federal agencies and concerned citizens.

Levee monitoring

Better protocols and cataloguing of woody vegetation and levee inspections and repairs could provide more useful data for future studies. Other recommendations for future investigation of the effects of woody vegetation and levee integrity could include monitoring of locations of tree removal recently performed in response to "unacceptable" ratings in the USACE 2010 Periodic Inspection Report. Monitoring these tree removal locations for levee stability and failure could be worthwhile to see if there is a long-term effect of tree removal. In addition, monitoring levees after each major flood and high water event via a float survey and recording any damage information is recommended. This information could be added to the Facility Inventory Database and used for future research.

References

Adams, A. 2013. A Literature Review of the Role of Woody Vegetation on Levees and Revetments. King County, WA.

Beeson, C. E., & P. E. Doyle. 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. *Water Resources Bulletin*. 31(6): 983-990.

Coffin, C. & S. Lee. 2011. Green River Temperature Total Maximum Daily Load Water Quality Improvement Report, Washington Department of Ecology, Bellevue, WA

Collins, B.D., and A.J. Sheikh. 2005. Historical Reconstruction, Classification, and Change Analysis of Puget Sound Tidal Marshes. Report to Washington Department of Natural Resources, Aquatic Resources Division, Olympia, Washington.

Cramer M., K. Bates, D. Miller, K. Boyd, L. Fotherby, P. Skidmore, T. Hoitsma. 2002. Integrated Streambank Protection Guidelines. Washington Department of Fish and Wildlife. http://wdfw.wa.gov/publications/00046/

Daar, S., Klitz, W. & W. Olkowski. 1984. The role of vegetation in integrated pest management approach to levee management. Proceedings: California Riparian Systems Conference, University of California-Davis: 551-555.

Gray, D. H. 1995. Influence of vegetation on the stability of slopes. Pp 2-25 inD.H. Barker, ed. Vegetation and slopes: Stabilization, protection, and ecology.

Gray, D. H. 2007. Factors affecting the stability and integrity of earthen levees. Presentation at the Vegetation Challenge Symposium, Sacramento, CA, 28 August 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm (Accessed 4/11/2012).

Gray, D. H., & W. Megahan. 1989. Forest Vegetation Removal and Slope Stability in the Idaho Batholith. USDA Research Paper INT-271, Intermountain Forest & Range Experiment Station, Ogden, UT, 23p.

Gyssels, G., & J. Poesen. 2003. The importance of plant root characteristics in controlling concentrated flow erosion rates. *Earth Surface Processes and Landforms.* 28:371-384.

Hershey, F., Wallace, D. & J. Dwyer. 1994. Forestry strategies to protect floodplain agricultural systems. Restoration of Aquatic Ecosystems Symposium, 1994. Association of State Wetland Managers, St. Paul, Minnesota, June 20-23, 1994.

Kabir, N. and F. Bean. 2011. The Influence of Vegetation on Levee Past Performance – a Review of Historic Data Based on the Levee Evaluation Program Database. Accessed Aug 2014. http://www.safca.org/Protection/NR_Documents/CLVRP_Influence_of_Vegetation_on_Levee_Past_Performance.pdf

Keogh, R.H. and D.R. Cox. 2014. Case-Control Studies. University of Oxford.

King County. 1993. Guidelines for Bank Stabilization Projects in the Riverine Environments of King County. http://www.kingcounty.gov/environment/waterandland/flooding/bank-stabilization-projects/guidelines.aspx, Seattle, WA

Koloski, J. W., Schwarz, S., & D. Tubbs. 1989. Geotechnical properties of geologic materials. Engineering Geology in Washington, Vol. 1, WA Division of Geology and Earth Resources Bulletin no. 78.

Pollen, N., & A. Simon. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*. 41, W07025.

Pollen-Bankhead, N., Simon, A., Jaeger, K. & E. Wohl. 2009. Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona. *Geomorphology*. 103:363–374.

SAFCA. 2013. Sacramento Flood Control Agency. http://www.safca.org/ Accessed November 2013

Sidle, R. C., Pearce, A. J. & C.L. O'Loughlin. 1985. Effects of land management on soil mass- movement. Hillslope Stability and Land Use. *Water Resources Monograph* Series 11, American Geophysical Union, Washington, DC. pp. 140. 1985.

