AN ABSTRACT OF THE THESIS OF

Jennifer Rose Wallick for the degree of Master of Science in Geology and Bioresource Engineering presented on June 4, 2004.
Title: Geology, Flooding & Human Activities: Establishing a Hierarchy of Influence for Controls on Historic Channel Change along the Willamette River, Oregon

Abstract approved:

Redacted for privacy Redacted for privacy

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Channel evolution and influences of changing floodplain characteristics, heterogenous bank materials, and altered flow regimes were examined along the Willamette River, a large alluvial river in northwestern Oregon. The Willamette River is composed of a series of geomorphically diverse reaches, which have each evolved uniquely in the century following Euro-American settlement. The river was divided into three large (30-50 km) alluvial reaches according to physiographic characteristics. The historically anastomosing and relatively steep McKenzie Reach (uppermost study reach), extends between the confluences of the McKenzie and Long Tom Rivers. The Willamette along the lower-gradient Santiam Reach (between the confluences of the Santiam and Yamhill Rivers) is primarily contained within a single

channel and has experienced lower rates of erosion than upper reaches. The Long Tom Reach (extending between the confluences of the Long Tom and Santiam Rivers), acts as a transition between the upper and lower Willamette, as it is here that the channel adopts a single-thread planform and becomes more stable.

To assess the role of bank materials on bank-erosion rates, a method for detecting relative differences in erodibility between bank materials along large floodplains was developed. Coupling historic patterns of channel change with a simple model of bank erodibility enabled tracking of relative changes in bank erodibility among time intervals and bank materials. The analysis was applied to the McKenzie Reach for three time periods: 1850-1895, 1895-1932, and 1972-1995, and relative differences in bank erodibility were calculated for Holocene alluvium, partially cemented Pleistocene gravels, and revetments constructed in the 20th century. This simple model of bank erodibility reveals that, for all three periods, banks composed of Holocene alluvium were at least 2-5 times more erodible than banks composed of Pleistocene gravels. Revetment installed in the twentieth century was highly resistant to erosion and was at least 10 times less erodible than Pleistocene gravels.

To examine larger-scale controls of geology, flooding, and human intervention on channel stability, rates and styles of historic channel change were determined for the McKenzie, Long Tom and Santiam Reaches and were linked with events or factors that may have triggered the observed patterns of channel change. Effects of anthropogenic activities on channel change were assessed by reviewing historic documents describing settlement patterns, riparian deforestation, channel improvements, and other actions. The role of flooding was assessed by compiling gauge records, anecdotal accounts of flooding, and by comparing stream-power distributions of large historic floods against smaller, post-dam floods with a 2-D flood model.

Analyses of these larger-scale controls revealed that between 1850 and 1895, a period marked by the 3 largest floods of record, all reaches experienced numerous avulsions, increases in channel width, and decreases in centerline length. During the interval 1895-1932, a period with frequent, moderate-sized floods, migration rates increased by 50-300%, sinuosity increased and channel width decreased. The interval 1932-1995 was initially marked by rapid migration, but channel stabilization and dam building slowed erosion rates, causing the Long Tom and Santiam Reaches to display similar migration rates as those recorded for 1850-1895. Along the upper Willamette (McKenzie Reach), channel change during 1972 to 1995 was primarily limited to lateral migration along areas unrestricted by revetments and occurred at rates similar to 1850-1895 levels. Channel width decreased along all reaches during the 20th century.

It is hypothesized that flooding may have been the primary factor responsible for the large-scale straightening and widening that occurred during 1850-1895. Actions taken to reduce streamside wood and side-channels along the McKenzie and Long Tom Reaches may have also contributed to widening. Along some areas of the floodplain, where the largely straightened and widened 1895 channel flowed through Holocene alluvium, the channel developed small bends that subsequently migrated rapidly downstream, and triggered rapid migration of adjacent bends. This concurrence of events and conditions suggests that accelerated erosion during the period 1895-1932 results from a combination of a "primed" planform, highly erodible bank materials, and a highly erosive flow regime with many moderate-sized floods. Migration rates 1895-1932 may have also increased as a result of land clearing and snag removal, as increasing numbers of settlers occupied floodplain lands in this interval. Anthropogenic activities have no clear effect on planform or erosion rates until the 1930's, when widespread bank stabilization and dam construction resulted in diminished migration rates, fewer avulsions, and channel narrowing. By the late 20th century, 30-45% of each reach was stabilized with revetments, while naturally resistant bank materials bordered an additional 13-30% of the channel length.

Results indicate that revetments, naturally resistant bank materials, and flow regulation restrict migration and channel movement along the modern Willamette River. Efforts aiming to increase lateral migration on the Willamette River might consider removing revetment from bends bordered by Holocene alluvium along higher-gradient areas of the floodplain. However, such efforts may not create the suite of floodplain dynamics displayed by the historic Willamette, as much of the rapid migration, side channel maintenance and avulsions were related to flooding, channel change along adjacent bends, and large wood; all of which are largely absent from the modern floodplain.

Geology, Flooding & Human Activities: Establishing a Hierarchy of Influence for Controls on Historic Channel Change, Willamette River, Oregon

By

Jennifer Rose Wallick

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 4, 2004

Commencement June 2005

Master of Science thesis of Jennifer Rose Wallick presented on June 4, 2004.

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ACKNOWLEDGEMENTS

I wish to thank many individuals for assisting me with my thesis research. First and foremost, I wish to extend my gratitude to Stephen Lancaster, who patiently guided my research. Stephen's insight and careful critiques allowed me to refine my ideas into defensible hypotheses. I am deeply indebted to John Bolte for providing financial support and research guidance. Thanks also to my advisors Gordon Grant and Andrew Meigs who gave helpful advice and reviews throughout my graduate studies and to Bruce Coblentz for reviewing this manuscript.

I received a great deal of assistance from individuals outside of my advisory committee. Roger Denlinger of Cascade Volcano Observatory modeled historic floods and lent considerable expertise on the possible effects of floods. This project relied heavily upon digital historic datasets compiled by the Pacific Northwest Ecosystem Research Consortium (PNWERC) under the direction of Stan Gregory. Linda Ashkenas shared many of these datasets with me and answered numerous questions on data processing and working with the historic maps. Thanks to Randy Wildman for taking us on a jet boat tour of the upper Willamette and providing insight on recent channel change. John Todd, Matt Rea, Chris Edwards, Pete Dickerson and others at the Corps of Engineers answered many questions and provided aerial photographs and historic channel surveys. Jim O'Connor, of the USGS, shared many helpful references, gave advice on studying historical channel change and lent us a canoe for field work.

Field assistance was provided by Meghan Blair, Sarah Johnston, Matt Cox, Ivan Hasica, and Frank Miller who accompanied me on canoe trips. Michelle Arsenault, Anne Jefferson, Sarah Lewis, Greg Stewart, Peter Wampler and Josh Wyrick all contributed ideas, critiques, and suggestions for which I am grateful. This manuscript was greatly improved following insightful comments from Anita Grunder and members of the GEO 608 Advanced Writers Workshop.

Finally, I would like to thank my friends and family for supporting me through my graduate career. I am grateful for the patience and kindness of Tim Brink and Laurel and Matt Kluber. Special thanks also to my parents Ruth, Jack, and Vivian for inspiration and support.

CONTRIBUTION OF AUTHORS

Stephen Lancaster assisted in developing research concepts and analytical methods, interpreting results and distilling the findings. Stephen Lancaster also reviewed and edited the manuscripts. Roger Denlinger modeled the 1996 flood using data provided by the author and assisted in interpreting flood model results. John Bolte provided guidance and funded the research.

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Chapter 1:
Introduction

In order to better understand how large rivers interact with their floodplains and evolve over time, we must first understand how individual elements of the floodplain such as bank materials or riparian vegetation influence channel planform and stability. Assessing the relative influence of one variable is often difficult, because channel change seldom occurs when all other factors are held constant. Interpreting channel change along large floodplains, for long time periods, (e.g, centuries), is thus particularly difficult because many floodplain properties can vary over time and space, and any causal linkages that may initially exist can be obscured by external factors such as flooding or human activities.

Here, we develop an approach for assessing the relative influence of geology, flooding, and human activities on channel stability. By examining temporal and spatial patterns of each variable we can assess how that variable might have affected historical channel change during different time periods. These preliminary hypotheses can then be assembled and used to evaluate the relative importance of multiple variables, thereby establishing a hierarchy of influence for controls on channel change. Such an analysis can be applied to any large river so long as there are (a) good historic channel maps with which to quantify rates and styles of channel change across several time periods; (b) historic records describing human interaction with the floodplain and channel; (c) discharge records accompanied by anecodotal flood accounts and other evidence of flow-related phenomena; and (d) geologic maps, cross-sections and descriptions of bank materials.

The Willamette River, a large alluvial river in northwestern Oregon, is well suited for such a study because previous work by Hulse et al, (2002) has generated excellent historic channel maps, while Sedell and Frogatt (1984), Benner and Sedell (1997), and others have shown that widespread planform simplification may be linked with land conversion and channel modifications following Euro-American settlement. However, these studies have not examined roles of other natural factors such as floods or geologic controls, although there are ample historical and recent resources that support such examination. There is also a rich set of historical documentation describing Willamette River floodplain dynamics and anthropogenic interaction with the floodplain that can be used to better assess effects of human activities on channel change.

We conduct our study along 200 km of the Willamette River and analyze channel change for three time periods between 1850-1995. Between the mid 19th century when Euro-American settlement began in earnest, and the late 20th century, the Willamette River floodplain experienced numerous floods, conversion of riparian forest to agriculture, channel modifications for navigation, flow regulation, and bank stabilization. These events occurred along a diverse floodplain characterized by three large (30-50 km), geomorphically distinct reaches. Initial work demonstrated that many parts of the Willamette are bordered by either naturally resistant bank materials or rock-revetments installed in the 20th century. We further found that bends flowing against these resistant materials appeared to migrate more slowly than those flowing through Holocene floodplain sediments. To examine differences in bank-erodibility and to determine the influence of resistant banks on channel migration we developed a method for quantifying erodibility for different bank materials and applied this analysis to the historically dynamic upper Willamette River, where resistant bank materials border a greater portion of the river than any other of our study reaches. This analysis is presented in Chapter 2.

In Chapter 3, we quantify rates and styles of historic channel change along the entire mainstem Willamette and link patterns of historic change with large-scale geological features, bank materials, flooding, and human actions. Much of this work is more qualitative in nature, as we explore the role of geologic controls by overlaying geological maps with historic channel maps, while human impacts are assessed by comparing historic documents with observed patterns of channel change. Similarly, we explore the importance of flooding and flow regulation by comparing gauge records, anecdotal flood accounts, and inundation modeling with flood-related channel change.

In linking historic channel change with natural and anthropogenic factors, these papers describe how the Willamette River transitioned from a dynamic, wood and sediment-rich stream to a highly stabilized and regulated river. Our work reveals that this transition did not occur systematically, but rather, net change during 1850-1995 resulted from a variety of inter-related factors that evolved uniquely along different areas of the floodplain.

Chapter 2:
Determination of bank erodibility for natural and anthropogenic bank materials using a model of lateral migration & observed erosion along the Willamette River, Oregon, USA

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2a. Abstract

Many large rivers flow through a variety of geologic materials. Within the span of several kilometers, bends may alternately flow against recently reworked sediments, older, more indurated sediments, or highly resistant materials. As sediment size, cementation, and other properties strongly influence the erodibility of river banks, erosion rates and channel planform are likely to vary significantly along the length of large rivers. In order to assess the role of bank materials on bank erosion rates, we develop a method for detecting relative differences in erodibility between bank materials along large floodplains. By coupling historic patterns of channel change with a simple model of bank erodibility we are able to track relative changes in bank erodibility among time intervals and bank materials. We apply our analysis to the upper Willamette River, in northwestern Oregon for three time periods: 1850-1895, 1895-1932 and 1972-1995 and compute relative differences in bank erodibility for Holocene alluvium, partially cemented Pleistocene gravels, and revetments constructed in the 20th century. Although the Willamette is fundamentally an anastomosing river, we apply the model to single-thread portions of the channel that evolved through lateral migration. Our simple model of bank erodibility reveals that for all three time periods, banks composed of Holocene alluvium are at least 2-5 times more erodible than banks composed of Pleistocene gravels. Revetment installed in the twentieth century is highly resistant to erosion and is at least 10 times less erodible than Pleistocene gravels.

2.1 Introduction

Society has a need for understanding the controls on lateral migration of rivers, especially those flowing through densely populated areas. Although channel stabilization efforts may be necessary to support a growing array of agricultural and urban communities, such actions reduce a river's creation of new geomorphic surfaces. Processes such as bank erosion, gravel-bar deposition, and side-channel maintenance promote healthy aquatic and riparian ecosystems by hyporheic flows, recruitment of woody vegetation, and creation of off-channel habitat (Dykaar and Wigington, 2000; Fernald et al., 2001); (Landers et al., 2002). Restoring natural floodplain functions while protecting community investments requires a strategy that addresses both intrinsic and anthropogenic controls on bank erodibility.

Several studies have used simple models of meander migration to predict channel movement and bank erosion along low-gradient streams (Johannesson and Parker, 1985; Garcia et al., 1994). Subsequent authors (e.g, Micheli and Kirchner, 2002; Micheli et al., in press) have used a similar approach to quantify the relationship between bank erodibility and riparian vegetation for stream reaches characterized by homogeneous riparian vegetation. To better understand how resistant bank materials influence channel migration along large floodplains (i.e., tens of kilometers), we adapt the methodology of Micheli and Kirchner (2002) to quantify bank erodibility at the scale of individual bends for rivers with heterogeneous bank materials.

Along the upper Willamette River in northwestern Oregon (Figure 2.1), resistant bank materials appear to have exerted an increasingly important role in channel evolution. In the mid-19th century, the upper Willamette was a dynamic, anastomosing stream flanked by loosely consolidated Holocene sediments. In contrast, the modern Willamette largely evolves through meander migration, yet much of the channel is presently flowing against naturally resistant Pleistocene gravels or bank stabilization structures (revetments) (Figure 2.2). Historical migration rates have fluctuated as the Willamette has transitioned from an anastomosing stream characterized by frequent avulsions to a more stabilized stream dominated by lateral migration, and it is unclear how the distribution of resistant bank materials has influenced historical channel change. Although Pleistocene gravels appear more consolidated than Holocene alluvium, it is unclear whether differences in bank erodibility between naturally occurring materials can be detected and how the erodibility of naturally resistant materials differs from revetments. It is also unknown whether the relative differences in bank materials have remained constant over time.

By linking historic records of channel change with patterns of bank erodibility we quantify the roles that resistant bank materials have played in determining channel change along the upper Willamette between 1850 and 1995. Our bank erodibility analysis provides a mechanism for tracking changes in erodibility over time and detecting relative differences in erodibility between materials. Such a strategy enables us to determine which areas of the floodplain are intrinsically more erodible than others and may provide a framework for field-based bank strength analyses and future restoration strategies.

2.2 Willamette River study area

The Willamette River is a large alluvial river draining a 29,800 km^2 basin in northwestern Oregon (Figure 2.1). The rugged and volcanically active Cascade Range forms the eastern boundary of the Willamette Basin, and the Oregon Coast Range forms the western boundary. The headwaters and major tributaries of the Willamette primarily drain the steep, degrading landscapes of the Cascade and Coast Ranges and differ sharply from the low-gradient, meandering streams of the valley-floor sedimentary basin. The mainstem Willamette begins at the confluence of the Coast and Middle Forks of the Willamette in the southern valley and flows northward for more than 300 km to its confluence with the Columbia River. The Willamette Valley is characterized by Mediterranean climate with cool, wet winters and warm, dry summers. Average precipitation in the valley floor is approximately 120 cm per year, which falls mainly as rainfall during the winter (Oregon Climate Service, 2004).

We conducted our study along the upper 30 km of the Willamette River floodplain between the confluences of the McKenzie and Long Tom Rivers, or according to the floodplain-based reference frame of Hulse et al. (2002), between floodplain kilometers (FPKM) 216 and 187 (Figure 2.3). Within the study area, the Willamette is predominantly an anastomosing stream in which flow was historically separated by large (1-10 km^2), semi-stable, forested islands. According to 19^{th} century Corps of Engineer reports:

> Each year new channels are opened, old ones closed; new chutes cut, old ones obstructed by masses of drift; sloughs become the main bed, while the latter assume the characteristics of the former; extensive rafts are piled up by one freshet only to be displaced by a succeeding one; the formation of islands and bars is in constant progress....
> (pg 766, Annual Report of the Chief of Engineers, (USACE, 1875).

Channel stabilization efforts have typically confined flows in the modern Willamette to a single channel, and the river primarily evolves through lateral migration (Figure 2.2). However, the floodplain retains many relict features characteristic of a multi-thread planform, and some side channels remain active during high flows. Channel shifting in the late 20^{th}century was more subtle than for historic periods; migration primarily occurred along areas unconfined by revetment and avulsions generally took place along secondary channels.

The Willamette Basin is blanketed with a series of Quaternary deposits that form three distinct types of bank materials in the study area (Figure 2.3). Indurated Pleistocene gravels (Qg2 map unit) were deposited as broad braidplains and crop out along the right bank in the middle and lower study reach (O'Connor et al., 2001). Between 15-12.7 ka, a series of catastrophic Missoula Floods back-filled the Willamette Valley, creating a lacustrine setting in which fine-grained sediments (Qff2) were deposited atop Qg2 gravels. As the Missoula Floods entered the Willamette Valley from the north, Qff2 thins southward, extending to FPKM 206 in the study area. Where Missoula Flood sediments form the surficial geological unit, Holocene incision exposes Qg2 gravels at river level such that flows interact with

Qg2 rather than Qff2 during all but exceptionally high discharges. The Holocene floodplain (Qalc map unit) of the Willamette is inset within Pleistocene deposits, forming a 2-4 km wide surface that borders the channel on one or both banks for much of the study area. Large boulders or revetments emplaced by the Army Corps of Engineers in the 20th century form the third type of bank material and are primarily used to stabilize banks composed of Qalc.

The Pleistocene Qg2 unit forms a uniform layer of sands and gravels deposited in a braided channel system and partially cemented by clay, calcite and iron oxide accumulation (Glen, 1965; Balster and Parsons, 1969; O'Connor et al., 2001). Exposures of Qg2 at river level are nearly vertical and reveal 2-3 m of cobbly gravel fining upward into sand and silt, which is overlain by a 1-2 m-thick paleosol (O'Connor, et al, 2001). Within the study reach, the uppermost surface of the Qg2 gravel layer is approximately level with modern bankful stage, while the fine-grained layers generally rise slightly above bankful (as determined during field observations). Though the entire Qg2 unit may range in age from 0.42 Ma to 15 ka, the top of the unit was probably deposited 23-27 ka (O'Connor et al., 2001).

Within the Qg2 gravel layer, individual clasts generally range up to 10 cm in diameter, and sands tightly fill the interstices. Disaggregation Qg2 gravels requires substantially more effort than for Qalc deposits and generally involves the use of implements (such as a rock hammer) to physically separate clasts. Fluvial erosion into Qg2 causes large scour holes to form along the bank toe. Missoula Flood deposits overlaying Qg2 are undermined by this scouring and frequently collapse through slab-type failures.

In contrast to indurated Qg2 gravels, Holocene alluvium encompasses a variety of young (<7,000 years) surfaces composed of unconsolidated silts, sands, and gravels (Balster and Parsons, 1968; O'Connor et al., 2001). Coarse deposits of cobbles and gravels near the active channel fine towards sands, silts and clays with increasing elevation. Modern floodplain surfaces bordering the channel typically rise 1-4 m above the low-water line and are composed of sandy, poorly formed soils capped by thin layers of silts (Balster and Parsons, 1968; Reckendorf, 1973). While there is a great diversity of Qalc surfaces, from recent point bars to forested floodplains, Qalc deposits are all generally poorly to weakly consolidated. Casual digging or scraping can easily disturb Holocene deposits, and even the most seemingly indurated exposures can be loosened by hand.

Historic and recent accounts indicate that the low bank height and loosely consolidated structure of Holocene Alluvium support high rates of erosion (USACE, 1867-1892; Balster and Parsons, 1968). Along unstabilized areas of the modern channel, both forested and non-vegetated banks composed of Qalc frequently erode at modest discharge levels.

In the 1930's the Corps of Engineers began a concerted effort to stabilize rapidly eroding banks with revetments. By 1972, nearly 50% of the channel length in the study area was stabilized, with the majority of revetment emplaced along banks composed of Qalc (Figure 2.3). Although there are several types of revetment used to stabilize banks, much of the revetment consists of large (~ 1 m in diameter) angular basaltic boulders extending from the bank toe to the top of the bank (Willingham, 1983; Gregory et al., 2002).

2.3 Determining patterns of bank erodibility

2.3.1 Model of bank erosion

The rates of bank erosion and, (assuming a constant channel width,) meander migration are the product of bank erodibility and near-bank streamflow erosivity. While erodibility is an intrinsic material property resulting from characteristics such as grain size and degree of cementation, erosivity depends upon hydraulic factors including discharge and channel curvature. Given a constant discharge, the product of erodibility and erosivity varies with planform and bank materials, both of which can vary substantially downstream such that bank erosion rates can be highly variable. In order to detect relative differences in erodibility between bank material types and time intervals, we must independently determine the erosivity of near-bank streamflow.

In a perfectly straight channel with a perfectly symmetrical cross-section, the fastest flow will follow the channel centerline. In curved channels, which usually have asymmetrical cross-sections, secondary flows tend to steer the fastest flow toward the bank at the outside of the bend. Near-bank streamflow erosivity is highest where the flow near that bank is fastest. Following Ikeda et al., (1981), we adapt a model of meander migration whereby bank erosion rate, $\dot{B}_e$, is the product of bank erodibility, E_0, and the deviation, U_b', of the near-bank flow velocity from the reach-average velocity:

$$\dot{B}_e = E_o * U_b' \qquad (1)$$

Bank erosion rate ($\dot{B}_e$) is measured in meters per year, while near-bank flow velocity is calculated in meters per second. When bank erosion rate is converted to meters per second, bank erodibility (E_o) becomes a dimensionless parameter, though values are typically quite small (on the order of 10^{-7}). Actual flow velocity near a particular bank is the sum of reach-average flow velocity, U, and the near-bank velocity perturbation (U_b'), which is generally defined as the solution for the velocity perturbation near one bank (Ikeda, 1981). When velocity is higher near the other bank, U_b' is negative, thus the sign of U_b' indicates which bank is experiencing the higher flow velocity.

For a given bend, the magnitude of the near-bank velocity perturbation will be greatest where the fastest flow appears to impinge against one bank, typically at the outside of the bend. Among bends, although the expression for U_b' is complicated (see Appendix), the near-bank velocity perturbation is usually greater in bends with greater curvature and, therefore, greater secondary flow strength. As shear stress at a flow boundary is given by the boundary-normal gradient of flow velocity, shear stress at a channel bank is greatest where the near-bank flow is fastest, (i.e., where the magnitude of U_b' is greatest). Therefore, our usage of near-bank velocity serves as a proxy for near-bank shear stress.

According to the hydraulic model of Johannesson and Parker, (1989), U_b' is a function of both local and upstream curvature. We may therefore calculate U_b' from hydraulic parameters and a map of the channel centerline at a particular time (see Appendix). We assume that the bank erosion apparent from a subsequent channel planform is, within reasonable limits, predicted by the product of E_o and U_b' at that earlier time. Given the observed bank erosion rate between two times and the calculated U_b', we can solve for bank erodibility:

$$E_o = \frac{\dot{B}_e}{U_b'} \qquad (2)$$

where $\dot{B}_e$ is the observed bank erosion rate, and E_o is the inferred bank erodibility. Conceptually, the U_b' calculated from the planform "normalizes" the observed migration rates so that we can isolate planform characteristics from bank material properties in explaining bank erosion.

2.III.2 Historic Channel Change

Bank erodibility is calculated using historic maps of the Willamette River for three intervals: 1850-1895, 1895-1932, and 1972-1995. The first interval, 1850-1895, was marked by the initial settlement and development of the Willamette Valley. Although the U.S. Army Corps of Engineers (USACE) began channel improvements in 1875, much of the floodplain was forested and the channel was highly dynamic throughout the interval. During the second interval, 1895-1932, navigational improvements to the channel continued, but the floodplain remained largely undeveloped. The interval 1932-1972 is excluded from analysis because extensive revetments and seven upstream flood-control dams were constructed during this period (Figure 2.2). The last interval, 1972-1995, provides insight into channel dynamics following this regulation and stabilization.

Digital historic maps of the Willamette River were compiled from survey data and aerial photographs (Table 2.1). For 1850, 1895 and 1932, we used maps of the active channel produced by the Pacific Northwest Ecosystem Research Consortium (PNWERC) from surveys conducted by the General Land Office in 1850 and USACE in 1895 and 1932 (Hulse et al., 2002). For the historic maps and the aerial photos, the active channel was defined as the area within the boundaries of the annual high water (1-2 year flow), although definition of these boundaries was sometimes subjective. Where present, steep banks defined more objective active channel boundaries. Gravel bars, small side channels, and surfaces vegetated with annual species (e.g., small shrubs, grasses, and willows) were included within the active channel, and channel-adjacent areas and islands containing larger woody vegetation were excluded (Gregory et al., 2000).

In our analysis, we were primarily concerned with channel dynamics related to the main thread of flow and edited our 1972 and 1995 maps accordingly. For 1972 and 1995, when the channel was relatively stable, we mapped both the "active" and "main" channels from aerial photos produced by the USACE (Table 2.1). Whereas the active channel contained gravel bars, side channels and other features within the annual high-water boundaries, the main channel was defined by the wetted perimeter of the largest channel. Using aerial photography, we edited the 1995 active channel map produced by the PNWERC so that the 1995 and 1972 active channel maps were consistent with our aim to primarily consider dynamics associated with the main channel.

In much of the late-20th-century floodplain, the main and active channels were nearly identical because bank stabilization and vegetation encroachment allowed the channel to adopt a well defined planform varying little with fluctuations in discharge. However, several dynamic reaches had a very wide active channel containing multiple gravel bars and side channels. In these areas, the centerline of active-channel often appeared to shift over time (typically due to narrowing and vegetation encroachment) though actual bank erosion was negligible. Thus, the boundaries of the main channel at relatively low water provide a more precise delineation of the channel and allow for more accurate bank erosion measurements.

We assume that because the active channel marks the boundaries of annual highwater, the active channel approximates the "bankfull" channel. Because we calculate U_b' for bankfull discharge, channel width measurements and centerline digitization for all time periods are primarily based on the active channel (Table 2.1). Measurements of bank erosion are based on active-channel boundaries for 1850, 1895 and 1932, and on the more accurate main-channel boundaries for 1972 and 1995.

2.3.3 Calculating bank erosion rates $(\dot{B}_e)$

The objective of our analysis is to interpret bank erosion at the scale of individual bends by linking U_b' with adjacent bank materials. We use 'bend-scale polygons' as a basis for defining spatially-explicit areas of channel change (Figure 2.4). Migration during each time interval is interpreted from two channel planforms bracketing that interval. For each pair, the latter planform was divided into a series of polygons defining bends and straight sections. Each polygon was classified with information according to the style of change, whether avulsion or lateral erosion, and a preliminary measurement of the erosion distance. Bends experiencing great erosion (e.g., >300 m) were excluded from the present analysis because the model can only characterize relatively small, incremental changes. Avulsing reaches were excluded because the model can only characterize continuous migration.

Bank erosion distances were calculated from areas and perimeters of bank-erosion polygons outlining the actual bank area eroded for each bend (Figure 2.4):

$$B_e = \frac{2A}{P} \qquad (3)$$

where B_e is the average distance of bank erosion perpendicular to the channel; A is the area of the bank-erosion polygon; P is its perimeter; and $\frac{P}{2}$ is the average bank length for the time period. Bank erosion rates are calculated by dividing the distance migrated by the time interval:

$$\dot{B}_e = \frac{B_e}{T} \qquad (4)$$

where T is the time interval in years, which is converted to seconds.

Similar studies of channel change have calculated migration rates by overlaying channel centerlines from two time periods (Nanson and Hickin, 1986;

Micheli and Kirchner, 2002; O'Connor et al., 2003; Micheli and Kirchner, in press). This approach is unsuitable for the Willamette River because significant changes in channel width between 1850 and 1995 (R. Wallick, unpublished data) cause centerline migration rates to misrepresent bank erosion rates.

