

**Determining the effects of vegetation on levee structural integrity on the
Green River in King County, Washington**

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Abstract

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Levee vegetation management has been a challenge in King County due to conflicting federal mandates. Since the early 1990s King County has been incorporating bioengineering techniques into levee repairs. These techniques entailed the use of vegetation to not only provide bank stability but to also improve conditions for salmon as required under the Endangered Species Act. However, the U.S. Army Corps of Engineers required the removal of any vegetation over two inches in diameter to remain eligible for federal emergency funding under Public Law 84-99, hypothesizing that it compromised levee stability as well as hindered inspections. While there have been many studies on vegetation's effect on stability in natural systems, less information is available on the effect of vegetation on the structural stability of levees and revetments

This research investigates the effect of vegetation on levee structural integrity on the Green River in King County, Washington State. Initially, the investigation set out to compare levees repaired using bioengineering techniques with levees repaired using traditional rock. However, 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. Based on information gleaned from the data mining and mapping exercises, it became clear that comparisons of stability of bioengineered versus non-bioengineered levees could not be made. As such, a retrospective pilot study was undertaken to directly address the issue of the role of vegetation in levee stability. Using a case control method, 12 documented levee sites that incurred damage during November 2006 flooding were matched with undamaged sites on a one to one basis. Basic land cover type (trees, shrubs, grass, bare ground, impervious surfaces) was delineated through aerial photography taken prior to the flooding and percent cover of each type was calculated from these measurements.

Study results reveal the paired differences between percent cover of trees, impervious surfaces, and bare ground were not statistically significantly different between damaged and control sites. However, of the paired sites where trees were present on both the case (damaged site) and the control, the control generally had more tree 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 would be needed to determine a more scientifically defensible and statistically robust result for the effect of tree cover on levee damage. The steps taken for the pilot study could be duplicated in any larger study. However, it is unlikely that all damages could be satisfactorily matched with bioengineered sites on the Green River given the number of variables to be considered when matching. The results from this study show the complexity of trying to isolate a single factor contributing to levee stability.

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Dedication

This thesis is dedicated to my family and friends for their continued support throughout my graduate career and for always cheering me on and believing in my abilities. I am so grateful for all of you and especially for my beautiful mother whom I could not have done this without. Most of all, I would like to dedicate this to my son, Felix, who has inspired me in countless ways and for whom I chose to pursue this degree. I love you to the moon and back

Chapter 1: Introduction

The Federal Emergency Management Agency (FEMA) defines a levee as “a man-made structure, usually of an earthen embankment, designed and constructed in accordance with sound engineering practices to contain, control, or divert the flow of water so as to provide protection from temporary flooding” (FEMA, 2006, p. 399). Essentially, a levee’s main purpose is flood protection. In the 1960s when most of the levees along the Green River in King County were constructed, river and floodplain management was based on an engineered approach involving levee and dam construction without consideration of environmental impacts. 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. This bioengineering approach entailed the use of vegetation to not only provide bank stability, but also improve habitat conditions for salmon as mandated under the Endangered Species Act. Riparian vegetation has been shown to provide shade that helps regulate stream temperatures, refugia for fish, allochthonous inputs of organic matter, habitat for insects and other wildlife, and water quality control by trapping of sediment (Beeson & Doyle, 1995; Clinton, Edwards, & Naiman, 2002; Connors & Naiman, 1984; Karr & Schlosser, 1977; Meehan, Swanson & Sedell, 1977; Naiman et al., 1992; Oakley et al., 1985; USACE, 1991; Wenger, 1999).

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 (USACE, 1995). 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 two 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 four 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. Gray & Megahan, 1989; Gyssels & Poesen, 2003; Pollen & Simon, 2005; Pollen-Bankhead, Simon, Jaeger & Wohl, 2009; Sidle, Pearce & O’Loughlin, 1985; Wynn et al., 2004) 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 recommendations for future study. By contributing to the body of knowledge about vegetation and levee integrity, resource managers will be better able to make informed decisions about ways to balance 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.

Chapter 2: Background

Vegetation and Riverbank Stability

There has been a considerable amount of research completed on the role of vegetation on the stability of streambanks in natural systems. Vegetation provides root reinforcement and reduces soil moisture through interception and transpiration (Sidle et al., 1985, Gray & 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, Schwarz & Tubbs, 1989). Riparian vegetation stabilizes streambanks by reducing erosion and mass wasting and removal of this vegetation leads to an increase in streambank erosion (Gyssels & Poesen, 2003, Wynn et al., 2004, Pollen & Simon, 2005, Pollen- Bankhead et al., 2009). Hershey, Wallace and Dwyer (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 et al. (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 five times more likely to have suffered detectable erosion than bends with vegetation.

There is less research on the role of vegetation on levees than there is on natural riverbanks due to the fact that traditionally, construction and repair of levees was completed using riprap and sod-producing vegetation. Only recently have levee sponsors been incorporating woody vegetation into these construction and repair projects. However, there

have also been instances where vegetation was not maintained to standard and woody vegetation has grown on levees, thus providing opportunities to study the effect of woody vegetation on levee stability.

Several retrospective studies have been completed looking at causes of levee failures including how vegetation may have played a role in those failures. URS Corporation (Kabir & 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.

Gray (1995) gives an overview on how vegetation influences the surficial and mass stability of slopes. Vegetation on slopes reduces surficial erosion through interception, retardation, restraint and infiltration. Vegetation foliage prevents soil detachment by raindrop splash, increases surface roughness thus slowing runoff velocity, and filters sediment out of runoff. Plant roots systems bind and restrain soil particles and help maintain soil permeability and porosity. On streambanks, scour and erosion caused by flowing water is reduced by the protective properties of roots and foliage of riparian vegetation. Vegetation positively affects the mass stability of slopes through root reinforcement of the soil, buttressing and arching that counteracts downslope shear forces, surcharge via increased normal stress on the failure surface, and soil moisture depletion by limiting the positive pore water pressure. He noted that woody plants with their stronger and deeper roots provide greater mechanical bank reinforcement and that some species are better than others. On levees, Gray 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. 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. Another study performed by researchers at the University of Georgia, looked at the resistance of California Central Valley trees to windthrow by completing a tree winching study (Peterson & Claassen, 2013). They successfully completed static winching tests on 66 trees and revealed a significant trend of

the largest tree size classes being more likely to uproot, however it would take substantial winds (>100 mph) to overturn large healthy trees of the species studied.

Interactions between plant roots and levee fill material, as well as soil type contribute to the stability of a levee or revetment. Zanetti, Vennetierb, Mériauxa, Royeta and Provansal (2011) found that substrate materials influenced root structure where low-density surface and mixed root systems occurred in gravelly material, while thicker, denser roots were found on silty or sandy material. The California Levee Vegetation Research Program (SAFCA, 2013) research show that roots appeared to favor silty clay pockets within sandy soil, perhaps due to the moisture difference between the soil types. In addition, results from the windthrow study mentioned earlier in this document reveal that wind-firmness of a tree is increased in denser substrates versus unconsolidated material when the roots are well established. Shields and Gray (1992) investigated the influence of woody vegetation on the structural integrity of sandy levees along the Sacramento River in California. Their 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 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 a 12-15 year-old walnut stump (SAFCA, 2013).

The location of vegetation on the levee and width of the riparian corridor have been shown to influence levee 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. He also found that none of the five damaged revetments supported woody vegetation before or after the flood and concluded that vegetation did not appear to affect revetment durability. USACE (2010) research results

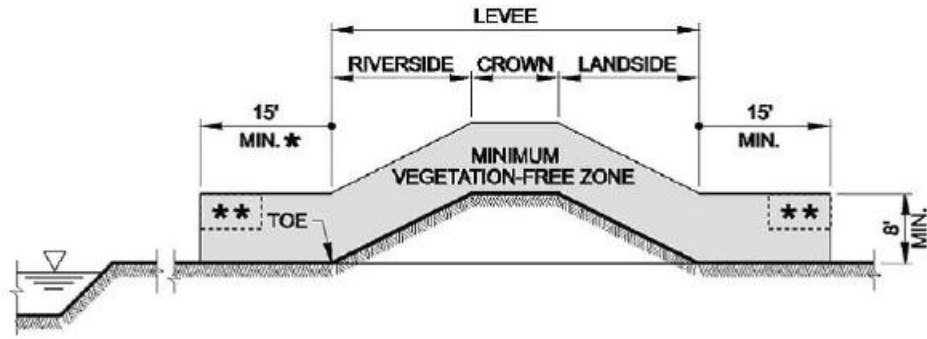
show that the location of vegetation on the levee itself can increase or decrease the stability of the levee. According to their numerical modeling, a single tree located at the levee toe (either side) produced a reinforcing effect and the factor of safety was increased. However, this reinforcing effect appeared to be limited to the area just below the roots. Dwyer, Wallace and Larsen (1997) found that there was an inverse relationship between width of riparian woody vegetation along a levee and the length of the levee failure following the Midwest flood of 1993; as vegetation width increased, length of failure decreased. The data suggest that a woody riparian corridor averaging at least 54.6 m (179 ft) in width is necessary to be effective in minimizing the average failure of the levee as compared to a non-wooded riparian corridor. When the corridor was less than 54.6 m (179 ft) in width there was no difference. However, there was a significant increase in levee stability with a woody riparian corridor of at least 91.5 m (300.2 ft) in width resulting in a 68% decrease in the length of the levee failure.