Sims, R. February 26, 2009. An examination of levee vegetation policy. U.S. Army Corps of Engineers' Seattle District Levee Vegetation Symposium. Keynote speech.

Shields, F. D. Jr. 1991. Woody vegetation and riprap stability along the Sacramento River mile 84.5 – 119. *Journal of the American Water Resources Association.* 27(3): 527-536.

Shields F. D., & D. H. Gray. 1992. Effects of woody vegetation on sandy levee integrity. *Water Resources Bulletin.* 28(5): 917-931.

Shriro, M., D. Cobos-Roa, J. Bray, N. Sitar, J. Licter, and R. Evans. 2014. California Levee Vegetation Research Program: Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 2. – Parallel Trench Wetting Front Test, North Levee of the American River at Cal Expo Sacramento, California. Geotechnical Engineering University of California, Berkeley Report UCB GT 13-03 vol.2
Accessed Aug 2014.
http://www.safca.org/Protection/NR_Documents/CLVRP_Vol_2_Parrallel%20Trench_Wetting_Front_Test_N_Levee_of_AR_at_CalExpo_Final.pdf

U.S. Army Corps of Engineers. 2010. Literature review – Vegetation on levees. ERDC SR-10- 2. Washington D.C.

Van Vuren, D and M Ordeñana. 2011. California Levee Vegetation Research Program Habitat Associations of Burrowing Mammals along Levees in the Sacramento Valley, California. Accessed Aug 2014.
http://www.safca.org/Protection/NR_Documents/CLVRP_Habitat_Associations_of_Burrowing_Mammals_%28Final%29.pdf

Wynn, T. M., Mostaghimi, S., Burger, J. A., Adrian, A., Harpold, A. A., Henderson, M. B., & Henry, L. 2004. Variation in root density along stream banks. *Journal of Environmental Quality*. 33:2030-2039.

Appendix A. Maps of Repaired Facilities with Date of Repair and River Mile. Red lines indicate King County Repairs, Blue lines USACE repairs. Maps in alphabetical order.

