AN ABSTRACT OF THE DISSERTATION OF

Peter J. Wampler for the degree of Doctor of Philosophy in Geology presented on July 14, 2004.

Title: Contrasting Geomorphic Responses to Climatic, Anthropogenic, and Fluvial Change Across Modern to Millennial Time Scales, Clackamas River, Oregon.

Abstract approved:

Gordon E. Grant

Geomorphic change along the lower Clackamas River is occurring at a millennial scale due to climate change; a decadal scale as a result River Mill Dam operation; and at an annual scale since 1996 due to a meander cutoff. Channel response to these three mechanisms is incision.

Holocene strath terraces, inset into Pleistocene terraces, are broadly synchronous with other terraces in the Pacific Northwest, suggesting a regional aggradational event at the Pleistocene/Holocene boundary. A maximum incision rate of 4.3 mm/year occurs where the river emerges from the Western Cascade Mountains and decreases to 1.4 mm/year near the river mouth. Tectonic uplift, bedrock erodibility, rapid base-level change

downstream, or a systematic decrease in Holocene sediment flux may be contributing to the extremely rapid incision rates observed.

The River Island mining site experienced a meander cutoff during flooding in 1996, resulting in channel length reduction of 1,100 meters as the river began flowing through a series of gravel pits. Within two days of the peak flow, 3.5 hectares of land and 105,500 m^3 of gravel were eroded from the river bank just above the cutoff location. Reach slope increased from 0.0022 to approximately 0.0035 in the cutoff reach. The knick point from the meander cutoff migrated 2,290 meters upstream between 1996 and 2003, resulting in increased bed load transport, incision of 1 to 2 meters, and rapid water table lowering. Ninety-six percent of the total migration distance occurred during the first winter following meander cutoff.

Hydrologic changes below River Mill Dam, completed in 1911, are minimal but a set of dam-induced geomorphic changes, resulting from sediment trapping behind the dam, have occurred. Degradation for 3 km below the dam is reflected by regularly spaced bedrock pools with an average spacing of 250 m, or approximately 3.6 channel widths. Measurable downstream effects include: 1) surface grain-size increase; 2) side channel area reduction; 3) gravel bar erosion and bedrock exposure; 4) lowering of water surface elevations; and 5) channel narrowing. Between 1908 and 2000, water surface elevation dropped an average of 0.8 m for 17 km below the dam, presumably due to bed degradation.

Contrasting Geomorphic Responses to Climatic, Anthropogenic, and Fluvial Change Across Modern to Millennial Time Scales, Clackamas River, Oregon

by

Peter J. Wampler

A DISSERTATION

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Doctor of Philosophy dissertation of Peter J. Wampler

presented on July 14, 2004.

APPROVED:

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Peter J. Wampler, Author

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CONTRASTING GEOMPHORIC RESPONSES TO CLIMATIC, ANTHROPOGENIC, AND FLUVIAL CHANGE ACROSS MODERN TO MILLENNIAL TIME SCALES, CLACKAMAS RIVER, OREGON

1 INTRODUCTION

When evaluating changes to a river system such as dam construction or meander cutoff, it is important to realize that observed changes may contain some component of other processes operating at different spatial and temporal scales. This is true of the Clackamas River, where both human-induced and climatic changes are occurring over a range of temporal and spatial time scales (Figure 1.1). Watershed-wide incision has occurred throughout the Holocene, punctuated by millennial-scale climate changes and aggradational phases. Geomorphic changes to the lower 38 km of the Clackamas River, resulting from the construction of River Mill Dam, have a decadal time scale. Reach-scale changes, such as meander cutoff, knick point migration and bed degradation resulting from a gravel extraction pond breach, have occurred within the last decade between river mile (RM) 13 and 16.

In this study, I examine river change using a combination of historic photos and survey data, field mapping of geomorphic surfaces, modern grain size analysis, and GIS analysis to explore the trajectories of channel evolution associated with anthropogenic and climate change.

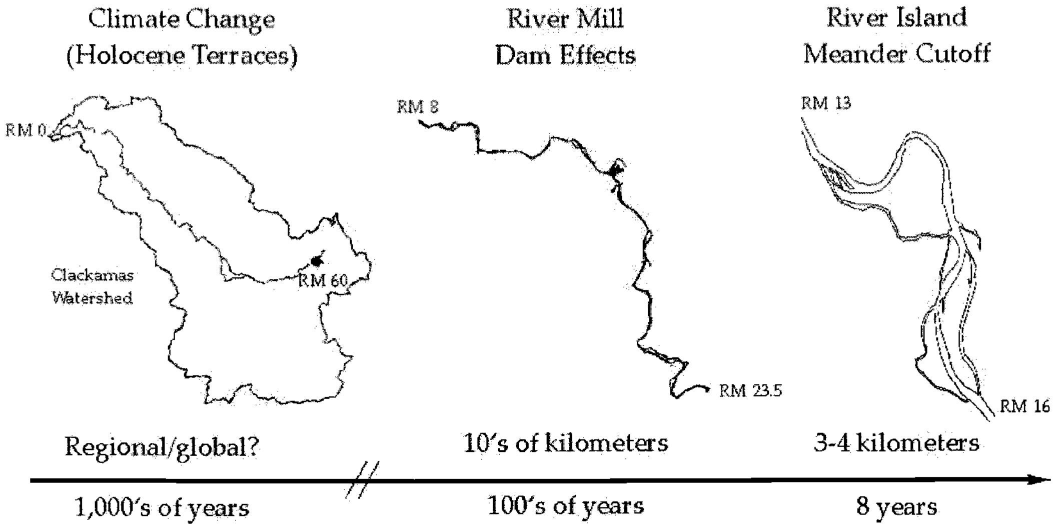

Figure 1.1 Spatial and temporal scales of change for the Clackamas River.

Channel evolution can be either rapid or slow. Engineers are familiar with changes that result from river works such as bank protection and bridges; while geologists, with their long view of time, see the river as a system with a history that cannot be separated from human changes which are superimposed upon it (Schumm, 1977). The Clackamas River has a complex geologic and geomorphic history which is strongly influenced by climate change. Superimposed upon this history of change are numerous athropogenic changes which also influence channel form and processes.

The ability to observe and measure change in a river system depends on the time and space scale with which observations are made (Schumm, 1965). Often several spatial and temporal scales of change are occurring at a given location in the river system. Changes due to athropogenic drivers can have trajectories which are in the same direction, resulting in a more pronounced channel response than would be observed from an isolated change; or these drivers may operate in opposing directions, resulting in a more subdued response.

Geomorphic changes described in the following three chapters explore alterations to the fluvial system resulting from climate, dam-related incision, and meander cutoff. These three drivers operate at different spatial and temporal scales. Over long time spans (> 10^4 years), the Clackamas River is in dynamic metastable equilibrium, experiencing episodic erosion and deposition with intervening periods of relative stability (Chorley and Kennedy, 1971). Superimposed upon this slowly changing equilibrium are short term modifications (Figure 1.2).

Channel form equilibrium depends largely on rearrangement of gravel and cobbles during geomorphically effective floods (Wolman and Miller, 1960; Wolman and Gerson, 1978; Miller, 1990). Channel response can be predicted based on four variables: L_s, D, Q, S; where L_s = sediment load (L^3/T); D = grain size (L), Q = discharge (L^3/T), and S = slope (L/L) (Lane, 1955).

$$L_s \cdot D \propto Q \cdot S$$

Anthropogenic or climatic changes may cause either increases or decreases to these variables. For example, if sediment load (L_s) is decreased due to trapping behind a dam while slope and discharge are largely unchanged, grain size (D) must increase to maintain proportionality. Changes to the variables can be long term trends, like climate, or discrete effects, such as building a dam or shortening a channel.

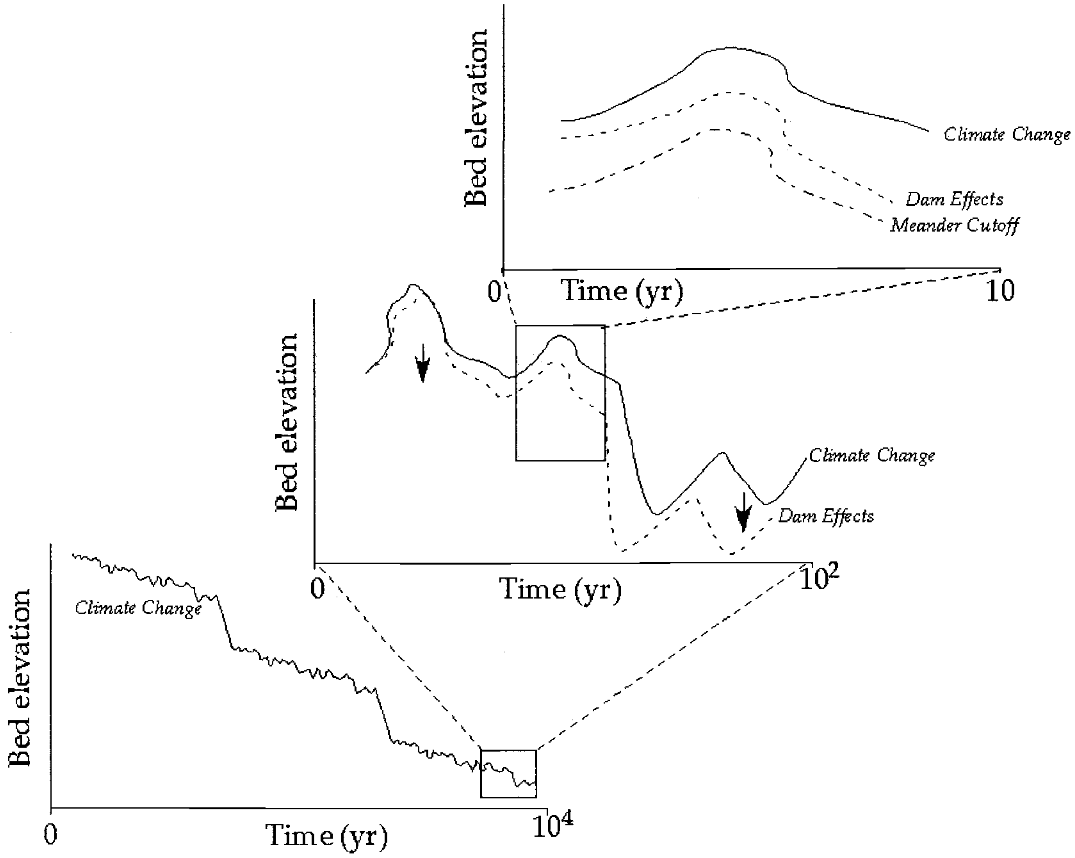

Figure 1.2 Conceptual model of short-term changes superimposed upon long-term dynamic metastable equilibrium (modified from Chorley and Kennedy, 1971).

Geomorphic change along the Clackamas River highlights the importance of considering geologic and geomorphic history when interpreting human impacts to river systems. Changes viewed without this important context could be misinterpreted or attributed to the wrong driving mechanism.

2 LATE PLEISTOCENE/HOLOCENE TERRACES ALONG THE CLACKAMAS RIVER, OREGON

Peter J. Wampler

Department of Geosciences, Oregon State University, Corvallis, OR 97331

To be submitted to Northwest Science.

2.1 Abstract

Well-preserved Holocene strath terraces, inset into Pleistocene terraces, have been mapped and dated along the Clackamas River, Oregon. A 3-km wide fill-cut wide terrace referred to as the Estacada Formation (Qt_3) has radiocarbon dates of 9,870 ± 50 and 10,180 ± 60 ^{14}C yrs B.P. An older fill terrace, Qt_2, into which Qt_3 is cut, has been dated at 22,840 ± 130 ^{14}C yrs B.P. The Qt_3 terrace is broadly synchronous with other terraces identified in the Oregon Coast Range, Willamette Valley, and the Olympic Mountains, suggesting a regional aggradational event at the Pleistocene/Holocene boundary. In the Clackamas Basin and the Willamette Valley, this regional aggradational event post-dates Missoula flood deposits.