Moving of soil and creation of tunnels by burrowing animals is a common factor that may lead to increased levee failure risk during flood events. A field study from University of California - 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 University of California - Davis (Van Vuren & Ordeñana, 2011) have found that trees and leaf litter are strongly negatively correlated with burrowing activity; burrow sites are preferentially located in barren areas, and low shrub cover, pavement, leaf litter, trees, gravel and riprap are avoided.

Traditional Levees vs. Bioengineered Levees

Traditionally, levee repairs were completed with the installation of riprap, a layering of rocks embedded in the levee that covers exposed soil to reduce erosion caused by repetitive hydrologic activity. However, riprap along streambanks can cause problems downstream as pointed out in the booklet "Engineering with Nature- Alternative Techniques to Riprap Bank Stabilization" (FEMA, 2009). The speed of water tends to increase at these armored locations because there are no points of friction to slow it down. This can lead to issues downstream as the increased speed and strength of the water deflects off the riprap to other points along the riverbank, requiring more riprap to hold these downstream banks in place. Yet, advanced technologies and techniques for riverbank stabilization have provided numerous alternative options to riprap, such as the use of woody plantings, large wood and erosion control blankets (FEMA, 2009).

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) as well as helping meet the objectives of the Endangered Species Act and Clean Water Act. They have also found that these projects reduce maintenance costs over time. Figure 1 illustrates the general design of a standard USACE levee and a King County bioengineered levee. Typical construction includes bioengineering methods (soil biostabilization) such as adding vegetative brush to help stabilize the bank and levee slope and toe-buttresses constructed with large stone as well as adding large wood that is firmly anchored at the base. Methods for bioengineered levees are described in manuals produced by the State of Washington (Cramer et al., 2002) and King County (King County, 1993).



- * 15' OR DISTANCE TO EDGE OF NORMAL WATER SURFACE, IF LESS
- ** IN THIS 4' X 7' TRANSITION ZONE, TEMPORARY OBSTRUCTION BY LIMBS AND CROWN IS ALLOWED DURING DEVELOPMENT OF NEW PLANTINGS, FOR UP TO 10 YEARS
- ▽ NORMAL WATER SURFACE

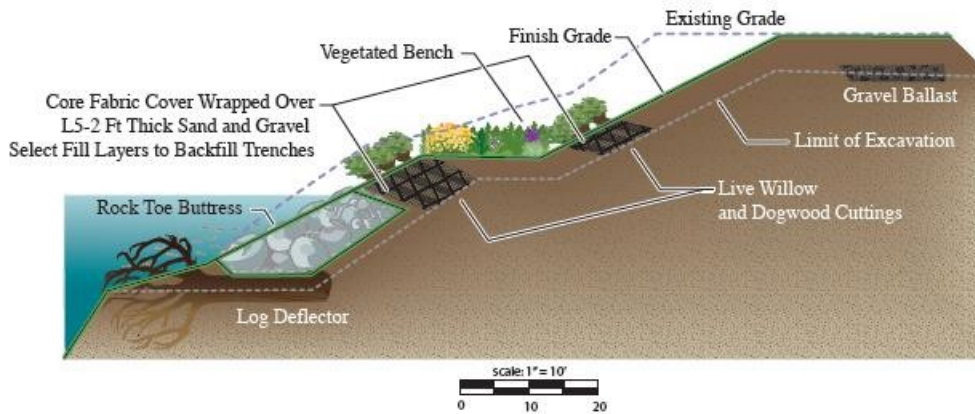


Figure 1. Schematics of a USACE standard levee cross-section (top, USACE 2014b) and a King County bioengineered levee design (bottom, figure courtesy of King County Water and Land Resources Division).

Levee Vegetation Management in the United States

In the wake of Hurricane Katrina, the U.S. Army Corps of Engineers reviewed their policy regarding vegetation on levees and adopted Engineering Technical Letter 1110-2-571 (ETL) to clarify its vegetation-management standards (USACE, 2009a). This letter superseded Engineering Manual (EM) 1110-2-301, *Guidelines for landscape planting and vegetation management at floodwalls, levees, and embankment dams* (USACE, 2000) and the memorandum from USACE Headquarters released on June 12, 2007 describing interim

vegetation guidelines for control of vegetation on levees (USACE, 2007). The ETL described suitable levee vegetation as sod-producing grasses and minimal woody vegetation that does not exceed two inches in diameter. These guidelines were originally created by the USACE in response to catastrophic flooding in the 1930s, in which it was concluded that many of the levees failed due to inadequate inspection because of unruly vegetation concealing the levee embankment (USACE, 1995).

King County, along with other counties located within the territory of the USACE Seattle District, worked with the USACE District on implementing an informal variance for levee vegetation in 1995 (USACE, 1995). The variance was approved following concern expressed by resource agencies regarding habitat loss, and recognized the importance of riparian vegetation in improving habitat for fish and wildlife. The variance allowed certain species of woody vegetation on levees that exceeded the national standard, so long as they did not significantly hinder inspection or conveyance, nor threaten structural integrity of the levee. Suitable vegetation for Western Washington under this variance included the traditional sod-producing legumes, forbs, ferns and grasses as well as certain shrubs and small trees such as *Corylus cornuta* (beaked hazelnut), *Prunus emarginata* (bitter cherry), *Cornus stolonifera* and cultivars (red-osier dogwood), *Spiraea douglasii* (douglas spirea), *Symphoricarpos albus* (snowberry), *Sambucus nigra* or *S. racemosa* (elderberry), *Acer circinatum* (vine maple), and *Salix spp.* (erect willows). The variance stated that the vegetation should be flexible with resilient stems as well as flood and drought tolerant. *Populus trichocarpa* (black cottonwood) and *Alnus rubra* (red alder) more than a few inches in diameter were considered to be unsuitable for levees, as were *Rubus armeniacus* and *R. laciniatus*. (Himalayan and evergreen blackberry). The variance noted that vegetation maintenance guidelines should take into account site-specific variables including levee materials, hydraulic conditions, and proximity to critical facilities.

On November 29th, 2011, the System-Wide Improvement Framework (SWIF) policy was proposed by USACE with the intent of working with levee sponsors to transition existing levees to USACE standards while remaining eligible for federal rehabilitation funding under PL 84-99 and adhering to federal environmental laws (USACE, 2011). Under this framework levee sponsors can submit a Letter of Intent followed by a SWIF plan outlining prioritized levee improvements. The SWIF process recognizes that situational differences exist across the nation and allows for regional variances. It also acknowledges that the SWIF process will need to be accomplished in a collaborative framework and must take into account complex situations and local challenges. King County is currently working on a SWIF for the economically and environmentally important Lower Green River.

During the course of this study, levee vegetation removal requirements set by the USACE changed. On March 21, 2014, USACE headquarters issued the Interim Policy for Determining Eligibility Status of Flood Risk Management Projects for the Rehabilitation Program Pursuant to Public Law (PL) 84-99 (USACE, 2014a). The purpose of the interim policy is to provide revised eligibility criteria for the Rehabilitation Program that is consistent with the anticipated direction of the Program while long-term revisions are being made to 33 Code of Federal Regulations, Section 203 through a rulemaking process. Recognizing the potential for adverse impacts on natural resources and tribal rights, vegetation on levees is no longer a criterion for determining eligibility in the Program. Along with this policy change, USACE also released the updated Engineering Technical Letter (ETL) 1110-2-583, to provide revised guidelines for vegetation management on levees (USACE, 2014b). The main difference between this ETL and the post-Katrina ETL released in 2009 are that tree trunks are now measured on their centerline, allowing half of the tree to be within the vegetation-free zone. In addition, the crowns of newly planted trees may enter the vegetation-free zone with the idea that in 10 years these crowns will clear the minimum height requirement of the zone. Otherwise, the only allowable vegetation within the zone is perennial grass

unless the levee sponsor obtains a vegetation variance. The ETL goes on to describe the criteria that must be met in order to obtain a variance, as well as additional guidance and requirements for vegetation management on levees and other appurtenant structures.

Chapter 3: Study Site Description

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). There are six major watersheds in the county; Vashon-Maury Island Watershed, Sammamish Watershed, Snoqualmie-Skykomish River Watershed, Cedar River-Lake Washington Watershed, Green-Duwamish River Watershed and the White River Watershed (Figure 2). This investigation is limited to the Green-Duwamish River Watershed, approximately from river mile 11 to river mile 32 (Figure 3). This section of river has the largest network of King County's levee systems, and is also home to the vast majority of bioengineered levee repair projects in the county.



Figure 2. Watersheds of King County, Washington (Accessed 2/6/2015 at <http://www.kingcounty.gov/services/environment/watersheds.aspx>).



Figure 3. Location map of section of the Green River in this study (Image courtesy of King County GIS).

The Green River begins at the crest of the Cascade Mountains and flows west 93 miles (150 km) to Elliot Bay (Herrera, 2005; Kerwin & Nelson, 2000). There have been major alterations to this watershed over the years, greatly affecting the flow paths and drainage area (Kerwin & Nelson, 2000). Historically, the White River, Cedar River and Green River flowed into the Duwamish River. However, in 1911 the White River was diverted to flow into the Puyallup River and a few years later in 1916, the Cedar and Black Rivers were diverted to flow into Lake Washington, thus reducing the total drainage area of 1,600 square miles (4162 km²) to 558 square miles (1452 km²). Starting around 1895 and continuing until 1980, the Green-Duwamish River was diked, straightened and channelized for flood control, navigation and industry. Land use varies greatly throughout the watershed from residential and industrial use in the lower watershed to agriculture and commercial in the middle watershed, to forest production in the upper watershed (Kerwin & Nelson, 2000).