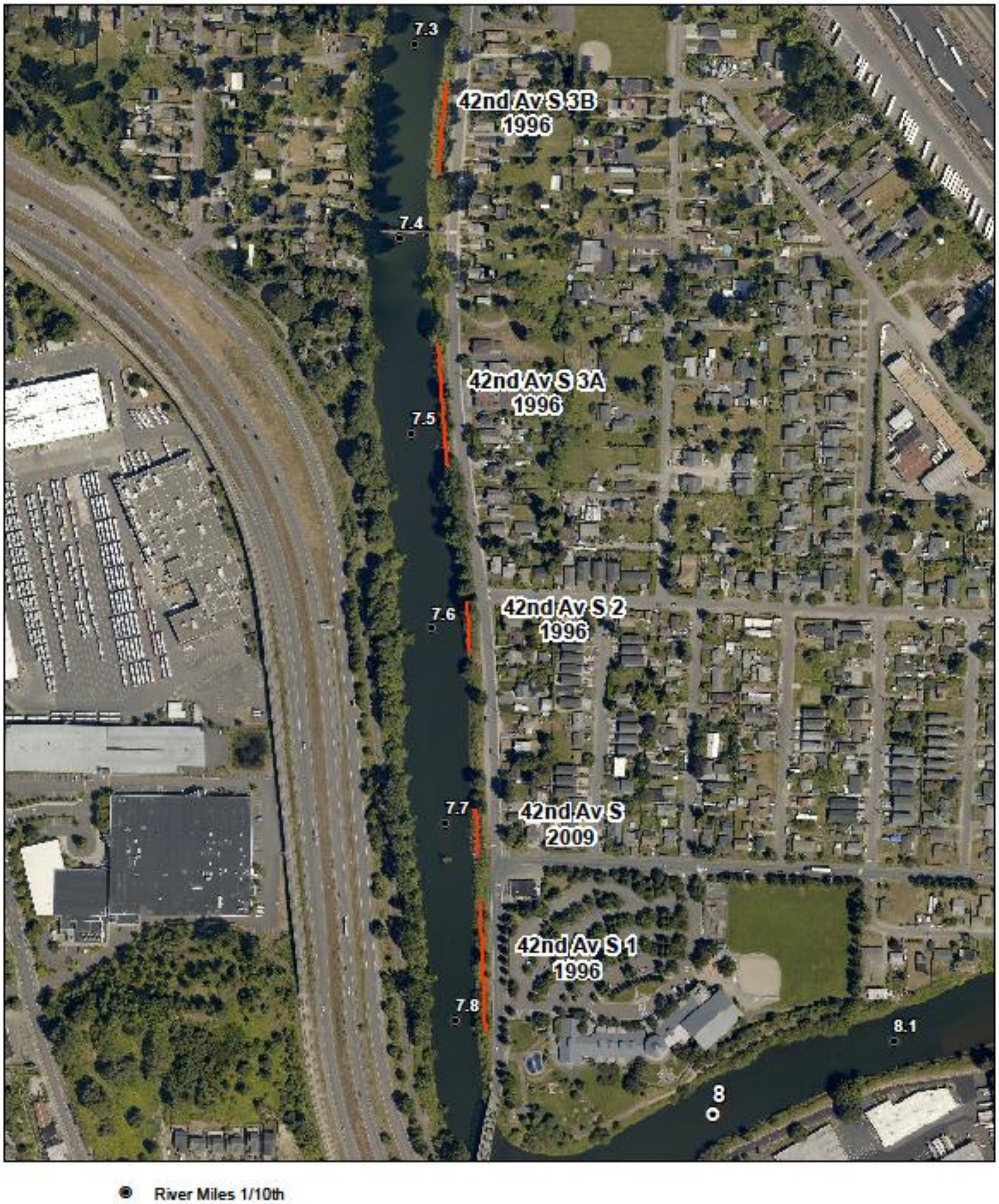

Figure A1. 42nd Ave S

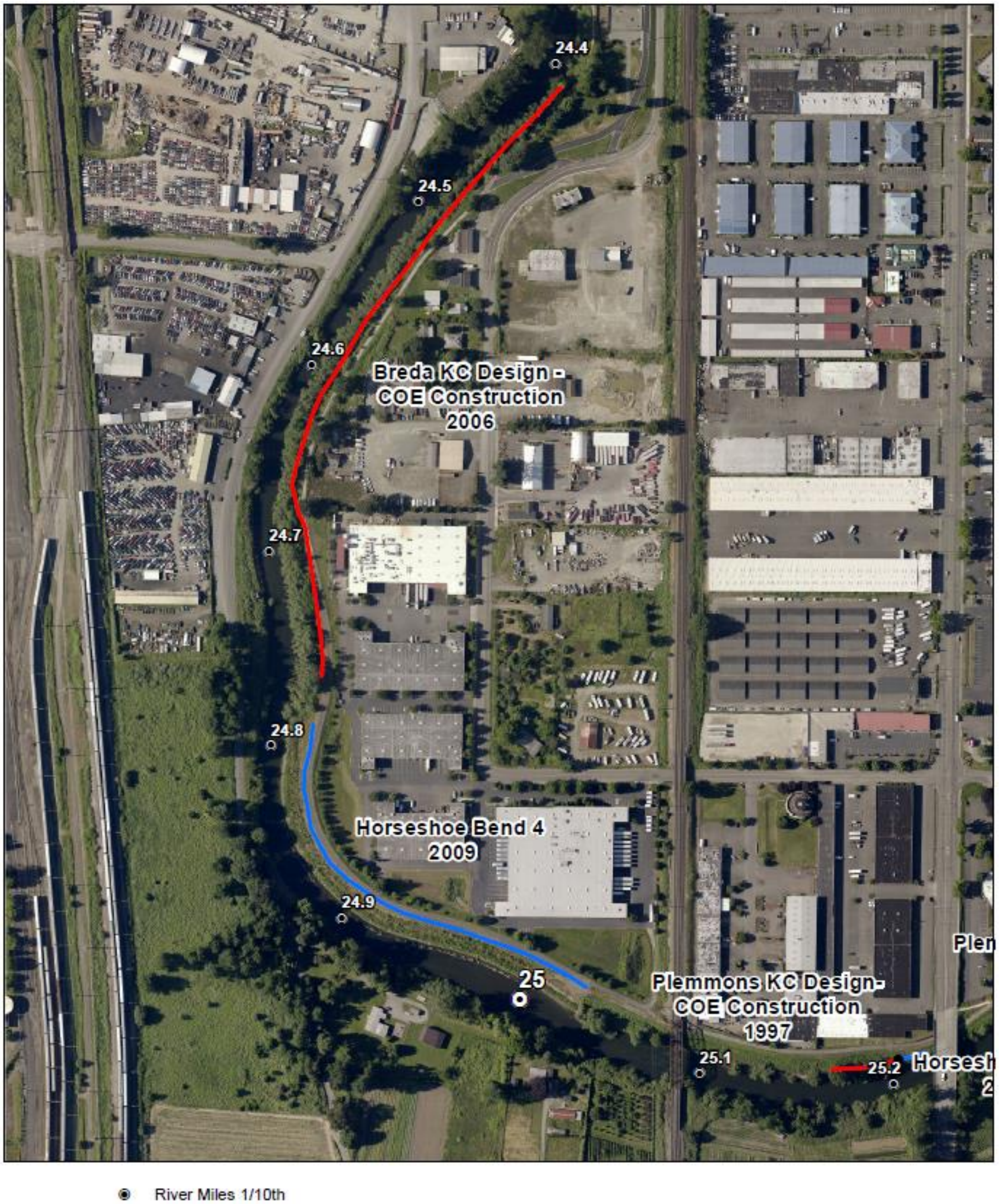