Incision rates, measured from the top of the Qt_3 terrace, generally increase upstream and reflect an increase in longitudinal profile concavity since the early Holocene. A maximum incision rate of approximately 4.3 mm/year occurs where the river emerges from the Western Cascade Mountains and decreases to 1.4 mm/year near the confluence with the Willamette River. A younger strath terrace (Qt_8), with an average age of 1,120 ± 40 ^{14}C yrs B.P., yields a maximum incision rate, measured from the top of the terrace, of approximately 4.9 mm/year. In addition to topographic uplift, bedrock erodibility, rapid base-level change downstream of the terraces, or a systematic decrease in Holocene sediment flux may be contributing to the rapid and consistent incision rates observed.

Vertical incision along the Clackamas River occurs on the time scale of decades to centuries in response to anthropogenic changes such as meander cutoff and dam construction; and on a millennial time scale in response to climate oscillations and sediment flux changes. The longitudinal profile and volume of gravel contained in the Qt_3 terrace suggest a sediment flux significantly greater than modern rates, resulting in a base level near the mouth of the Clackamas River as much as 15 meters higher than the modern level. This suggests that Willamette Falls may have been buried in sediment during the early Holocene, and effectively removed as an obstruction to anadromous fish passage at that time.

Alternating periods of aggradation and incision along the lower Clackamas River may correlate with global millennial-scale climate variability within the Holocene.

2.2 Introduction

Humans struggle to understand earth's changing climate and the amount of variability that is "natural". Fundamental to this is an understanding of paleoclimate, paleohydrology, and natural climate variability with a resolution adequate to discern changes during the Holocene. Much of our present understanding of climate change is derived from climate proxies and the geologic record.

Pollen records from lake and pond cores at Mt. Rainier, the Oregon Cascades, and the Coast Range suggest conditions were warmer and drier up until about 4,000 ^{14}C years B.P. At that time conditions became warmer and wetter, and have remained warm and wet into modern times

(Dunwiddie, 1986; Sea and Whitlock, 1995; Worona and Whitlock, 1995). Pollen record resolution is limited by the slow recovery time of vegetation to climate change. Fluvial records in the form of terrace deposits typically respond more quickly.

Terraces are remnants of formerly active floodplains isolated from fluvial processes through incision. Terraces are classified as fill, fill-cut, or strath (Bull, 1991). Fill terraces represent accumulation of alluvium and valley aggradation. The top of the fill terrace, or tread, represents the time at which the river began to incise and abandon the floodplain. Fill-cut terraces are formed when a river erodes laterally and vertically into a fill terrace. Strath terraces are formed when a floodplain or other geomorphic surface is eroded to bedrock prior to being abandoned by incision, leaving a bedrock surface, which may or may not be mantled with alluvium. All three types of terraces may be either paired or unpaired, with unpaired terraces more common on the inside of meander bends.

Incision that produces terraces can result from natural and/or anthropogenic mechanisms. Natural incision has been documented in response to changes in base-level (Schumm and Rea, 1995; Brocard et al., 2003), regional or global climate changes (Pazzaglia and Gardner, 1994; Fuller et al., 1998; Tebbens et al., 1999; Pazzaglia and Brandon, 2001; Hereford, 2002), tectonic uplift (Anderson, 1990; Bull, 1990; Rosenbloom and Anderson, 1994; Kiden et al., 1998; Casavant and Miller, 1999; Huisink et al., 1999; Stouthamer and Berendsen, 2000), and river avulsion and channel shortening (Slingerland and Smith, 2004). Anthropogenic changes resulting in incision include: forestation and peak flow reduction (Liebault and Piegay, 2001); deforestation and increased peak flows (Grant and Wolff, 1991; Miller et al., 1993; Kondolf et al., 2002); gravel extraction (Healy and Wo, 2002; Rinaldi, 2003); dam construction (Baxter, 1977; Simons and Li, 1980; Williams and Wolman, 1984; Kondolf, 1997; Brandt, 2000; Grant et al., 2003); and bank protection (Warner, 2000).

Holocene terrace chronologies and stratigraphy in the Pacific Northwest have been described along the Clearwater River in the Olympic Mountains (Wegmann and Pazzaglia, 2002), and several rivers in the Coast Range (Personius, 1993). These terrace histories suggest that numerous aggradation events have occurred during the Holocene with intervening periods of incision. A regional aggradation event is recorded by several Coast Range rivers at the Pleistocene/Holocene boundary.

Less is known about terrace chronologies and stratigraphy for western Oregon rivers draining the Cascade Mountains during the late Pleistocene and early Holocene. Holocene terraces along the Santiam River, although not dated, are 1 to 8 meters above the river and suggest a pattern of slow incision, interrupted by periods of aggradation (Thayer, 1939). The North and South Santiam Rivers, McKenzie River and Coast Fork of the Willamette River have extensive fill terraces which pre-date Missoula Floods (> 12,000 yrs) and cut-fill terraces that post-date Missoula Floods (O'Connor et al., 2001).

Late Pleistocene and Holocene terraces and strath terraces along the Clackamas River in northwestern Oregon provide a record of fluvial aggradation and incision that adds to our understanding of fluvial response in western Oregon rivers to Holocene climate; and may lend further support to millennial-scale climate variability found in deep sea sediment cores (Bond et al., 1997) and fluvial records in Europe (Starkel, 1991).

Hill slope and glacial erosion processes are typically greater during times of cool climate and glacial advance, and result in aggrading fluvial systems. During the Late Pleistocene, terrace aggradation and alluvial fills correspond with glacial periods, and incision with interglacial periods (Porter et al., 1992; Nott et al., 2002). In contrast, European researchers found that the transition between glacial and interglacial modes was the time of greatest fluvial activity, and the most severe cold period of the Little Ice Age (LIA) was associated with reduced fluvial activity (Rumsby and Macklin, 1996).

The timing of fluvial response to climate change appears to be variable and depends on the aspect, elevation, geology, and regional air flow patterns of a given watershed. Fluvial response variability may also be explained by moisture and climate cycles that are out of phase, resulting in periods where cold occurs with increased precipitation, as well as decreased precipitation. Climate variability and glacial advance may be globally synchronous for the late Holocene, but may be less so early in the Holocene (Grove, 1979). Prior to 5,000 years ago, cooling periods may have been associated with relatively dry conditions while cool periods after that time have been associated with relatively wet climate in the Cordillera of the west (Heusser et al., 1985).

The temporal scale of many climate studies is unable to resolve variability within the Holocene and studies simply describe the Holocene as an interglacial period. However, sedimentary facies of braided and anabranching rivers (Stouthamer and Berendsen, 2000); pollen records obtained from lake and peat deposits (Dunwiddie, 1986; Sea and Whitlock, 1995; Liu et al., 1998; Booth et al., 2004); fluvial records of incision and aggradation (Personius, 1993; Pazzaglia and Gardner, 1994; Tebbens et al., 1999; Mills, 2000; Wegmann and Pazzaglia, 2002, 2002); glacial retreat and advance derived from glacial deposits (Clark and Bartlein, 1995; Wiles et al., 2002; Starkel, 2003; Licciardi et al., 2004); and ice core records (Bond et al., 1997; Thompson et al., 2002) all provide evidence of pronounced Holocene climate variability.

Several distinct periods of increased ice-rafted debris in the North Atlantic, a proxy for cooler climate, provided evidence for a 1-2 ka cycle of climate variability within the Holocene (Bond et al., 1997). Climate models suggest that both Heinrich events and global climate are responding to the same global forcing, which does not appear to be an orbital forcing. Bond argued that the growth of the Laurentide ice sheet alone is enough to divert the jet stream and cause a cooling of 4-10 degrees in the west. However, both the Medieval Warm Period (MWP) and the LIA are consistent with Milankovitch forcings having a dominant frequency of about 1.5 ka (Campbell et al., 1998). Campbell argued that Milankovitch forcings alone were sufficient to account for millennial-scale variability within the Holocene without invoking thermohaline circulation changes as a causal mechanism.

The dominant process along the Clackamas River during the Holocene has been incision, punctuated by brief periods of aggradation which are preserved as strath terraces. The Clackamas River record, unlike many glacial records, appears to be relatively intact due to the high rate of Holocene incision. Clackamas strath terraces are unique in that almost the entire terrace sequence is young enough to be dated by radiocarbon methods. Clackamas River terraces provide valuable information about fluvial response to Holocene climate change in the Pacific Northwest, and may provide further support for millennial-scale Holocene climate variability.

In this paper, I describe and provide radiocarbon dates for several previously undated late Pleistocene/Holocene terraces along the lower Clackamas River. Terrace dates and stratigraphy are related to other dated terraces in Oregon and the Pacific Northwest. Clackamas terraces and fluvial response are correlated to millennial-scale global climate variability during the Holocene. Several mechanisms for anomalously high rates of incision along the Clackamas River are discussed and compared to incision rates for other rivers draining the Cascades.

2.3 Location and Geologic Setting

The lower Clackamas River is a gravel-bed river located in northwestern Oregon, U.S.A. The Clackamas watershed drains approximately 243,000 hectares and traverses three distinct physiographic provinces in its 97 km course from headwaters at Timothy Lake to the Willamette River near Oregon City (Figure 2.1)

In the High Cascades physiographic province, the Clackamas River is confined to a steep canyon and receives glacial inputs from tributary canyons during periods of glacial advance. As the river enters the Western

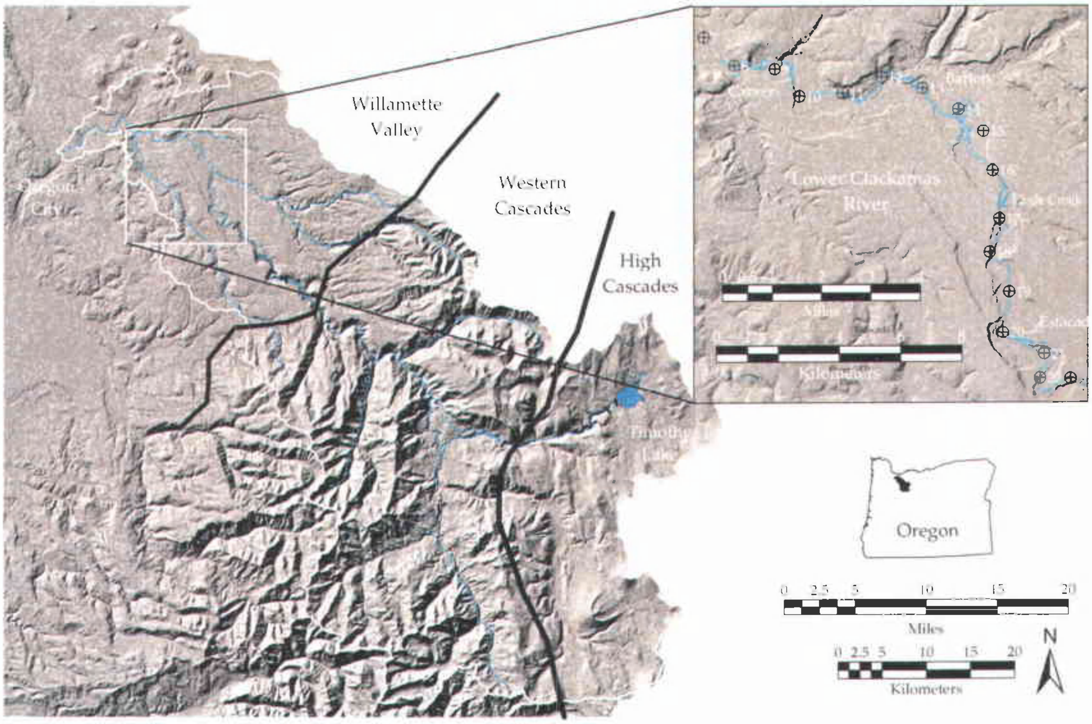

Figure 2.1 Location map for the Clackamas Basin. Inset map of the lower Clackamas River with USGS river miles.