Howard Hanson Dam was constructed and completed in 1962 at river mile 64 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 (cfs) 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 tshawytscha*) 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 & 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 circinnatum*) (Collins and Sheikh 2005), of which only the oldest and largest approach 32m.

Chapter 4: Methods

Data Mining

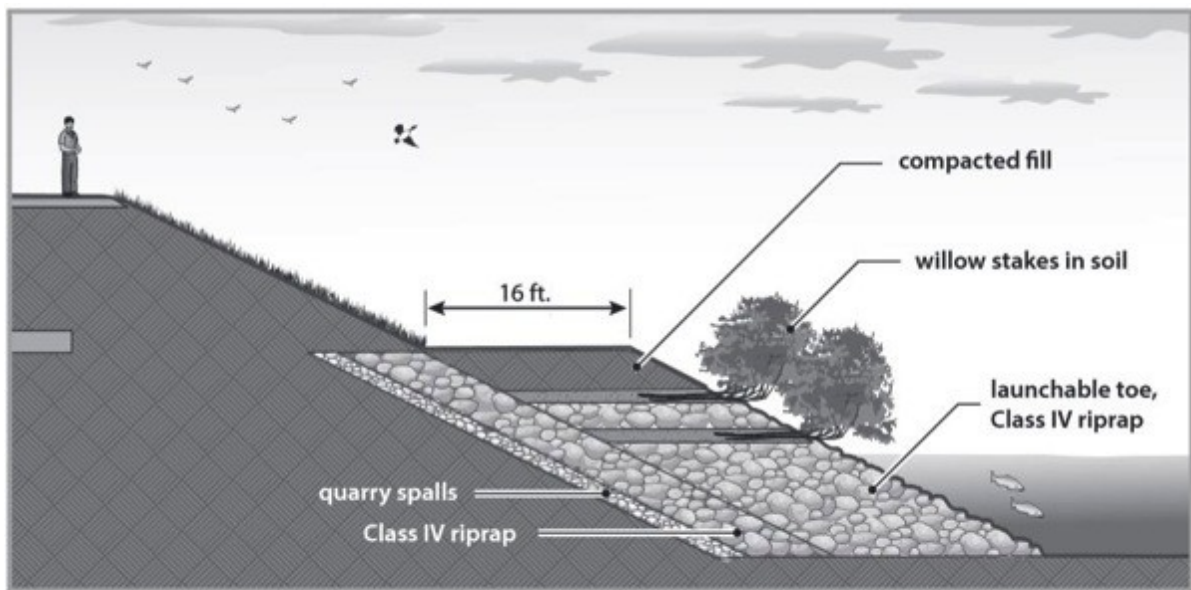
It was necessary to determine what data and other resources were available from King County and other agencies to conduct a research study on the effects of woody vegetation on levees in King County. Specifically, to find data on where and when damages and repairs occurred, as well as what vegetation 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 effort on this study was spent organizing files and documenting the institutional knowledge at King County on the levee projects along the Green River. 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 this document 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 the upstream and downstream end of each bioengineered levee repair project 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 Geographic Information Systems (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 4 depicts a typical cross section of a USACE-designed and constructed levee repair in King County. Some differences between these repairs and bioengineered repairs completed by King County were that the USACE repairs typically have wood that 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.



TUKWILA 205 TYPICAL SECTION

not to scale

Figure 4. Schematic of a bioengineered levee repair with a launchable toe design in King County (image courtesy of King County).

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.

Pilot Study

A retrospective pilot study was conducted that focused on levees damaged during flooding to determine what role vegetation 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, FEMA Disaster Declaration #1671, was used. The extent of these damages was outlined in an official request for emergency funding from King County to FEMA. 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; 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 photograph interpretation (Figure 5).

Within each polygon, percent cover was calculated for each of the five basic land cover categories created for this study: trees, shrubs, grass, impervious surfaces and bare ground. Trees were differentiated from shrubs based on height, where trees were identified as anything that appeared to be over five meters tall. In instances where it was difficult to distinguish height, first return Light Detection and Ranging (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 & Cox 2014). In this study, the "cases" were the 12 levee sites where damage 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 platform.

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 percentage of various land cover categories between sections of damaged and undamaged levees.



Figure 5. 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 different from zero. This was performed using the online calculator, Simple Interactive Statistical Analysis (SISA) <http://www.quantitativeskills.com/sisa/calculations/samsize.htm>).

Chapter 5: Results

Data Mining

Early in this study, physical factors were found to pose a high level of variability. Local rivers have dramatically different hydraulic and hydrologic regimes that cause different erosive potential. For example, the Green and Cedar Rivers have flood control dams while water in the Snoqualmie River is unregulated. The Green River is also lined with flood controls levees downstream of the Howard Hanson Dam. Although the Snoqualmie River has levees, they only influence the pattern and frequency of flooding but do not prevent it from occurring. While flood flows in the Green River are limited to a maximum of 12,000 cfs, Snoqualmie River floods are much larger during high flow events with values reaching upwards of 60,000 cfs. In order to avoid the large physical differences between rivers systems described above, this study was limited to the Green River. This river was chosen because flows are regulated and most of the work in King County to repair flood facilities with native riparian vegetation has been done along this river.

However, within a river there are also site-specific variables that influence study results such as where the vegetation is located on the planform of the river (e.g. outside bend, inside bend, straight reach), the age of the levee, what construction method and materials were used, how the vegetation has been managed over the years, and so forth. For this reason, pertinent information about the bioengineered repairs was gathered and 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.

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 during this study. In the U.S., the method commonly used to locate levees,

revetments and repair sites is the river mile (RM) 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.

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. In addition, some of the newer repairs completed by the USACE in 2008 and 2009 are unlikely to fail because along with the native vegetation, their construction also entailed

use of substantial quantities of rock. Some of these repairs have sacrificial parts (e.g. a 'launchable toe') so that even if portions of the levee wash away, it is still deemed intact. For these reasons, clearly defined and comparable case and control sites were unavailable for this study and so 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.

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 6) to complete removal of the native vegetation and replacement with turf grass (Figure 7).



Figure 6. 2004 Fenster levee repair - photos taken January 7, 2013.



Figure 7. 1995 Dystra levee repair - photos taken 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, which is now maintained by 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 was used.

Locations and characteristics of the case-control matched sites are 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 ft to over 1100 ft. 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 show percent covers for each case and control. Figure 8 shows the distribution and range of percent covers between cases and controls as box plots.

Tree cover ranged from 0-17% at the case (damaged) sites and 0-43% at the control (undamaged) sites. Median tree cover was 5% for the case 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 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 versus 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 (Sarah McCarthy, personal communication).

Table 1. List of cases (damaged) with corresponding matched control information. Planforms are inside (I), 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 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 case (damaged) sites. Note: 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 Site 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 Rehabilitation, Dykstra	Left	30.47	30.57	17,271	10	35	54	1	1

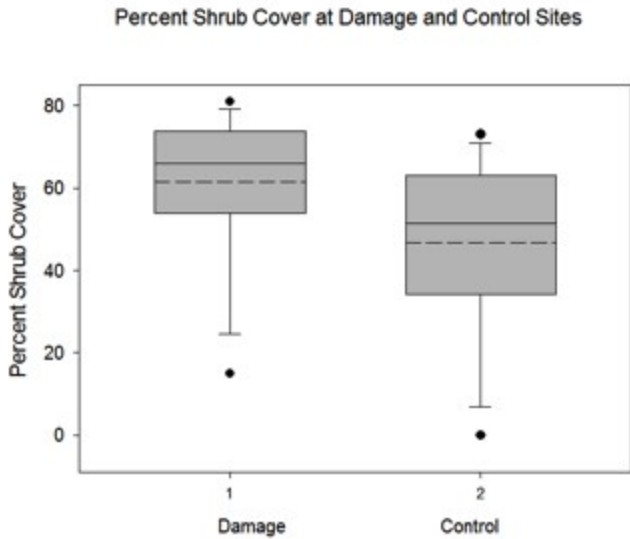
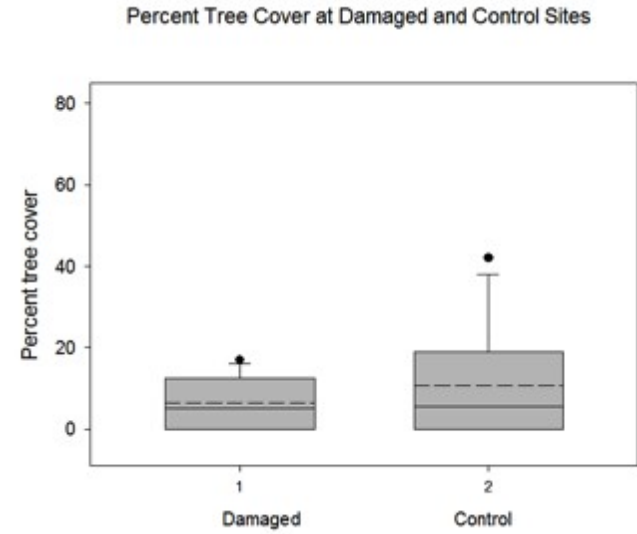
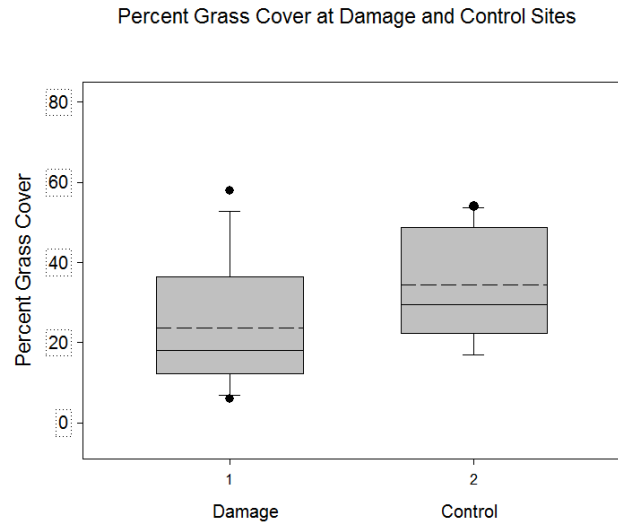


Figure 8. Box plots showing distribution of vegetation cover at sites prior to the November 2006 flood event. Solid line is median, dashed is average, box is 75th and 25th percentile, whiskers are 90th and 10th percentile. Dots are outliers.