2.3.4 Calculating near-bank stream velocity perturbations (U_b')

We use the near-bank velocity model of Johannesson and Parker, (1989) to calculate U_b' for points placed along the centerline during each time period (Appendix). The maximum value of U_b' associated with each bend-scale polygon is our surrogate for near-bank flow erosivity in equation (2). The JP model was derived using conservation of fluid momentum and mass for both streamwise and cross-stream directions. In addition to local and upstream curvature, bed topography is addressed through the coupling of transverse bedslope with effective curvature (a weighted average of upstream and local curvature). In this manner the JP model accounts for the phenomenon that maximum transverse bedslope, (i.e., the slope between the top of the point bar and the bottom of the pool), generally occurs slightly downstream from the point of maximum curvature.

Upon adaptation of the equations presented in Johannesson and Parker (1989), the model becomes more representative of the Willamette River. Our first adaptation is the usage of a formula for transverse bed slope in gravel bed rivers developed by Ikeda, (1989) (Appendix). Additionally, we found that the JP model is sensitive to small planform irregularities, which can be introduced by both natural fluctuations in centerline position and the digitization process. We used smoothed local curvature, calculated from a five-point moving average of local curvature, to calculate effective curvature and U_b'. After smoothing local curvature we obtained more realistic results than those produced in non-smoothed trials.

The JP model calculates effective curvature and U_b' for points placed along the channel centerlines digitized from historic maps and aerial photographs (Table 2.1). Points were placed every 50 m along the centerline. During all time periods, reach-average channel width was greater than 150 m, so centerline points are spaced at less than every one-third channel width.

The JP model requires reach-average width, average depth at bankfull discharge, median bed material grain size, and valley slope (Table 2.2). For each time period, reach-average width of the active channel was measured from transects drawn perpendicular to the downstream direction at 1 km intervals (Table 2.2). Reach-average bankfull flow velocity for 1995 was calculated from discharge, depth (both from USACE records), and width (measured from the 1995 active channel) at bankfull flow at the Harrisburg gauge (FPKM 199). We assumed that bankfull discharge and reach-average velocity were the same for the previous modeled times, (1850, 1895, and 1972). Bankfull depths, then, were calculated as:

$$H(t) = \frac{Q_0}{U_0 b(t)} \qquad (4)$$

where $H(t)$ and $b(t)$ are average bankfull depth and width, respectively, at each time, t (i.e., 1850, 1895, and 1972); and Q_0 and U_0 are bankfull discharge and average velocity, respectively, assumed constant. Annual USGS gauge records at Harrisburg verified both our measurement of width and estimated reach-average velocity.

We overlaid bend-scale polygons with the centerline points and their associated velocities to verify that the sign and magnitude of U_b' correlate with bend geometry. Along large bends, the maximum U_b' generally occurs at or near the bend apex, while maximum U_b' for small bends often occurs near the apex of the next downstream bend but along the inside of the bend (Howard, 1992). In some cases, problems associated with our smoothing routine or planform irregularities caused U_b' to not correlate with bend geometry. Such cases were excluded from our analysis. Where U_b' does correlate with bend direction and curvature, we attribute the bend-scale polygon with the maximum U_b' associated with each polygon (Figure 2.5).

2.3.5 Calculating Bank Erodibility (E_o)

Once each polygon has an associated bank erosion rate and velocity perturbation, erodibility is calculated from equation (2). Reach-average erodibilities for each material were obtained by averaging individual bend-scale E_o values for each bank material type for each time interval.

To calculate E_o for Qalc and Qg2 we classified each bend-scale polygon with the type of bank material eroded. Bank material eroded for the period 1972-1995 was easily determined by overlaying channel maps, the Quaternary geological map of O'Connor et al., (2001), and aerial photographs in which the Qalc/Qg2 boundary is well defined. Bends influenced by bank stabilization structures between 1972-1995 were identified from digital maps of revetment produced by the PNWERC.

Classification of bank materials for the periods 1850-1895 and 1895-1932 required overlaying the geology map of O'Connor et al., (2001) with the channel maps and bend-scale polygons. Where the channel was positioned within the Holocene Floodplain such that Qalc bordered both sides of the channel, bank material was classified as Qalc. Bends near the border of the floodplain were inspected to establish whether erosion occurred westward (into Qalc) or eastward (possibly into Qg2). For eastward-eroding bends, channel maps from preceding time periods were overlain to determine whether the observed erosion occurred in areas that were previously mapped as floodplain features (e.g. side channel, active channel, island). If erosion through previous floodplain features was slight (<10 m) and no other evidence suggested Qalc was eroded, we assumed the bank material eroded was Qg2. In some instances, considerable (~30 m) erosion into Qg2 apparently led to retreat of the historic terrace to its modern position. In these cases we assumed all erosion occurred in Qg2. If the bend appeared to migrate through some portion of relict floodplain features (Qalc) and Qg2, we excluded the bend from our analysis. For all time periods, bend geometry and the direction of near-bank flow velocity as indicated by U_b' is used to classify bank material for stable bends (<5 m of erosion).

2.3.6 *Limitations to the erodibility analysis*

There are several potential sources of uncertainty associated with our bank erodibility analysis. We apply a single-thread, constant-width model to a multi-thread, variable-width stream. We assume erosion occurred under constant (bankfull) discharge, yet actual peak flows have fluctuated greatly over the 150-year study period. Uncertainty is introduced through historic data used to measure bank erosion rates and the input parameters and equations used to calculate near-bank flow velocities with the JP model. Our interpretation of E_o results is also influenced by the amount of channel we are able to analyze, as our analysis is only applicable in areas where we are able to link U_b' from channel geometry of the initial planform with erosion occurring over the interval. There is also uncertainty associated with classifying bank material eroded during historic time periods. Our classification routine may cause us to label some eroded areas as Qg2, although the actual eroded area may have been composed of Qg2 and Qalc. Although each of these topics is potentially important, we are only able to quantify uncertainty for our bank erosion estimates and address that issue here.

The historic channel maps from 1850, 1895, and 1932 contain error associated with mapping, georeferencing and digitization. While it is difficult to estimate uncertainty associated with survey techniques and active channel definition, we estimate absolute and relative errors for the 1850, 1895, and 1932 maps to be less than 10 m in magnitude (Table 2.1). We estimate maximum error resulting from the georeferencing and digitization of aerial photographs to be between 5-10 m for the 1995 channel and 10 m for the 1972 channel. Thus each bank-erosion polygon could have up to 20 m of error associated with the actual distance migrated over the interval. For a bend that experienced significant erosion (e.g., 250 m) the maximum amount of uncertainty constitutes less than 10% of the distance migrated. Smaller bank-erosion polygons (e.g., 20 m of bank erosion) could have very high levels of uncertainty as the actual amount of erosion may range from 0-40 m.

2.4. Results

Following criteria that resulted in exclusion of some parts of the channel from analysis, we were able to calculate bank erodibility along 36-61% of the channel during each time period (Table 2.3). During earlier time periods, 1850-1895 and 1895-1932, many bends experienced avulsion or rapid migration such that the U_b' from the first time cannot be directly linked with observed erosion. Of the 96 bends analyzed over all three study intervals, we excluded 44 bends due to planform discrepancies and three bends due to problems with U_b'. Although we are able to model 10-20 km of the floodplain, our sample sizes are low because E_o is calculated at the scale of 0.5-3 km long bends. During each time period, E_o is calculated for 3 to 13 bends per bank material.

Two-tailed t-tests (assuming unequal variance) were used to determine whether the mean E_o values for Qalc, Qg2 and revetment were statistically different from each other and to detect temporal changes in erodibility within bank materials

(Table 2.4). The t-statistics reveal that the average E_o for Qalc was statistically different from Qg2 during 1850-1895 and 1972-1995 ($p<0.05$). Holocene alluvium from all periods was also statistically different from revetments ($p<0.05$), however there was no meaningful difference between Qg2 and revetments ($p>0.05$). Combining the average E_o values from all time periods reveals a three-fold difference in E_o between Qg2 and Qalc, with higher significance levels than for individual time periods ($p<<0.05$). Temporal variation in average E_o was greater for Qalc than for Qg2 ($p>>0.05$ when comparing mean Qg2 E_o between each interval).

These t-test results suggest that although our sample populations are small and typically yield relatively high variability (Table 2.3), there are distinct patterns of erodibility between bank materials and across time periods. During all time periods Qalc is, on average, 2-5 times more erodible than Qg2 (Table 2.3 and Figure 2.6). Revetted banks during the 1972-1995 period have very low erodibilities and are on average 11-84 times less erodible than Qg2 and Qalc. Average erodibility of Qalc decreased nearly 40% from the late-19th century to the late 20th century (Table 2.3, Figure 2.6). Erodibility for Qg2 does not follow the same temporal trend, but small sample sizes make any changes statistically insignificant (Table 2.4). Of the three study periods, the interval 1895-1932 displays the lowest erodibility for Qalc and the highest for Qg2.

Longitudinal trends in erodibilities are associated with the distribution of resistant bank materials relative to the position of the Willamette River (Figure 2.7). There is a higher number of lower erodibility bends in the downstream portion of the reach (FPKM 185-198) where the Willamette has impinged upon Qg2 gravels bordering the eastern margin of the floodplain. Bends upstream of FPKM 200 are bordered by Qalc and generally have displayed higher erodibilities, though revetments cause diminished erodibilities along some bends of the 1972-1995 floodplain (e.g., FPKM 210).

The coefficient of variation (COV) for E_o increases over time for both Qalc and Qg2. Pleistocene gravels and revetments display greater variability than Holocene Alluvium during all time periods, as the COV for Qg2 is twice that of Qalc for 1850-1895 and 1972-1995, while COV for revetment is 3-4 times greater than Qalc. This variability between bank materials appears to be linked with systematic error associated with measuring bank erosion distances from historic maps and aerial photos.

For 1850-1895 and 1895-1932 time periods, the average distance eroded for modeled bends is approximately 70 m, whereas the average eroded distance for 1972-1995 is approximately 20 m (Table 2.3). Assuming a maximum potential error of 20 m associated with each eroded distance, we estimate that E_o values from 1850-1895 and 1895-1932 may have up to 30% error while the smaller polygons from 1972-1995 yield much higher potential error, possibly as high as 90%. A similar relationship between eroded distance and error levels exists when comparing E_o values for Qalc against Qg2. On average, eroded distances for Qalc are 50-100 m, and therefore associated errors in E_o measurements could be as high as 20-50%. Average distances eroded for Qg2 are approximately 4-50 m and could have errors as great 40-300% (Table 2.3). These preliminary error estimates generally agree with calculated COV values; bend populations with less erosion tend to have higher variability than populations with larger bank erosion distances.

During each time period, channel width varies by 30-50% of reach-averaged width and potentially introduces error in our calculation of U_b' and may therefore influence E_o values. We investigated the importance of channel width on E_o by varying channel width (and stage) in the JP model and overlaying the adjusted U_b' values on our bend-scale polygons. For each 10% increase in channel width, bend-scale E_o decreased by about 10%, whereas a 10% decrease in channel width generally caused bend-scale E_o to increase by 14%. As channel width along most of our modeled bends varies by 10-20% of the reach-averaged width for that time period, error in our computed E_o due to planform fluctuation is probably on the order of 10-15%. Our sensitivity trials also revealed that near-bank flow velocity is most sensitive to planform irregularities and that while adjustments in width to depth ratios and discharge influenced the magnitude of U_b', the relative difference in maximum U_b' between individual bends remained similar.

2.5. Discussion

2.5.1 Applicability of a bank erosion analysis to the upper Willamette

Our analysis demonstrates that differences in erodibility due to bank materials can be detected at the scale of individual bends using a meander migration model and historic channel maps. The primary premise of the analysis is that, for single-thread, constant-width channels, bank erosion is a continuous process resulting from near-bank velocity and bank erodibility. On the historically anastomosing upper Willamette, application of such an analysis requires careful selection of reaches that best meet these assumptions. By excluding avulsions and avulsion-related migration, both of which primarily occurred along anastomosed reaches, we focus our study on single-thread areas that evolved through lateral migration. We further restrict our analysis to bends where channel planform from the first time is a good predictor of the actual lateral migration that occurred over the time interval.

The remaining assumptions of our meander migration model prove more problematic as the analysis assumes that bank erosion occurs at a constant rate, along constant width rivers characterized by constant (bankfull) discharge. Along the upper Willamette channel width and presumably, discharge, varies as the channel alternates between multi-thread and single thread reaches. Because the channel has adopted a more single-thread planform in the 20th century, the effect of multiple channels on apparent erodibility was probably greatest in the period 1850-1895 and increasingly less important in the intervals 1895-1932 and 1972-1995. Even as greater portions of the upper Willamette have become single-thread, channel width is variable, (Table 2), which potentially introduces error in our calculations of U_b' and E_o.

Our calculation of bank erodibility is based on estimated values of near-bank velocity, therefore the ability of the JP model to correctly compute variation in velocity perturbation due to channel curvature is critical to our analysis. Assessing the ability of the JP model to correctly estimate U_b' is difficult and would entail either forward modeling, in which we compared predicted migration against actual erosion, or comparison of simulated U_b' and actual near-bank velocity measurements taken at bankful discharge. In the absence of such comparisons we rely upon our own examination of model results and past studies to evaluate the ability of the JP model to predict channel migration.

We use the JP model to predict which bends are likely to migrate more rapidly than others based on channel curvature. For this reason, we are less concerned with local U_b' calculated at each point along the centerline and more concerned with bend-scale patterns in computed curvature and near-bank velocity. We evaluated the performance of the JP model by examining each bend and determining whether the model was able to correctly predict (a) which bank was likely to experience the greatest magnitude of near-bank velocity; (b) the general location of maximum U_b' relative to overall bend geometry; and (c) the location of maximum U_b' relative to actual erosion for that time interval. We found that along areas subject to moderate lateral migration (e.g. less than 300 m of erosion) the JP model was generally able to meet each of these criteria. Areas where the JP did not perform adequately were typically bends excluded from our analysis for other reasons, such as rapid migration or migration influenced by avulsion.

While rapid migration of bends is within the conceptual realm of model predictability, in practice rapid migration results in such large planform changes over the periods examined that the initial planforms do not provide sufficient information to predict such large changes. For example, many low-sinuosity sections of the 1895 channel developed into bends that subsequently migrated downstream, producing a more sinuous channel by 1932. The low-sinuosity sections of the 1895 channel have very low U_b' values, suggesting that small initial bends may have formed slowly, but later migrated more rapidly once sufficient curvature was established to drive higher near-bank velocities. Our analysis of historic erosion along the Willamette River floodplain is therefore biased towards bends with relatively low migration rates, as we exclude nearly half of the entire bend population over the three time periods due to rapid migration. If rapid migration were partly or wholly due to high erodibilities, then our estimate of E_o would be biased toward lower values. It seems just as likely, however, that the observed rapid migration is entirely driven by characteristics of the planform.

Our evaluation of the JP model is consistent with previous studies, which found that the model was generally able to simulate realistic meander migration. The primary problems encountered by other authors were found when using the model to predict channel migration rather than simply using it to compare maximum U_b' between bends. For example, Lancaster and Bras, (2002) found that the simulated bends were overly smooth in comparison to natural rivers and the model did not produce more complicated bend shapes such as double-headed meander bends. Johannesson and Parker (1985) found that an earlier version of the model required extensive calibration in order to determine proper bank-erodibility values necessary for correct prediction of channel migration. In the absence of such calibration, Garcia et al, (1994) found that an earlier version of the JP model was better at predicting the downstream migration of bends than outward erosion.

2.5.2 Ability of a simple analysis to detect differences in erodibility due to bank materials

Although our sample sizes are limited and significance levels in each time period are modest, consistent differences in relative erodibility between bank materials over all time periods boosts our confidence in the E_o results from individual time periods. In each time period, Holocene alluvium is on average 2-5 times more erodible than Pleistocene gravels. Moreover, by averaging E_o across all time periods, we detect a three-fold difference in E_o between Qalc and Qg2 and gain a much higher significance level than for individual periods.

Initially, we anticipated greater differences in erodibility between bank materials because casual field observations suggested Holocene alluvium was much less consolidated than partially-cemented Qg2 gravels. The relatively modest difference in bank erodibility as detected in our analysis may be due in part to vegetation, which exerts a greater influence on Qalc surfaces because few plant species have roots that are able to extend through the 3-5 m of Missoula Flood deposits overlying Qg2. Additionally, because Qg2 is typically exposed along steep (near vertical) banks, very little bank roughness is contributed by vegetation. In contrast, Qalc banks are more directly influenced by vegetation as bank height is typically less than 3 m and overlying alluvial soils are more conducive to plant growth. In the 19th century, the Holocene floodplain was densely forested, and though much of the modern floodplain has been converted to agriculture, there is still considerable riparian vegetation bordering the channel along Qalc banks.

Previous studies have shown vegetation to reduce bank erosion by increasing soil tensile strength, mass loading, and bank roughness (Thorne, 1990; Thorne and Furbish, 1995; Micheli and Kirchner, 2002; Simon and Collison, 2002). However, feedbacks between wood, sediment and floods have also been shown to trigger dynamic floodplain behavior including avulsions, bank attack and secondary channel formation (Keller and Swanson, 1979; Swanson and Lienkaemper, 1982; Fetherston et al., 1995; O'Connor et al., 2003). Although the riparian vegetation and land conversion may have had an important effect on channel change along the Willamette River, we do not have sufficient vegetation data to determine that effect. Moreover, historic trends in flow regime might obscure trends in land use. For example, decreased flow due to dams might decrease apparent erodibility, but decreased bank vegetation might increase apparent erodibility. Such scenarios would be consistent with the results of our analysis.

Variability in calculated values of E_0 seems most closely linked with error arising from our measurements of erosion distance. Bends with less erosion (e.g., <20 m) have much higher levels of uncertainty than bends that experienced greater levels of erosion (e.g., >100 m). Therefore time periods or bank materials that experienced small amounts of erosion are likely to have very high levels of uncertainty (often exceeding 100% of the computed E_o for that bend). This relationship between erosion distance and uncertainty may partially explain the high levels of variation associated with Qg2, which has coefficients of variation ranging from 77-170% whereas variation for Qalc is typically lower (40-70%). Although it is difficult to quantify total error associated with the JP model, we estimate that time periods having higher levels of variation in reach-average channel width are more likely to have higher error in U_b' and thus E_o.

The effect of floodplain variables such as sediment properties and riparian vegetation on bank erodibility is more difficult to quantify. Within both Qalc and Qg2, heterogeneity in consolidation, grainsize or bank height may cause some areas within each bank material to be more erodible than other areas. For instance, some areas of the upper Willamette floodplain are bordered by erodible Holocene Alluvium, yet they experience little to no bank erosion and have low apparent erodibilities. Nearly one-half of Qalc bends in the 1895-1932 interval, and about one-fourth of Qalc bends in the 1972-1995 interval display lower erodibilites along reaches where the channel alternates between Qalc and Qg2 banks in the lower study reach. Because we have relatively small sample sizes, each of these lower-erodibility Qalc bends have a potentially important effect on reach-average erodibility. The reason for low erodibility is unclear and may be due to over-estimation of U_b', vegetation or intrinsic differences in local erodibility. It is also possible that certain bends bordered by erodible material may experience 'secondary stabilization' in which resistant banks along adjacent bends impart some level of local stability.

While our analysis has shown that measurable differences in bank erodibility have persisted over the last century, the logical next step is to conduct field-based tests in order to quantify actual bank material strength properties. If conducted at the low-water line, such tests may reveal absolute differences in bank strength between partially-cemented Pleistocene gravels and Holocene alluvium and could also be used to determine the influence of riparian vegetation on bank strength. Simulation modeling of channel migration through various bank materials may be used to explore the effect of revetment removal or to discern whether resistant banks can exert a stabilizing influence on adjacent bends.

2.5.3 Implications of resistant bank materials

Throughout most of the 20th century, portions of channel flowing against Qg2 gravels generally do not migrate away from Qg2. Rather, as meander migration continues, bend enlargement causes greater portions of the channel to flow against Qg2 gravels. This pattern of steady increases in the percentage of Qg2 banks was not always the case. Between 1850-1895, avulsions and migration led to increases in the length of channel bordered by Qg2 (Figure 2.2), but during the interval 1895-1932 rapid migration and bend cut-off allowed several bends to migrate away from Qg2. We also observe that, prior to flow regulation, greater, more erosive flows and erodible banks allowed low-sinuosity reaches to develop bends that migrated rapidly downstream, triggering further channel change. Presently, revetments placed along Holocene alluvium restrict lateral migration and prevent avulsions. The combination of naturally resistant banks, revetment, and flood control causes stabilization of much of the modern Willamette.

While channel migration may result in economic losses due to property damage, channel movement has also been shown to have beneficial consequences for riparian-zone ecosystems. Bank erosion contributes sediment and large-wood to the river that can be deposited downstream leading to formation of bars and islands (Swanson and Lienkaemper, 1982; Gurnell et al., 2001; O'Connor et al., 2003). Migration leaves behind newly deposited gravel bars that allow for recruitment of pioneer vegetation species and over time provides a mosaic of geomorphic surfaces that increase the diversity of riparian habitat (Fetherston et al., 1995). Frequent reworking of floodplain sediments and redistribution of bed material enhances hyporheic flows, which support cooler stream temperatures and habitat for benthic organisms (Wondzell and Swanson, 1996; Fernald et al., 2001).

Efforts aiming to increase channel migration should focus on removing bend-size portions of the Willamette from resistant bank materials. As banks composed of Holocene alluvium are intrinsically more erodible than Pleistocene gravels, removing revetment from these bends may produce higher levels of migration than would be gained by removing revetments from Pleistocene gravels. Analysis of historic migration indicates that Qalc banks upstream of floodplain kilometer 200 tended to have higher levels of erodibility than banks in the lower study reach where bends alternate between Qalc and Qg2. Although more investigation is required to determine if there are significant differences in bank erodibility within Qalc, migration along upstream areas may be greater than for bends in the lower study reach. Historic patterns of channel change also indicate that even relatively low-sinuosity reaches bordered by erodible bank materials can display dynamic meander behavior. However, rapid migration may be due in part to flow regime and there may be a minimum bend length required for such behavior to develop. Thus, further investigation is needed to more fully understand meander migration along the upper Willamette.

2.6 Conclusion

Although bank erosion results from complex relationships between flow and floodplain characteristics, our simple model of bank erodibility reveals distinct patterns of erodibility linked to bank materials. Across three time periods spanning more than 100 years, we find that Holocene alluvium is on average 2-5 times more erodible than Pleistocene gravels. When erodibility values from all time periods are combined, significance levels are much higher, revealing that Holocene alluvium is about three times more erodible than Pleistocene gravels, which in turn are at least 11 times more erodible than revetments.

In the century following Euro-American settlement, the length of channel flowing against naturally resistant Qg2 gravels has steadily increased. Approximately 30% of the Willamette is presently stabilized by moderately resistant

Qg2 gravels while more than 40% is stabilized by highly resistant revetment. Even along bends bordered by erodible Holocene alluvium, migration rates may be low, as local variation in bank materials or vegetation may exert a stabilizing influence on bank erodibility. Our analysis also reveals migration rates are further influenced by planform, which can exert large influences on channel movement irrespective of bank material. The role of resistant bank materials on channel migration may be further explored through bank material strength tests and simulation modeling, both of which may provide absolute differences in bank erodibility for Holocene alluvium and Pleistocene gravels and may quantify the role of riparian vegetation on bank erosion. These results suggest that restoration efforts aiming to increase channel migration should focus on releasing bend-size portions of Holocene alluvium from revetment.

2.7 Acknowledgements

Thanks to Stan Gregory, Linda Ashkenas, Randy Wildman and other members of the Pacific Northwest Ecosystem Research Consortium whose previous work and expertise greatly enhanced this study. Thanks to Jim O'Connor for providing insight on Willamette Valley stratigraphy and field equipment. We thank Gordon Grant and Andrew Meigs for guidance and helpful reviews of this document. This work was supported by the National Science Foundation (Biocomplexity grant # 0120022).

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2.9, Appendix

Johannesson & Parker (1989) model of near-bank velocity perturbation (U_b')

The Johannesson & Parker (1989) model assumes that U_b' is largely driven by channel curvature:

$$U_b' = \chi_{20}UBC(s) + \frac{C_f UB^2}{H}\left[\chi_{20}\left(\frac{U^2}{gH}+2\right)-1\right]e^{\frac{-2C_f s}{H}}\int_0^s C(s')e^{\frac{2Cfs'}{H}}ds' \ldots$$

$$\ldots + \frac{C_f UB}{H}(K+A_s)e^{\frac{-2Cfs}{H}}\int_0^s C(s')e^{\frac{2Cfs'}{H}}ds' \qquad \text{(A1)}$$

We have made several adaptations to the JP model to make the model more representative of the Willamette River. We have substituted local curvature, C, for the effective curvature integral in the argument of the second integral of Equation (A1) and we use Ikeda's (1989) equation for transverse bedslope to calculate K in Equation (A7).

Coefficients used in the JP model:

χ_{20}, χ_1, χ — Coefficients used to describe secondary flow given by:

$$\chi_{20} = \frac{1}{\chi_1^3}\left(\chi^3+\chi^2+\frac{2\chi}{5}+\frac{2}{35}\right), \chi_1 = \frac{0.077}{\sqrt{C_f}}, \chi = \frac{0.077}{\sqrt{C_f}} - \frac{1}{3} \qquad \text{(A2-4)}$$

U, B, H — Reach-average velocity, channel width and stage for bankfull discharge; described in Table 2.2

$C(s)$ — Channel curvature at distance s along the centerline

s' — Distance to point upstream from s

C_f — Coefficient of friction, calculated as: $C_f = \frac{gHS}{U^2}$, (A5)
where g is gravitational constant and S is channel slope

A_s — Coefficient used to describe bed topography, calculated as:

$$A_s = \frac{181}{\chi_1}\left(\frac{2H}{B}\right)^2\left(2\chi^2+\frac{4\chi}{5}+\frac{1}{15}\right) \qquad \text{(A6)}$$

K — Coefficient used to calculate transverse bedslope in gravel-bed rivers, from Ikeda (1989):

$$K = \sqrt{\frac{\psi}{\psi_{cr}}}\left(\frac{0.2278}{\sqrt{C_f}} - 0.3606\right) \qquad \text{(A7)}$$

Table 2.1, Channel Maps used in Bank Erodibility Model

Channel Maps				
Map Date	**Original Survey or Photo Source**	**Map Description**	**Source for Georeferencing and Digitizing**	**Precision**
1850	General Land Office (GLO) Cadastral Surveys	Cadastral survey of townships and sections. Most of study area surveyed 1851-1853.	Hulse et al., 2002[1], Nature Conservancy (200?)	+/- 10m
1895	Army Corps of Engineers (USACE)	Navigational blue-line survey. Study area surveyed October-November of 1894.	Hulse et al, 2002	Unknown
1932	USACE	Navigational survey of study area conducted 1931-1932.	Hulse et al, 2002	+/- 5 m
1972	USACE	Main channel and active channel[2] digitized from mosaic of orthophotographs in 1972 Willamette River and Tributaries Map Book. Photography flown May 2, 1972 at ~300cms.	These authors	+/- 10 m
1995	USACE	Main channel and active channell[2] digitized from orthophotographs flown August 1994 and September 1995 (~150-200cms).	Spencer Gross Photography, PNWERC & these authors	+/- 5 m

1. Pacific Northwest Ecosystem Research Consortium (PNWERC) presented in Hulse et al, (2002).
2. For 1972 and 1995 we digitized both the actual water surface boundary and the active channel from aerial photographs. Although discharge at the time the 1972 photos were taken is about twice that of flow during the 1995 photos, there is little difference in the stage-discharge relationship for these flows (~1m) and reach-averaged channel width for the low-water channel varies by less than 2% between the photo series.

Table 2.2, Input data for JP Model
Parameters used to calculate near-bank flow velocity perturbation (U_b') for the 1850, 1895 and 1972 channels.

Variable	*Units*	*1850 value*	*1895 value*	*1972 value*	*Source*
Width (B)	Meters (m)	160	235	185	Measured from channel planforms
Coefficient of Variation (COV) in Width	Percent (%)	34%	52%	39%	Computed from width measurements
Stage (H)	Meters (m)	2.75	1.87	2.37	Back-calculated from reach-average velocity
Bankful Discharge (Qb)	Cubic meters per second (m^3/sec)	1190	1190	1190	Source: USACE, 2004
Valley relief	Meters (m)	36	36	36	Measured from 10m DEM
Median grainsize (D_{50})	Meters (m)	0.039	0.039	0.039	Source: Klingeman, 1981

Table 2.3, Summary of bank erodibility results

Time Period	% of channel length modeled[1]	Number of bends modeled			Reach averaged erodibility[2] (E_o) +/- 1 std dev (x 10^{-7})			Coefficient of Variation (COV) in E_o values (%)			Average distance eroded (m)		
		Qalc	Qg2	Rvtmt[3]	Qalc	Qg2	Rvtmt	Qalc	Qg2	Rvtmt	Qalc	Qg2	Rvtmt
1850-1895	42	9	6	-	1.25 +/- 0.52	0.27 +/- 0.25	-	41	95	-	106	24	-
1895-1932	36	8	3	-	0.66 +/- 0.42	0.36 +/- 0.28	-	64	77	-	77	48	-
1972-1995	61	11	5	7	0.80 +/- 0.41	0.17 +/- 0.32	0.015 +/- 0.028	51	195	190	47	4.3	2.2
All time periods	-	28	14	7	0.91 +/ 0.50	0.25 +/- 0.27	0.015 +/- 0.028	55	109	190	75	22	

1. Percentage approximates the length of channel for which we are able to link U_b' from the first time with erosion over the period. Centerline length is measured along the channel from the second time.