Cascades, it encounters a deeply eroded volcanic landscape with abundant mass wasting and high sediment yield during both glacial and interglacial times. Near Estacada, the river emerges from a confined canyon into a broad valley, which is part of the Willamette Valley physiographic province. Below Estacada, sediment generated in the Western and High Cascades, including periglacial sediment generated by glaciers in the Cascade Mountains, is deposited. During the Pleistocene and Holocene climate fluctuations, periglacial processes in the Cascade Mountains resulted in high sediment yield from the upper Clackamas River Basin.

Bedrock in the lower Clackamas River Basin is dominated by an easily erodible geologic unit called the Sandy River Mudstone (SRM) (Trimble, 1963), also referred to as the Troutdale Mudstone (Madin, 1994).

Glacial outburst floods, referred to as the Missoula or Spokane floods (Bretz, 1969) backed up into the Clackamas valley, blanketing the floodplain with silt several 10's of meters thick to an elevation of approximately 110-120 m above current mean sea level.

Pleistocene basalt near Barton, referred to as the Boring lavas, was emplaced between 400 ka and 3,646 ka (Madin, 1994). Outcrops of lava span the Clackamas River valley and likely altered the flow of the Clackamas River during emplacement.

Uplift in the Cascade Mountains to the east has caused tilting of Pliocene geomorphic surfaces (Hammond et al., 1980). Uplift in the central portion of the Western Cascades is on the order of 0.28 to 0.33 mm/year, averaged over the interval from 3.3 to 2.0 ma, and 0.14 to 0.17 mm/year during the last 2 ma (Sherrod, 1986).

A diffuse fault zone extends beneath the Clackamas River and may control its orientation (Blakely et al., 1995). No offset has been noted in Holocene terraces; however, the Pliocene to Pleistocene Springwater surface may be offset by faults (Figure 2.2). Northwest trending sections of the Clackamas River at river mile (RM) 20 to 21 and RM 18.1 to 18.3 may be exploiting the weakness provided by the fault zone.

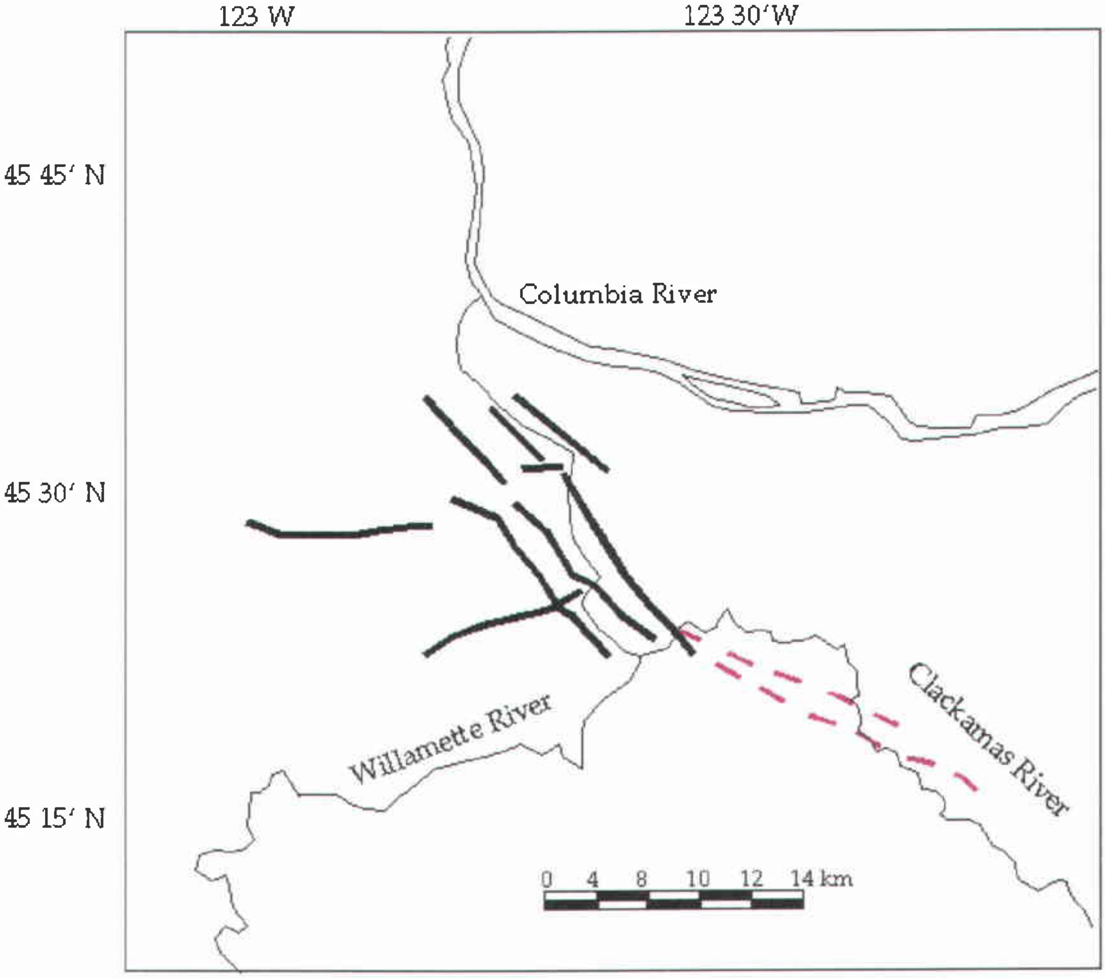

Figure 2.2 Inferred faults controlling portions of the lower Clackamas River (modified from (Blakely et al., 1995).

2.4 Methods

Geomorphic surfaces were mapped on a combination of aerial photos, United States Geological Survey (USGS) quadrangles, topography from the Metro Regional Land Information System (RLIS), a 5-foot digital elevation model obtained from the Metro Regional Government, and 2-foot contour maps provided by Portland General Electric (PGE). Sediment thickness was inferred from vertical exposures at eroded river banks and gravel pit exposures. Geomorphic surface boundaries were delineated based on inferred thicknesses. Terrace designation was based on correlation, height above the modern river, qualitative weathering rind thickness, soil development, and ^{14}C dates, where available. Qualitative and semi-quantitative weathering rind analysis was used to determine the relative age of terraces (Appendix A).

Terrace correlations were made with reference to distance along a line bisecting the entire valley (Figure 2.3). Twelve samples were collected for carbon dating (Table 2.1, Figure 2.4). Standard radiometric and Accelerated Mass Spectrometry (AMS) ^{14}C dating were employed to obtain

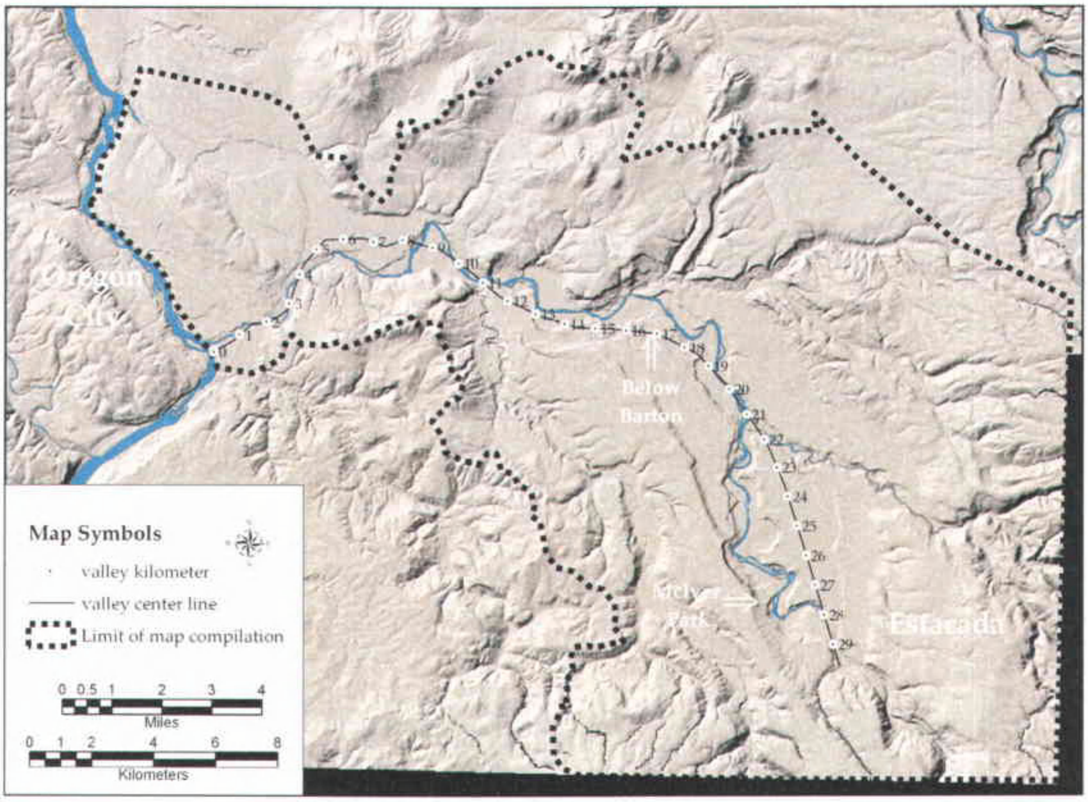

Figure 2.3 Shaded relief map of the lower Clackamas River with valley kilometers used for terrace correlation.

Table 2.1 Radiocarbon dates of terraces along the Clackamas River.

Sample Number	Lab ID #	Lab	Analysis Method	Geomorphic Unit	Materials Analyzed	^{14}C Years B.P.	Calibrated[a] Age B.P.	Relative Area[c] under Prob. Dist.
CD-001	T16773	Univ. of Arizona	AMS	QT$_8$	Charcoal fragments	1139 ± 37	**966-1146**	0.965
							1158-1169	0.035
CD-004	T16774A	Univ. of Arizona	AMS	QT$_8$ or Qt$_7$	Charcoal fragments	1654+-40	1419-1471	0.094
							1479-1628	0.825
							1652-1659	0.012
							1669-1690	0.069
072303-02	183581	Beta Analytical	Radiometric	SRM	Wood Fragment	> 45,220	N/A[b]	N/A[b]
072303-01	183580	Beta Analytical	AMS	Qt$_2$	Charcoal fragments	22,840 ± 130	N/A[b]	N/A[b]
050603-03	178944	Beta Analytical	AMS	Qt$_9$	Charcoal fragments	680 ± 40	**555-607**	0.453
							621-681	0.547
050603-01	178943	Beta Analytical	Radiometric	Qt$_9$	Wood Fragment	650 ± 70	526-693	1.000
032503-1	178261	Beta Analytical	Radiometric (extended count)	Qal	Charcoal fragments	60 ± 50	N/A[b]	N/A[b]
DPCK001	177584	Beta Analytical	Radiometric	SRM	Wood Fragment	>33,400	N/A[b]	N/A[b]
CD007	177583	Beta Analytical	Radiometric	Fire Ring in Qt$_8$	Charcoal fragments	420 ± 60	**315-407**	0.311
							418-539	0.689
CD001	177582	Beta Analytical	AMS	Qt$_8$	Charcoal fragments	1120 ± 40	934-938	0.004
							948-1095	0.916
							1105-1141	0.062
							1159-1168	0.019
121802-03	174351	Beta Analytical	AMS	Qt$_3$	Charcoal fragments	9870 ± 50	**11,175-11,340**	0.944
							11,391-11,399	0.009
							11,512-11,545	0.047
121802-02	174350	Beta Analytical	AMS	Qt$_3$	Charcoal fragments	10,180 ± 60	11,441-11,466	0.015
							11,492-11,495	0.001
							11,554-12,315	0.984

[a] Calibrated ages determined by CALIB 4.4; present is defined as 1950. Ages reported in text in bold.