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 9 shows the range of paired differences for each category of vegetation. Negative values mean that the case (damaged) site had less cover than its paired control; positive values mean that the case 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 (damaged) site. To test whether the paired differences were statistically significant a paired t-test was performed for each (Table 4).

PAIRED DIFFERENCES BETWEEN CASES AND CONTROLS % VEGETATION

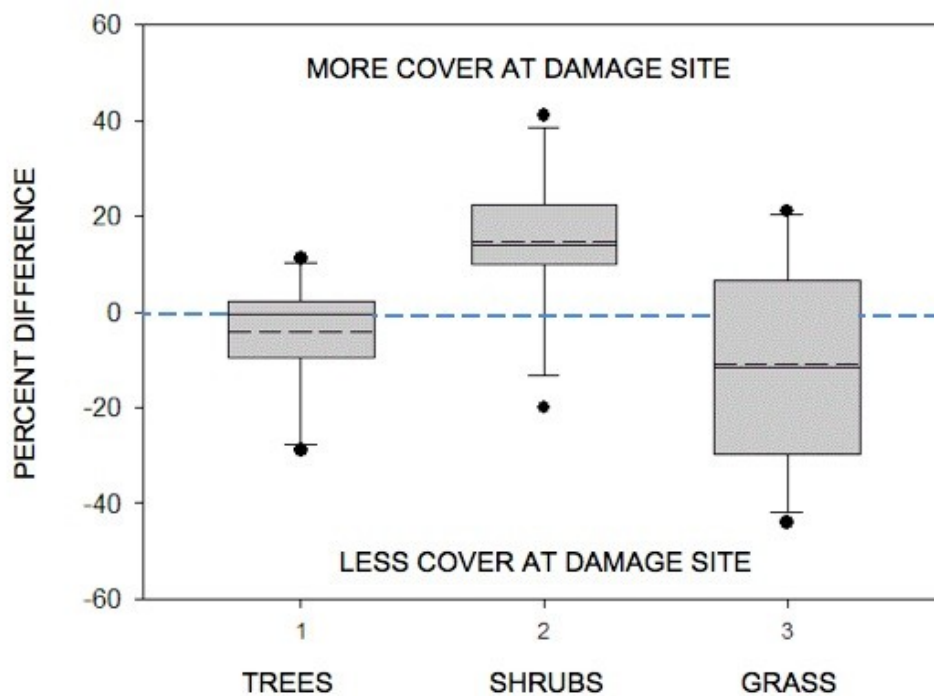


Figure 9. Box plots of paired differences in vegetation cover between damaged and undamaged sites. Solid line is median, dashed line in box is average, box is 7th and 25th percentile, whiskers are 90th and 10th percentile. Dots are outliers. Dashed blue line is zero percent difference.

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

		Paired Differences			t	df	p
		Mean	Standard Deviation	Standard 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	-.500	4.719	1.362	-0.367	11	0.721
Pair 5	BareGround_damaged - BareGround_undamaged	.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 tree cover than the damaged site.

The post-hoc power analysis indicates that a much larger sample size is needed. For this analysis the following parameters were used:

- Alpha (α) was set at 0.10, and is the probability of rejecting the null hypothesis given that it is true.
- Power ($1 - \beta$) was set at 0.80, and is the probability of correctly rejecting the null hypothesis when it is false.
- A two-tailed test was performed to determine whether the paired means were different from each other.

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	0.10	54
Shrubs	14.75	15.23	0.10	8
Grass	-10.92	20.87	0.10	24
Impervious	-0.5	4.72	0.10	553
Bare Ground	0.92	3.73	0.10	104

Chapter 6: Discussion and Conclusions

Discussion and Significance of Results

Determining the effect of woody vegetation on the structural integrity of levees and revetments in King County is a complex task. This study has revealed issues with policy, interpretation, terminology, and data gaps. In addition, 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.

Results from data mining show the importance of keeping complete and accurate records, however in many circumstances funding and staffing constraints make it difficult to execute this task. Collecting and reporting data has a cost and may be required for regulatory compliance. Levee data required for federal financial assistance are specified by the USACE, which Congress authorized in part c of Public Law 84-99 (PL 84-99). Levee data that are not required to obtain financial assistance for levee repair and maintenance are less abundant. In addition, it's important to document institutional knowledge in a timely and appropriate manner so that it is not lost when staff members move on to other positions. Now that important information about the bioengineered projects on the Green River has been gathered and centralized at King County in an Excel file entitled 'Master Green River Facility Repair Records', it will aid in future monitoring and research.

Prior to this study, no digital information was available on bioengineered levee projects on the Green River. During the mapping portion of this study, fifty-four bioengineered repairs on the Green River were visited and georeferenced. This information is now in a GIS file maintained by the King County River and Floodplain Management Section. This step was critical to the success of this project and will be of great value moving forward for management of these projects and future research on bioengineered levees in King County.

Although bioengineering projects on the Green River are abundant, with 54 total projects to date, site visits revealed that sites have been maintained very differently over the years. This adds to the complexity of trying to design a study comparing bioengineered sites with non-bioengineered sites because it's possible that, even though a site would have been bioengineered with native woody vegetation, it may in fact look more like a traditional repair site with sod-producing grasses, as was the case at the 1995 Dykstra levee repair site (Figure 7).

The pilot study has provided necessary preliminary information about the relationship between vegetation 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 with matches chosen to control for as many physical parameters as possible. 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. Overall, there does not appear to be a trend in regards to planform of damage locations. 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 possible, control sites were located on the same levee as the matched case. 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.

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, presence or absence of burrowing mammals, location of woody vegetation on the levee itself, and age of the levee. It's important to note that 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.

Study Limitations

When this study commenced, the original hypothesis involved looking at levees that had been repaired using bioengineered techniques to those that had not. However, this was not possible given the potential sample size and complexity of trying to match cases with controls that possessed similar characteristics such as the same planform, levee construction, etc. Even with the new question posed in the pilot study looking strictly at vegetation on levees with and without damage, it was difficult to find suitable matches.

Because the pilot study was a retrospective analysis of vegetation on levees, historic aerial photographs were utilized, however at this scale it was difficult to confirm whether

shrubs were native or non-native. Results from the pilot study show that there was a statistical significance of shrub cover between the cases and controls. Although identification of native versus non-native species of shrubs could be identified through photo analysis, recent field data reveal that at least 66% of the Lower Green River shrubs are non-native. However, these data were collected in 2010, four years after the aerial photographs were taken. Although the assumption is that percent native versus non-native is consistent within this timeframe, it cannot be confirmed.

Management Implications and Future Research

This study represents a first attempt at quantifying the effect of vegetation on levee stability in King County. As indicated by the results from the statistical analysis, 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. However, 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 a single flood events on a single river levee system 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 will have 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. Find 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.

The case-control method used for the pilot study looked at types of levees from King County and the USACE with respect to levee maintenance due to issues related to cover differences between damaged and undamaged sites on levees. Trees were the main issue due to the conflicts between USACE requirements for levee stability and ESA requirements for fish habitat. However, vegetation cover is but one aspect of bioengineered levees. An alternative study option to test the more holistic idea of bioengineered versus traditional levees using 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 damaged levee reaches and determine characteristics of these reaches such as construction type, year and geomorphic location (inside bend, outside bend, straight reach), then match undamaged levee reaches with the same characteristics from a single flood.. If one assumes equal probability of damage, then a chi square test could be used to compare the distribution of the particular characteristic between damaged and undamaged areas.

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.

It is clear that a number of factors affect whether vegetation is a beneficial or adverse factor on levee stability, and vegetation cannot be looked at in isolation. Recent research conducted on vegetation and levee integrity has contributed to the literature, but more research is needed on this complex subject, particularly as it pertains to King County levees. Additional research is needed on the effectiveness of various bioengineering techniques using woody vegetation with respect to levee integrity, particularly in King County and the Puget Sound Basin. Also, the effect of woody vegetation on levee inspection, maintenance and accessibility to the levee should be investigated. Although some studies have been completed on the effect of woody vegetation on population density of burrowing mammals as compared to traditional sod-producing vegetation, more studies are needed.

Effective management of levee vegetation on the Green River and in King County requires thoughtful evaluation of the environmental, economic and social impacts associated with this task. It's imperative that Best Management Practices (BMPs) are continually updated as new information becomes available so that methods used for riverbank stability are also allowing natural processes to happen.