2. Erodibility (E_o) is a dimensionless parameter obtained by dividing bank erosion rate (m/s) by near-bank flow velocity (m/s). Although erosion rates are measured in m/yr we convert the measured rates to m/s, which yields very low values (~10^{-7}) with identical units as velocity.

3 Of the 7 bends with revetment, 6 bends were composed of Qalc while Qg2 bordered 1 bend. Average E_o for Qalc with revetment was 0.017 x 10^{-7} +/- 0.030; the Qg2 revetted bend had E_o of 0.00.

Table 2.4, Significance levels (p-values) from Students t-tests used to compare average E_o values across time periods and between bank materials.

We computed the t-statistic using two-tailed t-test assuming unequal variance between samples. Lower values indicate lower probabilities that differences between average erodibilities are due to random chance.

	1850-1895		1895-1932		1972-1995		
	Qalc	**Qg2**	**Qalc**	**Qg2**	**Qalc**	**Qg2**	**Revetment**
1850-1895 Qalc	X	3.4×10^{-4}	0.021	6.7×10^{-3}	0.048	4.3×10^{-4}	9.1×10^{-5}
1850-1895 Qg2	3.4×10^{-4}	X	0.050	0.66	4.9×10^{-3}	0.58	0.059
1895-1932 Qalc	0.021	0.050	X	0.21	0.50	0.036	3.3×10^{-3}
1895-1932 Qg2	6.7×10^{-3}	0.66	0.21	X	0.084	0.41	0.17
1972-1995 Qalc	0.048	4.9×10^{-3}	0.50	0.084	X	7.6×10^{-3}	7.8×10^{-5}
1972-1995 Qg2	4.3×10^{-4}	0.58	0.036	0.41	7.6×10^{-3}	X	0.36
Revtmt	9.1×10^{-5}	0.059	3.3×10^{-3}	0.17	7.8×10^{-5}	0.36	X

All Time Periods	**Qalc**	**Qg2**	**Rvtmt**
Qalc	X	2.4×10^{-6}	4.3×10^{-10}
Qg2	2.4×10^{-6}	X	6.6×10^{-3}
Revetment	4.3×10^{-10}	6.6×10^{-3}	X

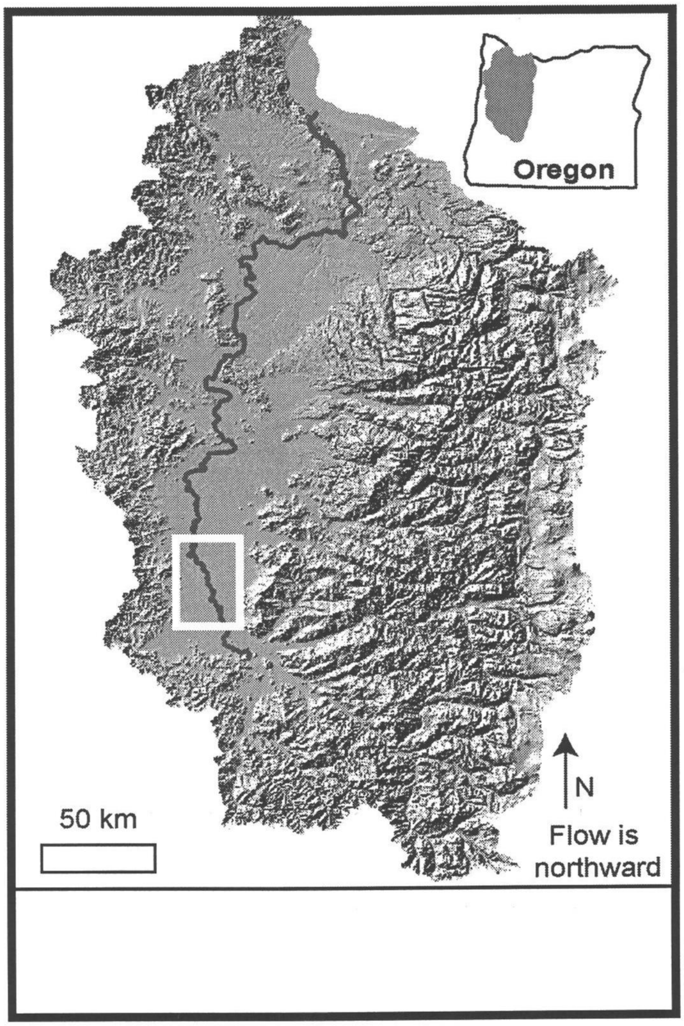

Figure 2.1.
Willamette River Basin in northwestern Oregon.
Box indicates upper Willamette study area.

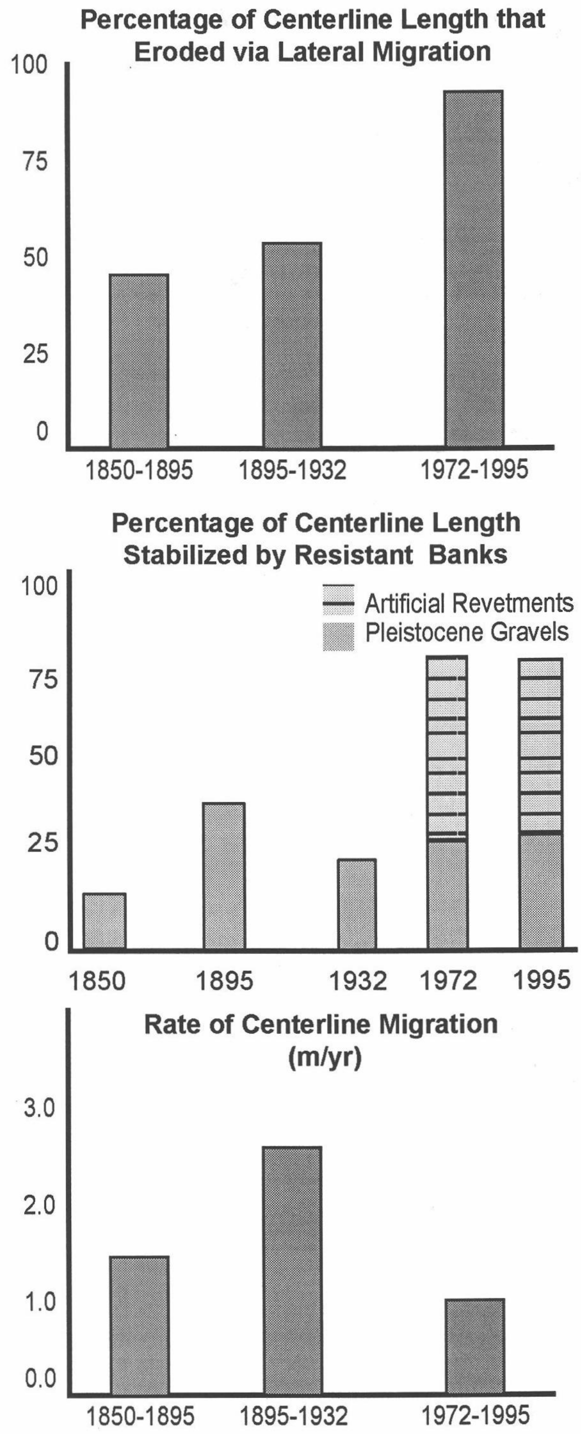

Figure 2.2, Migration patterns for upper Willamette 1850-1995. Large increases in both the length of channel prone to lateral migration and the length of resistant banks are accompanied by fluctuating migration rates.

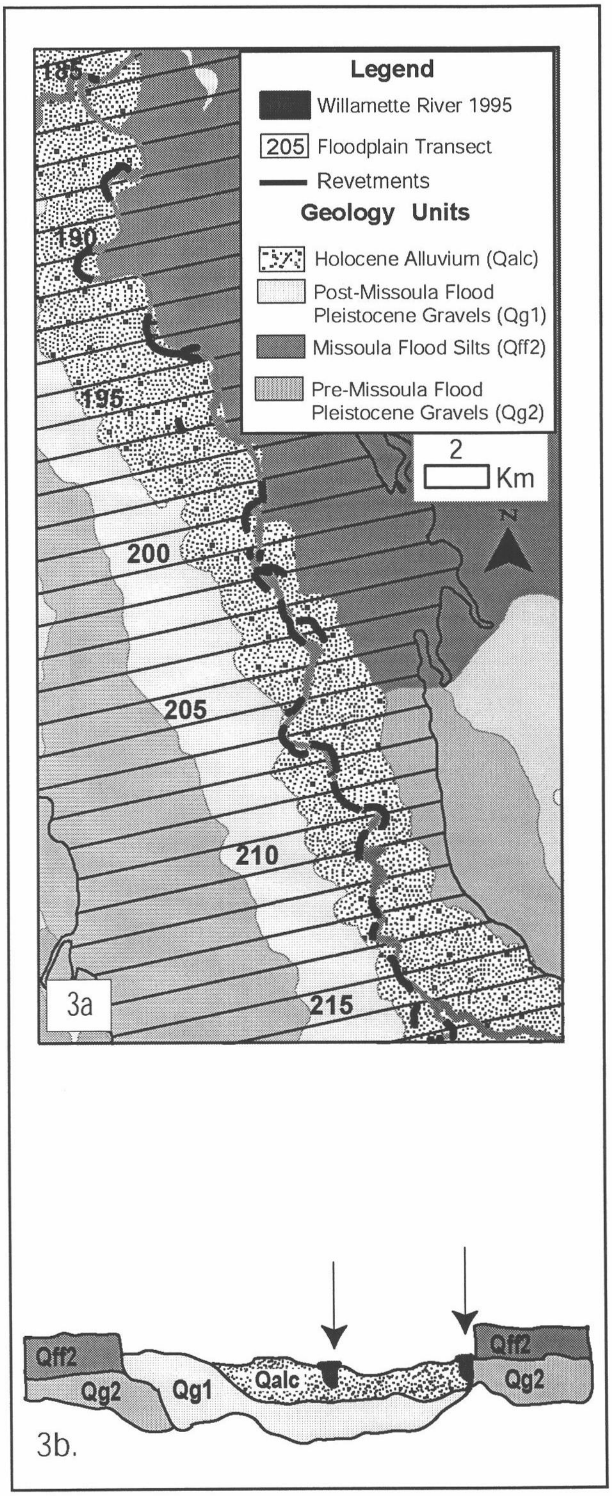

Figure 2.3, Upper Willamette study area

Figure 2.3a, Geologic setting of upper Willamette.
Primary bank materials are Holocene Alluvium and Pleistocene Gravels which underlay Missoula Flood Silts. Revetments are presently used to stabilize more than 40% of the channel.

Figure 2.3b, Generalized Cross Section of Willamette floodplain. Arrows indicate general location of Willamette River

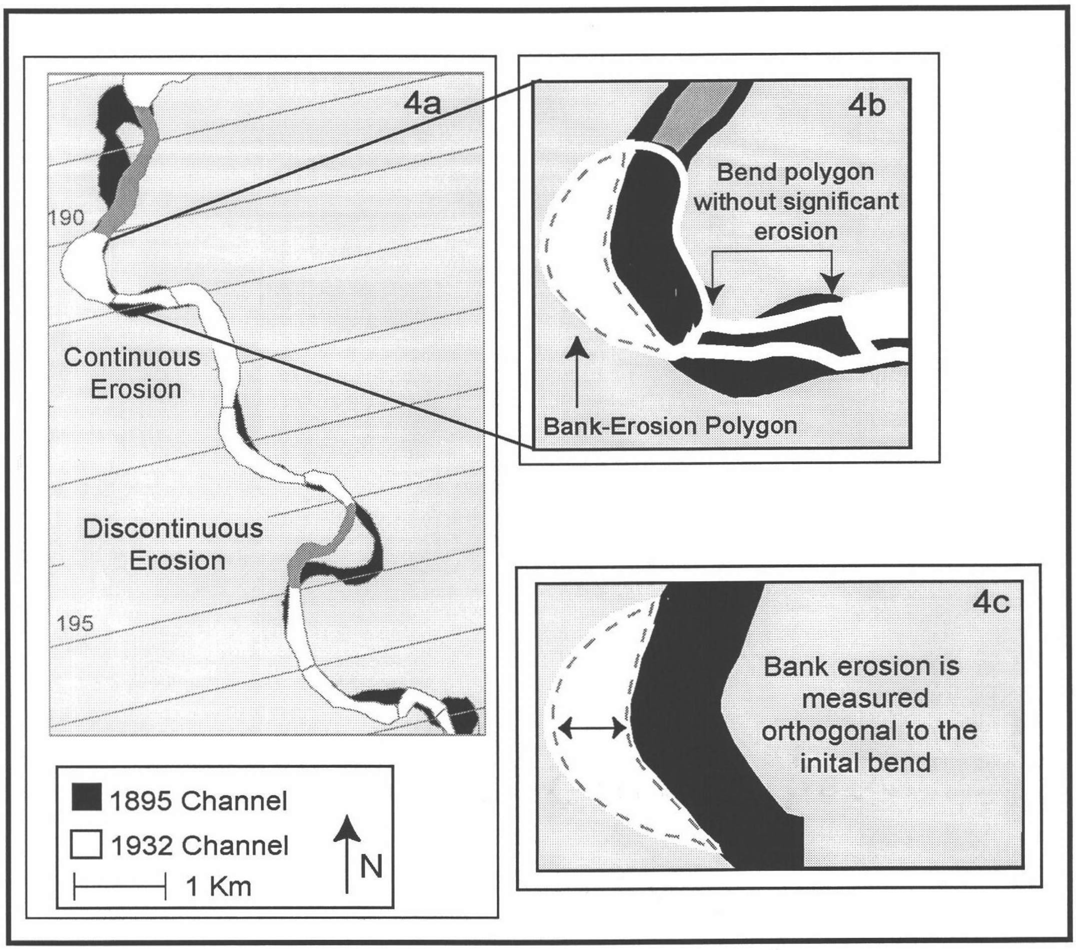

Figure 2.4. Calculating bank erosion rates with bend-scale & bank-erosion polygons.

(a) The channel was divided into contigous bend-scale polygons classified according to magnitude & style of erosion. Bends that experienced continuous erosion (e.g., moderate lateral migration) were selected for our analysis. Bends that experienced discontinous erosion (e.g., avulsion or extreme migration with >500 m of erosion) were excluded.

(b) For bends with significant erosion (i.e., >10 m), eroded areas define bank-erosion polygons.

(c) Average bank length is defined as half the perimeter of the bank-erosion polygon and bank erosion (a distance) is the ratio of polygon area to average bank length.

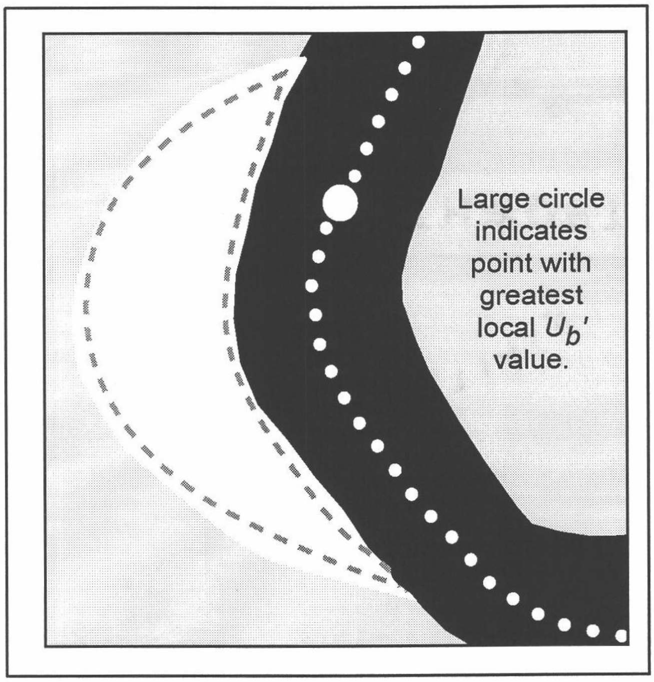

Figure 2.5. Overlaying Bend Polygons with Ub'.
Each point has a corresponding near-bank velocity.
We select the maximum U_b' for each bend & compute
E_o by dividing U_b' by bank erosion rate. .

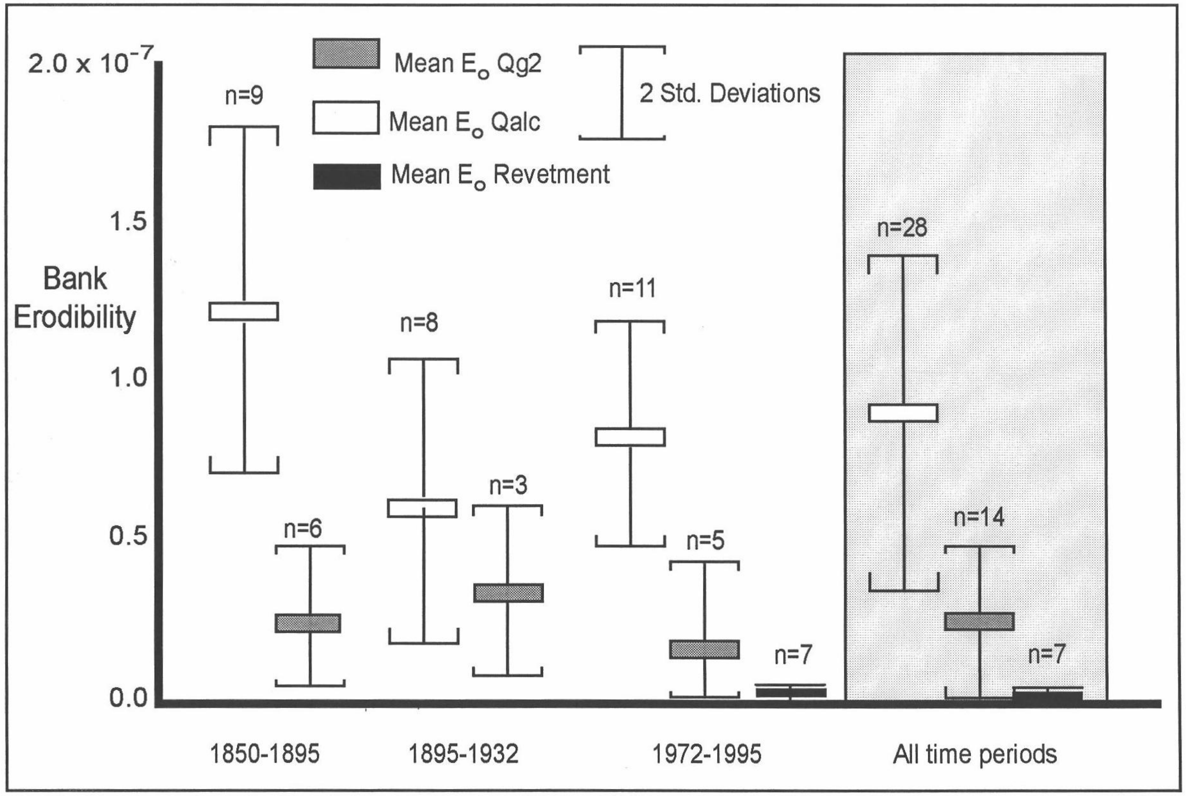

Figure 2.6. Bank Erodibility Trends for upper Willamette River 1850-1995

For all time intervals, Holocene Alluvium (Qalc) is on average 2-5 times more erodible than partially cemented Pleistocene Gravels (Qg2). Revetment installed along Qalc banks in the1930's through 1970's is highly resistant to erosion.

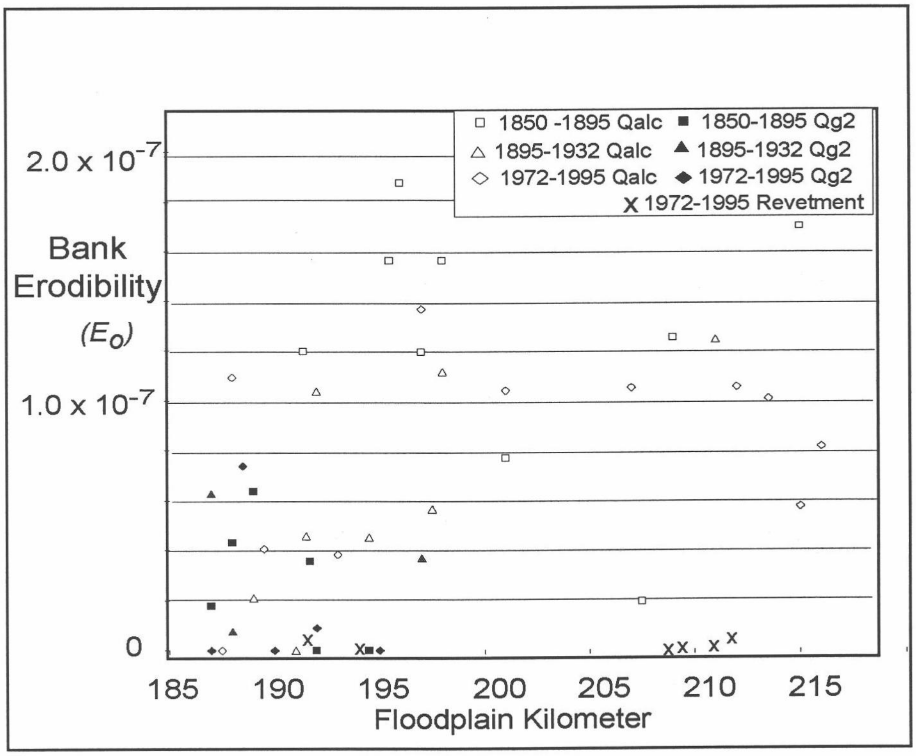

Figure 2.7. Longitudinal patterns in bank erodibility 1850-1995.
Holocene alluvium (Qalc) has historically been more erodible than Pleistocene gravels (Qg2), though there are several Qalc bends in the lower reach (FPKM 185-195) with lower erodibilities than the those in the upper reach. Bends stabilized with revetments in the mid-20th century have very low erodibilities.

Chapter 3:
Interpreting dominant channel change mechanisms from historical river data, Willamette River Oregon, USA

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3.a Abstract

We propose a hierarchical ranking of controls on channel change and evaluate this conceptual model by examining historical channel change along the Willamette River, in northwestern Oregon. As a large alluvial river, the Willamette is composed of a series of geomorphically diverse reaches, which have each evolved uniquely in the century following Euro-American settlement. We divided the Willamette into three large (30-50 km) alluvial reaches according to physiographic characteristics, calculated rates, and observed styles of historic channel change for three time intervals: 1850-1895, 1895-1932, and 1932-1995. To explore the effect of anthropogenic activities on channel change, we reviewed historic documents describing settlement patterns, riparian deforestation, channel improvements, and other actions. The role of flooding was examined through gauge records, inundation maps, anecdotal accounts of flooding and by comparing stream-power distributions using a 2-D flood model.

Our analysis reveals that in the absence of flow regulation and bank stabilization, periods marked by large historic floods would experience extensive channel widening and numerous avulsions. Intervals marked by frequent, smaller to moderate-sized floods experienced rapid migration, channel narrowing and heightened sinuosity. While these trends generally occurred across the entire Willamette floodplain, geologic controls cause upper reaches to respond more dynamically to flooding than lower, more stable reaches and bends bordered by resistant bank materials have typically remained fairly stable over time.

With the arrival of Euro-Americans in the mid-19th century, land conversion and navigation improvements may have led to local modifications of channel planform and erosion rates. However, anthropogenic activities do not appear to have had a significant effect on channel dynamics until construction of widespread bank stabilization and multiple flood control dams beginning in the 1930's. The combination of naturally resistant banks, revetments and flood control dams cause much of the modern Willamette to adopt a highly stable planform and erosion rates are presently much lower than were historically observed. This analysis shows that although large rivers are subject to a variety of influences, the importance of individual controls may shift over time. In any particular time period, some disturbance processes or intrinsic controls obscure the effects of other processes, thus forming a hierarchy of influence of controls on channel change.

3.1 Introduction

By studying historic patterns of channel change, we can better understand how large rivers interact with their floodplains under different scenarios. However, interpreting patterns of historical channel change is a complex task because large rivers are susceptible to many natural and anthropogenic influences. Additionally, large rivers generally occupy highly diverse floodplains wherein channel response to disturbances often varies longitudinally, with some reaches responding more dynamically than more intrinsically stable reaches. Therefore, linking channel change with a discrete disturbance process may be difficult because the response from a particular disturbance may be obscured by other events or by floodplain characteristics. The phenomenon that some disturbances or floodplain conditions may obscure the effects of other influences suggests that there may a hierarchical ranking of controls on change. If such a hierarchy exists, then understanding the relative importance of individual controls on channel change is fundamental to interpreting patterns of historical channel change. Moreover, a hierarchical ranking of controls on channel change may help to organize our overall understanding of how large rivers interact with their floodplains.

In this study, we propose a conceptual model of channel change in which disturbance processes and floodplain characteristics may be ranked hierarchically and we develop a methodology for testing this conceptual model. Our methodology draws upon historical observations to link patterns of channel change with floodplain characteristics (geology, physiography, bank materials, and riparian vegetation) and disturbance processes (flooding, human activities). By compiling relationships between floodplain characteristics and response to various disturbances, we assemble a conceptual model in which we rank controls on channel change in order of their ability to drive or resist channel change. Such a conceptual model can be further evaluated against modern observations and computer simulations to gain a more rigorous understanding of channel evolution under varying floodplain conditions and disturbance regimes. We apply this methodology to the Willamette River floodplain in northwestern Oregon and use our findings to assemble a model of channel evolution along diverse floodplains subject to a variety of influences.

3.2. Conceptual model of channel change along large rivers

3.2.1. Simple approach to interpreting historical patterns of channel change

We generally attribute certain styles of channel change with particular types of disturbance processes (Table 3.1). For example, highly erosive large magnitude floods tend to widen the channel, trigger avulsions and ultimately cause decreased sinuosity. In contrast, smaller floods (e.g., bankfull type events) are often associated with heightened migration and widening may be less severe. By measuring rates and styles of channel change for different time periods we can use a framework such as that presented in Table 3.1 to link patterns of channel change with the dominant disturbance processes.

However, large rivers are likely to experience multiple disturbances within a single time period, and intrinsic floodplain factors often control the sensitivity with which the river responds to a particular disturbance process. Establishing clear linkages between channel change and disturbance processes is often more complex than following the simplified trajectories proposed in Table 3.1. For instance, if migration rates increased four-fold during a period marked by moderate flooding and riparian deforestation, it would be difficult to use the simple approach to determine whether heightened erosion rates were due to flooding, land conversion or some combination of both processes. This is because disturbances often affect many aspects of the channel and floodplain, rates and styles of erosion may be altered for decades after the initial disturbance. Additionally, the sequential order in which disturbance events occur could have a potentially important effect on channel response, and there may be complex interactions between disturbances. Thus, interpreting patterns of historical channel change requires a comprehensive approach that embraces the complexity of large river floodplains while allowing us to systematically evaluate the roles of disturbances and floodplain characteristics.