Figure A2. Breda 2 Plemmons

Figure A3. Briscoe 2 Boeing

Figure A4. Dykstra 2 Lones

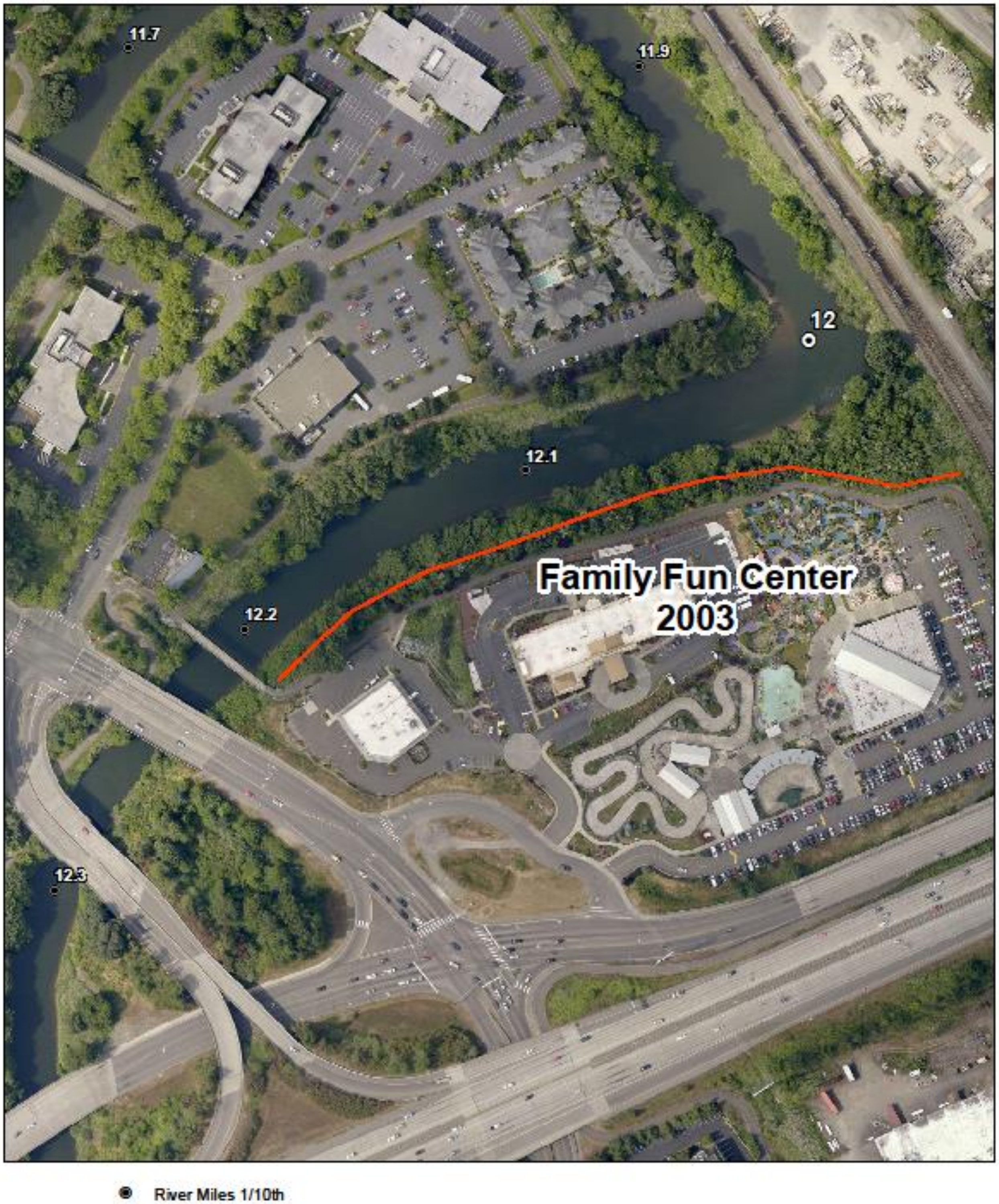