Final Remarks

Some floodplain management agencies such as King County have multiple goals that include long-term cost effectiveness, public safety and environmental quality. This multi-faceted approach to floodplain management needs to be considered when determining best management practices for managing vegetation and confirms the idea that a one-size-fits-all levee vegetation policy 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. In addition, the ever-increasing costs of flood damages may lead to more effective ways to achieve flood risk reduction than levee maintenance. Non-structural and risk-based strategies are likely to become more common moving forward.

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. 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.

References

- 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.
- Clinton, S. M., Edwards, R. T. & R. J. Naiman. 2002. Forest-river interactions: influence on hyporheic dissolved organic carbon concentrations in a floodplain terrace. *Journal of the American Water Resources Association*. 38(3): 619-631.
- 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. & 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.
- Connors, M. E. & R. J. Naiman. 1984. Particulate allochthonous input: relationship with stream size in an undisturbed watershed. *Can. J. Fish Aq. Sci.* 41:1473-1484.
- Cramer, M., Bates, K., Miller, D., Boyd, K., Fotherby, L., Skidmore, P. & 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.
- Dwyer, J. P., Wallace, D. & D. R. Larsen. 1997. Value of woody river corridors in levee protection along the Missouri River in 1993. *Journal of the American Water Resources Association*. 33(2):481-489.
- Federal Emergency Management Agency (FEMA), 2006. Department of Homeland Security. Emergency Management and Assistance, Title 44, vol. 1 (2006), p. 399
- Federal Emergency Mangement Agency (FEMA). 2009. Engineering with Nature: Alternative Techniques to Riprap Bank Stabilization. Washington D.C, p. 34.
- Gray, D. H. 1995. Influence of vegetation on the stability of slopes. Vegetation and slopes: Stabilization, protection, and ecology. D.H. Barker, ed.
- 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.
- Herrera Environmental Consultants, Inc. 2005. Year 2003 Water Quality Data Report, Green-Duwamish Watershed Water Quality Assessment. Report prepared for King County Department of Natural Resources and Parks in association with Anchor Environmental, LLC and Northwest Hydraulic Consultants, Inc.
- 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. & 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.
- Karr, J. R. & I. Schlosser. 1977. Impact of nearstream vegetation and stream morphology on water quality and stream biota. EPA 600/3-77/097. Washington, DC: U.S. Environmental Protection Agency. [Pages unknown].
- Keogh, R. H. & D. R. Cox. 2014. Case-Control Studies. Oxford, U.K.: University of Oxford.
- Kerwin, J. & T. S. Nelson (Eds.). December 2000. "Habitat Limiting Factors and Reconnaissance Assessment Report, Green/Duwamish and Central Puget Sound Watersheds (WRIA 9 and Vashon Island)." Washington Conservation Commission and the King County Department of Natural Resources.
- 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.
- Meehan, W. R., Swanson, F. J. & J. R. Sedell. 1977. Influences of riparian vegetation on aquatic ecosystems with particular reference to salmonid fishes and their food supply. Proceedings: Importance, preservation and management of riparian habitat: a symposium, Tuscan, AZ. Gen. Tech. Rep. RM-43.:137-145.
- Naiman, R. J., Beechie, T. J., Benda, L. E. [et al.]. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal region. In Naiman, R. J., ed. Watershed management: balancing sustainability and environmental change. Seattle, WA: University of Washington, Center for Streamside Studies: 127-188.
- Oakley, A. L., Collins, J. A., Everson, L. B. [et al.]. 1985. Riparian zones and freshwater wetlands. In: Brown, E. R., ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1–Chapter narratives. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region: 57-80.

- Peterson, C. J. & V. Claassen. 2013. An evaluation of the stability of *Quercus lobata* and *Populus fremontii* on river levees assessed using static winching tests. *Forestry*. 86(2): 201-209.
- 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.
- Sidele, 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., Cobos-Roa, D., Bray, J., Sitar, N., Lictor, J. & 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.
- U.S. Army Corps of Engineers (USACE). 1991. Buffer strips for riparian zone management. Waltham, MA: New England Division. 56 p.
- U.S. Army Corps of Engineers (USACE), Seattle District. Feb 28, 1995. PL 84-99 Levee Vegetation Management.
- U.S. Army Corps of Engineers (USACE). 2000. Guidelines for Landscape Planting and Vegetation Management at Floodwalls, Levees, and Embankment Dams. Engineering Manual (EM) 1110-2-301. Washington, D.C.
- U.S. Army Corps of Engineers (USACE). 2007. Interim Vegetation Guidance for control of Vegetation on Levees. Washington D.C.
- U.S. Army Corps of Engineers (USACE). 2009. Engineering and design: guidelines for landscape planting and vegetation management at levees, floodwalls, embankment dams, and appurtenant structures. Engineer Technical Letter (ETL) 1110-2-571. Washington D.C.

- U.S. Army Corps of Engineers (USACE). 2010. Literature review – Vegetation on levees. ERDC SR-10-2. Washington D.C.
- U.S. Army Corps of Engineers (USACE). 2011. Policy for development and implementation of System-Wide Improvement Frameworks (SWIFs). Washington D.C.
- U.S. Army Corps of Engineers (USACE). 2014a. Interim Policy for Determining Eligibility Status of Flood Risk Management Projects for the Rehabilitation Program Pursuant to Public Law (PL) 84-99. Washington D.C.
- U.S. Army Corps of Engineers (USACE). 2014b. Engineering and design: guidelines for landscape planting and vegetation management at levees, floodwalls, embankment dams, and appurtenant structures. Engineer Technical Letter (ETL) 1110-2-583. Washington D.C.
- Van Vuren, D. & 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.
- Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent and vegetation. Athens, GA: Office of Public Service and Outreach, Institute of Ecology, University of Georgia. 59 p.
- Wynn, T. M., Mostaghimi, S., Burger, J. A., Adrian, A., Harpold, A. A., Henderson, M. B. & L. Henry. 2004. Variation in root density along stream banks. *Journal of Environmental Quality*. 33:2030-2039.
- Zanetti, C., Vennetierb, M., Mériauxa, P., Royeta, P. & M. Provansal. 2011. Managing woody vegetation on earth dikes: risks assessment and maintenance solutions. *Procedia Environmental Sciences*. 9: 196 – 200.

Appendix – Maps of repaired facilities with date of repair and river mile (produced by King County Water and Land Resources Division GIS staff) - Red lines indicate King County repairs, Blue lines USACE repairs. Maps in alphabetical order.