3.2.2. Hierarchical ranking of controls on channel change

Our hypothesis is that large alluvial rivers generally respond to disturbances such as flooding, snag removal, bank stabilization, dam construction and deforestation according to the trajectories displayed in Table 3.1. While these trajectories of provide a basis for understanding how large rivers respond to various disturbances, we propose that in actuality, channel evolution results from the complex interaction of multiple factors and that some floodplain variables and disturbances may be more important than others in either driving or resisting channel change. In particular we suggest that:

a). The geologic history of a floodplain exerts a first order control on channel change because large-scale geologic features often determine floodplain physiography, bank erodibility and other variables, which in turn have a strong influence on planform and erosion rates. Geology can therefore control the sensitivity to which a channel and its floodplain respond to disturbances. For example, reaches with low slope and resistant bank materials are more stable than other reaches, and therefore would respond less dynamically to any sort of disturbance (natural or anthropogenic).

b). Floods come in many magnitudes and frequencies, and each event may exert unique influences on channel planform. We hypothesize that large floods will lead to avulsions and channel widening whereas smaller to moderate floods may cause accelerated migration. In either case, the geomorphic effectiveness of a flood depends not only on its magnitude, but on other variables such as channel slope, planform, bank materials, large wood accumulations and sediment load. Thus, a large-magnitude flood may not initiate much channel change along a reach bordered by resistant banks, but a small flood might trigger extensive change along a reach bordered by highly erodible materials.

c). For human activities to cause a measurable, lasting effect on channel planform or erosion rates, anthropogenic actions need to be more geomorphically effective than the dynamics of the natural system. For instance, the effectiveness of snag removal depends on the rate at which large wood is removed from the channel relative to the amount in stored in the channel and the rate at which large wood is delivered to the river via bank erosion and upstream inputs. We hypothesize that the most geomorphically effective human activities will be those that alter both erosivity and erodibility for large areas of floodplain. Smaller scale, local activities may not trigger a measurable change in planform or erosion rates or may be obscured by larger scale natural or anthropogenic disturbances.

d). The sequential order in which disturbances occur will have a potentially important effect on channel response. For instance, riparian deforestation followed by flooding may result in a different set of changes then flooding followed by deforestation. We hypothesize that although trajectories of channel change are dependent upon the order in which disturbances occur, these trajectories may be predictable once the role of individual disturbances is better understood for a range of floodplain and channel characteristics.

3.2.3. Methodology for evaluating hierarchical controls on channel change.

In order to systematically evaluate controls on channel change we propose a methodology in which a series of parallel studies are conducted. We first examine the physical and geological setting of the river system in order to define a series of large, geomorphically distinct reaches. Each reach is described according to physiographic characteristics (e.g., slope, planform, bank height, type and extent of resistant bank materials). We then rely upon historical channel maps to measure rates and styles of channel change for each reach across multiple time periods. Ideally, the time periods should delineate distinct historical intervals marked by unique disturbances and or changing floodplain characteristics. These measurements form the primary basis of our analysis and provide the data we insert into the simple trajectories of channel change (Table 3.1) in order to develop initial hypothesis on the dominant controls of channel change for each time period. Where our initial results differ from existing paradigms, we draw upon historical records and additional data to further develop the conceptual model.

While conducting the initial reconnaissance on the geologic setting of our study area we begin developing a historical timeline of human interaction with the floodplain and river channel. Although the specific actions undertaken will vary from river to river and across time periods, our goal is to better understand what major anthropogenic actions may have triggered large-scale changes in planform, erosion style and erosion rates. For each general type of activity (e.g., deforestation, dam building, snag removal etc), we attempt to quantify the how these actions evolved over time and to determine spatial patterns in these actions. We also develop a timeline of flooding, gathering evidence of floods from anecdotal accounts and gauge records. While we focus our study on disturbances triggered by human activities and flooding, a similar approach could be used to examine a suite of other disturbances. In studying flooding and human activities independent from our measurements of channel change, we are able to more objectively determine how different disturbances influenced the channel and floodplain.

Our last step is to couple patterns of channel change with geologic controls, human actions, and historical floods. By analyzing our initial results with respect to historical events and floodplain characteristics we determine whether our observations support our hypotheses that controls on channel change follow a hierarchical ranking and that trajectories of channel change depend upon both factors that control local stability and the order and magnitude in which disturbances occur.

3.3 Introduction to Willamette River study area

Historic channel change along more than 200 km of the Willamette River floodplain in northwestern Oregon has resulted from a unique interplay between geologic controls, flooding and human intervention. In the century following Euro-American settlement, the Willamette has evolved from a dynamic, wood- and sediment-rich stream to a regulated river flanked by agricultural fields and revetments. Like other large alluvial rivers, the Willamette is composed of a series of geomorphically diverse reaches with higher-gradient, dynamic sections giving way to lower-gradient, entrenched reaches. These longitudinal differences in floodplain physiography exert large-scale controls on channel dynamics and appear to control the floodplain's response to both natural and anthropogenic disturbances.

Previous work on the Willamette has emphasized the role of humans on channel change and has primarily targeted the upstream areas, leaving much of the downstream floodplain largely unstudied (Sedell and Froggatt, 1984; Benner and Sedell, 1997; Dykaar and Jr., 2000; Gutowsky, 2000). The Willamette Basin Planning Atlas, (Hulse et al., 2002), tracks channel change along the entire valley and provides generalized geologic and historical descriptions to accompany channel change metrics. The Atlas provides a good framework for future studies because it generated excellent historic channel maps. These previous studies generally conclude that there has been an overall decrease in channel dynamics following Euro-American settlement, and that this change is largely due to anthropogenic activities including riparian logging, bank stabilization and flow regulation. We believe that this is an overly simplified view of historic channel change. Here, we seek to develop a more comprehensive model of channel evolution in which we examine the Willamette's transition from pre-settlement conditions to its highly regulated present status, and link these patterns of historic change with factors that have influenced change.

The primary basis of our analysis stems from quantitative measurements of the rates and styles of channel change along 200 km of Willamette River for three periods: 1850-1895, 1895-1932, 1932-1995. Our study periods span Euro-

American settlement, conversion of riparian forests to agriculture, construction of flood control dams and installation of stabilizing revetments. For each time period we measure channel width, centerline length, and reach-average stream power and compute several metrics of channel change including length of channel that experienced migration, migration rates, avulsion frequency, and area eroded due to various processes.

In order to better understand the role that humans have played in altering channel planform and dynamics, we draw upon a diverse set of historical documentation to form a general timeline for understanding when Euro-Americans began altering the floodplain, what actions they undertook and how these land-use patterns evolved spatially. We also use historic documents and anecdotal evidence to describe 19th and 20th century flooding. The role of floods is more quantitatively examined using gage records, historic floodplain maps and a two-dimensional flow model to compare the erosivity of large historic floods against smaller, post-dam floods.

3.4 Setting of the Willamette River

We examine the geological history and setting of the Willamette River channel and floodplain in order to better understand large-scale controls on channel dynamics. The geological processes responsible for creating the Willamette Valley and subsequent deposition of valley floor sediments have caused the modern floodplain to contain a mosaic of geomorphic surfaces. Bank erodibility, channel slope, and planform all vary as the Willamette flows through this mosaic of surfaces. In this section, we provide a generalized description and geological history of the Willamette Valley as well as more in-depth descriptions of our three study reaches. We focus our discussion of geological history on events that have had the strongest influence on modern channel characteristics.

3.4.1 Watershed physiography & climate

The Willamette River is a large alluvial river draining a 29,800-km^2 basin in northwestern Oregon (Figure 3.1). The rugged and volcanically active Cascade Range forms the eastern margin of the Willamette Basin while the Coast Range rises to the west. The headwaters and major tributaries of the Willamette primarily drain the steep, degrading landscapes of the Cascade and Coast Ranges and differ sharply from the low- gradient, meandering streams of the valley-floor sedimentary basin. The mainstem Willamette begins at the confluence of the Coast and Middle Forks of the Willamette in the southern valley and flows northward through alluvial materials for more than 200 km. In the northern valley, the Willamette River incises a gorge through Tertiary basalt flows and passes over the 15 m high Willamette Falls. Below Willamette Falls, the river is tidally influenced for 20 km upstream from the confluence with the Columbia River.

The Willamette Valley is characterized by Mediterranean climate with cool, wet winters and warm, dry summers. Average precipitation in the valley floor is approximately 120 cm per year, which falls mainly as rainfall during the winter (Oregon Climate Service, 2004).

3.4.2 Geologic History of the Willamette Valley

Tertiary marine sandstones and submarine volcanics underlie the Willamette Basin. Approximately 20-16 Ma, the Coast Range was formed as Eocene submarine volcanic rocks were uplifted. The Coast Range separated the Willamette Valley from the Pacific Ocean, forming a broad lowland which has filled with sediments throughout the late Tertiary and Quaternary. Subareal flood basalt flows of the Columbia River Basalt Group (CRBG) covered large portions of the northern Willamette Valley approximately 15 Ma (Hooper, 1997). Subsequent fluvial and lacustrine deposition has blanketed much of these flows, but in some areas (e.g., unit Tcr near Salem on Plate 1), structural deformation has created local uplands of CRBG flows. These uplands locally restrict valley width and separate the Willamette Valley into northern and southern components. The northern valley is considered to be a tectonic depression, whereas the southern valley has been classified a strike valley oriented orthogonal to westward flowing CRBG flows (Yeats et al., 1996).

Quaternary sedimentation has filled the Willamette Valley with sediment that forms the main valley floor and floodplain deposits. Extensive aggradation during the Pleistocene resulted from volcanic construction of the High Cascades and a climate that became cooler and moister in response to glacial conditions.

Pleistocene gravels deposited in a braided stream environment 420 to 12 Ka are preserved in valley fill deposits of the Qg2 unit (O'Connor, et al., 2001). Large fans at the mouths of major Cascade tributaries prograded across the valley floor and pushed the Willamette to the western margin of the valley.

Between 15-12.7 Ka, dozens of catastrophic floods originating in Glacial Lake Missoula swept through eastern Washington and the Columbia River. These Missoula Floods back-filled the Willamette Valley, creating lacustrine settings in which up to 35 m of fine-grained sediments blanked much of the valley floor (O'Connor, et al., 2001). As the Missoula Floods entered the Willamette Valley from its confluence with the Columbia, flood deposits thin southward, extending to FPKM 206. The majority of surface deposits are fine-grained silts and clays from eastern Washington, which range in thickness from 35 m in the northern valley to less than 10 m in the southern valley, forming a near-planar surface across much of the Willamette Valley floor (O'Connor et al., 2001). A brief period of post-Missoula Flood Pleistocene aggradation occurred approximately 12,000 years ago as braidplains excavated Missoula Flood sediments and deposited a layer of sands and gravels that are preserved as Qg1 terraces in the southern Willamette Valley (O'Connor et al., 2001).

The Holocene floodplain is inset within Pleistocene deposits and forms a wide swath of silts, sands, and gravels deposited less than 12,000 years ago. In historic documents, the Holocene floodplain is frequently termed the valley bottom as it is situated 3 – 35 m below the surfaces of the terraces comprising the main valley floor. Holocene floodplain surfaces range from recent point-bar and active-channel deposits to forested floodplains. The elevation of the maximum floodplain surface relative to low-water level increases downstream. In the southern valley, floodplain surfaces typically rise 2-5 m above low-water stage, whereas the floodplain surfaces in the northern valley are up to 15 m higher than low-water stage (O'Connor et al., 2001). Prior to flow regulation in the 20^{th} century, much of the Holocene floodplain was inundated during annual high water.

We use the floodplain reference frame of Hulse et al., (2001) to describe longitudinal and temporal changes floodplain characteristics. The floodplain boundaries were drawn to include the maximum extent of historic floods and as such, floodplain transects often include many areas that are outside of Holocene floodplain. Transects were drawn orthogonal to the floodplain axis at 1-km intervals and are numbered according to their distance upstream from the mouth of the Willamette. A floodplain-based reference frame avoids the bias of a river-based system (e.g, kilometers upstream along centerline), which changes over time due to channel shifting as demonstrated by O'Connor et al. (2003).

3.4.3 Study reaches & longitudinal floodplain characteristics

The Willamette can be broadly delineated into three alluvial reaches on the basis of valley slope, planform, bankful discharge and location of major tributary junctions. Our uppermost reach, (the McKenzie Reach), spans the relatively steep and historically anastomosing Willamette River between the confluences of the McKenzie and Long Tom Rivers. The Santiam Reach is our lowest-gradient study reach, extending from the confluence of the Santiam River to the confluence of the Yamhill River. As the Yamhill confluence marks the upstream extent of the Newburg Pool (a 40 km long backwater area created by ponding upstream of Willamette Falls), the low gradient Santiam reach essentially flows into a lake. The Long Tom Reach acts as a transition between the McKenzie and Santiam reaches as it has features common to both reaches. The Long Tom Reach spans portions of both the upper and middle Willamette Valley and extends between the confluences of the Willamette with the Long Tom and Santiam Rivers.

The Willamette River generally occupies two positions with respect to the Holocene floodplain. Along much of the floodplain, the river is flanked on both sides by Holocene alluvium, whereas in other areas, the Willamette flows against older, more indurated bank materials along the floodplain margins. There are several types of naturally resistant bank materials, the most prominent of which are partially cemented Pleistocene gravels, (Qg2), which underlay Missoula Flood sediments. The elevation of the top of the Qg2 unit relative to the low water line increases downstream, so that along the McKenzie Reach Qg2 gravels are 1-2 m above low water whereas Qg2 rises 5-10 m above low water along the Santiam Reach. Other resistant geological units are locally important and include Tertiary marine sandstones (Tm) that crop out near Albany (FPKM 110) and Tertiary volcanic deposits (Tvc or Tcr) that border the channel near Salem (FPKM 70).

3.5 Data & methods for quantifying channel change

3.5.1 Study intervals & historic channel maps

We calculate rates and styles of channel change using historical maps and aerial photographs from 1850, 1895, 1932, 1972 and 1995. Between 1850 and 1895, Euro-American settlements expanded across the Willamette Valley while navigation improvements beginning in the 1860's sought to confine and stabilize the channel. Population increased at the turn of the century, causing the period 1895-1932 to experience heightened floodplain settlement and increased riparian logging. The interval 1932-1995 spans two eras: the Development Era, 1932-1972, which was marked by dam building and revetment construction, and a relatively stable Post-Development period, 1972-1995.

Inspection of the 1932 and 1995 channel maps for much of the Long Tom Reach and the entire Santiam Reach reveals that these reaches did not experience significant change over the 1932-1995 interval. In contrast, the McKenzie Reach contained numerous bends that initially migrated rapidly in the 1930's-1950's and were subsequently stabilized with revetment by 1972. Averaging migration over the interval 1932-1995 would therefore provide inaccurate results for areas that experienced channel shifting followed by several decades of stability. To avoid these problems, we measure channel change along the McKenzie Reach for the periods 1850-1895, 1895-1932, and 1972-1995. Along the Long Tom and Santiam Reaches we calculate change for the periods 1850-1895, 1895-1932 and 1932-1995.

Digital historic maps of the Willamette River were produced by the Pacific Northwest Ecosystem Research Consortium (PNWERC) from surveys conducted by the General Land Office (1850) and the Corps of Engineers (1895) (Table 3.2). Aerial photographs provided by the Corps of Engineers were digitized by the PNWERC and used to map the active channel of the Willamette River for 1932 and 1995. We digitized the 1972 active channel from aerial photograph mosaics compiled in the Willamette River and Tributaries River Book (USACE, 1972). In each time period, the active channel was defined as the area within the boundaries of the annual high water (1-2 year flow), although definitions of these boundaries were sometimes subjective. Gravel bars, small side channels, and surfaces vegetated with annual species (e.g., small shrubs, grasses, and salix) were included within the active channel, and channel-adjacent areas and islands containing larger woody vegetation were excluded (Gregory et al., 2000).

For each time period, we digitized channel centerlines at a scale of 1:5,000. In multi-channeled areas, the centerline was drawn for the largest channel. Several wide bends (e.g., width >500 m) appeared to contain backwater areas such that water may have extended across low-lying point bars. In such cases the centerline was drawn to reflect the assumed position of the thalweg rather than the center of the channel.

3.5.2 Measuring changes in channel planform

3.5.2a Channel width

Channel width was measured by digitizing transects orthogonal to the channel centerline for each time interval. Transects were drawn at the intersection of the active channel with each floodplain kilometer boundary for kilometers 18-223. In instances where the river contained large islands or backwater areas, a more suitable site was selected slightly upstream or downstream of the original position. By tracking changes in active channel width at the floodplain slices for each time interval we are able to measure similar locations in the in the floodplain four times over the study period. This allows us to determine how portions of the floodplain evolved over time and provides a method of determining patterns in channel adjustment. We also calculate the percentage of floodplain kilometers within each reach that widen or narrow. These combined analyses provide a mechanism for determining (a) reach-average trends in channel widening or narrowing, (b) variation in width measurements, and (c) whether certain areas of the floodplain are prone to a particular process (e.g., narrowing or widening) or whether a reach is relatively stable with respect to width changes.

3.5.2b Sinuosity

Temporal and longitudinal trends in sinuosity were tracked by two methods. Channel centerline length, calculated in ArcGIS for each time period and combined with valley length of the corresponding reach, provides a gauge of reach-scale sinuosity. Bend-length scales developed by Lancaster and Bras (2002) were used to examine smaller-scale planform features and to detect changes in the length and sinuousity of simple and compound bends and multi-bend loops for each reach at each time. Because these sinuosity scales were developed to detect inherent length scales for meandering streams, we evaluated each of the length scales to determine whether they were applicable to the Willamette (e.g., compound bends and multi-bend loops do not really exist along much of the Willamette but were historically present along the upper Willamette).

3.5.2c Bank Materials

We measure the length of channel bordered by resistant bank materials for each time period by overlaying channel maps with the surficial geology map of O'Connor et al., (2001). Along the Willamette, we consider resistant banks materials to be revetments or any geological unit more indurated (and older) than Holocene alluvium. Descriptions provided by O'Connor et al, (2001) and field observations corroborate this classification scheme. For each reach and time period, we divide the centerline according to the bank material that section of channel was most likely to erode. By summing the length of channel flowing against various bank materials in each time period, we can track changes in both the percentage of naturally resistant bank materials relative to the length of channel bordered by revetments.

3.5.2d Stream power

Using the values of reach-average width and centerline length for each time period, we calculate unit stream power for each reach. Stream power (ω) is computed as

$$\omega = \frac{\rho g Q S}{b} \qquad (1)$$

where Q is bankfull discharge; b is reach-average width; ρ is water density; and g is acceleration due to gravity. For each time period, we use a constant bankfull discharge as determined by the Corps of Engineers for that reach (USACE, 2004).

3.5. 3 Calculating rates & styles of channel change

3.5.3a Eroded-area polygons

To quantify the rates at which different styles of erosion occur along the Willamette, we calculate channel change in several ways. We use eroded-area polygons as a primary basis for describing rates of channel change and classify the polygons according to their style of erosion. Eroded-area polygons are created by overlaying digitized channel centerlines from two times. Areas that remain stable are characterized by very slender polygons such that the two centerlines are nearly adjacent. Larger polygons indicate areas where the channel either migrated or avulsed away from its original position.

3.5.3b Polygon processing

Once eroded-area polygons are created from the centerlines, we process the polygon files to ensure that each polygon reflects centerline migration at the scale of a bend. Simply building polygons from centerlines yields a series of polygons of various sizes, some of which may be 1-5 m in length, whereas others may span several kilometers. We examine each polygon and edit the boundaries such that each polygon represents channel change arising from a distinct style at the scale of a bend or (in limited cases) multiple bends. Each polygon is then classified according to style of erosion (lateral migration versus avulsion). Lateral-migration polygons are further classified according to whether the centerline shifted towards the inside of the bend ("straightening") or whether the centerline shifted towards the outside of the bend ("normal migration").

Meander migration frequently involves both straightening-type processes and normal migration as bends elongate and migrate downstream. We therefore restrict our classification of straightening to polygons where the centerline clearly moved to the inside of the bend and resulted in significant (e.g., >15 m) of erosion. Our definition of straightening is thus similar to the processes that lead to bend-cut off, except that straightening is a continuous process and chute-formation typically occurs as a discrete event. All erosion related to the elongation and downstream migration of bends is considered normal migration. Furthermore, if the centerline appeared to shift towards the inside of the bend but bank erosion was minimal, then the change is classified as normal migration because, during periods of channel narrowing, the centerline may appear to shift laterally though the actual position of the thawleg may remain constant.

3.5.3c Calculating migration rates

We measure channel migration as distance traveled orthogonal to the centerline for a particular time interval. Because our polygon processing ensures that polygons are associated with a single planform unit (e.g., a simple bend or straight section between bends), individual migration rates reflect the rate of centerline movement associated with each unit. Following the methodology of Micheli and Kirchner (2002), polygon width serves as a proxy for average distance traveled orthogonal to the centerline and is calculated by dividing polygon area by one-half of the polygon perimeter. Migration rates for each polygon are then calculated by dividing polygon width by the number of years in the time interval. We calculate reach-average migration rates for three styles of erosion: normal migration, straightening, and lateral migration (an average of both normal migration and straightening).

We assess the relative dominance of each type of erosion by computing the percentage of centerline length subject avulsion, straightening and lateral migration. We also compute the annual area eroded per length of channel for lateral migration and avulsion. This latter analysis avoids the bias introduced by averaging migration rates derived from various-sized polygons and provides a better indication of the area of floodplain reworked by different styles of erosion. Comparisons between reaches and time intervals allow us to link process dominance with historic events such as flooding or land conversion and allow us to determine whether certain reaches are more prone to particular styles of erosion.

3.5.3 Limitations of analysis

The historic channel maps from 1850, 1895 and 1932 contain error associated with mapping, georeferencing and digitization. While it is difficult to estimate uncertainty associated with survey techniques and active channel definition, we estimate absolute and relative errors for the 1850, 1895 and 1932 maps to be less than 10 m in magnitude (Table 3.2). We estimate maximum error resulting from the georeferencing and digitization of aerial photographs to be between 5-10 m for 1995 channel and 10 m for the 1972 channel. Thus each eroded area polygon could have up to 20 m of error associated with the actual distance migrated over the interval. For a bend that experienced significant erosion (e.g. 250 m) the maximum amount of uncertainty constitutes less than 10% of the distance migrated. Smaller eroded area polygons (e.g. 20 m of bank erosion) could have very high levels of uncertainty as the actual amount of erosion may range from 0-40 m.

Although centerline migration rates provide a convenient mechanism for quantifying the rate of channel shifting, centerline migration is not always a good substitute for bank erosion rates. We found that, during periods of channel narrowing, migration rates might be quite large even though no significant bank erosion occurred. Thus, centerline migration rates provide a good first-order approximation of the rate of channel shifting but may have higher levels of error during periods with little actual bank erosion (e.g., during the post-development era 1972-1995 on McKenzie Reach).

3.6 Rates & styles of channel change by reach

3.6.1 Summary of changes to McKenzie Reach, 1850-1995

Between 1850 and 1995, the McKenzie Reach transitioned from a narrow, sinuous anastomosing channel to a wider, predominantly single thread channel (Tables 3.3, 3.4, Figure 3.2). Whereas the historic channel was highly dynamic and supported numerous avulsions and rapid migration, the modern channel is much more stable and primarily evolves through modest rates of lateral migration. This transition occurred in three stages; between 1850-1895, the McKenzie Reach experienced 46% increase in channel width, numerous avulsions and overall straightening. During the interval 1895-1932, the channel narrowed by 15% and migration rates more than doubled, leading to slight increases in sinuosity. Channel change 1972-1995 was more subtle than during earlier periods; migration rates decreased by 60% from 1895-1932, avulsions decreased and channel width narrowed slightly.

3.6.1a Changes to McKenzie Reach, 1850-1895

The McKenzie Reach of the Willamette River experienced widespread widening and decreased channel length during 1850-1895 (Table 3.3, Figure 3.2). Centerline shortening was primarily accomplished through avulsions and erosion along the inside of meander bends. While the 1850 McKenzie Reach supported a variety of bend shapes and sizes, the 1895 channel had less planform diversity. The length and sinuosity of simple bends decreased slightly, whereas the more sinuous compound bends of the 1850 channel were replaced with straighter sections and multi-bend loops were absent by 1895. Although channel slope increased through the loss of sinuosity, the relatively wide 1895 channel apparently had lower unit stream power (Table 3.3).

Avulsion and chute-formation were dominant processes, as avulsions influenced four times more floodplain area than did migration (Table 3.4, Figure 3.2). Many of the avulsions involved the re-occupation of 1-4-km-long side-channels spanning large-amplitude bends (Plate 1). Although normal migration occurred over nearly three times the stream length experiencing straightening, the rate of straightening was about twice that of normal migration.

3.6.1b Changes to McKenzie Reach 1895-1932

After experiencing a general widening and straightening during 1850-1895, the McKenzie reach narrowed and increased in sinuosity as lateral migration became dominant during 1895-1932 (Tables 3.3, 3.4). Whereas the 1895 channel contained many extremely wide bends (e.g., local width >500 m), interspersed with narrow reaches, the 1932 channel was more uniform and has lower variability in active channel width.

Both the rate and length of channel subject to lateral migration increased significantly between 1895 and 1932 such that meander migration assumed a more important role in floodplain evolution. Several low-sinuosity portions of the 1895 channel developed into bends that subsequently migrated downstream (e.g., FPKM 203-211). Although the rate and extent of migration increased, erosion was not sufficient to create more complex bend forms such as the compound bends present in the 1850 channel.

Although avulsion and bend cut-offs occurred along a smaller portion of the 1895 centerline, on average they influenced a greater amount of the floodplain than did meander migration. Most of the centerline abandoned by avulsion resulted from one large (6 km) avulsion near the confluence of the McKenzie and Willamette. The remaining bend cut-offs were much smaller (<1 km). Only four bends (9% of the channel) experienced straightening.

3.6.1c Changes to the McKenzie Reach, 1932-1972

Channel change during 1932-1972 was marked by several avulsions and rapid migration, which largely occurred before the construction of flood-control dams and revetments. Near the confluence of the McKenzie and Willamette a 2 km avulsion caused the mainstem to shift several hundred meters to the east and reoccupy the 1895 channel. A second large (3 km) avulsion at FPKM 195-197 led to reoccupation of a secondary channel adjacent to Qg2 gravels and abandonment of a large-amplitude bend situated in Qalc (Plate 3).

3. 6.1d Changes to the McKenzie Reach 1972-1995

Channel change during the late 20th century was more subtle than during historic intervals. Channel width decreased slightly and became increasingly more uniform while the centerline length remained essentially stable (Table 3.3, Figure 3.2). Meander migration and avulsions were limited to areas of the floodplain where revetments did not restrict channel movement. Normal migration was the dominant style of migration, as only two bends experienced straightening, and only two avulsions occurred, each of which was less than 1 km in length (Table 3.4, Figure 3.2).

Although much of the centerline experienced some movement during the late 20th century, there was very little actual bank erosion in comparison with the historic time periods. In many areas of floodplain, channel narrowing caused the centerline to appear to shift laterally though actual bank erosion was minimal.

Avulsions historically led to the bypassing of large areas of the floodplain, but during 1972-1995, the combination of lower migration rates, decreased avulsion frequency, and smaller avulsion distance caused significant decreases in the amount of floodplain reworked annually (Figure 3.2).

3.6.2 Long Tom Reach channel change 1850-1995

3.6.2 Summary of Long Tom Reach channel change 1850-1995

Because the Long Tom Reach acts as a transition between the dynamic, anastomosing McKenzie Reach and the more stable, single-thread Santiam Reach, historical channel change along the Long Tom Reach has been greatest along the upper reach whereas the lower reach has been more stable. Between 1850 and 1995, the Long Tom Reach experienced an 18% decrease in channel width and a 7% decrease in channel length (Table 3.5, Figure 3.2). Whereas the McKenzie and Santiam Reaches experienced large increases in width 1850-1895, the Long Tom only widened by about 10% and seems more prone to narrowing, as channel width decreased by 20% between 1895-1932 and by 6% from 1932 to1995. Much of the net decrease in sinuosity was accomplished 1850-1895 by avulsions along the upper, anastomosing Long Tom Reach (Tables 3.5, 3.6). Since the mid-19th century, erosion on the Long Tom Reach has been dominated by lateral migration and migration rates have only fluctuated slightly over the three study periods (Table 3.6).

3. 6.2a Changes to the Long Tom Reach 1850-1895

The interval 1850-1895 along the Long Tom reach of the Willamette River was marked by modest increases in channel width and diminished centerline length (Table 3.5, Figure 3.2). A slight decrease in centerline length was largely accomplished through the combined processes of avulsion and erosion on the inside of bends. Avulsions led to the elimination of complex bend from anastomosed areas of the 1850 channel (FPKM 170-175) and simple bends became shorter and less sinuous (Plate 1).

Lateral migration was the dominant form of channel evolution for the period 1850-1895. Much of the lateral migration was associated with 20-200 m of bank erosion along the outside of long (>3 km) bends. Low-sinuosity portions of the 1850 Long Tom floodplain remained fairly similar over the interval. Although lateral migration resulted in up to 250 m of local bank erosion, migration did not lead to the development of new bends but, rather, caused entire 3-5 km straight sections to shift towards one bank (e.g., FPKMs 150-154, 160-165) (Plate 1).

The two largest avulsions spanned 3-4 floodplain kilometers and led to reoccupation of secondary channels in anastomosed regions upstream of Corvallis (FPKM 170-175). Bend cut-offs influenced smaller portions of the floodplain and resulted in the formation of 1-2 km long chutes across four bends.