[b] Ages outside of calibration range.

[c] From Stuiver et al. 1998a.

dates for terrace alluvium. Samples were collected from sand lenses within terrace alluvium. AMS samples consisted of rounded charcoal fragments to avoid contamination of the samples by in-situ burned wood or roots. Since the charcoal fragments are assumed to have traveled with the sediments in the terrace, they provide a maximum age for terrace alluvium. Some terraces contained wood that was of sufficient quantity to date by standard radiocarbon techniques.

Samples were analyzed by the University of Arizona - Department of Geosciences, Laboratory of Isotope Geochemistry; and Beta Analytic Radiocarbon Dating Inc. Calibrated radiocarbon ages were determined using the on-line calibration program Calib 4.4 (http://radiocarbon.pa. qub.ac.uk/calib/calib.html) (Stuiver et al., 1998). All dates reported in the

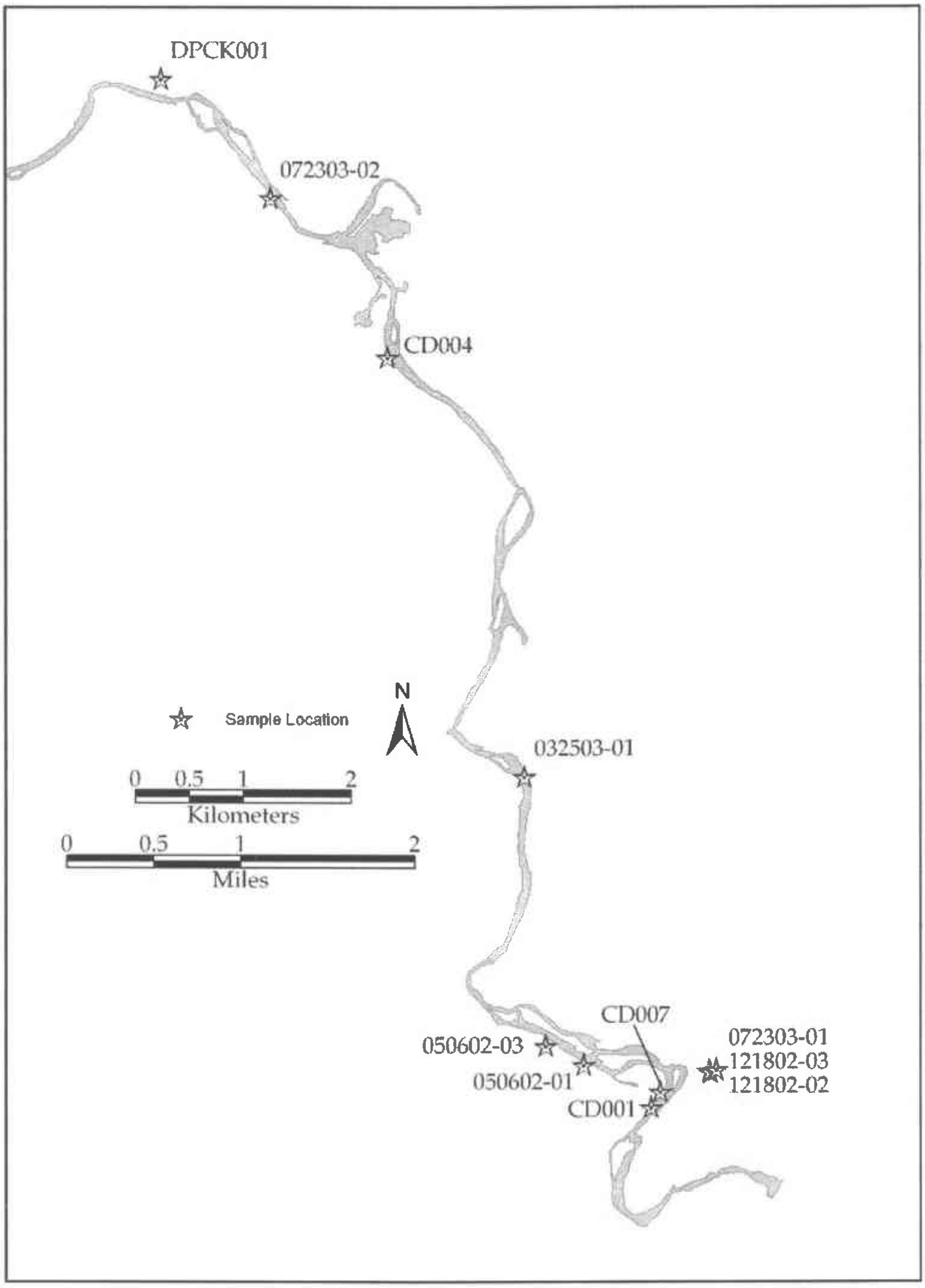

Figure 2.4 Radiocarbon dating samples on Clackamas River terraces.

text are in radiocarbon years before the present (^{14}C yrs B.P.). Calibrated ages are reported relative to the 1950 datum. Complete calibration data can be found in Appendix B.

Geomorphic surfaces and geologic units were mapped and compiled in a roughly 440 km^2 area (Figure 2.3, Sheet 1). The southern and eastern map boundaries coincide with USGS quadrangle boundaries, while the north and east boundaries are the Clackamas watershed boundary. A portion of the modern basin boundary was extended in the northwest corner of the map to include the area through which the Clackamas River flowed during the late Pleistocene and early Holocene. Original mapping was combined with data from previous maps (Trimble, 1963; Madin, 1994; Sherrod and Smith, 2000), Priest (unpublished mapping of Redland and Estacada Quads) and Madin, 2004 (unpublished mapping). Incision was typically measured from terrace treads rather than bedrock surfaces due to the lack of exposure on basal bedrock.

2.5 Results

Paired and unpaired terraces occur along the Clackamas River. Preservation is excellent for Qt_3 and Qt_2 terraces, while younger terraces are primarily preserved at McIver Park and below Barton.

Rind thickness on basaltic clasts from the Estacada surface (Qt_3) ranged from too thin to measure with the unaided eye to 1.5 mm. Weathering rinds were thickest for clasts from the Springwater surface (Qt_s), which is 1 to 1.7 ma old (Madin, personal communication 2004), and had weathering rinds which ranged from 3 to 16 mm and averaged 10 mm (Figure 2.5).

Figure 2.5 a. Weathering rinds on clasts from the Springwater geomorphic surface. b. Weathering rinds on basaltic clasts from Qt_3 the Estacada terrace.

Estacada Rock Quarry, located at the end of River Mill Dam road, provides the best terrace exposure along the Clackamas River. Several hundred meters of vertical exposure have been created as gravel mining progresses into the Estacada (Qt_3) and Gresham terraces (Qt_2) (Figure 2.6). The excellent exposure allowed several radiocarbon samples to be collected from Qt_3 terrace and one sample from the Qt_2 terrace. One section of a terrace face was mapped on photos taken from the ground (Figure 2.7).

A trench was excavated in the quarry floor to determine alluvium thickness and obtain carbon material suitable for dating at the base of the Qt_3 terrace. Bedrock was not reached after excavating to approximately 4 m (the maximum depth possible with the Komatsu PC300LC Excavator).

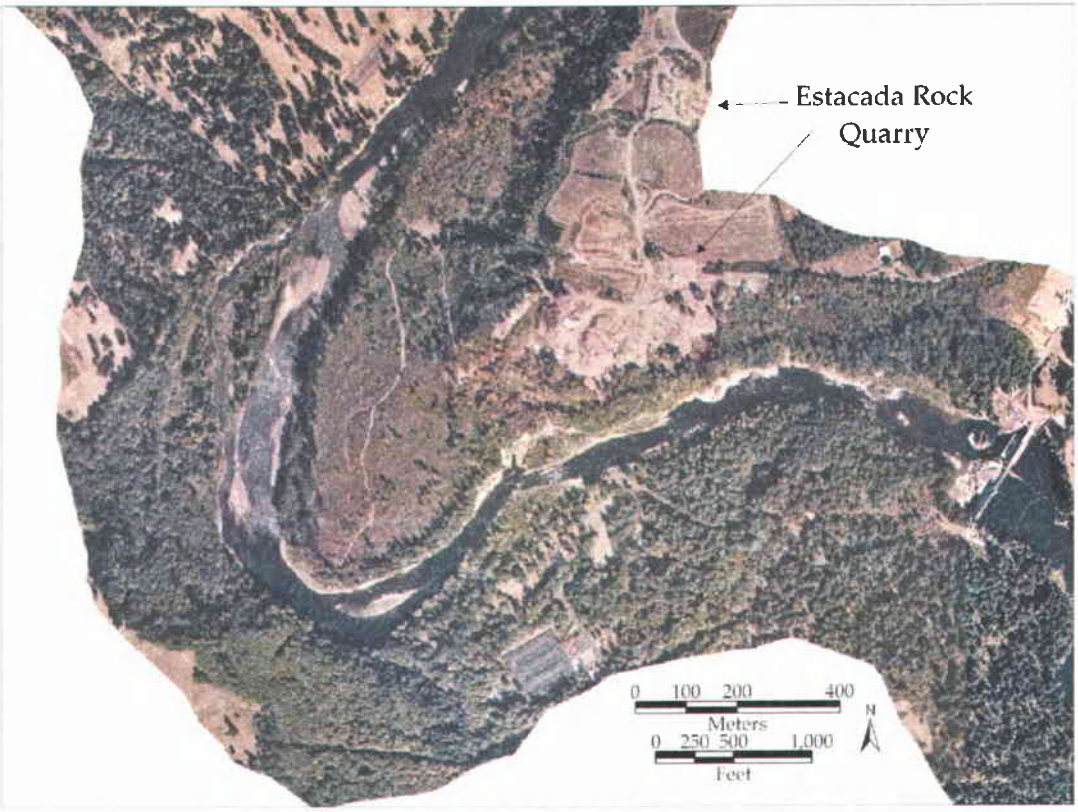

Figure 2.6 Aerial photo of Estacada Rock Quarry. River Mill Dam, built in 1911, can be seen in the right portion of the photo.

According to Estacada Rock personnel, later excavation hit SRM bedrock at approximately 5 m below the present quarry floor (~ 340 ft AMSL; NAVD88 datum). The total thickness of the combined Qt_2 and Qt_3 terraces at this location is approximately12 m.