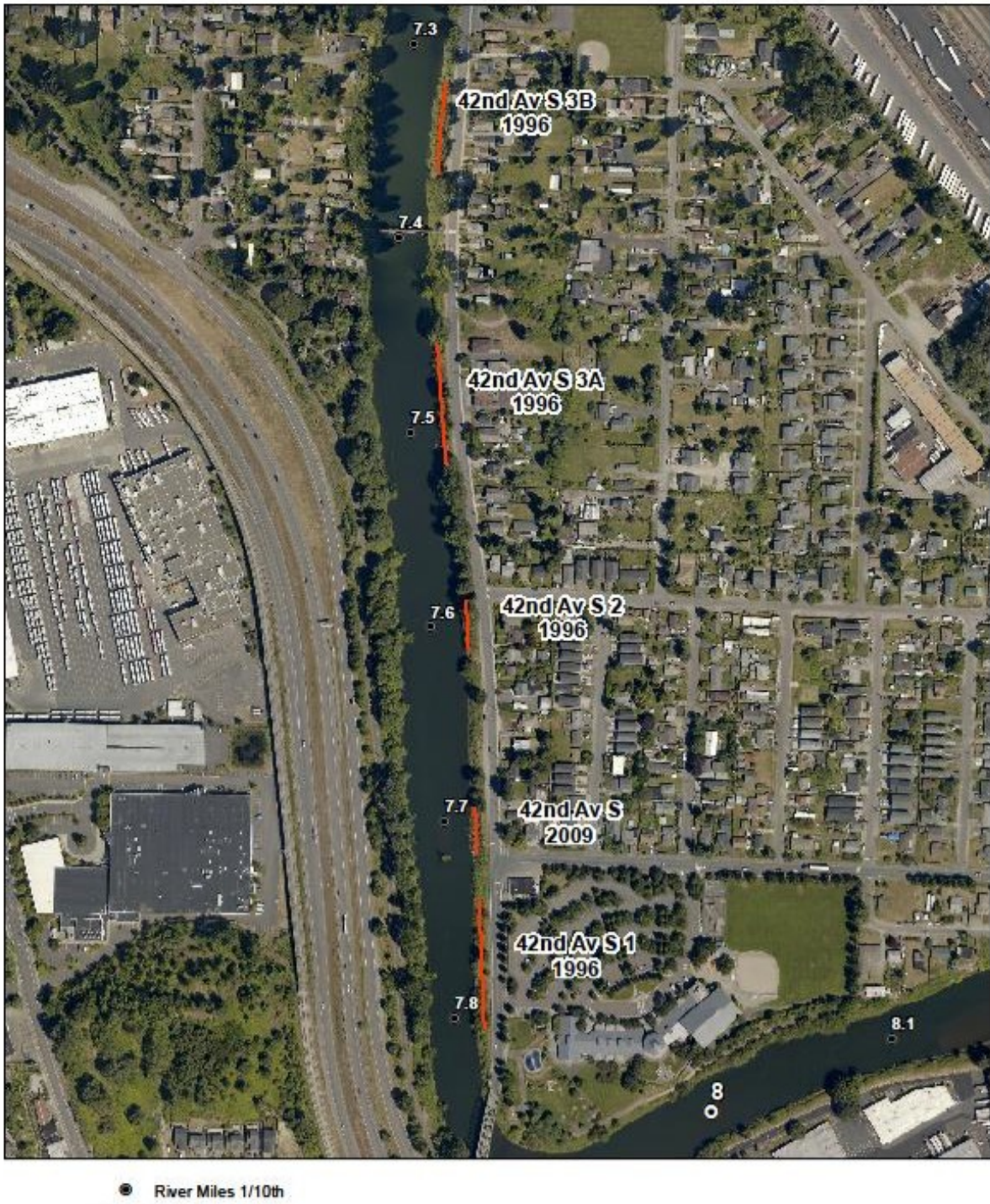


Figure A1. 42nd Ave S

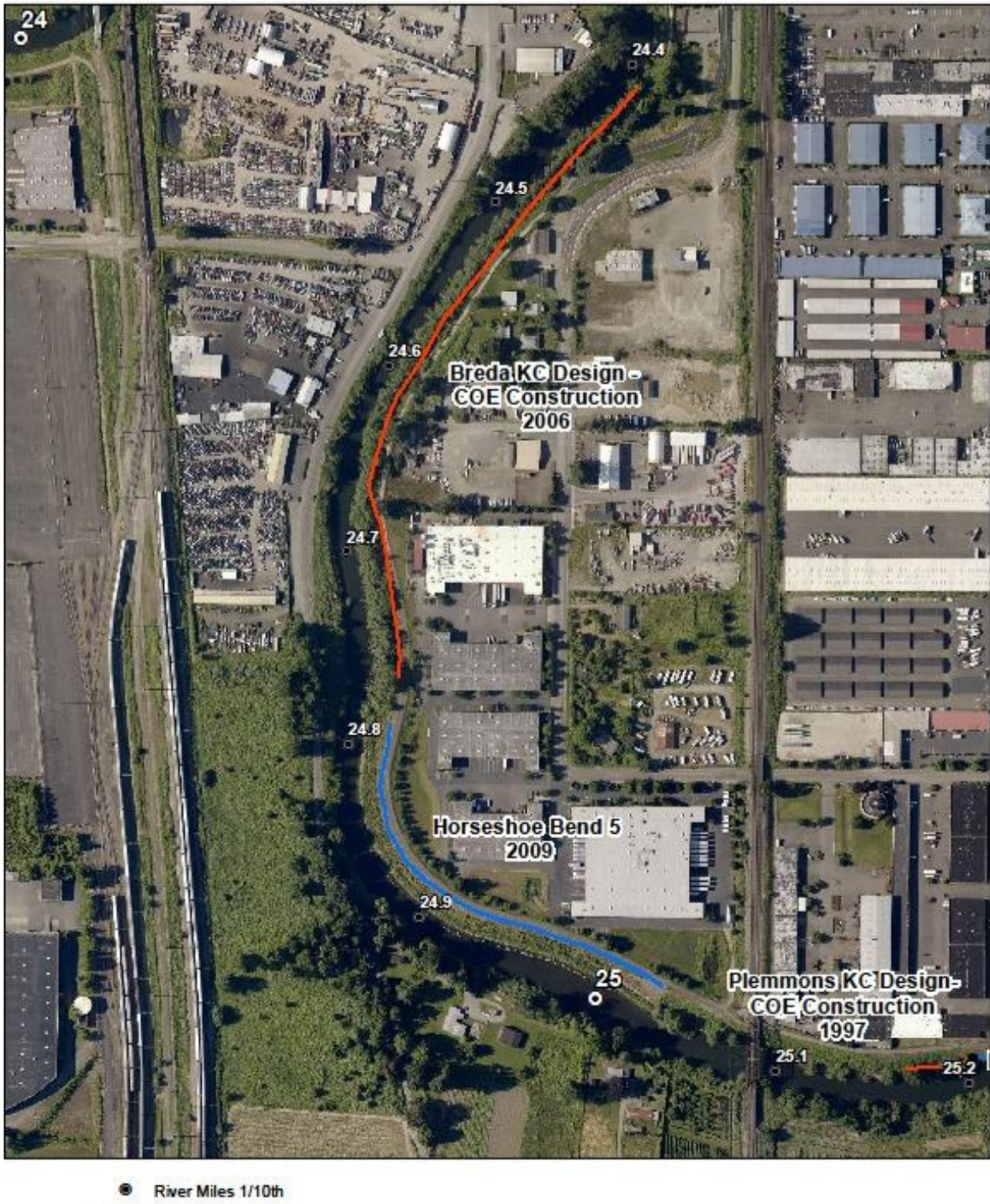


Figure A2. Breda 2 Plemmons



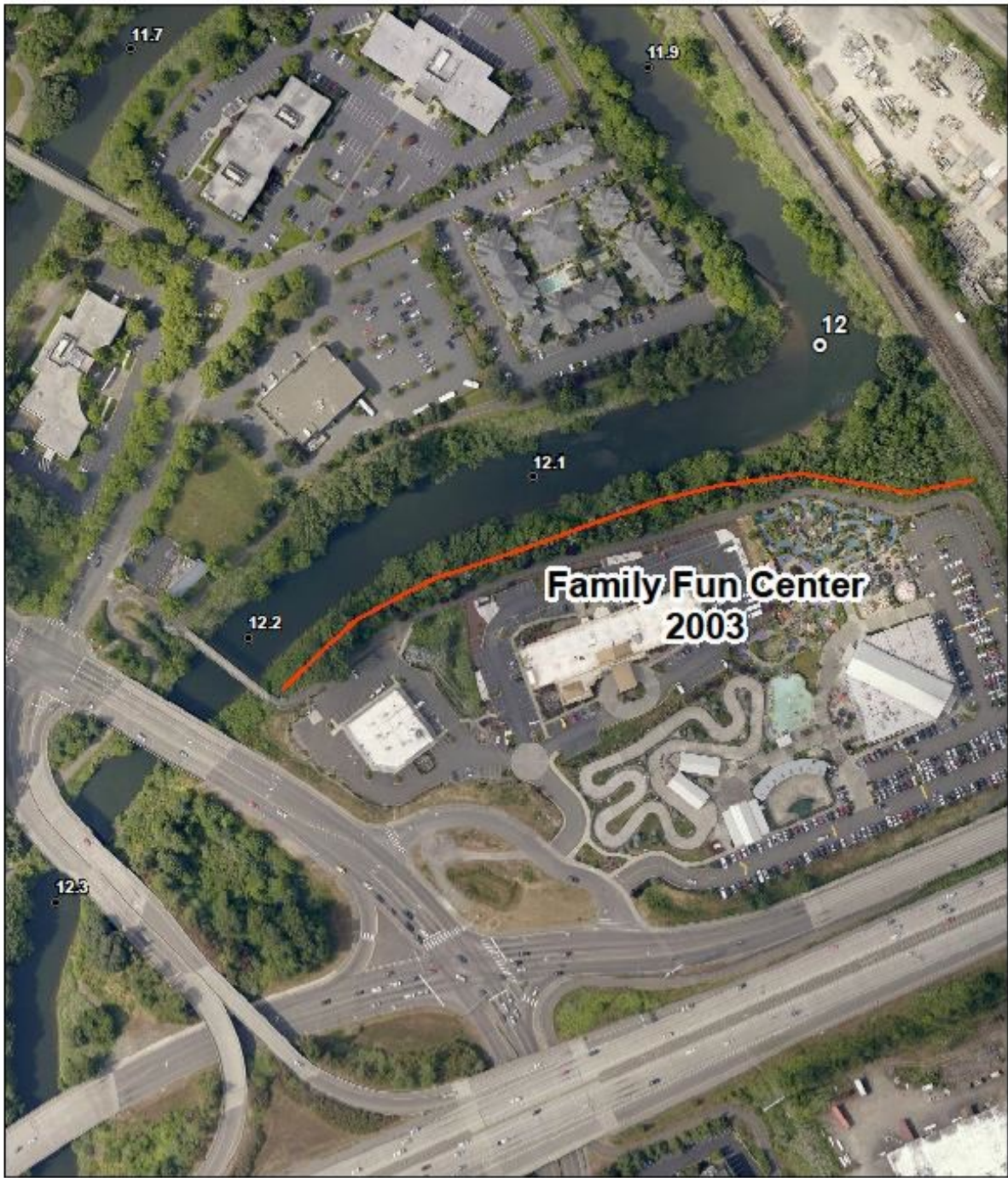
● River Miles 1/10th

Figure A3. Briscoe 2 Boeing



● River Miles 1/10th

Figure A4. Dykstra 2 Lones



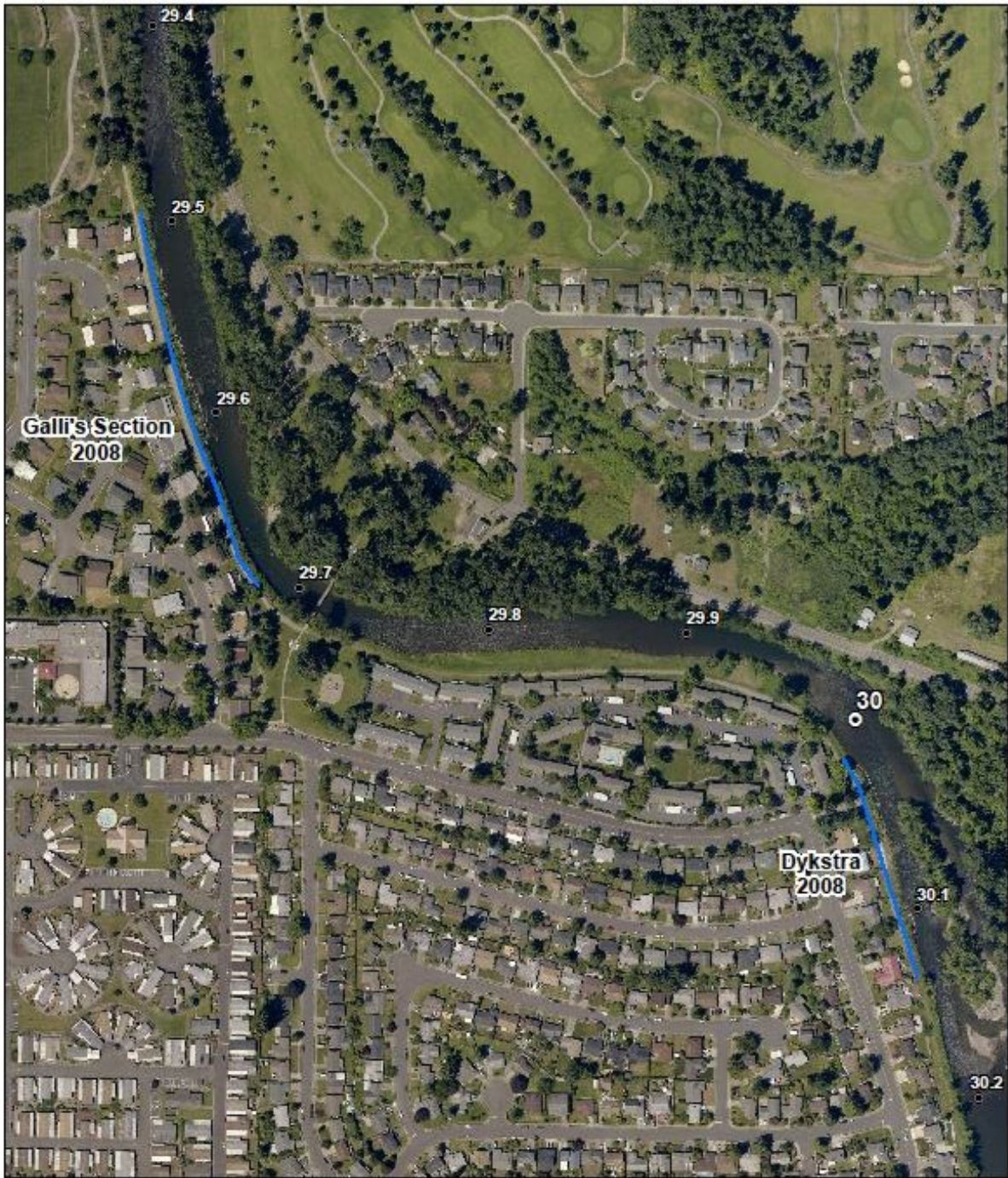