With the exception of channel change due to avulsions and bend cut-offs, the 1850 and 1895 planforms are very similar. Even along areas adjacent to avulsions, the Long Tom reach did not display the dynamic behavior characterized by the McKenzie Reach, where avulsions triggered rapid migration along adjacent bends.

3.VI.2c Changes to Long Tom Reach 1895-1932

Lateral migration and channel narrowing became increasingly dominant in the early 20th century (Tables 3.5, 3.6, Figure 3.2). Narrowing primarily occurred in areas that had widened during 1850-1895 such that nearly 50% of floodplain transects followed this 'recovery trend' of widening 1850-1895 followed by narrowing 1895-1932.

Both the extent and rate of lateral migration increased 1895-1932. In contrast to 1850-1895 interval, several low-sinuosity sections experienced dynamic meander behavior as small initial bends were developed from straight areas and some existing bends migrated downstream (eg FPKMs 156-160, 180-183) (Plate 2). Other low-sinuosity sections evolved through the lateral shifting of long (>5 km) sections towards the outside bank. Although normal migration occurred along a much greater extent of the channel than straightening, normal migration tended to produce slender polygons with lower migration rates than did straightening. The only two avulsions formed 1-km-long cut-offs across large amplitude bends at FPKM's 166 and 186.

While reach-average sinuosity remained similar 1895-1932, channel migration led to slight increases in the length and sinuosity of simple bends and allowed the uniform 1895 channel to develop a slightly more diverse array of bend sizes by 1932. Changes in planform were limited to the creation of a few simple bends of about 6 channel widths in length and the migration of several small bends, as migration was not sufficient to develop the complex bend forms found in multi-thread areas of the 1850 channel. The lower half of the reach was generally stable with the exception of some migration near FPKM 160 (Plate 2).

3.VI.2d Changes to Long Tom Reach 1932-1995

The upper and lower portions of the Long Tom reach experienced different styles of channel change during the 20th century. Aerial photographs show that the interval 1932-1972 was marked by rapid migration along the upper Long Tom reach, while the period 1972-1995 was much more stable. In contrast, the Long Tom reach downstream of Corvallis experienced little net change over the entire 1932-1995 interval. As our quantitative analysis of channel change spans the era 1932-1995, we qualitatively describe changes for 1932-1972 and 1972-1995 along the upper Long Tom in order to better interpret reach-average rates of channel change 1932-1995.

From 1932 to 1972, the Long Tom reach upstream of Corvallis displayed dynamic meandering behavior, and two bends were replaced with 0.5-km-long cut-off chutes. Lateral migration led to the rapid enlargement of several bends, such as at the confluence of the Willamette and Long Tom, where more than 400 m of erosion occurred. Several other bends migrated downstream, which locally caused 300 m or more of erosion over the 40-year interval. Much of the rapid erosion occurred along bends flowing through Qalc. Bends adjacent to Qg2 largely remained in place and more slowly migrated outwards.

During the post-development era, channel change along the upper Long Tom Reach was more subtle. Most of the revetment was installed between 1947 and 1968 and stabilized many bends flanked by Qalc. Although the apices of many bends were stabilized with revetment, some bends migrated downstream 50-100 m, while others remained essentially stable. Along many stable bends with little bank erosion, the 1972 active channel was relatively wide near bend apices but, by 1995, had narrowed as vegetation colonized point-bar surfaces.

Downstream of Corvallis, channel change 1932-1995 was less dramatic than the upper reach. The most extensive migration occurred in the historically dynamic area between FPKM 155-160, where several small (<1 km) bends experienced 75-100m of erosion before 1964. However, much of the lower Long Tom reach was quite stable, and bank erosion was largely negligible, although several long bends (e.g. >5 km) shifted laterally resulting in 30-60 m of bank erosion over the 65-year interval (Plate 3). .

Reach-average channel change trends 1932-1995 indicate that lateral migration and channel narrowing dominated the entire Long Tom Reach (Tables 3.5 and 3.6, Figure 3.2). The two avulsions of the interval were bend cut-offs that occurred before 1972 along the upper Long Tom reach. The combination of decreased migration rates and diminished avulsion magnitude and frequency caused the annual area eroded per length of channel to be about one-fourth to one-third of historic rates.

3.6.3 Santiam Reach Channel Changes, 1850-1995

3.6.3 Summary of Santiam Reach channel change 1850-1995

Although the Santiam Reach has generally been much more stable than upper reaches, this lower study reach has followed similar trends as other reaches. Similar to the Long Tom Reach, the Santiam Reach experienced a net decrease in channel width and slight decreases in channel length between 1850 and 1995 (Tables 3.7, 3.8). Much of the loss in centerline length was accomplished through several large avulsions 1850-1895 though subsequent migration 1895-1932 nearly recovered much of the 1850 sinuosity. Like the McKenzie Reach, the Santiam Reach initially experienced large (~30%) increases in channel width between 1850 and 1895. However, during the intervals 1895-1932 and 1932-1995, channel width decreased by 15% and 18%, resulting in a 10% net decrease in reach-average width by 1995. In all time periods, the Santiam Reach has been dominated by lateral migration and the overall rate of migration has fluctuated slightly.

3.6.3a Description of changes to Santiam Reach, 1850-1895

Channel change along the Santiam reach 1850-1895 was primarily limited to several avulsions and increased channel width (Tables 3.7 and 3.8, Figure 3.2). Unlike upstream reaches, increases in channel width were not accompanied by significant decreases in centerline length. Because centerline length losses were minimal, most of the Santiam Reach bends maintained their 1850 planform throughout the 1850-1895 interval.

Lateral migration was the dominant erosion mechanism. Much of the 1895 channel is very similar to that of 1850, as migration generally resulted in the enlargement of large (3-5 km) bends. Many long (>5 km), low-sinuosity sections remained fairly stable with only minor changes near bend apices where local migration occasionally led to 100-200 m of bank erosion. Erosion along the most dynamic areas of the Santiam Reach occurred through both migration and bend cut-offs (e.g., FPKM 90-100), as these two mechanisms appeared to trigger a series of changes in planform whereby existing bends were cut-off and straight sections developed small bends (Plate 1). The two largest avulsions were located in areas of Holocene Alluvium, where 1-2-km-long cut-off chutes spanned large-amplitude meander bends at FPKMs 115 and 92. Three smaller avulsions resulted in the abandonment of smaller bends (<1 km) located in Qalc.

3.VI.3c Description of changes to Santiam Reach 1895-1932

Between 1895 and 1932 the Santiam reach maintained a similar overall planform, although the channel narrowed and centerline length increased slightly. A small relative increase in centerline length was largely accomplished through the development of several small bends. Two small (<1 km) avulsions occurred near the Luckiamute-Santiam-Willamette confluence, where the channel reoccupied a secondary channel (FPKM 135) and cut-off an existing bend (FPKM 138) (Plate 2). Both avulsions resulted in the net lateral movement of less than 300 m.

Most of the lateral migration occurred in Holocene Alluvium in the lower portion of the reach downstream of Salem at FPKM 110. Portions of the Santiam reach flowing against Qg2 gravels appeared to remain "locked" against Qg2 and only migrated slowly outward against Qg2. The most dynamic areas of the 1895-1932 Santiam Reach floodplain were located along a series of bends between FPKM's 80-94, where 100-200 m of bank erosion occurred. Bends along the Santiam reach generally did not display the dynamic migration behavior seen on upper reaches. Although a few small bends developed at FPKMs 117 and 90, migration was dominated by lateral shifting of large (>5 km) bends, rather than the development and subsequent downstream migration of small bends.

3.VI.3d Description of changes to Santiam reach 1932-1995

Twentieth century channel change along the Santiam Reach was marked by channel narrowing and an overall decrease in floodplain erosion (Tables 3.7 and 3.8, Figure 3.2). Although three avulsions occurred, they generally bypassed small portions of the floodplain compared with larger, historic avulsions. Two of the avulsions caused small bends to be cut-off at FPKM's 116 and 90 (Plate 3). These bends were recent (formed between 1895 and 1932) and the cut-off channels were short (<0.5 km) and appeared to have formed at or near the 1895 channel position.

Migration rates were similar to rates experienced during the mid-late 19^{th} century, but the area affected by migration much less than for historic periods. Decreased migration combined with small avulsions caused centerline length to remain fairly similar over the interval. Along much of the reach, the 1995 channel is positioned within the boundaries of the 1932 channel. In these areas, it seems as though migration has caused the 1995 channel to shift slightly from the 1932 position, but actual bank erosion is probably minimal.

3.6.. Temporal patterns in resistant bank materials

The percentage of each reach flowing against resistant bank materials increased over time (Figure 3.3). In 1850, about 15% of the mainstem Willamette was bordered by naturally resistant materials. By 1895, migration and avulsions caused nearly 40% of the McKenzie reach to flow against resistant banks, yet the

Long Tom and Santiam reaches have only experienced modest increases in the length of channel stabilized by resistant geological units. Beginning in the 1930's, the Corps of Engineers began stabilizing rapidly eroding banks with rock revetments. Most revetments were placed along bends flowing through Qalc, though some more resistant banks were also stabilized so that 40-70% of each reach is presently stabilized with resistant banks (Figure 3.3).

3.6.5 Summary of Willamette River channel change 1850-1995

Our results revealed that, between 1850 and 1895, all reaches experienced numerous avulsions, increases in channel width, and decreases in centerline length. Between 1895 and 1932, migration rates increased by 50-300%, which led to increases in sinuosity while channel width decreased. During the period 1932-1995, the Long Tom and Santiam Reaches displayed similar migration rates as during 1850-1895, yet channel width continued to narrow. Along the McKenzie Reach, channel change 1972-1995 was primarily limited to lateral migration along areas unrestricted by revetments and occurred at rates similar to 1850-1895 levels. While sinuosity decreased along all reached between 1850 and 1995, the Long Tom and Santiam Reaches experienced an overall decrease in channel width whereas the McKenzie Reach experienced net widening.

These results differ from the general paradigm that the Willamette has become increasingly less dynamic following Euro-American settlement in the mid-19th century. In order to determine why the Willamette remained dynamic throughout the early-20th century, we used the disturbance/response trajectories in

Table 3.1 to form initial hypothesis relating channel change with natural and anthropogenic disturbances. This analysis suggests that large magnitude floods may have caused the avulsions, channel widening and decreased sinuosity that occurred 1850-1895. This interpretation is consistent with gauge records indicating that the three largest historical floods occurred between 1850 and 1895. However land conversion, snag removal and channel modifications for navigation improvements were also occurring during this time period and it is unclear what effect these anthropogenic disturbances had on channel change.

Increased migration rates and channel narrowing from 1895 to 1932 is more difficult to interpret, as these responses do not fall into a single disturbance category. Historical records indicate that land conversion, moderate-sized flooding and channel modifications continued through the late-19th century and into the 20th century, yet none of these disturbances appears to be a dominant driver of the observed channel change.

The decreased migration rates and channel narrowing that occurred in the 20th century is broadly consistent with patterns of change following dam construction and bank stabilization. However, multiple disturbances continue to introduce complexity, as rapid migration in the 1930's-1940's was followed by bank stabilization and dam building while historical records indicate that land conversion and moderate-sized floods continued throughout the 1930's-1960's.

Historical channel change along the Willamette clearly does not follow simple disturbance/response scenarios and it appears that in any time period, multiple disturbances were influencing channel change. Although numerous authors have described both anthropogenic activities and flooding along the Willamette, such descriptions do not readily provide an explanation of how floods or human activities might have influenced our observed rates and styles of channel change. In order to evaluate the individual importance of disturbance processes and better understand how various disturbances interact, we separately examine Euro-American activities that may have influenced channel processes and the flood history of the Willamette River.

3. 7 Timeline of Euro-American interaction with Willamette River

Humans affect many aspects of large rivers as land conversion, channel modification, bank hardening and flow regulation can alter properties of the channel bed, banks, flow regime, sediment load and floodplain vegetation. Understanding what actions were taken, as well as their timing, spatial extent, and efficiency, is critical in relating channel change to anthropogenic activities because human actions often coincide with natural events such as floods. In order to determine the role of either factor, anthropogenic activities must be understood more fully. In this section, we develop a generalized timeline for understanding both floodplain characteristics and human actions that impacted the Willamette River floodplain 1850-1995. Although humans have impacted many areas of the Willamette Basin, we focused our historic research on large-scale actions that had a direct effect on channel planform, erosion rates, or related dynamics.

We draw upon historic government documents including Annual Reports to the Chief of Engineers published by the U.S. Army Corps of Engineers (USACE) from 1868 to 1930 and water resource studies conducted by the USGS, USACE and State of Oregon. In addition to these documents, we compile previously published work describing historic land use and channel change and various master's and doctoral theses. Because we focused on large-scale actions such as those undertaken by the Corps of Engineers, we are not able to satisfactorily account for actions by individuals except in a generalized manner. Although the cumulative effects of floodplain logging and other land-use actions by individuals or families may have been significant, records quantifying these impacts are not readily available. We did not verify accuracy of early reports, published works, or theses, but in many cases, similar accounts are documented in multiple sources, and such corroboration lends validity to historic accounts.

3.7.1 Historical Events of Pre-settlement Era (prior to 1850)

Unlike other large rivers (e.g., the Ain in France, or the Mississippi in North America), the Willamette did not experience significant Euro-American settlement until the mid to late 19th century. Euro-Americans first entered the Willamette Valley in 1805 when Lewis and Clark arrived near the confluence of the Columbia and Willamette Rivers. Settlement in the decades following the Lewis and Clark Expedition was initially slow and limited to fur trappers employed by the Northwest Fur Company who plied Coast Range and Cascade streams for beaver pelts. By the 1830's the first agricultural settlements were established by former fur traders in the northern Willamette Valley, near the present-day site of Champoeg at FPKM 65 (Johannessen et al., 1970; Bowen, 1978). The development of the Oregon Trail and promise of fertile, unoccupied land motivated thousands of settlers to migrate to Oregon, with the first substantial waves of settlers arriving in the 1840's. The 1841 census indicates only 400 Euro-Americans were living in the Willamette Valley. By 1850 that number climbed to nearly 12,000 (Bowen, 1978; Branscomb et al, 2001). Early settlers to the Willamette Valley generally avoided the floodplain, preferring to homestead along the intersection between the prairie of the high terraces and forested hills. This location provided fertile soils and safety from floods, while allowing access to both prairie and upland timber (Bowen, 1978; Towle, 1982).

Records from trappers and pioneers show that the valley floor was an extensive prairie maintained by Native Americans through annual burning. The extent of the fires was remarked upon by many settlers including David Douglas in September of 1826, who wrote that in 15 days of travel from Willamette Falls to the southern Willamette Valley his party witnessed blackened grasses along the length of the valley and Douglas complained about the lack of forage for stock animals and game (Johannessen et al., 1970). Although high terraces were burned, the sloughs and river bottom retained dense vegetation as early settlers refer to floodplain areas as "impassable thickets" (Johannessen et al., 1970). By the 1850's, settlement pressure increased and annual fires no longer swept across the valley floor.

The California Gold Rush in 1849, along with expansion of urban centers along the west coast changed the nature of farming and commerce in the Willamette Valley. Prior to 1850, most Willamette Valley farms were subsistence-based and little surplus agriculture was grown for trade, but the Gold Rush and expansion of new markets created an immediate demand for surplus agriculture. Prairie lands of the valley floor were well suited for wheat, and large-scale farms (300-600acres) were brought into production. Steamboats were used to deliver wheat from agricultural lands in the upper valley to export markets down-river in Portland. Many steamboat landings became towns in this era, as Albany was platted in 1848 with Corvallis (1851), Eugene (1850), Harrisburg (1852) and Monroe (1853) following shortly afterwards (McArthur, 1952; Anderson, 1974).

3.7. 2 Historical Events of 1850-1895

The passage of the Oregon Donation Land Act in 1850 motivated thousands of immigrants to settle in the Willamette Valley. Claimants were awarded land depending on marital status and date of arrival. Because much prime land had been settled prior to 1850, the available land was quickly claimed with later settlers occupying partial claims, urban areas or marginal land (Anderson, 1974; Bowen, 1978). When the Act expired in 1855, only rugged areas along the Valley margins remained unclaimed (Towle, 1982). Areas near the river were less desirable due to frequent flooding, poor drainage, thick vegetation, and fears of disease-causing "Swamp Vapors" (Anderson, 1974; Towle, 1982). The Donation Land Act also appointed a surveyor-general to the Oregon Territory and ordered a survey of the Willamette Valley so that township and section lines could be delineated (U.S. Congress, 1850).

Between 1850 and 1909 the General Land Office (GLO) initiated a comprehensive survey of the Willamette Valley and produced detailed township maps that included descriptions of soil characteristics, land cover, and generalized topographic features such as terraces and hills. The Willamette River and floodplain were surveyed during 1851-1853, and maps of these features show several (generally less than 5) claims, fields or houses on the floodplain in each township (individual claims ranged in size from one-quarter section to one full section). Most floodplain claims were apparently situated on terraces above the lowest floodplain level, though a few fields and 'warehouses' were on the lowest floodplain level. In all GLO maps, the majority of developments are located above the floodplain on the main valley floor.

The GLO survey and Army Corps of Engineers Annual Reports to the Chief of Engineers also provide insight to 19th century floodplain dynamics. Channel maps from the early 1850's show that the Willamette along the Santiam and lower Long Tom reaches was predominantly single-threaded with several multi-threaded areas. Upstream of Corvallis, flow along the upper Long Tom and

McKenzie reaches was divided among multiple channels characterized by low banks, frequent gravel bars, and large wood rafts. The Corps recorded the number of "hazardous" downed trees (snags) along the middle and lower Willamette, yet such snags were "too numerous to count between Harrisburg and Eugene" (1875, pg 761). Many snags along the McKenzie reach were great logs up to 100 m long and 7 m in circumference. According to USACE reports:

> "A great portion of these [snags] were deeply imbedded in the center of the steamboat channel, oftentimes entire bodies of trees would be covered in gravel with nothing but a single root standing erect to bid defiance to passing boats" (USACE, 1875, pg 763).

By the mid 1850's, steamboats became the main transportation for the Willamette Valley, and riverboats were hauling timber and surplus wheat to Oregon City and Portland (Anderson, 1974). With increased reliance upon navigation, there was heightened demand to improve and maintain a navigable channel between towns along the upper Willamette and trading centers downstream. Channel improvement efforts were primarily targeted along the Willamette upstream of Corvallis, where the channel was most dynamic and navigation was particularly difficult. Between Harrisburg and Eugene, annual channel changes were so great that Corps reports indicate steamboat pilots seldom traveled the same channel in subsequent years (USACE 1875, pg 766).

Channel improvement upstream of Portland began in 1868 when the Corps of Engineers began removing downed trees from the river (USACE, 1867-1892; Sedell and Froggatt, 1984). Yearly snagging records show that about 1,000 downed and streamside trees were removed from the mainstem Willamette annually between 1868-1935, with most snagging occurring upstream of Corvallis (Figure 3.4) (Sedell and Froggatt, 1984). Snagging crews worked the upper Willamette from the last freshet in spring until high water in the fall, (approximately 101 days in 1882 were spent on snagging duties while 29 days were spent on scraping shoal bars and constructing dams) (pg 2659,USACE, 1882). Dynamite or "giant-powder" was used to extract particularly stubborn snags, as reports from 1872 stated, "In a great many cases giant-powder was successfully used in blowing to pieces and loosening such snags as were deeply embedded in the gravel or sand, and which resisted power of the boat" (USACE 1875, pg 760).

The Rivers and Harbors Act in 1870 facilitated additional channel improvements by authorizing and funding the construction of wing dams, shoal bars, and other efforts to channelize flow (Benner and Sedell, 1997). By filling secondary channels with drift and placing felled trees and cut-off dams near the head of side channels, flow was forced into a single channel "in order to narrow and thereby obtain a greater depth of water and a more uniform steamboat channel" (1875, pg 765). Additionally, shoal bars were scraped and low dams were built in the center of the main channel to sluice and deepen the bed (Benner and Sedell, 1997). While much of the snagging occurred in the upper river, most of the wing-dam construction took place along the lower river where the river was more confined to a single channel. Upstream of Corvallis, it seems that numerous channels and frequent changes were best remedied through continued snag removal rather than through the construction of wing dams (USACE, 1875, pg 765).

Although actual lengths or numbers of wing dams annually constructed are not presented in most Annual Reports of the Chief of Engineers, the reports do provide the locations of areas where such structures would have benefited navigation. For example, in 1882, the Corps proposed that the Willamette downstream of Corvallis should receive more than 5,000 ft (1.6 km) of wing dams, whereas the reach between Harrisburg and Corvallis required 6,300 ft (2.1 km) of dams, but no dams were proposed for the river upstream of Harrisburg. The 1895 navigational survey conducted by the Corps depicts approximately 18 km of man-made structures (which includes wing dams, check dams, retaining walls, bridges and revetments) bordering the Willamette. While efforts to confine the Willamette with such structures may have had a potentially important effect on channel dynamics, the longevity and effectiveness of these structures is unknown. It also appears that construction (and snagging efforts) varied from year to year depending on flow conditions, appropriated funds, and objectives defined by the Chief of Engineers.

By the 1880's the Corps reported that channel improvement efforts were successful. Although earlier reports claimed, "[The] Willamette above Corvallis is cut into so many useless sloughs, and at each liable to undergo very marked and frequent changes, it would be impossible to confine its waters into one main and permanent bed" (pg 765, 1875), by 1882 the Corps was more optimistic, stating that in early April of 1881, the river was "free from material obstructions below Harrisburg" (USACE, 1882, pg 2659). Furthermore,

> "[The] systematic and judicious removal of snags from the channel has gone far toward preventing the accumulation of drift on the shoals and consequent growth of gravel bars by accretions, so that this section of the river is now in better condition, both as regards depth and freedom from obstructions, than it has ever been before' (USACE, 1882, pg 2659).

Such optimism may have been short lived, as by the early 1890's, one author described a particularly laborious season and then concluded his passage by writing, "this work, however is but temporary, and in the nature of things much of it may have to be done over again" (USACE, 1892, pg 2836).

Originally, Eugene was considered the most upstream point of navigation on the Willamette, though several steamboats were able to venture as far Springfield six miles upriver from Eugene. However, by 1882, efforts to maintain the channel above Harrisburg were largely abandoned as:

> "There was no special demand for navigation between Harrisburg and Eugene City; this reach is an exceedingly troublesome one... Moreover, the main valley railroad crosses the river at Harrisburg, touches at Eugene, and affords more convenient transportation than the river would. It is probable that hereafter Harrisburg will continue to be the practical head of navigation instead of Eugene" (USACE, 1882, pg 2655).

It is unclear whether this statement indicates that channel improvement along the upper river was actually abandoned, or whether the author was suggesting that efforts be scaled back, because snag removal by the Corps continued throughout the 1930's.

While the Corps of Engineers was improving navigation along the Willamette, overall population in the Willamette Valley increased from approximately 12,000 in 1850 to more than 200,000 in the 1890's (Hulse et al, 2002). To accommodate increasing population pressure, Willamette Valley agriculture underwent another transition in the 1880's as large wheat farms were partitioned into smaller, more profitable fields of orchards and row crops. Floodplain lands were increasingly utilized during this time, though much of the floodplain probably remained sparsely settled. Maps from 1895 indicate that 23% of the Willamette between Albany and Newburg and 11% of river upstream from Albany was bordered by agriculture (Gregory et al., 2002a). Locally, floodplain agriculture was probably important. In 1904 Wallace Nash described soil fertility of each county within the Willamette Valley and wrote, "In [Linn County] the level bottoms by the Willamette hop yards abound on the black rich soil, the dry-houses forming a feature in the landscape." (Nash, 1904, pg. 27).

Riparian logging resulted in removal of large quantities of wood from the floodplain throughout the mid to late 19th century, though large-scale exploitation began in the 1890's. Steamboats used 10-30 cords of wood per day and timber was also used to support growing urban centers, in paper mills, and for export (Sedell and Froggatt, 1984). Logging occurred both along the floodplain and on upslope areas. According to Nash:

> The course of the Willamette itself is bordered by masses of soft wood trees, willows, cotton wood, white poplar, bass-wood, white fir of great height and thickness. But a few years ago this timber was called worthless, nowadays the steamboats tow great rafts to

> the paper mills of Oregon City every year, and many thousands of feet of softwood are utilized in several industries of the city.

Despite increasing utilization of floodplain lands for agriculture, we speculate that the late 19th century floodplain probably consisted of a patchwork of original riparian forest, logged areas, rough hay pasture, abandoned farms, and actively cultivated areas. Most floodplain farmers probably utilized local topographic highs, as Corps of Engineer reports indicate that flooding caused frequent problems for farmers:

> Several farms have been inundated and washed away, the river entirely devastating them by cutting a net-work of sloughs through their broad fields; the farmer along its banks cannot tell at what time his hundreds of acres may be swamped and disappear from his sight forever (USACE, 1875, pg 766).

3.7.3 Historical Events of 1895-1932

The period 1895-1932 was marked by increased development in the Willamette River floodplain, as channel improvements, riparian logging, and expansion of floodplain agriculture continued. In 1896 the River and Harbor Dredging Act was passed by Congress and authorized dredging, which ultimately enabled paddle wheelers to navigate the Willamette between Portland and Eugene (USACE, 1969b). The Corps of Engineers began reporting dredging activities above Willamette Falls in 1908, and in 1908-1929 about 102,000 cubic yards of material were removed annually from the channel with most dredging occurring along areas downstream of Independence at FPKM 126 in the middle Willamette Valley (Willingham, 1983; Benner and Sedell, 1997).

The Corps also continued to improve navigation along the Willamette and sought to maintain a navigable channel between Oregon City and Eugene through snag removal and construction of wing dams and other structures. The navigational survey of 1932 shows that nearly 16 km of wing-dams and other structures (bridges, dikes, retaining walls, revetments etc) bordered the Willamette. Along the lower river between Portland and Oregon City, the Corps endeavored to maintain a channel 12 ft in depth, whereas a 3.5 ft channel was maintained between Oregon City and Corvallis and a 2.5 ft channel between Corvallis and Eugene (pg 54, Willingham, 1983). These improvements enabled steamboat traffic to Corvallis year-round, though travel to Eugene was limited to high-water periods (generally lasting 9 months) (Willingham, 1983). The annual number of streamside logs and snags removed fluctuated greatly over the interval, but on average about 1,000 trees were removed per year, with most snagging occurring upstream from Corvallis (Figure 3.4, Sedell and Froggatt, 1984).

Logging of riparian forests for paper production and timber export also increased during this period and caused the percentage of forested lands bordering the river to decrease by more than 50% along much of the Willamette. For the lower river (downstream of Newburg) the length of channel bordered by forest decreased from 40% in 1895 to 16% in 1932; on the middle Willamette between Albany and Newburg the length of channel bordered by forest decreased from

65% to 31% and along the upper river between Albany to Eugene the length of channel bordered by forest decreased from 77% to 50% (Gregory et al., 2002a).

Between 1895 and 1932 increasing numbers of settlers arrived in the Willamette Valley and heightened the demand for arable land. Although logging led to increases in cleared floodplain lands, much of the floodplain was still avoided because bottomlands were plagued by frequent floods, high erosion rates, and poor drainage (Anderson, 1974). To sustain high yields, many crops cultivated on the floodplain required late-summer irrigation, which was expensive, labor intensive, and dependent on reliable river flows. Despite these problems, floodplain agriculture continued to increase. By 1932, 40-50% of the Willamette was bordered by agriculture, with the most substantial increases occurring upstream of Albany, where there was a four-fold increase in the length of channel bordered by cultivated crops (Gregory et al., 2002a).

An indication of the perceived value of floodplain soils is given by the 1920 Benton County Soil Survey, which describes the Newberg Fine Sandy loam (an alluvial soil found on 1-2 year floodplain levels) as of "no great importance" and noted that 15-20% of the soil was cultivated while the majority of the unit was forested (Towle, 1982). In contrast, the Newberg and other soils formed on Holocene Alluvium are described in the 1975 Soil Survey as "prime farmland if irrigated" (Knezevich, 1975).

Channel maps from 1895 and 1932 indicate that rapid erosion occurred in many areas of the floodplain. With increased occupation of floodplain lands, damages due to annual flooding rose steadily in the early 20th century. Societal demand for flood control grew, and citizens requested relief from bank erosion, inundation, and other flood-related problems. Additionally, poor drainage plagued both floodplain lands and the heavy clay soils of the former prairie. This problem, combined with low wheat prices, resulted in abandonment of numerous farms in the 1920's (Towle, 1982). In March of 1925, Congress directed the Secretary of War through the Corps of Engineers and Federal Power Commission to investigate the costs of improving power, flood control, irrigation and navigation on all navigable streams in national boundaries (Oregon State Planning Board, 1938). This authorization initiated a series of studies in the Willamette Valley and ultimately led to construction of flood-control dams, extensive revetments, and other projects.