Figure A5. Family Fun Center

Figure A6. Fenster

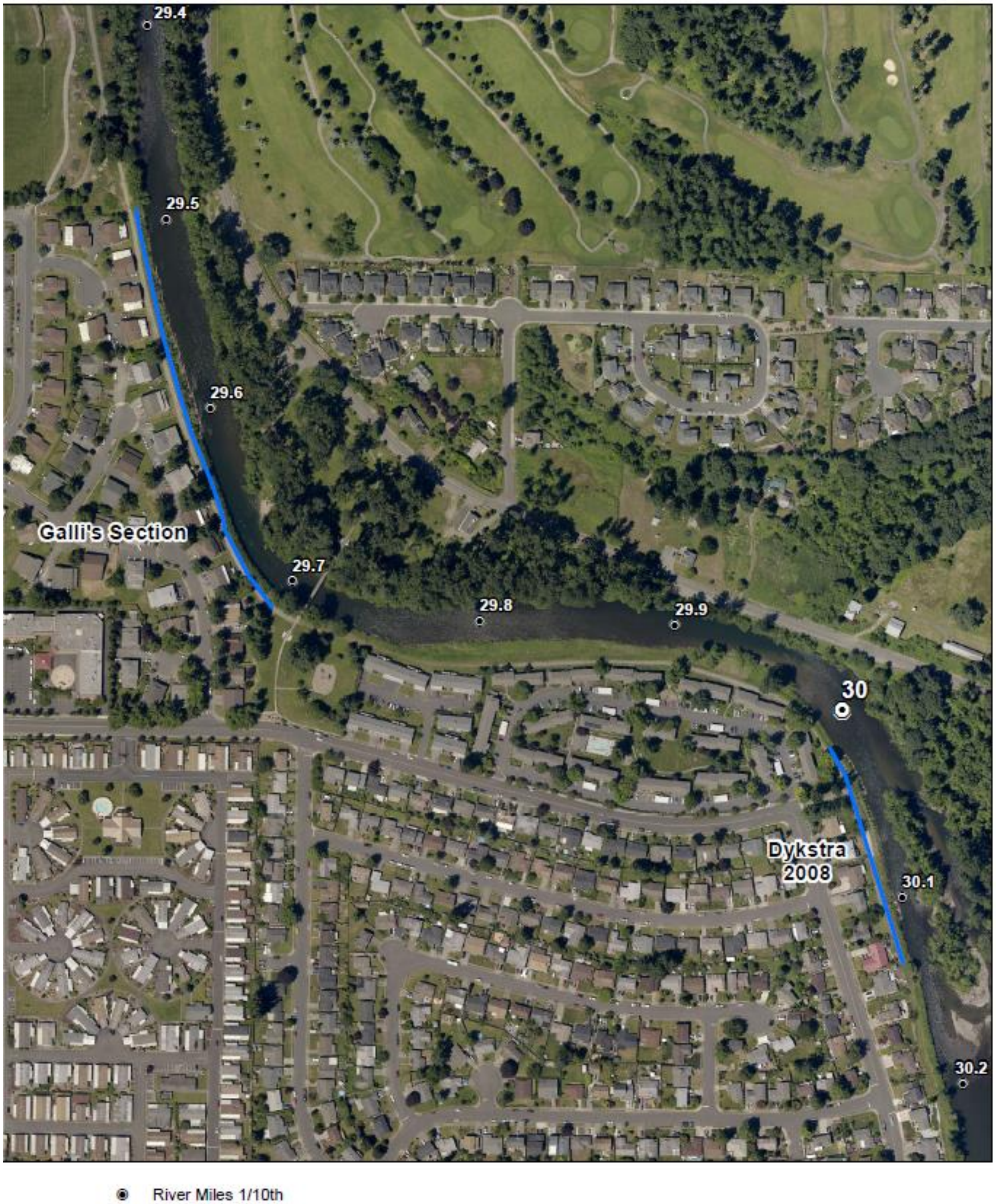

Figure A7. Galli 2 Dykstra