Terraces are best preserved at two locations along the lower Clackamas River: RM 13 below Barton; and just below River Mill Dam near McIver Park (RM 21-22) (Figure 2.3). Preferential preservation near River Mill Dam is likely due to the geomorphic transition that occurs at this location. The river expands from a confined valley into a wide valley

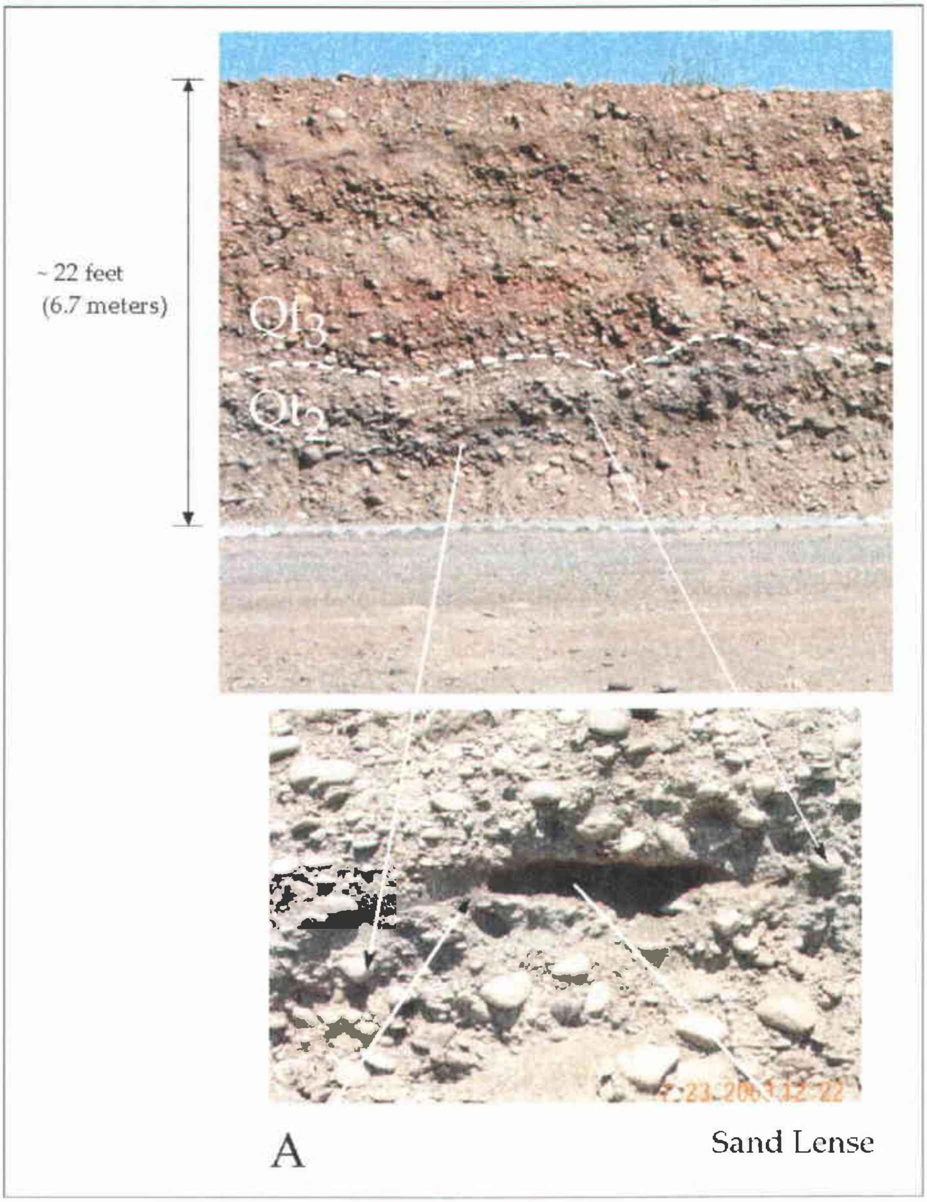

Figure 2.7 Estacada Rock quarry face. The contact between Qt_2 and Qt_3 is delineated by the oxidation change. A ^{14}C sample was collected from the sand lens in Qt_2 indicated by A.

resulting in reduced flow competence, periodic aggradation, and increased accommodation/ preservation space. It is unclear why terrace preservation is prominent below Barton. Detailed descriptions of geologic and geomorphic units can be found in Appendix C.

In order to correlate terrace surfaces, modern water surface elevation and the elevation of the midpoint of each terrace remnant were recorded at each valley kilometer. The gradient of the modern river is 0.0029 and the two most extensive terraces, Qt$_2$ and Qt$_3$, have slopes of 0.0043 and 0.0050, respectively (Figure 2.8, Table 2.2).

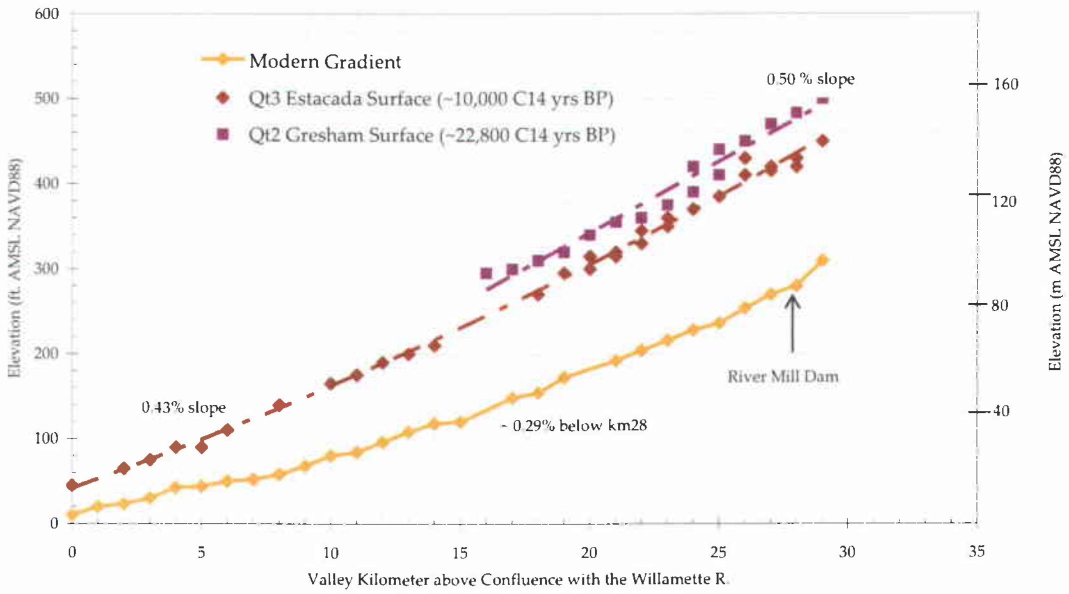

Figure 2.8 Correlation of Qt$_2$ and Qt$_3$ terraces along the lower Clackamas River.

Table 2.2 Terrace ages, heights, slopes, and incision rates along the lower Clackamas River.

Geomorphic Unit	Height[b] Above Modern River (m)	Terrace Age (Cal yrs BP)	Terrace age (^{14}C yrs BP)	Surface Area Preserved (km^2)	Approximate Slope	Incision Rate[a] (mm/yr)
Qal	0	Modern	modern	12.8	0.0024	
Qt_{10}	4	600 ± 83	650 ± 70; 680 ± 40	2.3	0.0090	6.67
Qt_9	5	No Data > 600 and < 960	no data	<5	Insufficient Data	
Qt_8	6	960 ± 23	1,120 ± 40; 1,139 ± 37	0.7	0.0157	6.25
Qt_7	13	No Data > 1,000 and < 11,000	no data	<.5	0.0110	
Qt_6	23		no data	<.5	0.0031	
Qt_5	31		no data	<5	0.0036	
Qt_4	35		no data	<5	0.0078	
Qt_3	46	11,258 ± 83; 11,934 ± 380	10,180 ± 60; 9,870 ± 50	45.2	0.0050	3.92
Qt_2	57	22,840 ± 130	22,840 ± 130	18.0	0.0053	2.47
Qt_1	108	> 22,840 ± 130	> 22,840 ± 130	3.1	0.0048	

[a] Calibrated ^{14}C dates were used to determine incision rates.
[b] Height is measured from the top of the terrace surface (tread).

2.6 Discussion

Missoula flood silts are absent from most terraces along the Clackamas River. This is consistent with carbon dating that indicates most Clackamas River terraces post-date Missoula floods. Missoula deposits were presumably eroded away from Holocene floodplains in the lower Clackamas Basin during lateral planation and Qt_3 terrace deposition.

2.6.1 Holocene Incision Rates and Patterns

Holocene terraces along the lower Clackamas River, such as the Qt_3 (Estacada) and the Qt_2 surfaces are very wide and composed of thick alluvial fill. Terrace width is largely controlled by the length of time that lateral planation is greater than vertical incision, and is a measure of the size and duration of climate change (Hancock and Anderson, 2002). This suggests Qt_2 and Qt_3 aggradation events were larger and of greater magnitude than younger Holocene aggradation events. Holocene strath terraces are inset into older fill terraces, suggesting incision has been greater than lateral planation since the beginning of the Holocene. The lower Clackamas River experienced alternating periods of aggradation, meandering, braiding, and valley widening; followed by periods of reduced sediment supply, during which the river degraded and incised into its floodplain and the underlying bedrock.

Terrace ages and elevation differences between the modern and historic floodplain surfaces indicate that the Clackamas River has experienced rapid incision over the last 10,000 years (3.9 mm/year). Incision measured from the tread of a 22,800 year-old terrace is approximately 2.5 mm/year. This suggests the rate of incision has increased in the last 10,000 years. Incision rates over the last 650 years are roughly 3 times the rate near the end of the last glacial maximum (Table 2.2). Elevation differences between the 10,000 year-old Estacada Surface and the current river bed suggest long-term incision is greatest near the present location of River Mill Dam and decreases downstream.

2.6.2 *Implications for Holocene Climate Change*

The modern Clackamas River has a meandering, braided, and locally anabranching form. Based on the slope, lateral extent, ages and stratigraphy of Qt_3 and Qt_2 terraces, these abandoned floodplains were braided channels receiving sediment supply beyond the transport capacity of the river at that time. Radiocarbon dates and terrace stratigraphy suggest that the Clackamas River experienced valley aggradation during the last glacial maximum (LGM) to form the fill terrace referred to as Qt_2. A change to warmer conditions and reduced sediment flux at the end of the LGM resulted in incision. Subsequent aggradation and lateral planation roughly 10,000 years ago resulted in the formation of Qt_3 fill-cut terrace inset into Qt_2. Since the abandonment and incision of the Qt_3, the Clackamas River has experienced incision interrupted by brief periods of aggradation resulting in strath terraces (Figure 2.9).

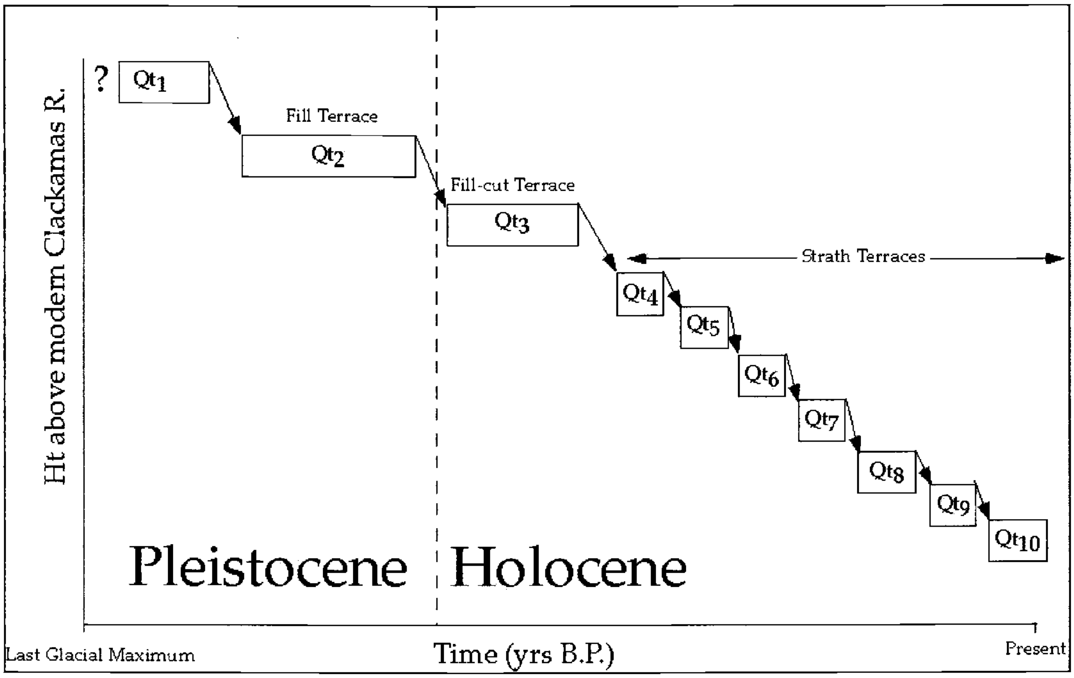

Figure 2.9 Digrammatic representation of terrace formation along the lower Clackamas River since the last glacial maxium.