3.7.4 Historical Events of Development Era 1932-1972

The interval 1932-1972 was marked by rapid development of the Willamette River floodplain. Within the span of several decades, dams, revetments, and drainage-control and irrigation projects were constructed that enabled agriculture and suburban development to expand onto the historic floodplain. The Great Depression and Dust Bowl motivated immigrants to move to Oregon, and the state population climbed by more than 300,000 between 1920 and 1940 (Dearborn and Duclos, 2002), Oregon State Planning Board, 1938)). About three-quarters of the new settlers moved to the Willamette Valley which posed challenges for State planners. The Oregon Land Board determined that, in order for the Willamette Valley to support a larger population in a "better overall condition", three objectives would need to be met: (1) intensive growth of high-value crops on smaller farms; (2) cultivation of marginal land such that previously under-utilized areas could be utilized; and (3) subdivision of large, 300-600 acre farms into smaller, 30-60 acre farms (Oregon State Planning Board, 1938).

Although there was a clear need to bring marginal lands into production, most farmers continued to feel that it was futile to invest in intensive floodplain agriculture. Flow regulation and erosion control were required to protect floodplain lands and infrastructure, while high-value crops required both late-summer irrigation and soil drainage to support high yields. In the 1930's irrigation was expensive, cumbersome, and depended upon reliable late-summer river flows. Studies by the state of Oregon in 1931 and 1934 showed that tile drainage on wetlands could double crop production, potentially allowing the Willamette Valley to support an additional 1500-2000 families (Oregon State Planning Board, 1938). Nationwide studies of drainage basin problems led to the publication, *Present and Potential Land Development in Oregon*, which detailed the need for coordinated effort to increase both the amount and value of farmland in the state through the combined efforts of flood control, drainage, and irrigation (Oregon State Planning Board, 1938). The multiple-purpose flood control, irrigation, and drainage-improvement project was termed the "Coordinated Plan," which called for the construction of 7 storage reservoirs on major tributaries. The benefits of the Coordinated Plan were numerous:

> By preventing the flooding of large areas, problems of drainage will be greatly simplified. Elimination of spring inundation will permit earlier tilling of over-flow lands and long growing season...Increased and regulated streamflow will assist navigation, will provide hydro-power as needed in the future, will enhance the values of the watershed and will tend to reduce pollution by diluting deleterious wastes discharged into streams...Drainage will convert much pasture land to valuable cropland, clearing will produce new pasture and irrigation will change low crop yields to the maximum of production. (Oregon State Planning Board, 1938, pg 127)

Though not specifically stated in the Coordinated Plan, flood control in the form of channel clearing and bank protection were also needed to protect floodplain lands. Thus, "Both plans—bank revetment and channel clearing in flood danger zone, and flood-water storage in foothills–will provide adequate protection from damaging floods and thereby increase productivity and value of approximately 273,000 acres of farmland, part of which is now used only intermittently" (Oregon State Planning Board, 1938, pg 91).

Throughout the 1930's Congress ratified a series of flood-related bills, which shifted the focus of the Corps of Engineers from navigation improvements to flood control (Willingham, 1983). The 1925 Flood Control Act authorized feasibility studies of multi-purpose flood-control, hydropower, and navigation projects, which led to extensive studies of the water resources of the Willamette Basin. In June 1936, a subsequent version of the Flood Control Act authorized 211 flood-control projects in the United States, including the Willamette Valley.

The 1936 Flood Control Act primarily authorized bank-protection and channel-clearing programs, while revisions in 1938 authorized the Willamette Valley Project, a multi-agency, comprehensive effort that replaced the Coordinated Plan. The Willamette Valley Project entailed the construction of the multiple-purpose projects to improve flood control, land drainage, navigation, irrigation, hydropower, and streamflow regulation while also decreasing pollution (USACE, 1969; Oregon State Planning Board, 1938).

While lawmakers were authorizing flood-control and dam-building legislation, the Corps of Engineers was stabilizing rapidly eroding banks. Although bank protection had begun in the late 19^{th} century, the extent and rate of bank stabilization efforts increased dramatically in the mid 1930's (Figure 3.5). Beginning in the fall of 1935 and continuing through early 1936, emergency construction of bank protection stabilized nearly 54,000 lineal bank feet between Eugene and Harrisburg, where erosion was causing significant damage to farmlands (Oregon State Planning Board, 1938). Emergency bank stabilization also followed large floods of 1943, 1945, 1951, 1955 and 1964 (Gregory et al., 2002b). Revetment construction by the Corps and private individuals continued through the late twentieth century, and by the 1970's, 90% of all revetments were constructed (Figure 3.5). Most revetment construction occurred along the upper river, upstream of Albany, and was generally used to stabilize bends adjacent to agricultural lands (Gregory et al., 2002b). Much of the revetment was placed along banks composed of Holocene Alluvium, though revetments were also used to protect more resistant banks in urban areas (e.g., Pleistocene gravels at Harrisburg, Corvallis and Albany or Tertiary sandstone and basalts near Salem) (Plate 3).

Dam building quickly followed authorization of the Willamette Valley Project. Just three years after the 1938 Flood Control Act, Fern Ridge Dam and Reservoir were completed on the Long Tom River, and Cottage Grove Reservoir was completed on the Coast Fork of the Willamette in 1942. By 1960, five more dams were constructed, and by 1970, a total of 13 reservoirs. Of the 13 reservoirs, 11 are major flood control projects and two are primarily re-regulating reservoirs (Willingham, 1983). The multiple-purpose projects reduce flood peaks, support higher summer flows, and in some cases, provide hydropower (USACE, 1969a).

The amount of irrigated farmland increased rapidly following construction of flood control reservoirs (Figure 3.6). While flow regulation ensured affordable and reliable late-summer water, post-WWII technologies made irrigation equipment inexpensive and easy to use (Towle, 1982). Irrigation and other agricultural investments were protected by channel stabilization and flow regulation. As a result, irrigated acreage quadrupled between 1945 and 1969 as farmers began cultivating fruit and vegetable crops on floodplain lands (Towle, 1982; Sedell and Frogatt, 1984).

During this period there was a general sense that flooding, bank erosion, and other problems associated with the "flood menace" could most effectively be addressed through large projects such as dams and widespread bank-stabilization efforts. Joe Bohls, a farmer on the South Santiam and member of the South Santiam Water Control District, summarized both the problems associated with floodplain farming and their obvious solution:

> We need a dam on the South Santiam to stop these floods that periodically overflow the river banks and damage everybody in the valley…landowners immediately adjacent to the stream lose land completely by the acre sometimes from bank erosion. Now bank erosion has no relation to flood damage because bank erosion goes on just as fast as when the river is only partly full as it does at flood stage. I have lived on my place 13 years and in that time have witnessed the complete destruction through bank erosion of well over 200 acres of fine land. With it went houses, barns, orchards and fences. It's gone—no more crops, no more taxes, just thistles, briers, gravel and debris.
> Now when more water comes down the river than the banks can contain we have a flood, our topsoil drifts or washes away entirely, our crops are damaged or destroyed, and sometimes, when they sneak up on us quick or come at night, we lose livestock and other property. Then we have a twofold problem, bank erosion which is the complete destruction of good land next to the river bank and overflow which does minor or major surface damage to the land over a [broad] area. One of the biggest mis-statements is made by the fellow who tells you how much virgin soil each flood brings out of the mountains and spreads over the inundated farm lands. Don't believe it, only a dam on the South Santiam will stop overflow commonly called a flood and floods do no good, only damage. (Joe Bohls, speech to Congressmen Norblad and Ellsworth in support of Green Peter Dam, October 7, 1953, Sweet Home; Willamette Project Bulletin 1951, Willamette Basin Commission, 1951)

Whether it was due to heightened sense of safety, ignorance of floods, population pressure, or some combination thereof, occupancy of the agricultural and suburban floodplain lands increased. Many low-lying areas experienced development, including the Ferry Street Bridge District and communities of Santa Clara and Coburg near Eugene and the town of Keizer, downstream of Salem

(Anderson, 1974). According to Joe Ingram, Portland District Corps of Engineers Chief of Project Planning Branch:

> You may remember my earlier statement that flood problems are basically caused by people. Such is the case in the Willamette Valley. In the early days, and I speak from experience as I was reared in the valley, people did not encroach too far into known flood areas. Beginning in the thirties, however, people started clearing lands and building homes and other structures in the flood plain in an attempt to wrest it way from the rivers in defiance of nature. This influx, which has continued throughout the years, has resulted in constantly increasing flood damages in the valley.
> *(Ingram, 1964, pg 82-83)*

3.VII.5 Historical Events of Post-development Era 1972-1995

Development of floodplain lands slowed in the late 20^{th} century as many farms were converted to hobby farms or rural residences (Towle, 1982). Although the majority of revetment had been constructed by the early 1970's, the Corps of Engineers and private agencies continued to maintain and extend existing bank stabilization projects (Gregory et al., 2002b). The major actions undertaken between 1972-1995 that affected channel change involved dredging, gravel mining and management of riparian lands. Channel improvements for navigation were limited to the lower Willamette River (primarily downstream of Willamette Falls) whereas instream gravel mining occurrs at many locations along the mainstem.

Several environmental laws were enacted by the State of Oregon and by Congress pertaining to river management; however these bills do not appear to have had a significant effect on channel change. The Clean Water Act and subsequent revisions in the late 1970's, regulates pollution discharge and stream temperature. The primary impact this law may have on bank erosion, is that late-summer dam releases used to maintain cool stream temperatures and to dilute pollution and may cause accelerated erosion in some unstabilized areas.

In 1967 the Willamette River Park System was established by Oregon legislature "to expand and enhance public recreational use of riparian environment of mainstem Willamette River from Dexter Dam and Cottage Grove reservoir to Columbia River" (Frenkel et al., 1984). Subsequent revisions in 1973 and 1975 required the Department of Transportation to coordinate with local governments to prepare plans for the development and management of Greenway Lands. However, the Greenway program may not have significantly improved natural vegetation or affected channel migration as between 1972-1981, almost 13% of riparian vegetation along Greenway properties in Benton and Linn counties was converted to agriculture or sand and gravel pits (Frenkel et al., 1984).

During the late 20th century, there has been an increasing demand by some community members to restore certain natural functions to the Willamette River (Jerrick, 2001). Although several large-scale restoration projects have been proposed, the most significant restoration projects actually enacted are generally smaller-scale endeavors that involve using 'natural' materials to stabilize banks or planting native vegetation along riparian areas.

3. 8 Flooding along the Willamette River

To explore the effect of flooding on channel change we reviewed a variety of flood-related literature, including anecdotal accounts, gage records, aerial photographs, and flood inundation maps, which describe the magnitude and frequency of flooding in the Willamette Valley. We also compared the streampower of large historic events against smaller post-dam floods using a two-dimensional flood model in order to quantify how different magnitude floods might effect the channel. Although the topic of flooding is quite broad, we focus our discussion on (1) establishing a brief overview of flooding in the Willamette Valley and (2) assembling evidence that would allow us to assess the role of floods in triggering observed patterns of channel change.

We found that multiple sources describe widespread erosion and inundation during high-discharge events. These anecdotal descriptions, combined with more quantitative evidence from historic channel maps and flood modeling, indicate that floods were an important component of channel evolution in the Willamette Valley. The importance of floods has apparently decreased over time, however: The largest historic flood occurred in the mid 19th century, and many other large floods appear to have occurred in the early 19th and 20th centuries prior to flow regulation (Figure 3.7).

3. 8.1 Evidence of floods from floodplain features & channel maps

The Willamette River floodplain and historic channel maps indicate that many large-amplitude bends have been abandoned through avulsions (Plates 1-3). These avulsions presumably occurred during periods of high flow, in which discharge was sufficient to overtop the banks and carve cut-off channels through the floodplain. Channel maps from 1850 and 1895 show numerous avulsions along the entire Willamette River (Plate 1). Conversely, there are relatively few examples in the historic channel maps of remnant floodplain features depicting meander bends that have evolved entirely through lateral migration (Figure 3.8). Along many meandering streams, bend enlargement eventually causes the distance between the upstream and downstream ends of the bend to be quite small (e.g., the neck of the bend may span a distance of several channel widths). Because there are many examples of avulsions and little evidence of bends with narrow necks, we assume that, in the absence of flow regulation or human influences, meander bends along the Willamette would typically migrate outward until flooding cut-off that bend

3. 8.2 Historical descriptions of flooding 1813-1996

The first known accounts of flooding are provided by Native Americans, who informed early settlers that floods had turned the Willamette Valley into a lake (Brands, 1947; Ingram, 1964; USACE, 1969a). It is unclear what this statement means, though later records do describe significant ponding in the densely forested, low-gradient floodplain. Fur trappers and settlers provide the first flood accounts from which we can tentatively estimate flood magnitude. Most of these early accounts are recorded in the journals of settlers homesteading in the northern Willamette Valley. It is difficult to accurately assign discharges to these events because observations are sparse and few measurements exist. Despite these limitations, it appears that the first major flood encountered by Euro-Americans occurred in December of 1813. On January 24, 1814, Alexander Henry, Chief Factor of the Northwest Fur Company, was searching for a new home site on higher ground because "the present situation is overflowed at highwater, 'altho' its level above low water is between 30 and 40 feet." Henry's home was actually located 52 ft (17 m) above low water near Champoeg (FPKM 65), and later estimates by the USGS indicate that this flood may have been the third largest of the 19^{th} century (Figure 3.7, Brands, 1947).

Between 1813 and the largest recorded flood in 1861, there were at least three large floods as well as general references to more frequent events. Fur trappers became well acquainted with annual freshets, as they complained of goods and furs lost when crossing swollen rivers, disrupted trap lines, and that groups of trappers were stranded by high water (Brands, 1947). In early February of 1843, the Willamette was higher than it had been since 1813, and this flood was probably the first of several floods that substantial numbers of settlers witnessed. The following year the Willamette rose even higher during November of 1844, when "dark and rainy weather" continued for nearly five weeks. The 1844 flood had an estimated stage of 42 ft at Salem and was probably the 5th- or 6th-largest event of the 19th century. Five years later, a rain on snow event occurred in late December of 1849 and triggered a flood of magnitude about equal to the 1843 event (Brands, 1947). On January 1, 1853, flooding caused a great deal of damage to Oregon City, Dayton and Linn County (Brands, 1947). However, damage may have been partly due to increased development of floodplain lands, as the 1853 event appears to be smaller than the 1813 and 1840's floods (Figure 3.7).

The largest flood recorded since Euro-American settlement occurred in early December of 1861. The flood lasted nearly two weeks and crested twice, on December 1st and again on the 8th. There are numerous accounts of property damage, as floodwaters swept many farm buildings, animals, and implements into the water and destroyed much farmland. Several communities, including Orleans, Independence, Keizer, and Champoeg, were wholly or partially destroyed, while most other towns along the river experienced some inundation (Anderson, 1974). According to several accounts, residents of Orleans were awakened by the sound of driftwood hitting their homes, (Anderson, 1974; Miller, 1999). In Salem, people gathered along the Willamette's banks and watched as houses (some with lanterns still burning and occupants inside), barns, stock animals and large rafts of timber floated by (Miller, 1999). Spectators witnessed several dramatic rescues as steamboats and paddle boats extracted people from buildings, barn doors, and other objects to which they clung. There are also numerous accounts of large rafts of timber floating down the Willamette.

The 1861 flood inundated all of the Holocene floodplain and in some areas overtopped the Pleistocene terraces bordering the floodplain. Along most of the Willamette, discharge for the 1861 flood was at least 2,000 cms greater than for any subsequent events. At Albany, estimated discharge was 10,000 cms, and at Salem discharge was nearly 12,50 cms (Figure 3.7). Accounts of flood damage typically provide estimates of the inundated lands or monies lost as a result of destroyed or missing property and do not describe channel changes that occurred during the flood. Although we do not have sufficient data to determine how the 1861 flood might have affected the Willamette River, later records indicate that channel shifting and bank erosion frequently occurred after smaller floods. It therefore seems reasonable to assume that the much larger 1861 flood must have also caused widespread channel changes.

Large floods also occurred in 1881 and 1890, with multiple smaller events occurring more frequently. The Corps of Engineers began commenting on annual floods and providing general descriptions of flood conditions during the late 1860's. These descriptions provide insight into flood-related dynamics along the largely forested floodplain and indicate that, even during annual flow events, the river inundated the floodplain to a depth of several meters (USACE, 1875). The Corps also reported on the frequency of "freshets," which would fill the

Willamette and adjacent sloughs with drift and logs. According to a USACE reports from 1875:

> The Willamette River had risen...so high as to render it unsafe and risky to venture with boat into the channel, owing to the number of floating logs and large trees displaced from the banks. The water was so thick with mud as to render it impossible to discern the positions of snags below its surface. [pg 763, U.S. Army Corps of Engineers, 1875].

Although the discharge from the event to which the author refers is unknown, similar conditions often resulted from relatively small floods. During the flood of 1882, discharge at Albany was approximately 3,600 cms (about one-third of the 1861 flow), yet the event still delivered considerable quantities of wood to the river (pg 2659, USACE, 1882). It also appears that these frequent events may have mobilized large quantities of sediment, as there are multiple descriptions of channel shifting and bar movement that occurred annually during high water. There are multiple indications that the Willamette carried significant quantities of suspended sediment during winter flows, as various sources describe the river as being "thick with mud" (e.g, USACE, 1875, 1882). Specific references to gravel transport are rare, but at the Lone Tree and Buena Vista bars (near FPKM 138 in Santiam Reach) the Corps reported that "large quantities of heavy pebbles and cobblestones [were] borne along by the current during floods" (USACE, 1882, pg 2659).

These statements indicate that the number and magnitude of floods varied annually. During some years, high water prevented snagging crews from working during much of the winter, and individual floods lasted many weeks. In other years, crews were able to work through a greater portion of the winter and halted only when relatively short-duration floods caused high water for 1-2 weeks. Similarly, there are references to different flood hydrographs. Some, typically smaller-magnitude events were marked by the rapid rise and fall of water levels, but other floods were characterized by the steady rise of water levels for several weeks and culminated with a more rapid rise during the flood peak. Historical documents generally do not provide sufficient information to form hypotheses regarding the bank erosion or sediment transport of these different flood styles. Historic documents do indicate that it was not unusual for water levels to rise rapidly during the night, and that these "night rise" floods were the most damaging to communities because families typically had little notice to move themselves, their possessions, and stock animals to higher ground.

Although we did not find many specific descriptions of channel change resulting from the large floods of 1881 and 1890, anecdotal accounts indicate that these floods caused widespread damage along much of the Willamette Valley. The 1881 flood is the third largest flood of record (Figure 3.7) and occurred in early January as a result of warm rains falling on a heavy snowpack (Brands, 1947). Peak discharge at Albany was approximately 7,500 cms and 12,000 cms at Salem, though during the same season the Willamette experienced at least one other "prominent freshet" and three moderate events (USGS, 2004; USACE, 1881). The Corps reported that the 1881 floods caused significant erosion and flood damages due in part to a tornado that had uprooted many large trees the previous year. Logs 30–100 m in length formed giant rafts that extended across the Willamette, sweeping all drift that had accumulated along the banks into the river (Brands, 1947; USACE, 1881).

The 1890 flood was the second largest flood of record and peaked on February 4th with estimated discharge at Albany of 8,000 cms and 12,000 cms at Salem. The 1890 flood heavily damaged the town of Champoeg (which had been rebuilt following the 1861 flood) and destroyed most of the bridges and ferries in the Willamette Valley (Anderson, 1974). Like other large floods in the Willamette Valley, the 1890 flood was caused by heavy rain and warm weather, which melted a deep snowpack.

Between 1890 and the construction of flood-control dams in the 1940's, there were many moderate-size floods and numerous smaller, but still significant, discharge events (Figure 3.7). Flooding in January of 1900 and 1903 was followed by two floods in 1907 and another moderate event in 1909. Of these five floods, occurring in a ten-year interval, four exceeded 4,000 cms at Albany (or 8,000 cms at Salem). This relatively flood-rich interval was followed by fewer large events during 1910-1940, though most annual peak flows were still well above modern bankfull discharge. Although Fern Ridge Reservoir was completed in 1941, a relatively large flood (20-year event) occurring in January of 1943 inundated much of the floodplain and caused extensive damage to recently developed areas of the floodplain. Subsequent floods in 1945 and 1948 caused increasing levels of damage, though peak flows were slightly less than for the 1943 flood.

Flood magnitude began to decrease in the 1950's as more dams were constructed. In 1949, Dorena Reservoir was completed on the Coast Fork of the Willamette; by 1953 Big Cliff and Detroit reservoirs were operating on the North Santiam; and Lookout Point and Dexter dams were completed in 1954 on the Middle Fork of the Willamette. Despite increasing levels of flow regulation, there were several floods greater than 4,000 cms at Albany (8,000 cms at Salem) between 1950 and 1960. Anecdotal descriptions indicate that at least eight small farms south of Harrisburg were abandoned during 1946-1966 following extensive erosion of farmlands. Flooding stripped soils from fields and revealed cobbly alluvium along broad swaths of the floodplain. In 1951 and 1955, erosion was so great that several fields were isolated on newly created islands (Anderson, 1974).

The largest flood of the regulated era occurred on Christmas Eve of 1964. Even as discharge was regulated by seven flood-control dams, the 1964 flood remains the 12th largest flood of record (8th in magnitude at Salem) with peak discharge of 5,300 cms at Albany (8,700 cms at Salem). In the absence of flow reduction, the 1964 flood would have been similar in magnitude to the 1861 flood (approximately 13,400 cms as estimated by the USACE (1969a). Like other large Willamette Valley floods, high flows resulted when a near-record snowpack was rapidly melted by intense rainfall and relatively warm temperatures (USACE, 1969a). Several post-flood reports document extensive property damage and provide estimates of inundation, yet few reports document channel change or specific instances of bank erosion resulting from the flood. Comparison of the 1932 and 1972 channel maps for the upper Willamette between Corvallis and Eugene depicts many areas where rapid migration and bend –cut-offs occurred, but without finer temporal resolution it is difficult to link specific channel changes with floods that occurred over the interval.

Between 1964 and the present, only minor floods have occurred, as flow is currently regulated by 11 major flood-control reservoirs. The February 1996 flood was the largest post-dam event, though its discharge was similar in magnitude to floods experienced every few years between 1890 and 1950 (approximately 2,800 cms at Albany and 6,900 cms at Salem). Channel change resulting from the 1996 flood was relatively minor and was primarily contained within unrevetted areas of the upper Willamette. Most of the channel changes that resulted from either the February 1996 flood or a smaller event that occurred in November of the same year consisted of lateral migration through gravel bars and side channels where the active channel was fairly wide. Local migration rates in some areas of the McKenzie Reach (e.g., FPKM 210-212) exceeded 20 m/yr for the five-year interval 1995-2000, a rate that is much higher than reach-average migration rates for the interval 1972-1995 and is probably due in part to elevated flows (Figure 3.2).

3. 8. 3 Comparison of flood magnitude from inundation maps

During historic floods, the Willamette often overtopped its banks and inundated the Holocene floodplain. Terraces composed of Pleistocene gravels (Qg2) and Missoula Flood sediments (e.g., Qff2) generally bound the floodwaters of the mainstem Willamette. Flood inundation maps compiled by the Corps of Engineers from historic high-water marks and aerial photographs indicate that much of the Holocene floodplain and portions of the main valley floor were inundated during floods. However, inundation along the main valley floor generally resulted from ponding on poorly drained soils and from tributary contributions rather than direct overflow from the Holocene floodplain. For example, towns such as Harrisburg are situated on high terraces that appear inundated on the 1861 flood map (Figure 3.9), but historic accounts indicate that Harrisburg was protected from most floods and that, during the 1861 flood, inundation was minor and limited to water flowing through city streets (Anderson, 1974). Thus, we presume that water entered the town from swales and channels incised in the valley floor and that overtopping of the terrace would have been minor.

Comparison of flood inundation maps from 1861, 1943, and 1996 shows that, in all historic floods greater than the approximate level of the 1996 flood (3,500 cms at Albany), large portions of the Holocene floodplain were inundated (Figure 3.9). However, in the southern Willamette Valley, inundation during the 1996 flood was generally limited to lower Holocene terraces or swales along higher surfaces. In the northern Willamette Valley (downstream of Corvallis), slope decreases downstream as discharge increases, leading to greater inundation. These observations are consistent with flood profiles produced by the Corps of Engineers that depict the1943 flood as rising 5 m above the low water line at Harrisburg, a difference which increases to about 8 m near Corvallis and more than 30 m at Salem. With increasing flood magnitude, the backwater area behind Willamette Falls extends upstream so that, during the 1861 flood, water was ponded nearly to Salem, more than 30 Km upriver from Newburg.

3.8.4 Comparison of streampower for modern & historic floods

We initially hypothesized that the large, 19^{th} century floods led to avulsions and channel widening 1850-1895, whereas moderate floods may have supported higher migration rates 1895-1932. While anecdotal records, inundation maps and historical gage data show that channel shifting frequently occurred during floods, these sources do not describe how floods actually altered the channel. In order to better understand how different magnitude floods influenced avulsions, migration rates and widening, we rely upon the two-dimensional flood model of Denlinger (2002) to examine streampower generated during different sized floods. We use the model to compute the magnitude and distribution of streampower for the 1861 flood and the 1996 flood along the McKenzie Reach, which allows us to compare patterns of erosion and deposition from large-scale floods and moderate floods.

3.8.4a Two-dimensional flood model

We estimate streampower from the 1861 and 1996 floods using the depth-averaged two-dimensional finite difference flow model of Denlinger (2002). The model solves the shallow-water flow equations on a 2 -dimensional grid of any surface. We built the grid from the spatial coordinates of the ground surface (a DEM) of the upper Willamette, forming a rectangular mesh with square cells 20 m on each side. The flow solutions are constrained with stage and discharge records of the 1861 flood and the 1996 flood at Harrisburg to establish preliminary models of each event. A single value for bed friction is used to parameterize velocity gradient w with depth, and this resistance combined with the forcing of the topography determines the three dimensional variation of stage throughout the reach.

By comparing modeled stage with observed high-water marks over the three-dimensional terrain we can constrain both the average value for bed friction and discharge (Ref). Along the upper Willamette, there are few well-defined highwater marks for the 1861 flood and 1996 flood and we therefore rely upon digital inundation maps to constrain our modeled stage. The variation of streampower, which is the product of bed friction and depth-averaged velocity, then provides a means to compare where erosion and deposition will occur for a flood with the modeled discharge.

3.8.4b Flood model results

On the upper Willamette, large-magnitude floods such as the 1861 event (~ 9,800 cms at Harrisburg) inundate the entire Holocene floodplain and generate erosive overbank flows (Figure 3.10). In many areas, flow follows the regional (floodplain) topography rather than channel topography, causing streampower to be concentrated in areas outside of the main channel. Power is typically highest along inside, rather than the outside, of meander bends. Such patterns of erosive flows could have led to scouring of point bars, and may have caused widening of the channel or migration towards inside of bend (straightening). Streampower is also high at the downstream end of bends, but on outside of channel where chute formation and avulsions would have likely occurred. Overbank flows in areas not adjacent to channel could have carved new side-channels, or triggered migration and avulsions along existing secondary channels.

Moderate sized floods such as the 1996 event (~2,100 cms at Harrisburg) and those experienced every few years in the early 20th century may inundate the floodplain but do not produce erosive overbank flows (Figure 3.11). Stream power from modern, post-dam floods is generally greatest in the channel and more likely leads to within-channel scouring and local bank erosion rather than chute formation. Overbank stream power for moderate-sized floods is much lower than power generated by large-scale floods (typically <10 w/m^2 vs >40w/m^2 for large floods). These streampower patterns indicate that avulsions may have only been possible in areas with low erodibility, e.g., sparsely vegetated point bars or along multi-thread reaches. Model results are consistent with post-1996 channel changes, which indicate bank erosion was greatest in areas where the active channel is relatively wide and characterized by gravel bars and side channels.

3. 9 Discussion

3.9.1. Willamette River historical channel change 1850-1995

Combining historical patterns of channel change with records of flooding and anthropogenic activities reveals that much of the Willamette River remained highly dynamic through the mid 20th century. Large-scale floods in 1861, 1880 and 1891 likely triggered the numerous avulsions and extensive channel widening which occurred between 1850 and 1895. Although the Corps of Engineers was working to confine the upper Willamette to a single channel by reducing streamside wood and side-channels, these efforts may have initially had little effect on the channel. Whereas large-magnitude floods inundated much of the floodplain, navigation improvements targeted a small percentage of the entire channel (<10 % of total river length). Furthermore, historical records indicate that much of the wing-dams and other structures were swept away or disrupted by channel shifting following high water. Land conversion and riparian deforestation may have accelerated bank erosion locally, but few settlements were established along floodplain lands in the mid-to-late 19th century.