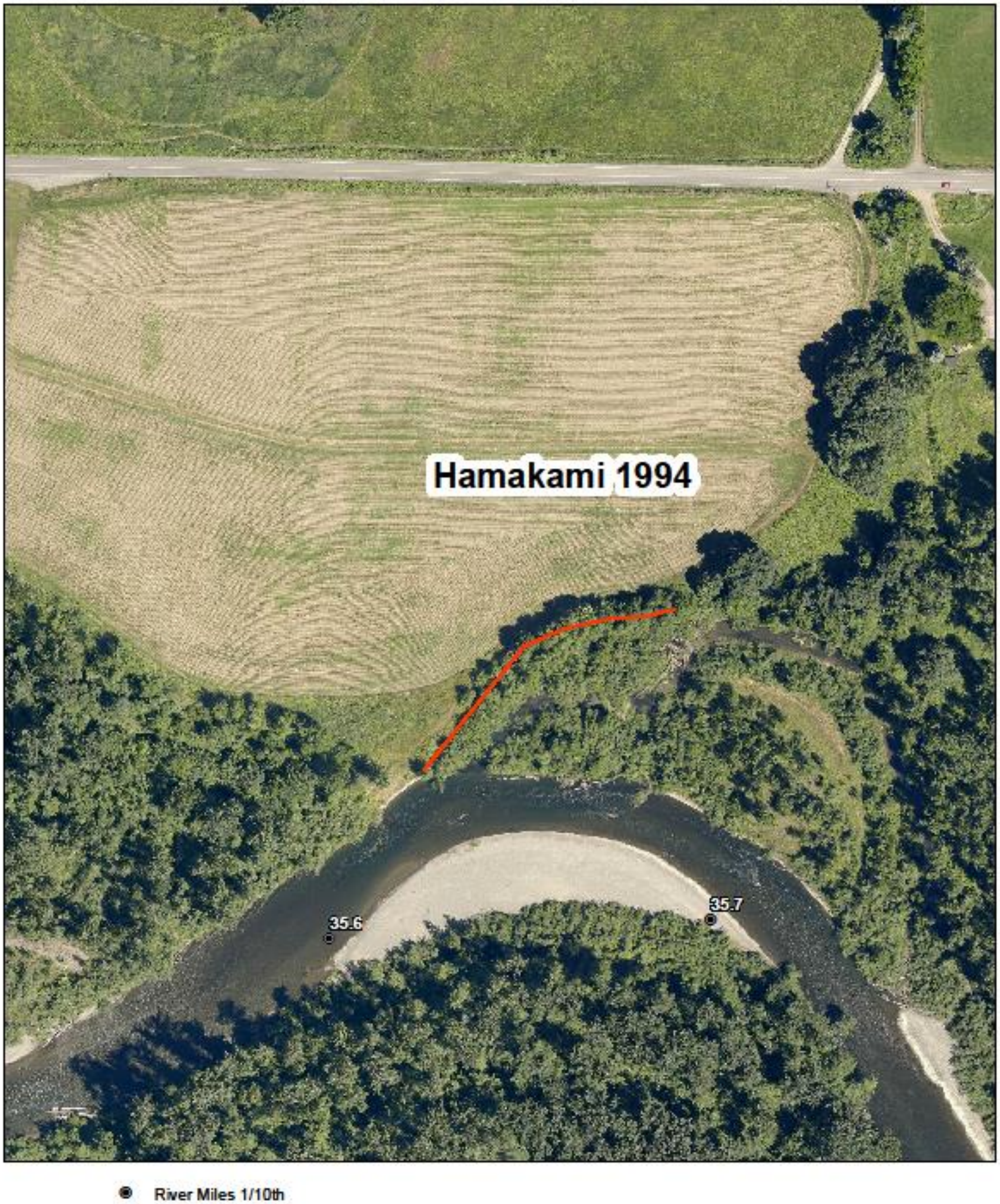

Figure A8. Hamakami

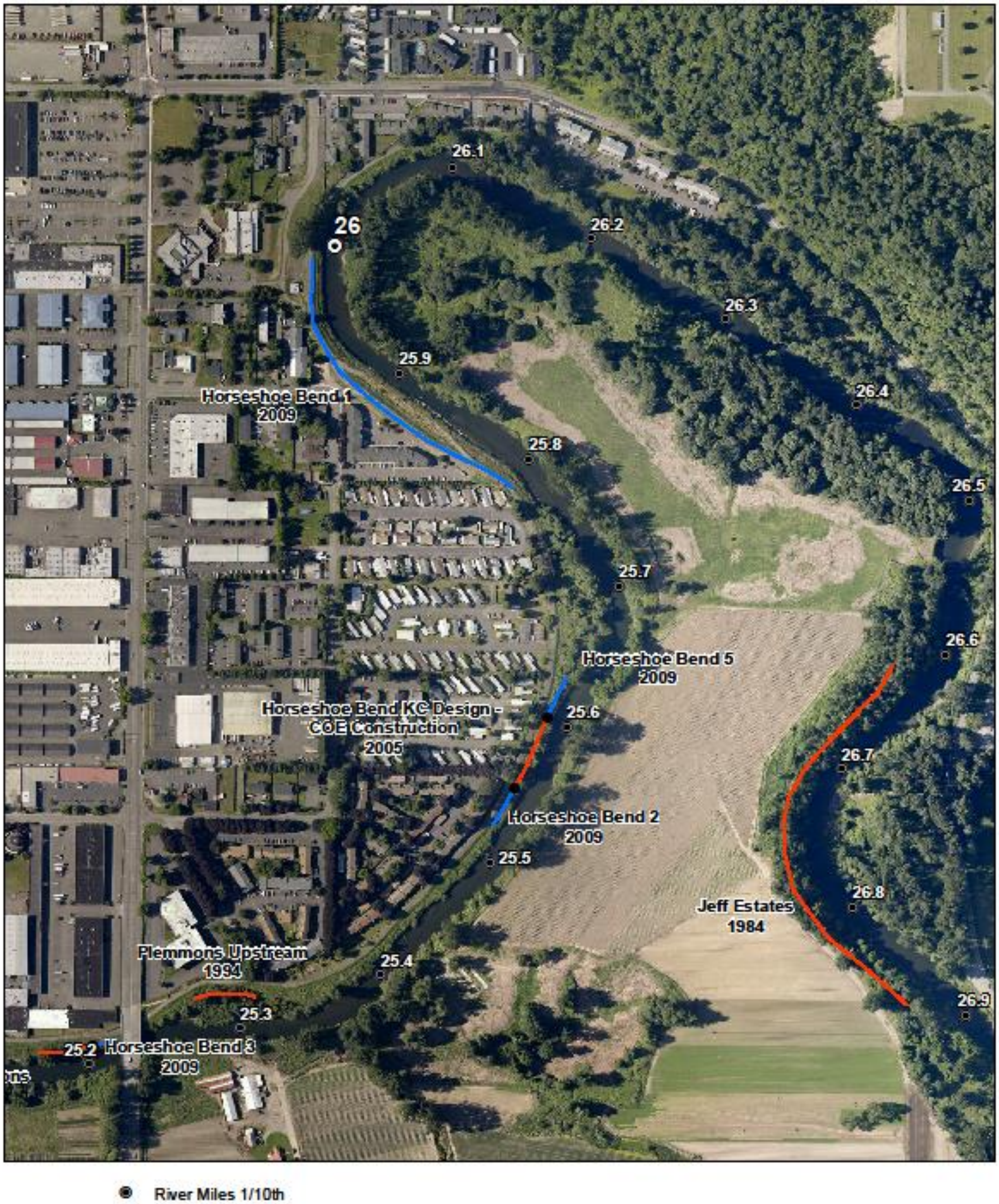