Conditions that would favor the formation of fill terraces Qt_2 and Qt_3 would be high stream power combined with high sediment flux from the upper watershed. Both of these conditions would likely have been present during periods of glacial advance in the Cascade Mountains. Carbon dating for this study lacks sufficient resolution to determine whether aggradation is associated with periods of cold climate (Porter et al., 1992; Nott et al., 2002) or periods of transition between climate cycles (Rumsby and Macklin, 1996).

Dates from the Qt_3 terrace suggest that this surface may have formed during the warming after the Younger Dryas cold event. Since the Younger Dryas, incision and valley narrowing have been the dominant processes along the lower Clackamas River with periods of aggradation. Unpaired strath terraces, preserved on a slowly migrating meander bend, at approximately RM 21 provide an excellent example of Holocene incision and aggradation (Figure 2.10).

The preservation of numerous terraces suggests that during the Holocene, the Clackamas River historically operated and continues to operate near the critical threshold of stream power (Bull, 1979). Lateral erosion and valley widening are most prominent during times when stream power and critical stream power are in balance and sediment flux is high. Wide terraces, such as Qt_2 and Qt_3, represent relatively long periods of increased sediment load and aggradation, whereas younger terraces likely represent minor hiatuses in an overall trend of decreasing steam power and the sediment flux.

2.6.3 *Fluvial Response to Millennial-Scale Climate Variability*

Clackamas terrace Qt_3 correlates well with the global cooling referred to as the Younger Dryas which occurred about 11,500 years ago.

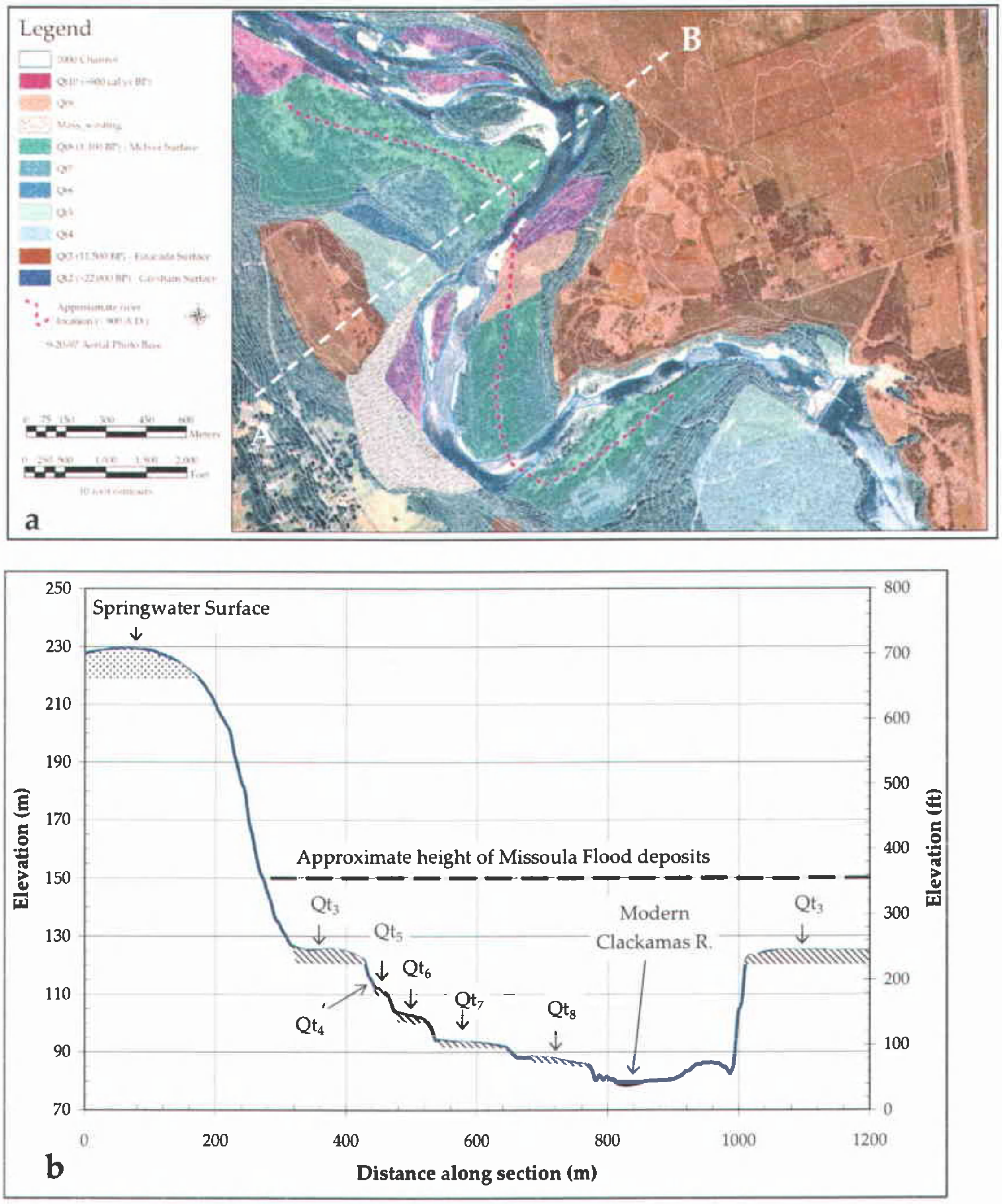

Figure 2.10 a. Terraces in the vicinity of McIver Park. b. Profile A-B of Holocene terraces.

The number of terraces preserved at McIver Park matches the number of climate cycles described for Europe (Starkel, 1991) and modeled by (Campbell et al., 1998) (Figure 2.11).

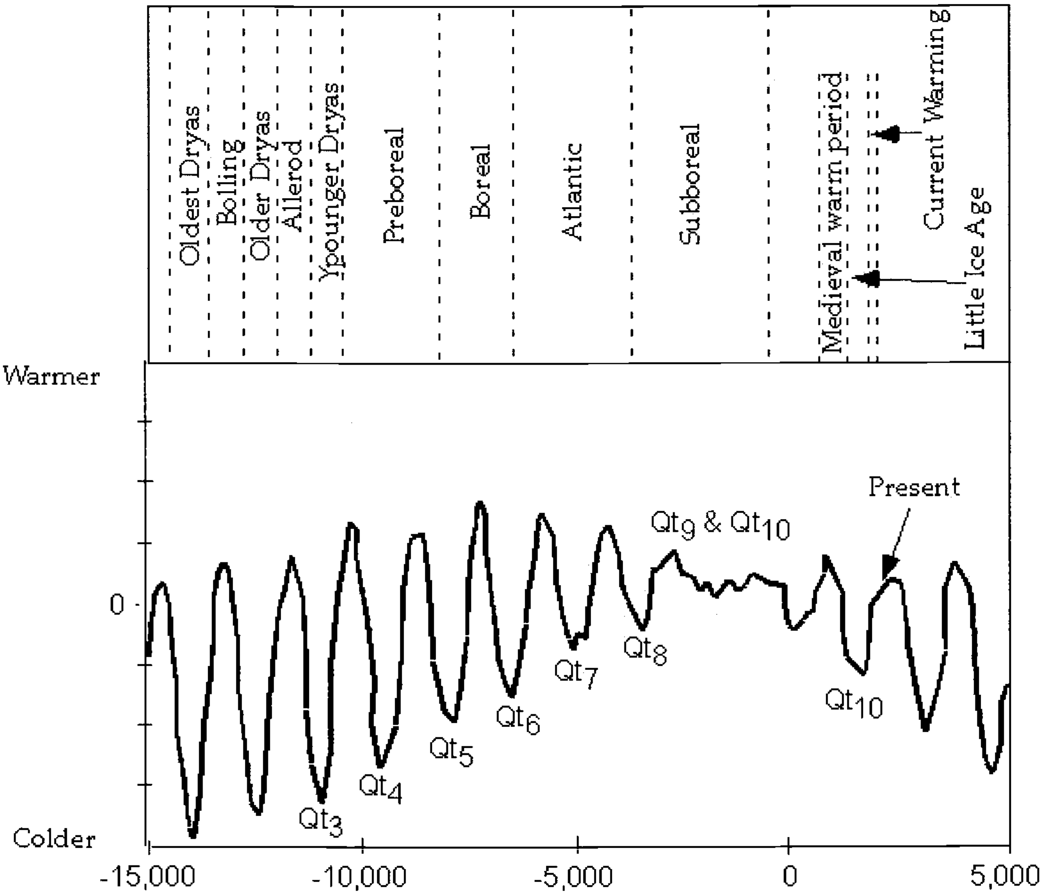

Figure 2.11 Modeled climate cycles which may correlate with Clackamas strath terraces (modified from Campbell et al., 1998).

Steadily decreasing valley widths suggest the severity of the climate episodes has steadily decreased along the Clackamas River since at least the Older Dryas cold period. This is consistent with the pattern observed on the Clackamas River of systematic incision punctuated by periods of aggradation. Periods of aggradation occur during glacial episodes or transitions between climate modes, and incision occurs during warm-dry periods.

Widespread aggradation during the Younger Dryas in the Willamette Valley (O'Connor et al., 2001); the Coast Range of Oregon (Personius, 1993); and the Olympic Mountains of Washington (Wegmann and Pazzaglia, 2002) suggests a regional rather than a local aggradational trigger.

2.6.4 *Rapid Incision Mechanisms*

Holocene incision rates for the Clackamas River are roughly an order of magnitude greater than other rivers draining the Cascade Mountains (Figure 2.12). Since Holocene incision rates are high only for the Clackamas River, it is logical to assume that the mechanism that is causing the incision is restricted to the Clackamas Basin. This eliminates sediment flux changes related to regional climate or weather patterns that would have affected other Western Cascade rivers.