● River Miles 1/10th

Figure A5. Family Fun Center



● River Miles 1/10th

Figure A6. Fenster



● River Miles 1/10th

Figure A7. Galli 2 Dykstra



● River Miles 1/10th

Figure A8. Hamakami

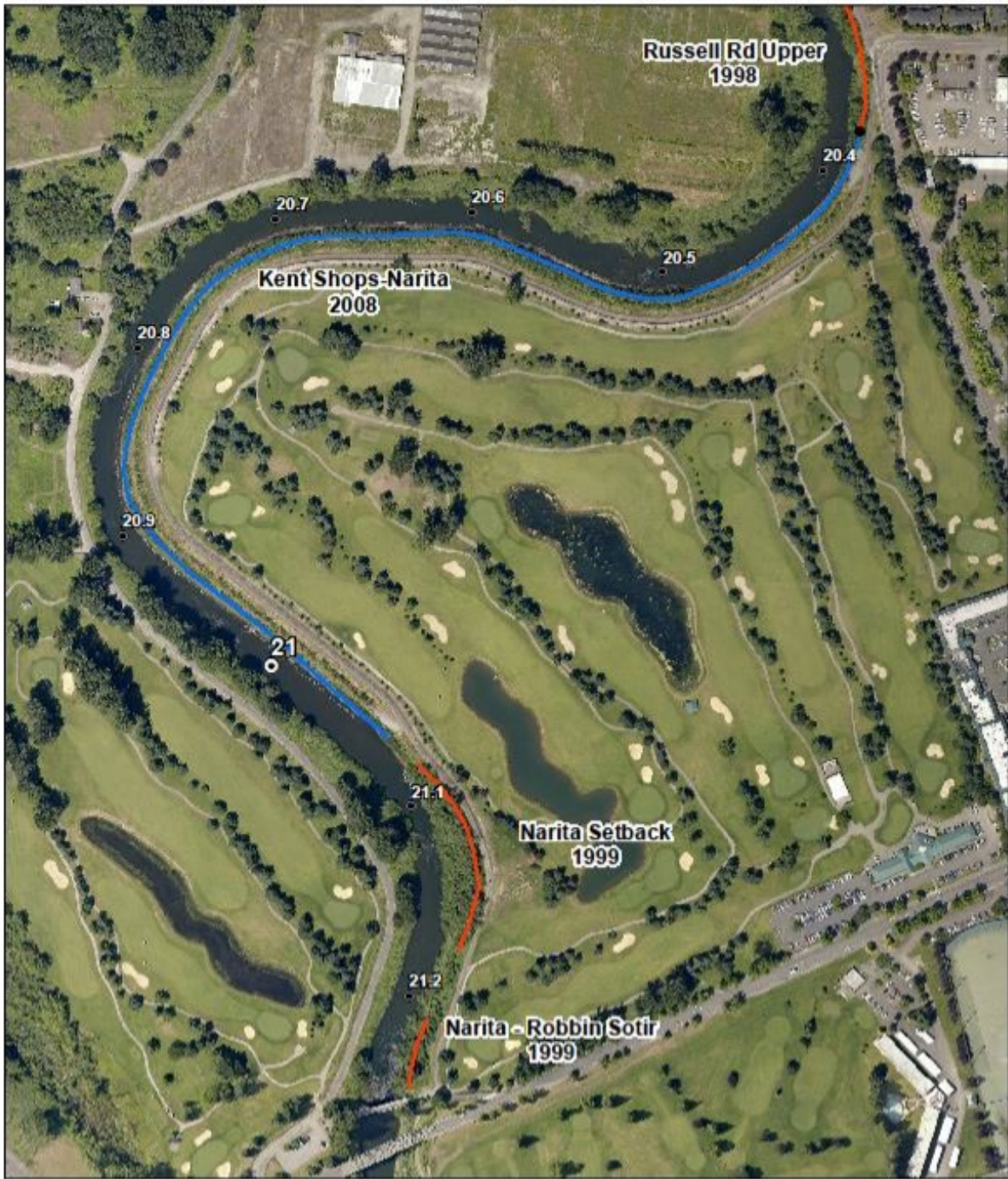


● River Miles 1/10th

Figure A9. Horseshoe Bend and Plemmons

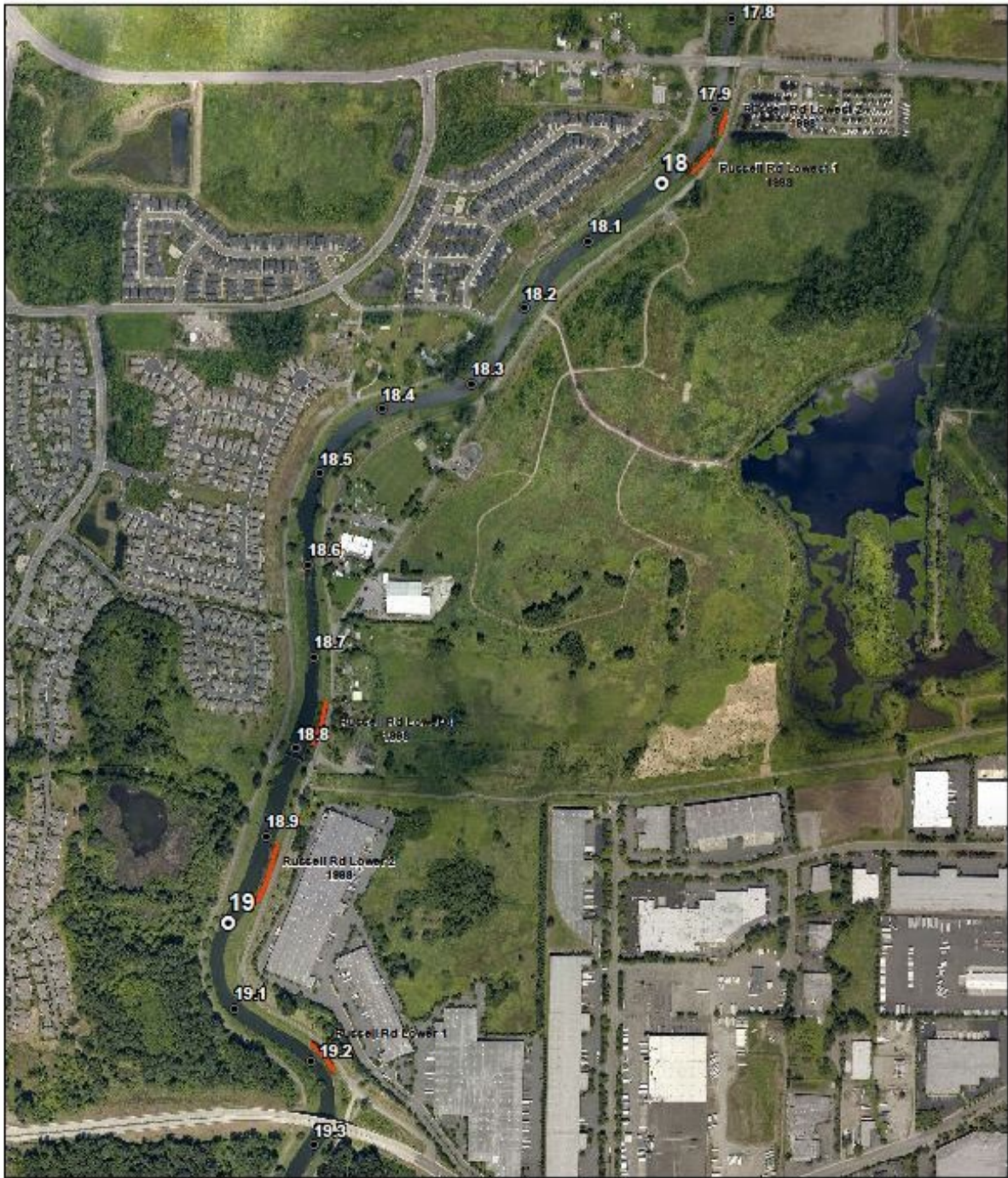