The largely straightened and widened 1895 channel experienced increased migration rates between 1895 and 1932 as a result of bank materials, planform, and flow regime. Along many areas of the floodplain in which the channel was bordered on both sides by Holocene alluvium, small initial bends developed into larger bends which subsequently migrated downstream. These low-sinuosity bends probably migrated slowly initially, but as curvature increased, migration accelerated. Bank erosion was facilitated by the frequent small to moderate-sized floods that occurred in this interval. Deforestation may have destabilized portions of the floodplain and led to heightened migration rates, as logging increased at the turn of the century and growing numbers of settlers occupied floodplain lands.

Channel change from 1932 to 1995 is complicated because migration in the 1930's-1950's was immediately checked by revetment construction which stabilized rapidly eroding bends. Revetment construction continued through the 1970's, resulting in stabilization of large portions of the Willamette River, while flood-control reservoirs began reducing flood peaks in the 1940's. We hypothesize that erosion in the 1930's-1940's may have been a continuation of the dynamic migration experienced 1895-1932. Because this period of erosion coincides with widespread expansion of agriculture and suburban communities onto the historic floodplain, it is possible that erosion may have increased as riparian forests were replaced with agriculture.

On the McKenzie Reach, erosion rates between 1972 and 1995 were lower than for previous time periods. This leads us to believe that that migration rates calculated for the period 1932-1995 along the Long Tom and Santiam reaches may underestimate erosion rates experienced during the development era, 1932-

1972 and may overestimate erosion rates for the post-development era, 1972-1995. These results show that the post-development Willamette River floodplain is much less dynamic than during historic periods, and that stabilization is due to a combination of flow reduction, revetments and intrinsic geologic control.

Patterns of channel width appear closely linked with peak flows, as large increases in channel width between 1850 and 1895 were followed by narrowing in subsequent intervals. During the 20th century, channel width continued to decrease and the channel became increasingly uniform with fewer fluctuations in width. Although these trends occurred along the entire floodplain, the McKenzie Reach experienced net widening 1850-1995 whereas the Long Tom and Santiam Reaches experienced a net narrowing 1850-1995. Initial widening 1850-1895 was probably triggered by large floods, but along the McKenzie Reach, closure of side channels and planform simplification may have forced greater amounts of discharge into a single main channel, thus dimininishing the amount of post-flood narrowing. On the Santiam and Long Tom Reaches, narrowing may be partially a function of channel improvement efforts, which sought to maintain a deeper channel for navigation. Narrowing and overall uniformity along all reaches is probably also linked to the revetment construction and flow regulation. Aerial photographs of all reaches show maturation of riparian vegetation and decreases in the number of bare gravel bars adjacent to the main channel (Gutowsky, 2000). Such observations indicates that many near-channel surfaces are becoming more stable as erosive flows and channel shifting are diminished.

3. IX.2. Evaluating the roles of geology, flooding & human activities

3.IX.2.a. The role of geology & physiography

Large-scale geological controls influence overall floodplain physiography and establish a series of reaches in which slope decreases while bank height increases with distance downstream. In each time period, the overall style of channel change was fairly similar across the entire Willamette floodplain, but the magnitude of channel change generally decreased downstream. Within each reach, there are smaller-scale differences in bank materials, valley width and channel slope that cause some bends to remain fairly stable while adjacent bends display more dynamic migration or avulsion behavior.

Regional geologic processes have resulted in local uplift of Tertiary sandstones and basalts which, combined with Holocene incision, causes the modern Willamette to flow against a series of resistant bank materials. Bends impinging upon partially cemented Pleistocene gravels, Tertiary sandstones and Columbia River Basalts have historically displayed low rates of erosion and are generally more stable than bends flanked by Holocene alluvium. Many bends flowing against resistant banks typically do not migrate away from these materials, causing the length of channel bordered by resistant banks to remain similar or increase over time.

In some cases, resistant banks appear to establish a very stable planform that extends across multiple bends, even those bordered by erodible banks. Along the Santiam and lower Long Tom Reaches, the position of the river alternates between paired terraces formed of partially cemented Pleistocene gravels. Lateral migration along the relatively straight sections in which the Willamette traverses the Holocene floodplain en route to the floodplain margins is generally slight. Although these sections may shift laterally, they maintain their overall planform and typically do not develop individual bends or display dynamic migration behavior characteristic of other bends situated in Holocene alluvium.

3. 9.2.b The role of flooding

The Willamette River historically experienced a spectrum of flood magnitudes which had a significant effect on planform and channel evolution. Low frequency, large-magnitude floods such as those experienced in 1861, 1881 and 1890 probably triggered avulsions, channel widening and straightening (migration toward the inside of a meander bend). Avulsions often led to the abandonment of large amplitude bends, causing large decreases in centerline length.

During moderate-sized floods, (such as the 1996 flood and those experienced every few years prior to flood control), streampower is concentrated in the channel rather than on the floodplain, which likely led to within channel scouring and accelerated erosion. While moderate floods inundate the floodplain, overbank streampower may not have been sufficient to carve cut-off channels or trigger avulsions except in areas with high erodibility. Periods marked by frequent moderate sized floods (e.g., 1895-1932 and 1932-1940's) display higher migration rates than the time interval marked by large-magnitude floods (1850-1895).

By altering planform, flooding initiates a suite of processes that have long-term implications on rates and styles of channel change. When large-amplitude bends are eliminated during extreme flow events, the straightened channel may be more likely to migrate rather than avulse during subsequent flow events. Conversely, heightened migration and increased sinuosity following a period of moderate-sized floods may cause the channel to be more sensitive to avulsions during large-magnitude floods.

3. 9.2.c The role of Euro-American activities

The most geomorphically effective Euro-American activities along the Willamette River were the construction of revetments and flood control dams in the 20th century. By decreasing bank erodibility and streamflow erosivity across much of the floodplain, these actions effectively stabilized the Willamette River. As lateral migration has decreased and avulsions are infrequent, centerline length has remained fairly constant and channel width has steadily decreased during the 20th century. Depending on sediment transport and erodibility of the channel bed, these conditions may cause the Willamette to incise in some areas.

Efforts to channelize and stabilize the Willamette between the 1860's and the 1930's appear to have been only marginally successful. Wing-dams, retaining walls, dikes and other structures built to confine the flow may have been locally successful for short periods (e.g., several years), but they only bordered a fraction of the channel and required frequent maintenance after high water. The most effective navigation improvements might have been the systematic closure of side-channels along the upper Willamette. By forcing greater quantities of discharge into a single-channel, such efforts may have 'preserved' the widening initially triggered by 19th century floods.

Between the 1860's and 1930's, the Corps of Engineers removed thousands of snags annually from the upper Willamette River. However, snagging may not have had measurable effect on planform or migration rates until the 20th century, because prior to dam construction and extensive riparian logging, annual flooding introduced large quantities of wood. Indeed, much of the late 19th century floodplain was probably a dense, riparian forest wherein large wood was introduced to the river both locally, and from tributaries. Although avulsion frequency decreased between the intervals 1850-1895 and 1895-1932, this decrease may have been due to characteristics of the 1895 planform and flow regime, rather than due to removal of large wood rafts. Even if no snagging occurred, the largely straightened 1895 channel may not have been as susceptible to avulsions as the more narrow and sinuous 1850 channel.

The role of deforestation on channel processes is not immediately clear. Euro-Americans began establishing settlements on the valley floor and logged portions of the floodplain in the mid-19th century, but conversion of riparian forest to agriculture did not fully occur until the 20th century following flood control and bank stabilization. Erosion rates increased at the turn of the century and rapid migration continued throughout the early 20th century, suggesting that land clearing may have led to heightened erosion. However, rapid migration was also due in part to frequent, moderate-sized floods, erodible bank materials, and a low-sinuosity planform that may have been 'primed' for accelerated erosion.

3. 9.d Hierarchical ranking of controls on channel change

During all time periods, larger-scale disturbances have greater and more lasting effect than smaller, more local disturbances. In studying channel change across large reaches (tens of kilometers) over broad time periods (tens of years) in which a range of natural and anthropogenic disturbance processes influenced the channel, the influence of smaller events was generally obscured by larger-scale processes. Along the Willamette River, the most significant channel changes were caused by large-magnitude floods, a high frequency of moderate-sized floods and large-scale anthropogenic activities. Large-scale geologic controls influence floodplain physiography and determine the sensitivity with which the channel responds to disturbances.

We also see evidence that the sequential order of disturbances can have important effects on rates and styles of channel change in subsequent time periods. Periods of moderate floods enhance lateral migration which causes the channel to develop a sinuous planform. Bends created by migration are then susceptible to avulsions and straightening by large-magnitude floods. In the absence of anthropogenic activities, flooding patterns probably caused the Willamette to alternate between a narrow, sinuous planform and a wider, straighter planform. However, it seems that the upper Willamette never recovered its pre-large flood planform because closure of side channels and other Euro-American activities forced greater amounts of flow into a larger, single channel while also reducing lateral migration. Thus, a century after the large-magnitude floods of the late 19th century, the upper Willamette still maintains a wider, straighter planform then was observed in 1850. The disturbances with the greatest impact on future channel processes are the construction of dams and revetments which will likely stabilize the Willamette for many decades.

3. 10 Conclusion

By examining 150 years of historical channel change along the Willamette River, we see evidence that geologic controls, flooding and human activities have exerted large influences on channel change, but that the relative importance of these variables has shifted over time. During all time periods, the sensitivity to which the river has responded to disturbances has depended upon both the intrinsic stability of a particular reach and disturbance magnitude. Channel change is also strongly dependent upon the sequential order in which disturbances occur, because disturbances such as flooding or anthropogenic activities can initiate a series of processes that extend across multiple decades.

Prior to flow regulation and bank stabilization, the Willamette was an anastomosing river flowing through a densely forested floodplain. During periods of moderate floods, meander migration led to the development of bends along both the mainstem Willamette and side channels. Large-scale floods led to avulsions and extensive increases in channel width and decreases in sinuosity. In the periods following these large floods, meander migration likely led to the redevelopment of bends with migration occurring rapidly along reaches flanked by Holocene alluvium.

Following Euro-American settlement in the mid-19th century, floodplain logging and expansion of agriculture may have locally increased migration rates. Efforts to enhance navigation in the late 19th and early 20th centuries included snag removal and construction of various structures which sought to channelize dynamic areas of the Willamette. More intrinsically stable reaches along the lower Willamette and along bends bordered by resistant banks required little to no effort to maintain a navigable channel. In contrast, more dynamic reaches along the upper Willamette required substantial maintenance and were not fully stabilized until the flood control dams and extensive revetments were constructed. Early navigation improvements along dynamic reaches may have been only locally successful for short-periods because flooding introduced large wood, initiated avulsions and rapid migration, and destroyed many structures. The systematic closure of side channels by cut-off dams may have caused net-widening along the upper Willamette, as greater amounts of discharge were confined to a single channel.

Channel change along the historically dynamic Willamette River is presently limited to lateral migration along reaches unconfined by revetments or naturally resistant banks. Avulsions are infrequent but may occur during moderate sized floods particularly along side-channel areas. Restoration efforts aiming to increase lateral migration, side-channel connectivity and avulsions will likely be most successful along historically dynamic reaches bordered by Holocene alluvium. These reaches tend to have erodible banks, relict side channels and have historically responded more sensitively to flooding and other disturbances.

3.11 Acknowledgements

Thanks to Stan Gregory, Linda Ashkenas, Randy Wildman and other members of the Pacific Northwest Ecosystem Research Consortium for sharing datasets and wisdom on the workings of the Willamette. Jim O'Connor graciously provided field equipment and advice on studying historical channel change. Andrew Meigs provided guidance and comments which helped to structure this paper. We especially thank Gordon Grant for extensive reviews of this lengthy document-his comments greatly helped us to organize this paper into a more manageable format. This work was supported by the National Science Foundation (Biocomplexity grant # 0120022).

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Table 3.1 Predicted channel response to natural and anthropogenic disturbance processes.

Channel Disturbance Process	Predicted channel response			
	Channel Width	Migration Rate	Avulsion Rate	Channel length
Large floods	Increase	Increase	Increase	Decrease due to avulsions
Moderate floods (bankfull)	Increase	Increase	Increase	Increase thru migration
Loss of riparian vegetation	Increase	Increase	Not clear	Increase
Snag removal	Decrease	Decrease	Decrease	Increase or decrease
Revetment construction	Decrease	Decrease	Decrease	Stabilize
Dam construction	Decrease	Decrease	Decrease	Stabilize
Channel modifications (wing dams, cut-off dikes)	Decrease	Decrease	Decrease	Stabilize

Table 3.2, Channel maps used to quantify channel change

Channel Maps				
Map Date	**Original Survey or Photo Source**	**Map Description**	**Source for Georeferencing and Digitizing**	**Precision**
1850	General Land Office (GLO) Cadastral Surveys	Cadastral survey of townships and sections. Most of study area surveyed 1851-1853.	Hulse et al., 2002[1]	+/- 10m
1895	Army Corps of Engineers (USACE)	Navigational blue-line survey. Study area surveyed October-November of 1894.	Hulse et al, 2002	Unknown
1932	USACE	Navigational survey of study area conducted 1931-1932.	Hulse et al, 2002	+/- 5 m
1972	USACE	Main channel and active channel[2] digitized from mosaic of orthophotographs in 1972 Willamette River and Tributaries Map Book. Photography flown May 2, 1972 at ~300cms.	These authors	+/- 10 m
1995	USACE	Main channel and active channel[2] digitized from orthophotographs flown August 1994 and September 1995 (~150-200cms).	Spencer Gross Photography, PNWERC & these authors	+/- 5 m

1. Pacific Northwest Ecosystem Research Consortium (PNWERC) presented in Hulse et al, (2002).
2. For 1972 and 1995 we digitized both the actual water surface boundary and the active channel from aerial photographs. Although discharge at the time the 1972 photos were taken is about twice that of flow during the 1995 photos, there is little difference in the stage-discharge relationship for these flows (~1m) and reach-averaged channel width for the low-water channel varies by less than 2% between the photo series.

Table 3.3, McKenzie Reach planform characteristics 1850-1995

Time Period	Reach Avg. channel width[1] (m)	Change in channel width (%)	COV in width (%)	Portion of FPKM that narrowed (%)	Portion of FPKM that widened	Length from GIS (Km)	Change in Channel Length (%)	Sinuosity	Length Simple Bend[2]	Length Compound Bend	Length Multi-bend Loop	Reach Avg. Slope (%)[3]	Reach Avg. Stream-power[4] (w/m^2)
1850	160 +/- 55	-	34	-	-	49.1	-	1.61	6.1	17.3	165.2	0.074	53.8
1895	234 +/- 122	46.3	52	37.0	63.0	39.2	-20.2	1.29	4.1	16.2	57.0	0.093	46.2
1932	198 +/- 76	-15.4	38	62.0	38.0	40.7	3.9	1.34	4.9	15.5	29.8	0.089	52.5
1972	185 +/- 72	-7.0	39	57.0	43.0	40.1	-1.6	1.31	-	-	-	0.091	57.1
1995	181 +/- 8	-2.2	4	50.0	50.0	40.2	0.3	1.32	6.2	18.6	40.8	0.090	58.2
1850-1995 Net Change		13.1		33.0	67.0		-18.2	-18.2					4.4

[1] Values refer to time at beginning of interval (e.g. reach averaged channel width was 137 m in 1850)

[2] Bend length scales are given in terms of channel width-thus, a simple bend length of 10 refers to a bend 10 channel widths in length.

[3] We assume a constant elevation drop for all time periods as measured from 1995 data

[4] Streampower computed as w=pghS*V where we subsitute V=Q/A so w=pgS*Q/b; we use bankfull discharge Qb=1190 cms for all time periods & assume constant elevation drop

Table 3.4, McKenzie Reach rates & styles of channel change 1850-1995												
Time Period	**Length of channel that avulsed (%)**	**Length of channel that migrated (%)**	**Length of channel that experienced normal migration (%)**	**Length of channel that straightened through migration (%)**	**Length of channel that experienced straightening or avulsion (%)**	**Avulsion area eroded per length of channel per year (m/yr)**	**Migration area eroded per length of channel per year (m/yr)**	**Average rate lateral migration[1] (m/yr)**	**Average rate normal migration[2] (m/yr)**	**Average rate of straightening[3] (m/yr)**	**# Avulsions**
1850-1895	53.3	46.7	35.0	11.7	65.0	4.4	0.9	1.5 +/- 1.1	1.3 +/- 1.0	2.5 +/- 0.9	11
1895-1932	33.4	66.6	57.6	9.0	42.4	5.0	4.0	3.5 +/-2.9	3.9 +/- 3.0	1.7 +/- 0.4	4
1972-1995	6.7	93.3	87.8	5.6	12.2	0.6	1.6	1.1 +/- 1.4	1.0 +/- 1.33	3.3 +/- 2.17	2

1. Average rate of lateral migration refers to the annual rate at which the centerline shifted laterally & accounts for both straightening (migration towards inside of bend) and normal migration (erosion along outside of bend)
2. The average rate of normal migration refers specifically to the rate at which the centerline shifted towards the outside of meander bends & was only calculated for bends that experienced this style of erosion.
3. The average rate of straightening refers specifically to the rate at which the centerline shifted towards the inside of the meander bends & was only calculated for bends that experienced this style of erosion.

Table 3.5 Long Tom Reach planform characteristics 1850-1995

Time Period	Reach Avg. channel width[1]	Change in channel width (%)	COV in width (%)	% of FPKM that narrowed	% of FPKM that widened	Length from GIS (Km)	% Change in Channel Length	Sinuosity	Length Simple Bend[2]	Length Compound Bend	Length Multi-bend Loop	Reach Avg. Slope (%)[3]	Reach Avg. Stream-power[4] (w/m^2)
1850	178 +/- 84	-	47.2	-	-	69.96	-	1.69	3.8	14.7	16.4	0.039	40.46
1895	195 +/- 69	9.6	35.4	35	65	64.80	-7.4	1.57	3.5	17.3	156.0	0.042	39.87
1932	155 +/- 48	-20.5	31.0	68	32	64.46	-0.5	1.56	4.4	11.1	91.3	0.042	50.42
1995	145 +/- 14	-6.5	9.7	65	35	65.19	1.1	1.57	5.7	24.2	89.1	0.042	53.29
1850-1995 Net Change		-18%			67.0		-6.8						12.8

[1] Values refer to time at beginning of interval (e.g. reach averaged channel width was 178 m in 1850)
[2] Bend length scales are given in terms of channel width-thus, a simple bend length of 10 refers to a bend 10 channel widths in length.

[3] We assume a constant elevation drop for all time periods as measured from 1995 data
[4] Streampower computed as w=pghS*V where we subsitute V=Q/A so w=pgS*Q/b; we use bankfull discharge Qb=1190 cms for all time periods & assume constant elevation drop

Table 3.6, Long Tom Reach rates & styles of channel change 1850-1995

Time Period	Length of channel that avulsed (%)	Length of channel that migrated (%)	Length of channel that experienced normal migration (%)	Length of channel that straightened through migration (%)	Length of channel that experienced straightening or avulsion (%)	Avulsion area eroded per length of channel per year (m/yr)	Migration area eroded per length of channel per year (m/yr)	Average rate lateral migration[1] (m/yr)	Average rate normal migration[2] (m/yr)	Average rate of straightening[3] (m/yr)	# Avulsions
1850-1895	28.0	70.0	55.0	15	43.0	3.0	0.9	1.1 +/- 0.7	1.1 +/- 0.74	1.06 +/- 0.73	6
1895-1932	10.0	90.0	86.0	4.2	14.0	0.8	2.1	1.7 +/- 1.9	1.6 +/- 1.9	3.08 +/- 2.2	2
1932-1995	12.0	85.0	73.0	10.8	23	0.2	1.0	0.93 +/- 0.95	0.94 +/- 0.97	0.88 +/- 0.82	2

[1] Average rate of lateral migration refers to the annual rate at which the centerline shifted laterally & accounts for both straightening (migration towards inside of bend) and normal migration (erosion along outside of bend)

[2.] The average rate of normal migration refers specifically to the rate at which the centerline shifted towards the outside of meander bends & was only calculated for bends that experienced this style of erosion.

[3.] The average rate of straightening refers specifically to the rate at which the centerline shifted towards the inside of the meander bends & was only calculated for bends that experienced this style of erosion.

Table 3.7 Santiam Reach planform characteristics 1850-1995

Time Period	Reach Avg. channel width[1]	% Change in channel width	COV in width (%)	% of FPKM that narrowed	% of FPKM that widened	Length from GIS (Km)	% Change in Channel Length	Sinuosity	Length Simple Bend[2]	Length Compound Bend	Length Multi-bend Loop	Reach Avg. Slope (%)[3]	Reach Avg. Stream-power[4] (w/m^2)
1850	219 +/- 81	-	37.0	-	-	88.07	-	1.60	3.8	16.7	32.4	0.032	36.47
1895	283 +/- 89	29.0	31.4	22.0	78.0	84.62	-3.91	1.54	4.5	26.7	32.0	0.033	29.37
1932	240 +/- 95	-15.0	37.6	70.0	30.0	87.49	3.39	1.60	2.8	15.3	31.4	0.032	33.50
1995	197 +/- 17	-18	8.6	67.0	33.0	86.11	-1.58	1.57	2.7	39.1	376.0	0.033	41.46
1850-1995 Net Change		-10.0		37.0	-2.0	-2.2	-10.0						12.8

[1] Values refer to time at beginning of interval (e.g. reach averaged channel width was 219 m in 1850)

[2] Bend length scales are given in terms of channel width-thus, a simple bend length of 10 refers to a bend 10 channel widths in length.

[3] We assume a constant elevation drop for all time periods as measured from 1995 data

[4] Streampower computed as w=pghS*V where we subsitute V=Q/A so w=pgS*Q/b; we use bankfull discharge Qb=1190 cms for all time periods & assume constant elevation drop

Table 3.8, Santiam Reach rates & styles of channel change 1850-1995

Time Period	Length of channel that avulsed (%)	Length of channel that migrated (%)	Length of channel that experienced normal migration (%)	Length of channel that straightened through migration (%)	Length of channel that experienced straightening or avulsion	Avulsion area eroded per length of channel per year (m/yr)	Migration area eroded per length of channel per year (m/yr)	Average rate lateral migration[1] (m/yr)	Average rate normal migration[2] (m/yr)	Average rate of straightening[3] (m/yr)	# Avulsions
1850-1895	16	84	60.2	24	40	1.4	1.4	1.2 +/- 1.1	1.2 +/- 1.2	0.86 +/- 1.24	5
1895-1932	4.0	96	86	9.8	14	0.18	2.2	1.6 +/- 1.5	1.6 +/- 1.5	0.76 +/- 1.63	2
1932-1995	10.2	90.0	74	15	26	0.55	1.0	1.0 +/- 0.8	0.9 +/- 0.72	0.93 +/- 1.0	3

1. Average rate of lateral migration refers to the annual rate at which the centerline shifted laterally & accounts for both straightening (migration towards inside of bend) and normal migration (erosion along outside of bend)
2. The average rate of normal migration refers specifically to the rate at which the centerline shifted towards the outside of meander bends & was only calculated for bends that experienced this style of erosion.
3. The average rate of straightening refers specifically to the rate at which the centerline shifted towards the inside of the meander bends & was only calculated for bends that experienced this style of erosion.

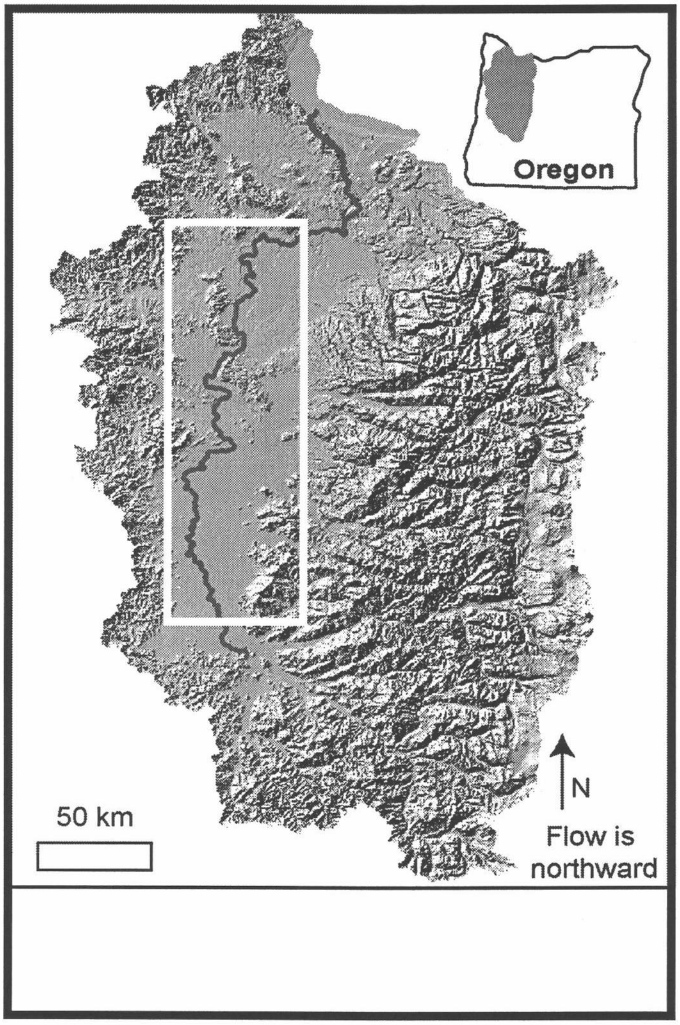


Figure 3.1. Willamette River Basin in northwestern Oregon. Box indicates 200 km study area which is divided into 3 reaches.

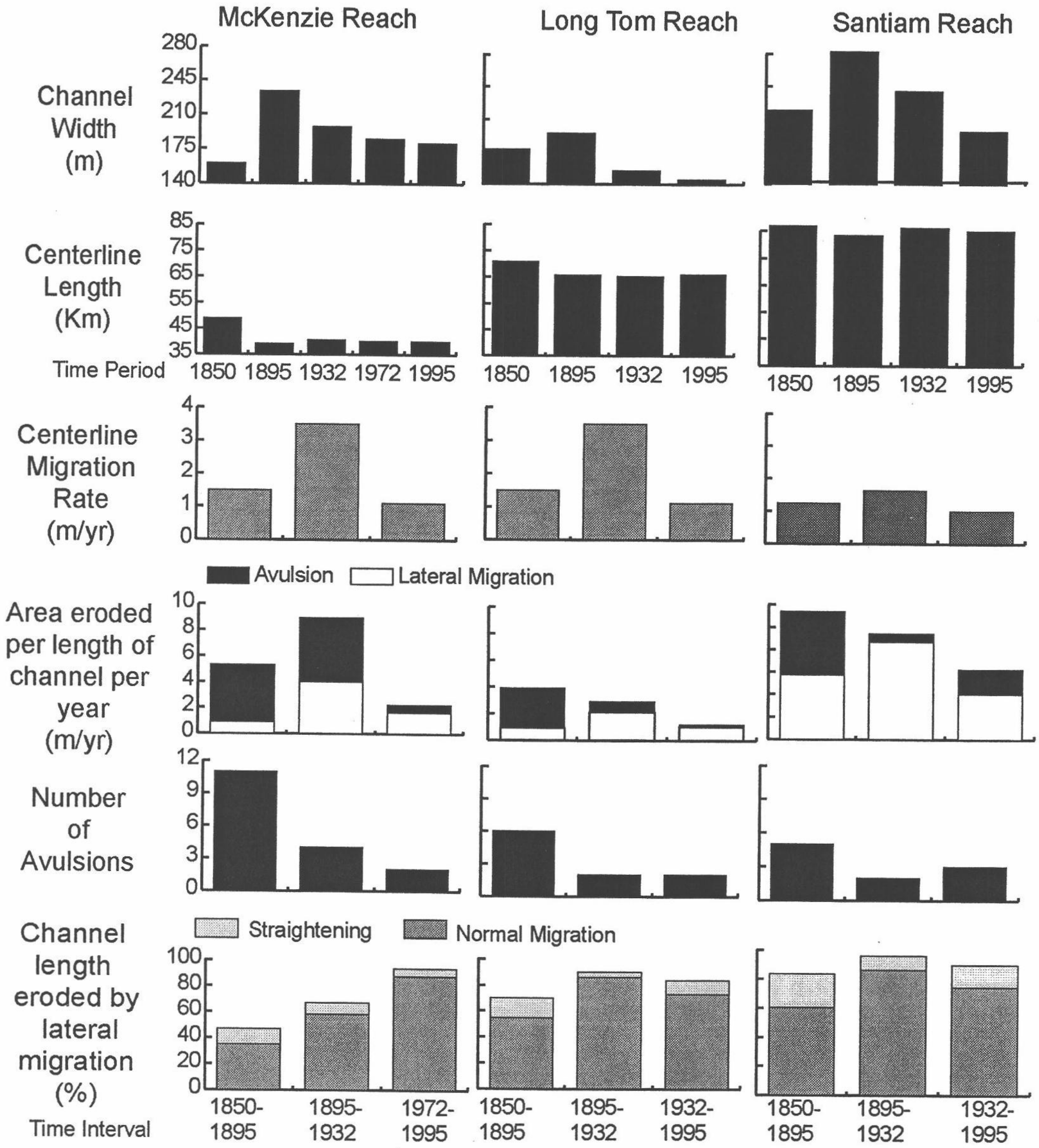


Figure 3.2, Patterns of channel change for mainstem Willamette River 1850-1995.