The geology and geomorphology of the lower Clackamas Basin differs from other Western Cascade river basins in that: 1) bedrock consists of SRM, which is widespread and highly erodible; 2) young volcanic rocks (Boring lavas) were emplaced within a short distance of the mouth of the river; 3) the river has eroded a deep gorge into Columbia River Basalt for 10's of river kilometers in the central portion of the Clackamas Watershed; 4) the mouth of the Clackamas River enters the Willamette River downstream of the prominent bedrock knick point at Willamette Falls; and

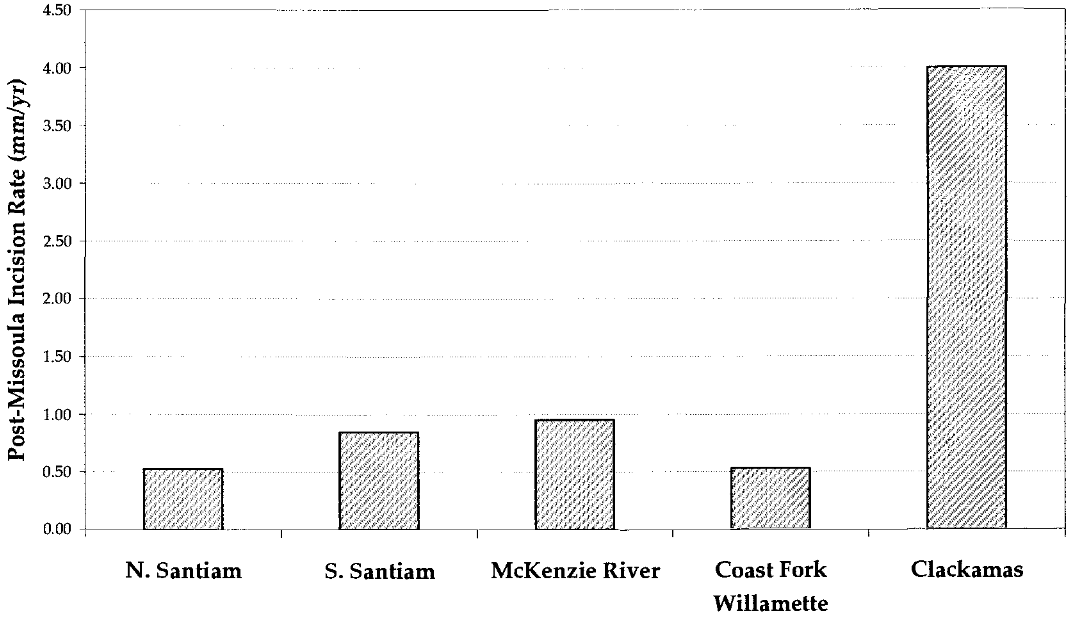

Figure 2.12 Post-Missoula flood incision rates as measured from terrace treads for rivers draining the Cascade Mountains, based on Holocene terrace mapping and USGS topography (O'Connor et al., 2001).

5) the mouth of the Clackamas River joins the Willamette River at a location where there was abundant deposition of coarse-grained Missoula flood deposits.

Terrace Qt_3 tread height above the modern river increases from the mouth upstream, suggesting that the cause of the incision that generated the vertical offset is upstream or in the upper part of the lower basin. This makes changes near the mouth unlikely to be the cause of rapid incision. This leaves either the presence of Columbia River Basalt in the central portion of the watershed or bedrock erodility as most likely mechanisms.

The bedrock gorge eroded into Columbia River Basalt serves as an efficient transport reach for sediment generated in the Western Cascades portion of the watershed. Mass wasting in Fish Creek and Collawash basins has generated large amounts of sediment which can be efficiently transported to the lower basin and may explain, at least in part, high incision and erosion rates observed. However, bedrock erodibility is a more likely mechanism for rapid incision.

The fact that the SRM is highly erodible is demonstrated by: 1) rapid formation of flutes and potholes in newly exposed bedrock surfaces; 2) exposed boulders of SRM are quickly disaggregated into silt and clay; and 3) mass wasting features are common in SRM when vertical exposures are created by river erosion.

The highest observed incision rates occur near the contact between the SRM and the Miocene Sardine Formation, a volcanic breccia generally resistant to erosion. This is also the location of a prominent change in valley morphology from a confined channel to a wide valley. The presence of a wide valley is likely due to the contrast in geologic materials that occurs at this location. Softer bedrock allowed lateral planation during times of high sediment yield (Qt_2 and Qt_3) that provided more storage capacity for transported sediments. Sediments stored in alluvial fill terraces and perhaps in paleo-channels filled with alluvium are more easily eroded during times of decreased sediment yield and incision than if the bed were composed of durable bedrock, as is the case in many other Western Cascades rivers. This combination of bedrock erodibility and alluvial storage are the most plausible explanation.

2.7 Conclusions

Clackamas River terraces provide an excellent fluvial record of Holocene incision and decreased sediment flux since the last glacial maximum roughly 22,000 years ago. Holocene incision has been interrupted by at least six post-Younger Dryas aggradational phases. Although radiocarbon dates have been obtained for only two of the six aggradational events, the number of events and systematic reduction in severity are consistent with 1,500-year climate periodicity suggested by (Campbell et al., 1998) and (Bond et al., 1997; Bond et al., 1999). Additional carbon dating of Holocene terraces is planned and may provide a record of fluvial response to climate change extending the global pattern of millennial-scale climate variability to the Pacific Northwest. Additional dating may also provide a better understanding of the timing between climate oscillations and fluvial system response.

Holocene aggradation revealed by terraces along the Clackamas River may have implications for salmon populations in the greater Willamette Basin. Terrace heights near the mouth of the Clackamas River suggest that during the Younger Dryas, the bed of the Willamette River may have been as much as 50 feet higher than the modern height. This amount of alluvium would be sufficient to overwhelm and cover the basalt knick point at Willamette Falls, allowing anadromous fish to pass Willamette Falls unhindered and utilize the upper Willamette Basin for spawning.

2.8 Acknowledgements

A special thanks go to the owners and operators of Estacada Rock Products for the use of their equipment and access to the quarry. Jim O'Connor's sharp eyes found small bits of carbon in large river terraces. I also appreciate discussions with Ian Madin, who shared geologic information on the area.

3 A MEANDER CUTOFF INTO A GRAVEL EXTRACTION POND, CLACKAMAS RIVER, OREGON

Peter J. Wampler[†], E. Frank Schnitzer[§], Doug Cramer[‡],
Chris Lidstone[ⅅ]

† Department of Geosciences, Oregon State University, Corvallis, OR 97331
§ Oregon Department of Geology and Mineral Industries, Albany, OR 97321
‡ Portland General Electric, Estacada, OR 97023
ⅅ Lidstone and Associates, Fort Collins, CO 80525

To be submitted to Environmental Geology.

3.1 Abstract

The River Island mining site is located at approximately river mile (RM) 15 on the Clackamas River, a large gravel-bed river in northwest Oregon. During major flooding in February 1996, rapid channel change occurred. In a matter of hours, the river cut off a meander and began flowing through a series of gravel pits located on the inside of a meander bend. The cutoff resulted in a reduction in reach length, between RM 13 and 16, of approximately 1,100 m. At River Island, the natural process of meander cutoff was slowed by dike construction, and then accelerated by erosion into gravel extraction ponds on the inside of a meander bend.

Erosion by knick point retreat and lateral erosion of upstream river banks was dramatic and rapid. Within two days of the peak flow, 3.5 hectares of land and 105,500 m^3 of gravel were eroded from the river bank just above the cutoff location. Much of this gravel moved a short distance downstream into the excavation. Reach slope increased from 0.0022 to approximately 0.0035 in the cutoff reach. Since 1996, the knick point from the meander cutoff has migrated 2,292 m upstream, resulting in increased bed load transport, incision, and rapid lowering of the water table, causing some riparian trees to die.

In 1993, prior to the meander cutoff, transects were surveyed in the River Island reach upstream of the cutoff location. Resurvey of these transects and aerial photo analysis indicates that 96% of the knick point migration occurred during the first winter following meander cutoff. The average knick point migration rate for seven years is 287 m/yr.

Water temperature data suggests that thermal changes resulting from extraction pond incorporation into the river are minimal. Temperature changes will likely decrease over time as ponds are isolated from active river flow by gravel bar deposition.

Fish netting in spring 2002, suggests that salmonid use of the pond in the spring is minimal. The most abundant native species netted were large-scale sucker and northern pikeminnow. The most abundant non-native species netted was brown bullhead.

This paper examines the physical and biological changes that have resulted from the meander cutoff and the implications for mining in the channel migration zone of large gravel-bed rivers.

3.2 Introduction

An avulsion is a lateral migration or cutoff of a river. It involves the diversion of water from the primary channel into a new channel that is either created during the event or reoccupied. Avulsions may be rapid or take many years to complete (Slingerland and Smith, 2004). Meander cutoff is a specific type of avulsion where channel length and sinuosity are reduced through lateral erosion of the neck on the inside of a meander bend (Allen, 1965). Channel migration and meander cutoff are natural processes that create aquatic habitat, off-channel refuge, and rejuvenate riparian species. Avulsions are typically related to aggrading systems, such as braided rivers (Ashworth et al., 2004), alluvial fans (Brizga and Finlayson, 1990), anastomosing rivers (Tornqvist, 1994), deltas (Smith et al., 1989;

Stouthamer and Berendsen, 2000); and meandering systems (Slingerland and Smith, 1998).

Channel avulsions are more likely to occur in channels with slope, discharge, and width near the threshold between meandering and braided patterns (Leopold and Wolman, 1957; Gilvear, 1999). The threshold for discharge is related to available stream power and the ability of the stream channel to carry available sediment. River reaches where meandering and cutoffs occur are typically locations where sediment supply exceeds the available stream power for sediment transport (Thompson, 2003).

In-stream and floodplain gravel extraction can result in increased likelihood of avulsions (Collins and Dunne, 1990). Predicted impacts for in-stream, floodplain, and channel migration zone extraction ponds that become part of the channel through avulsion or meander cutoff, include: 1) bed lowering (incision or degradation) upstream and downstream of the extraction site and related scour adjacent to bridge supports, pipelines, or other structures; 2) changes to channel bed morphology and exposure of bedrock; 3) lowering of the water table and loss of riparian vegetation; 4) reduction in flood height for a given frequency due to bed lowering; 5) reduction of floodplain sedimentation; and 6) increase in lateral erosion of river banks.

Impacts from gravel pit avulsions typically viewed as positive include: 1) increase in side-channel refuge and habitat for juvenile salmonids; 2) introduction of sediment and large wood through lateral erosion; and 3) increase in overall edge habitat and channel complexity

(Peterson, 1982a; Swales and Levings, 1989; Bayley, 1995; Minakawa and Kraft, 1999; Bayley et al., 2001; Bell et al., 2001).

The use of the River Island site for gravel extraction has been controversial virtually since mining began. Controversial aspects of mining the site included potential downstream impacts and dike construction to protect the site from flooding which blocked secondary channels and directed the river into a single channel. In 1974, a local ordinance was struck down by the courts which would have resulted in closure of the mine site.

Mining at River Island has included both in-stream and floodplain mining. In-stream, or in-channel, mining is defined in Oregon statutes as mining within the beds and banks of the stream or river. This is typically interpreted as mining below the elevation of the ordinary high-water mark. Floodplain mining is considered "upland" extraction in Oregon and is defined as mining above the ordinary high-water mark. The term "upland" refers to mining within the 100-year floodplain, and terraces adjacent to rivers, and areas not near rivers. Both in-stream and floodplain mining can result in similar geomorphic changes.

The availability of pre-meander cutoff survey data at the River Island site provides a unique opportunity to evaluate a meander cutoff into a gravel extraction pond and resulting changes to river geometry, sediment transport, temperature, habitat, and channel form.

3.3 Geologic Setting and Site Location

The Clackamas River has a drainage area of 243,460 hectares, and traverses three distinct physiographic provinces in its 97 km course from Timothy Lake to the Willamette River at Oregon City (Figure 3.1). The River Island reach is located between RM 13 and 17.