Figure A9. Horseshoe 2 Jeff

Figure A10. Myers Golf 2 Signature Pointe

Figure A11. Narita

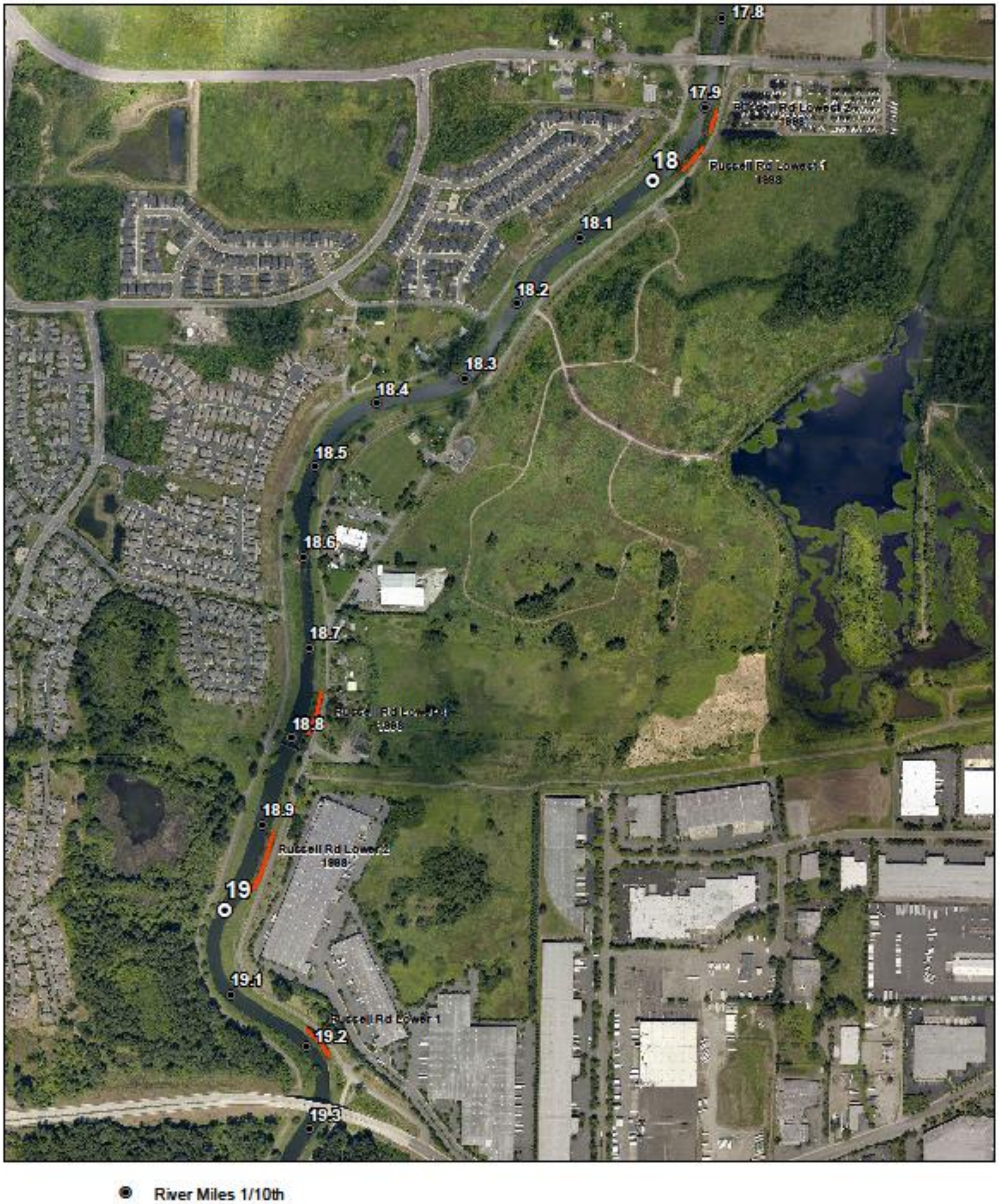

Figure A12. Russell Lowest

Figure A13. Stoneway 2 Russell

Figure A14. Tukwila 2 Desimone