Figure A10. Myers Golf 2 Signature Pointe



● River Miles 1/10th

Figure A11. Narita



● River Miles 1/10th

Figure A12. Russell Lowest

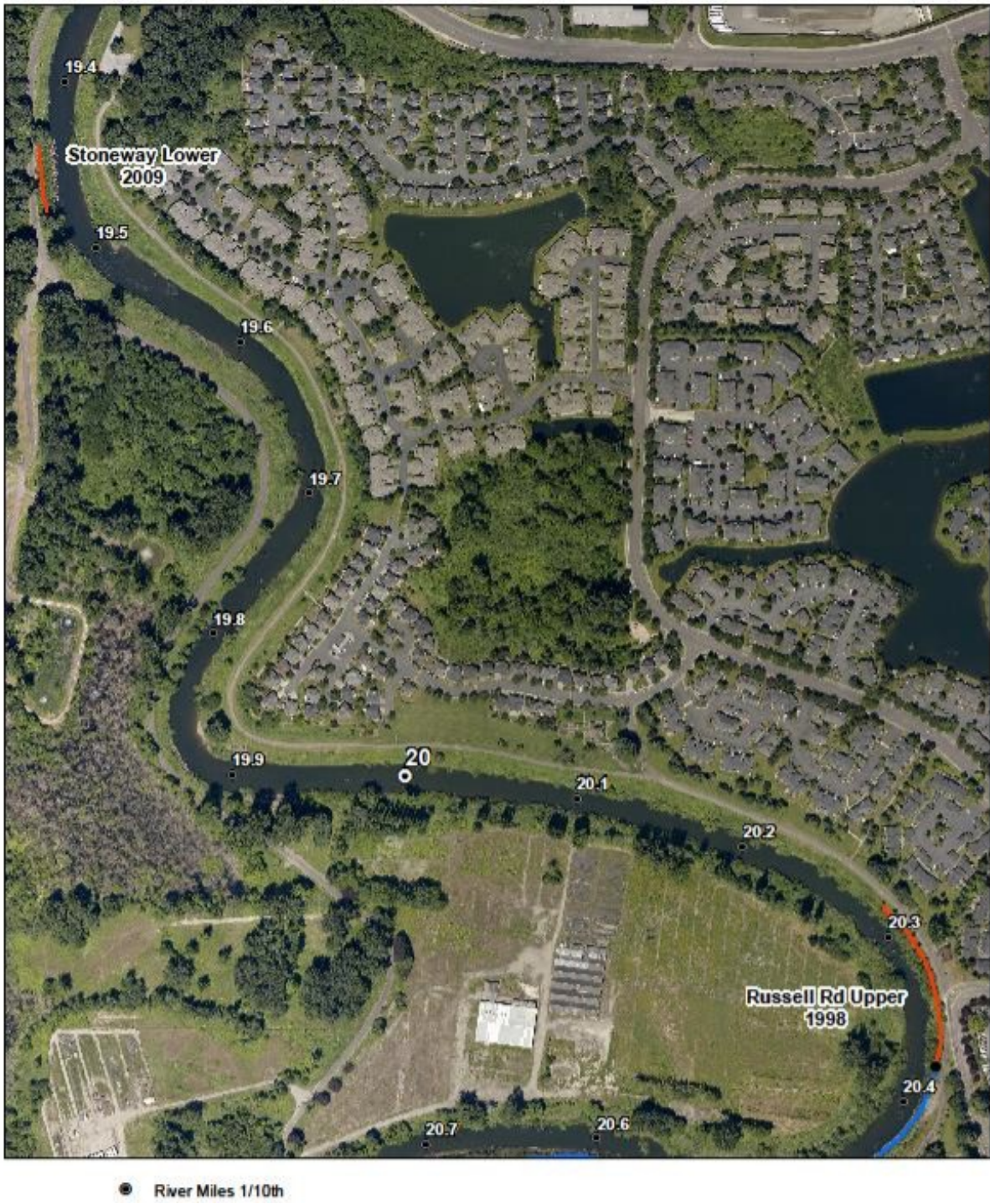
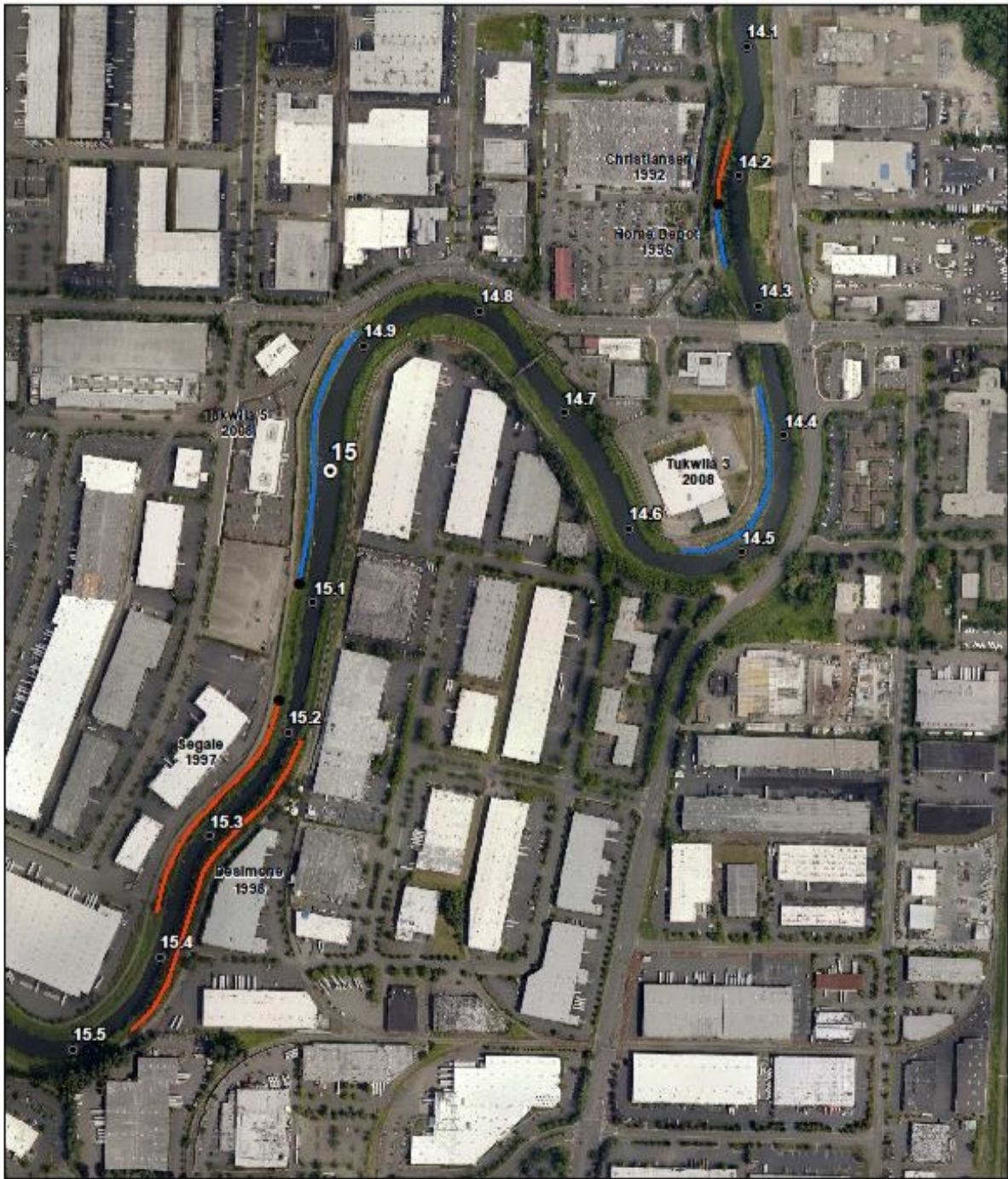


Figure A13. Stoneway 2 Russell



● River Miles 1/10th

Figure A14. Tukwila Desimone