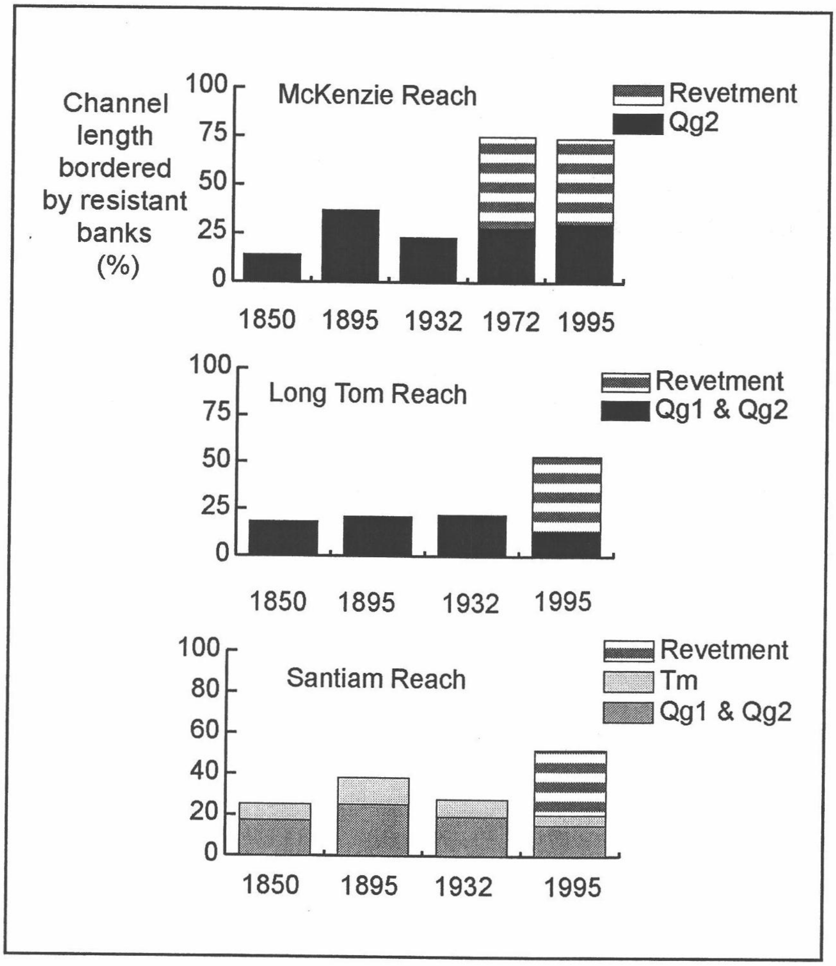


Figure 3.3, Channel length bordered by resistant bank materials. Revetment installed in the 1930's-1970 stabilizes large areas of the Willamette River, though naturally resistant banks have historically bordered 13-40% of each reach.

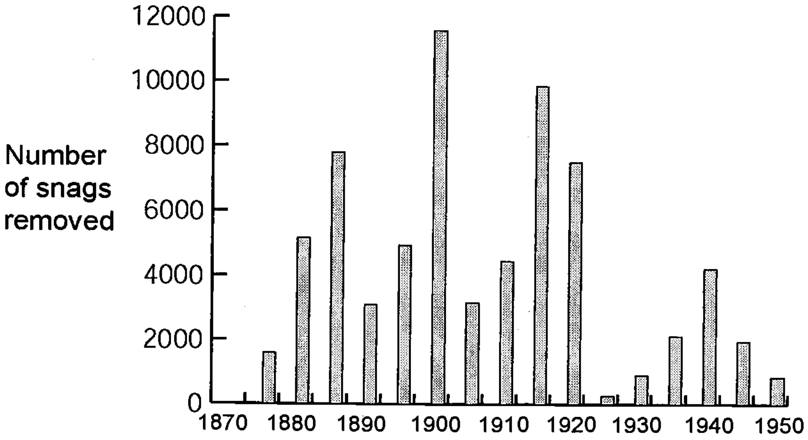


Figure 3.4, Snag removal 1870-1950 along upper Willamette. Plot shows total number of snags removed per 5 year interval between Albany and Eugene (FPKMs 150-220). Logs removed include harvested streamside trees and downed trees (snags). Adapted from data provided by Sedell & Frogatt, 1984.

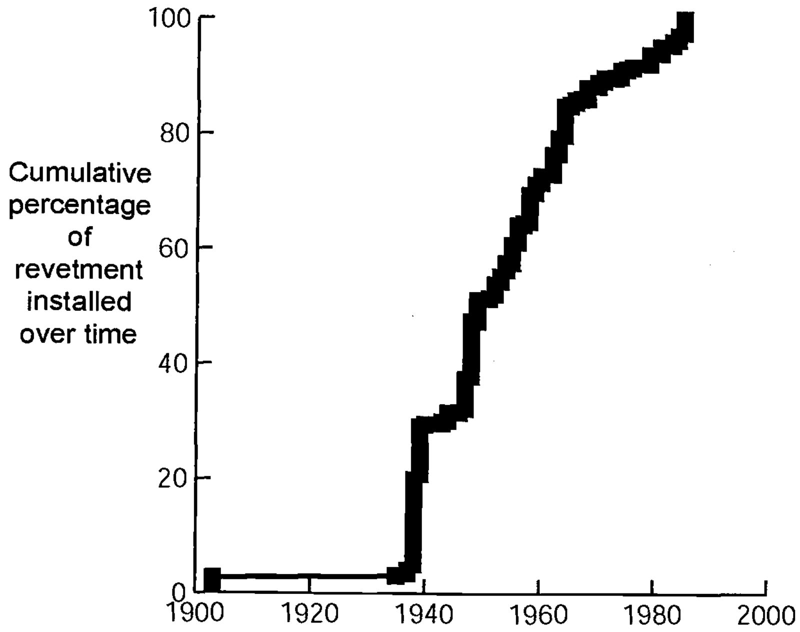


Figure 3.5 Cumulative percentage of revetment constructed along Willamette River, 1900-1985 Percentage is computed from lengths of revetment for which the construction date is known (about 45% of total revetments). Adapted from data provided by Gregory et al., 2002.

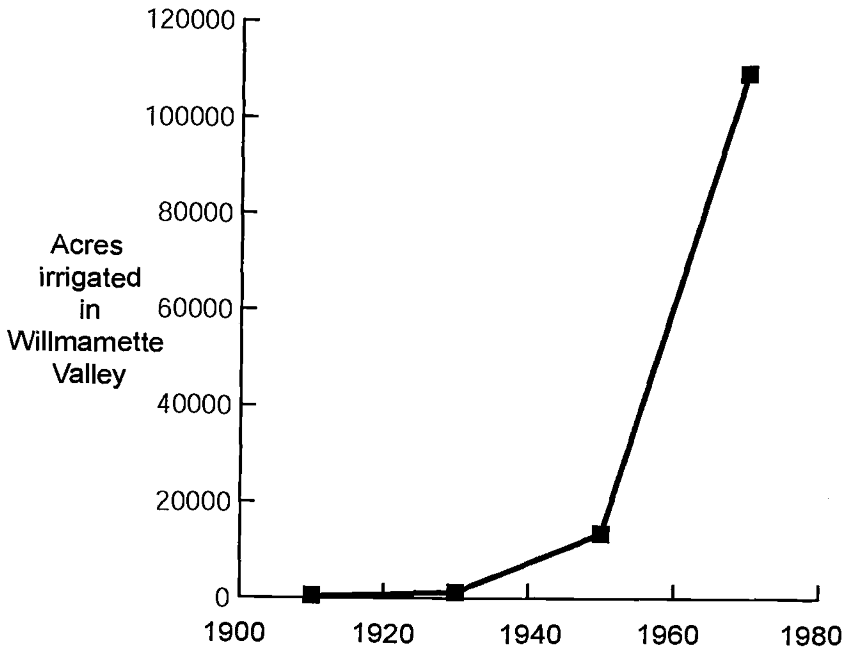


Figure 3.6, Expansion of irrigated acreage 1900-1980. Irrigation began increasing in the 1930's following bank stabilization, flow regulation and technological improvements. Much of the irrigated lands were located along the former floodplain. Adapted from data presented in Sedell and Frogatt, 1984.

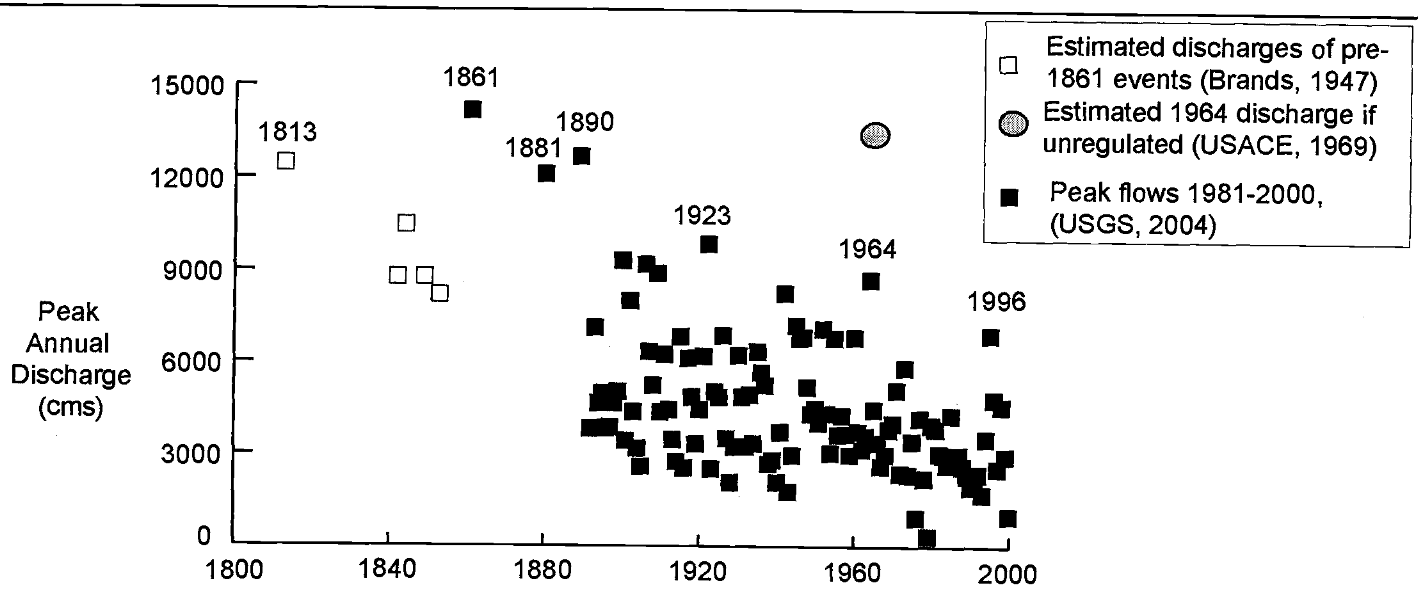


Figure 3.7, Peak Discharge 1813-2000 for Willamette River at Salem
Peak flows have decreased steadily following construction of 11 major flood control reservoirs
Discharge for pre-1861 events was estimated from historic highwater marks (Brands, 1947).

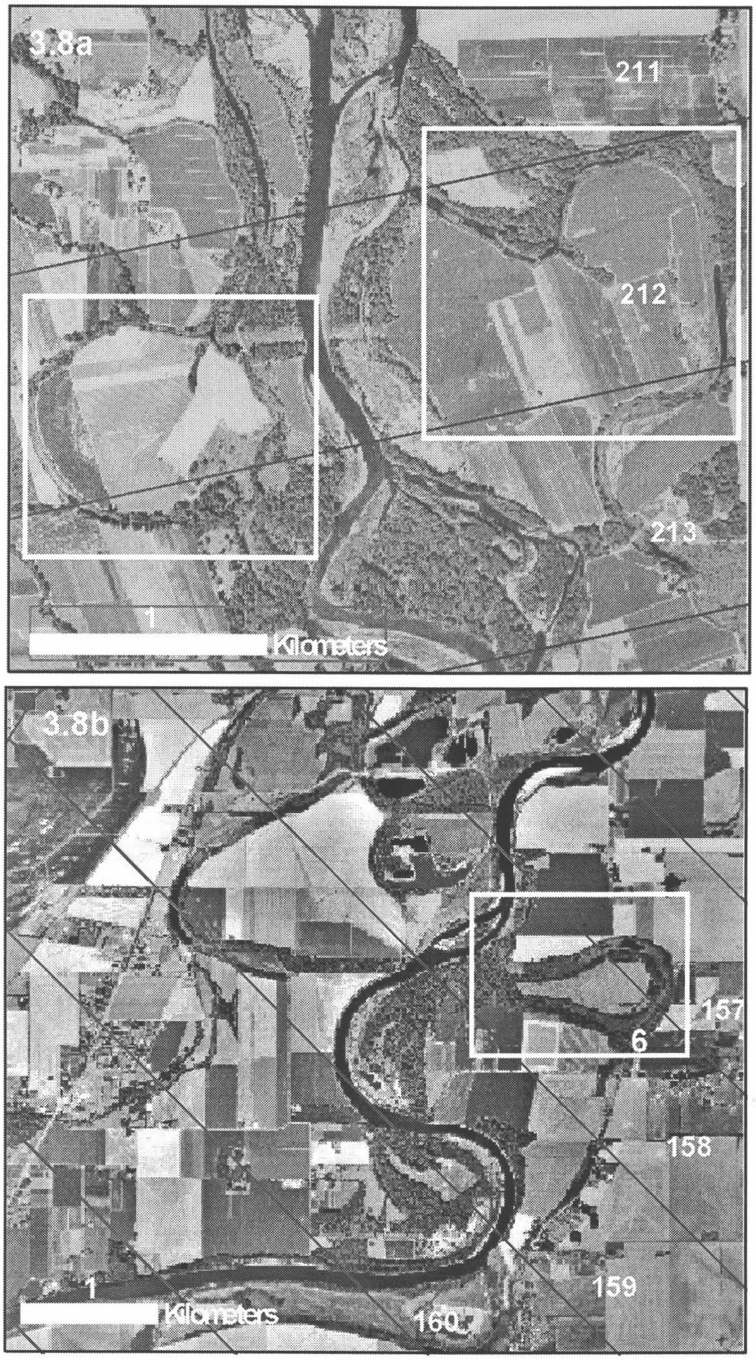


Figure 3.8, Examples of avulsions & meander migration recorded in remnant floodplain features.

Figure 3.8a, Examples of abandoned large-amplitude bends as recorded in aerial photographs of Willamette River floodplain. These bends were probably active in the 19th century. Similar features are found in many other areas of the southern Willamette Valley.

Figure 3.8b, Example of meander bend that evolved entirely through lateral migration. Such bends are rare in the Willamette Valley floodplain. This bend is located between Corvallis and Albany and probably formed along a side channel in the early 20th century.

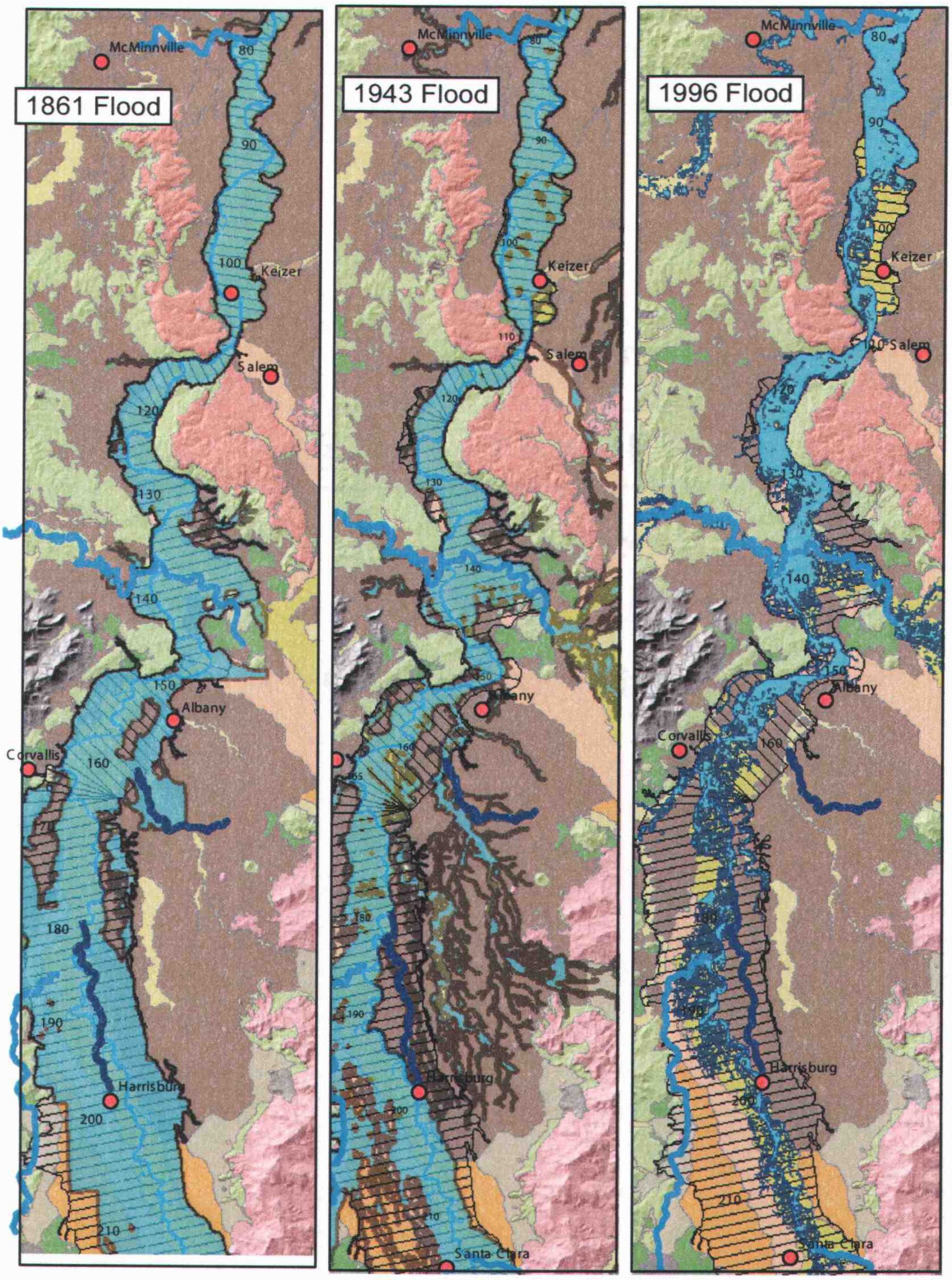


Figure 3.9, Inundation maps for 1861, 1943 and 1996 floods. Digital maps flood compiled by USACE and PNWERC.

Figure 3.10a, Innundation at 9,800 m^3/sec.

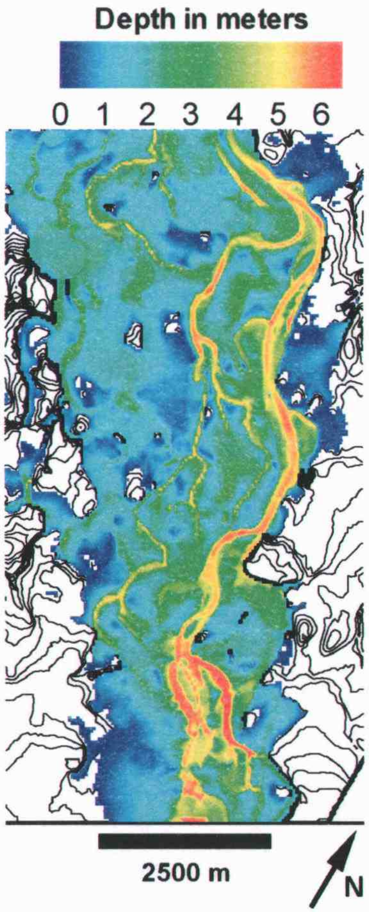
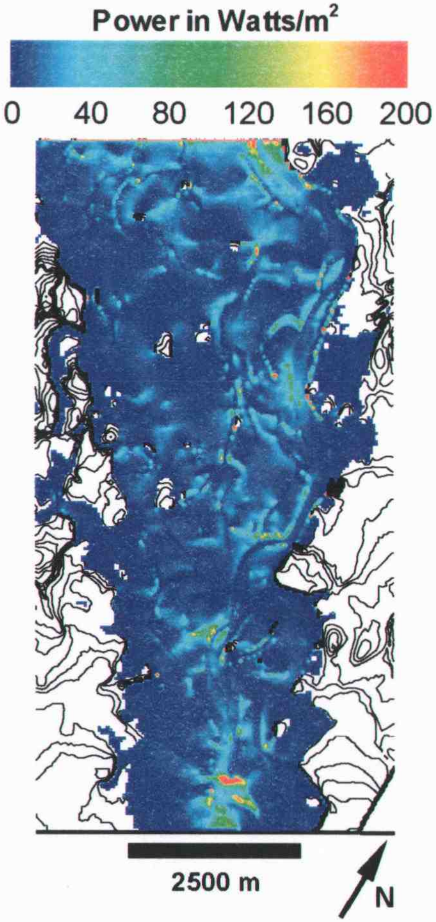


Figure 3.10b, Streampower at 9,800 m^3/sec.



Area modeled is between FPKM 206 (Scandia Landing) and FPKM 199 (Harrisburg).

Figure 3.11a, Innundation at 2,100 m^3/sec.

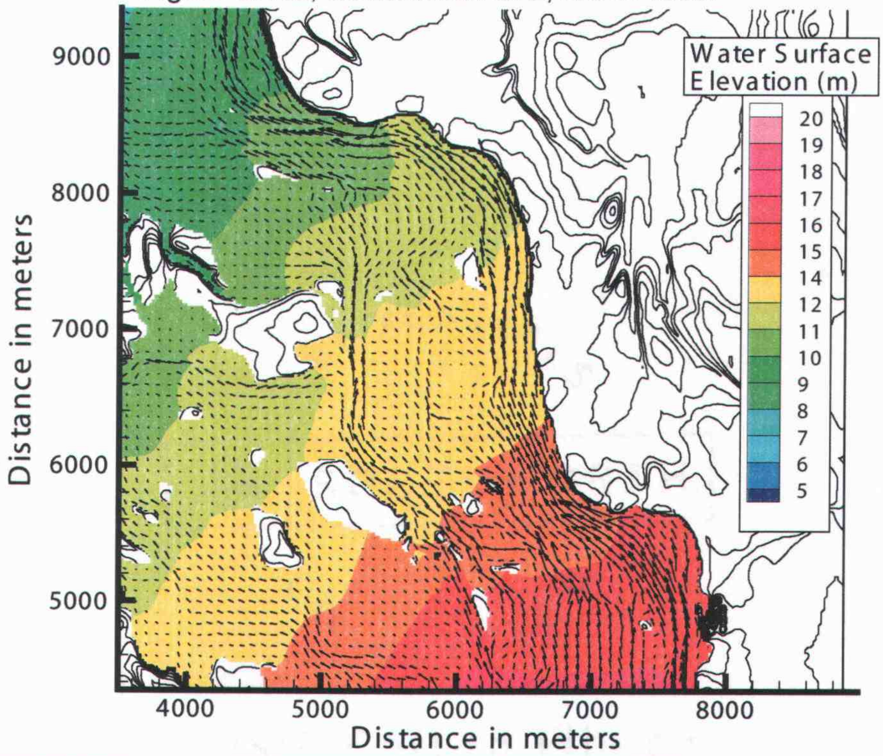
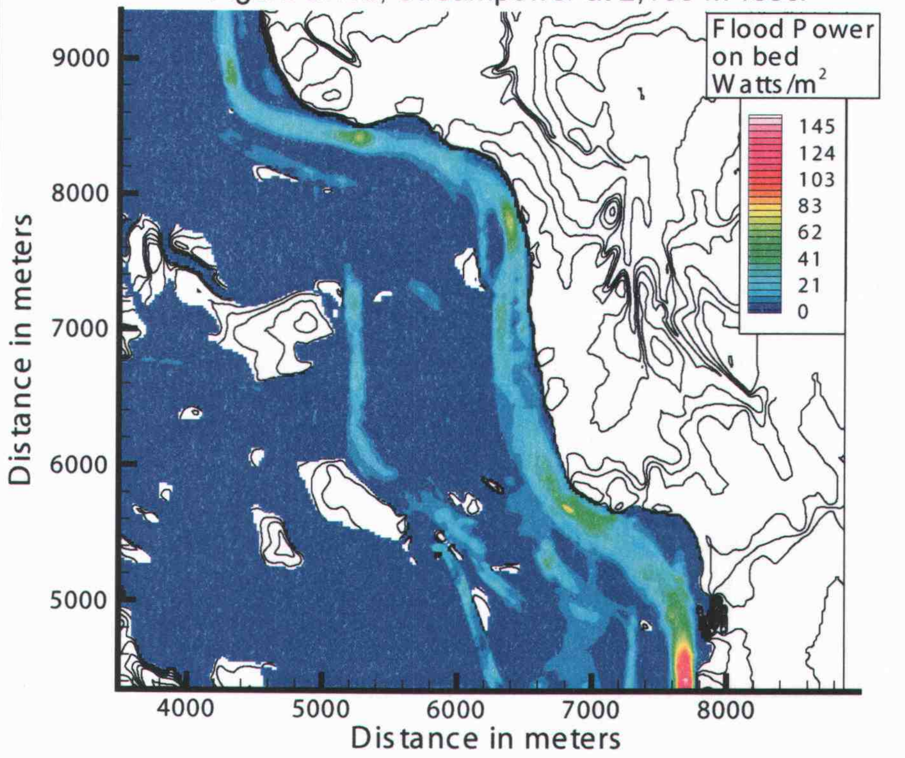


Figure 3.11b, Streampower at 2,100 m^3/sec.



Modeled area is near Harrisburg at FPKMs 199-195

Chapter 4:
Conclusion

We developed an approach for interpreting patterns of historic channel change along large rivers. Independent examination of the roles of geologic controls, flow regime, and anthropogenic activities enabled ranking of the importance of each factor across time periods and for different areas of the floodplain. To determine the importance of resistant bank materials, we developed a method for computing the erodibilities of natural and artificial bank materials. This analysis reveals that along the upper Willamette, Holocene alluvium is about 3 times more erodible than Pleistocene gravels, which in turn are at least 10 times more erodible than revetments. We examined the role of floods by comparing anecodotal accounts, gauge records, and stream-power modeling with patterns of channel change and found that floods historically triggered extnsive widening and straightening as many bends were abandoned following avulsions.

During the 19th century, actions such as riparian logging and navigation improvements may have been locally important, but stabilization of the dynamic, pre-settlement Willamette required the large-scale flow regulation and bank stabilization projects that were not fully in place until the mid-to-late 20th century.

We suggest that, in the absence of artificial stabilization and flow regulation, meander migration along the Willamette would lead to development of bends that were frequently abandoned through bend cut-off and avulsion during floods. Peak flows may also have triggered channel widening, as all reaches display large increases in channel width during periods with large historic floods. Following widening and straightening, migration along the Willamette would lead to rapid development of bends, and channel width would decrease. Along upper reaches, this sequence of events would be more dynamic than for lower gradient reaches, and bends impinging on resistant banks would generally migrate slowly outward or remain stable rather than follow general floodplain trends. As the percentage of resistant banks has increased over time and flow regulation suppresses peak flows, erosion rates have diminished and many areas of the Willamette experienced little net change during the late 20^{th} century. Efforts aiming to increase lateral migration may consider removing revetment from bends stabilized by revetment, but such actions may not recreate the planform diversity of the historic floodplain, which formed in response to complex interactions among multiple factors including peak flows, migration along adjacent bends and the riparian forest.

Chapter 5:
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