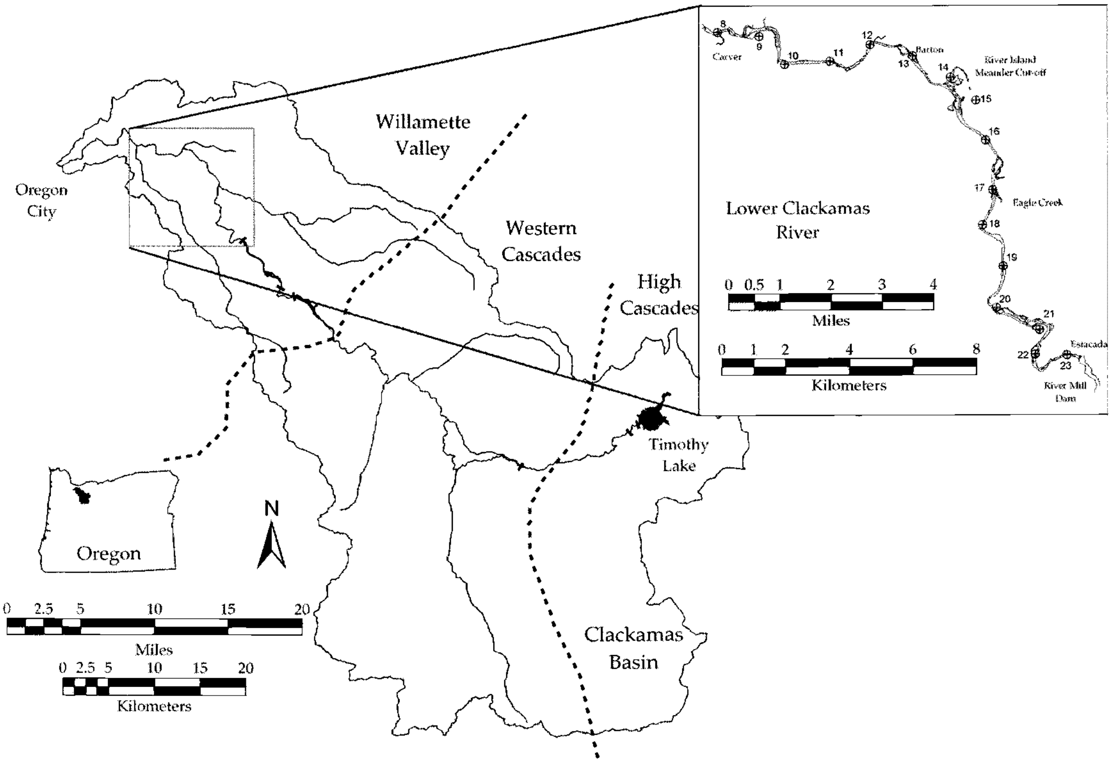

Figure 3.1 Location map for the Clackamas Basin and River Island meander cutoff.

The headwaters in the High Cascades provide the river with a relatively constant supply of cold, clean water throughout the year. As the river enters the Western Cascades, it encounters a deeply eroded volcanic landscape with numerous landslides and high sediment yield. Near

Estacada, the river emerges from a confined canyon into a broad valley, which is part of the Willamette Valley physiographic province. As it travels, geomorphic processes are altered by human activities such as dam construction, in-stream and floodplain mining, bank protection, riparian removal, and bridge construction.

Throughout the Pleistocene, the lower Clackamas River accumulated sediment generated in the Western and High Cascades, including glacial outwash from Cascade glaciers and mass wasting processes. Dramatic climate fluctuations, advance and retreat of glacial ice in the Cascade Mountains, and changes in sediment yield from the upper Clackamas Basin have generated alternating periods of aggradation and incision in the River Island reach (Wampler, 2004). Systematic incision since the last glacial maximum has resulted in the preservation of floodplain remnants, known as terraces.

Bedrock in the vicinity of River Island is the Sandy River Mudstone (SRM) (Trimble, 1963). The SRM is a silty, volcanic mudstone that was deposited in a lake environment and is easily eroded once exposed to fluvial processes to form flutes and potholes. The lower Clackamas River is constrained in many reaches by steep cliffs of SRM due to Holocene incision.

The lower Clackamas River exhibits a combination of channel forms including meandering, braided, and anabranching reaches. The River Island reach has historically had multiple channels and exhibited dynamic river behavior in some sub-reaches while remaining quite fixed in others (Figure 3.2). This pattern reflects longitudinal changes in transport

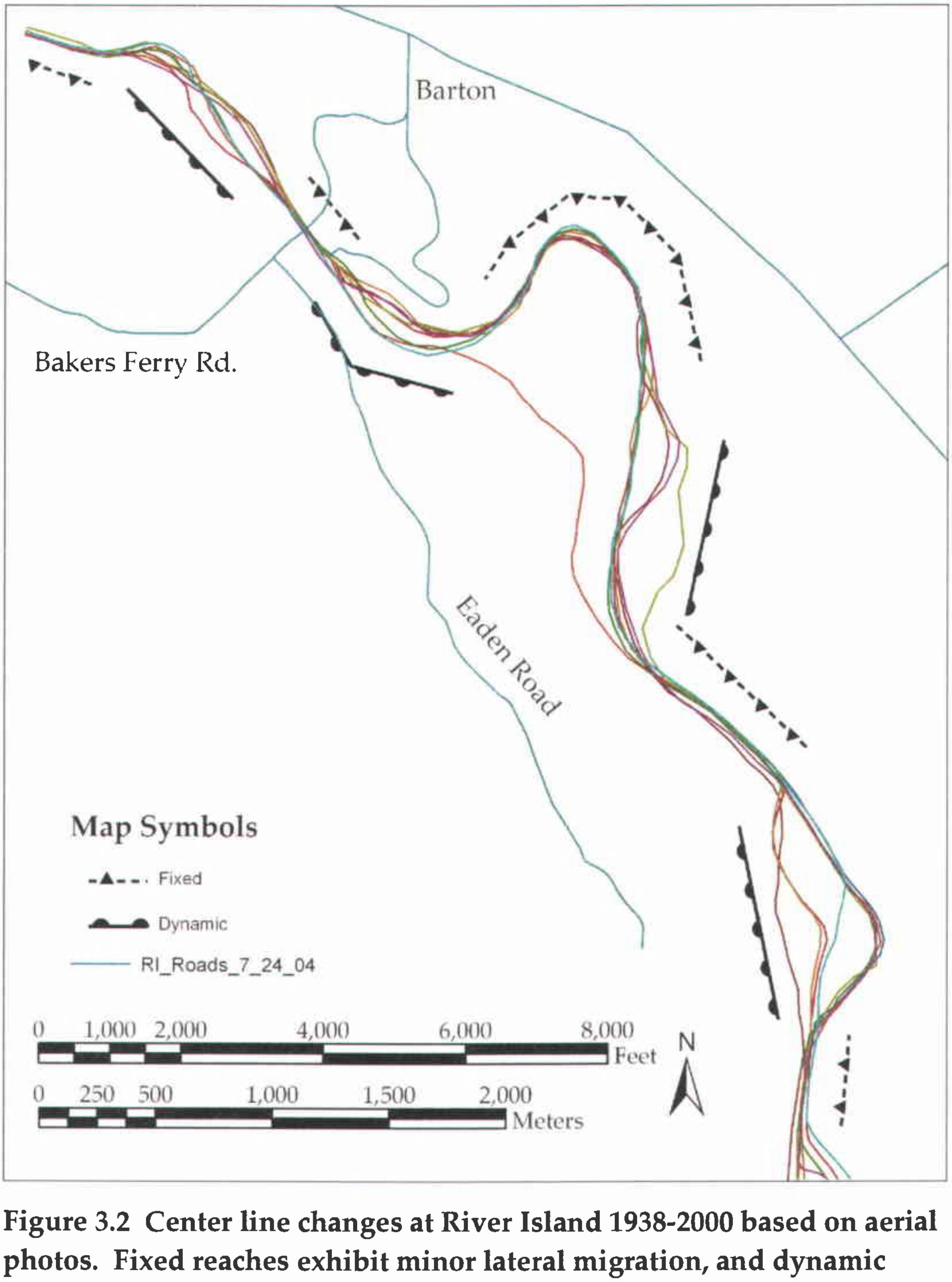

Figure 3.2 Center line changes at River Island 1938-2000 based on aerial photos. Fixed reaches exhibit minor lateral migration, and dynamic reaches exhibit avulsions and lateral erosion.

efficiency. Incised straight reaches and the outside of many meander bends are confined and more capable of transporting available sediment. Expansion into unconfined reaches results in decreased transport capacity, sediment deposition, and channel migration. Channel plan form area and length have decreased systematically from 1938 to 2000 in the River Island reach (Figure 3.3).

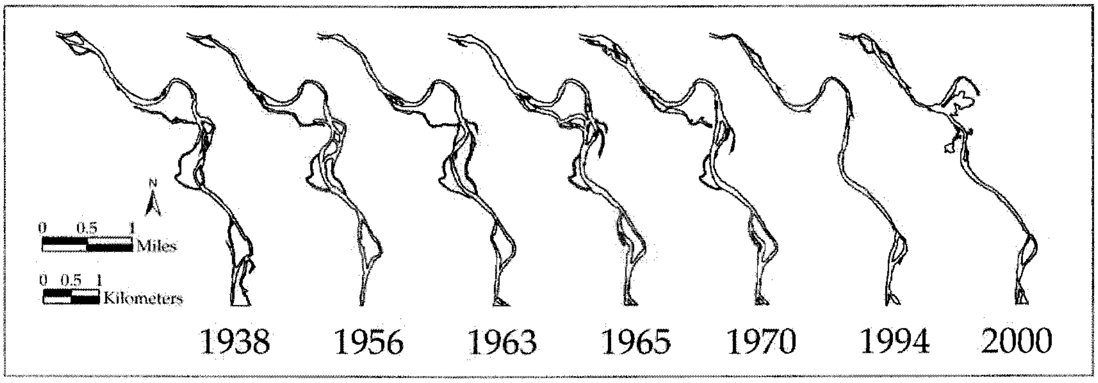

Figure 3.3 Historic channel plan form changes in River Island reach 1938-2000, based on aerial photos.

3.4 Mine History at River Island

Total aggregate production from the River Island site between 1967-1996 was approximately 2.7 million cubic meters (Table 3.1).

The Oregon Division of State Lands (DSL), formed in 1967, regulates in-stream mining in Oregon. According to DSL records, mining first began on the site in 1966 (Harbert, 1975), although aerial photos from 1963 suggest that at least some mining in the cutoff channel and the adjacent main channel were occurring at that time. Flow of water through the meander cutoff channel is evident in historic aerial photos even during low flow

Table 3.1 Aggregate production from the River Island mining site.

Years of Activity	Mining Type	Permitting Authority	Average Annual Production (yd^3)	Average Annual Production (m^3)
1960's-1967	In-stream	None	Unknown	Unknown
1967-1972	In-stream	Division of State Lands	150,000	115,000
1972-1978	Floodplain	Department of Geology and Mineral Industries	112,500	86,000
1979-1990	Floodplain	Clackamas County	161,000	123,000
1991-1999	Floodplain	Department of Geology and Mineral Industries	66,700	51,000
Total Estimated Production 1967-1996[a]			**3,500,000**	**2,676,000**

[a] Total production does not include years during which production was not known: 1973-74, 1979, and prior to 1967.

periods. This gave rise to the term "River Island" when referring to the meander bend (Figure 3.4a). River bank protection and dike construction began in 1967, with the construction of a 74.4 meter-long dike to prevent the river from utilizing the cutoff channel during floods. The dike was extended 30 m in 1968, 137 m in 1969, and 366 m in 1971 (total length 777 m) (Figure 3.4b). Prior to diking, at least 30-40% of the river was flowing in the cutoff channel (Harbert, 1975).

Early interactions between the mining company and the DSL were contentious, and resulted in legal action over permit requirements. In 1972, miners reported that annual in-stream gravel removal volumes were averaging 110,000 m^3 (150,000 yd^3). In 1973, an on-site evaluation by DSL determined that mining was also occurring outside of DSL jurisdiction on the adjacent floodplain, within the meander bend, and behind the dike completed in 1971.

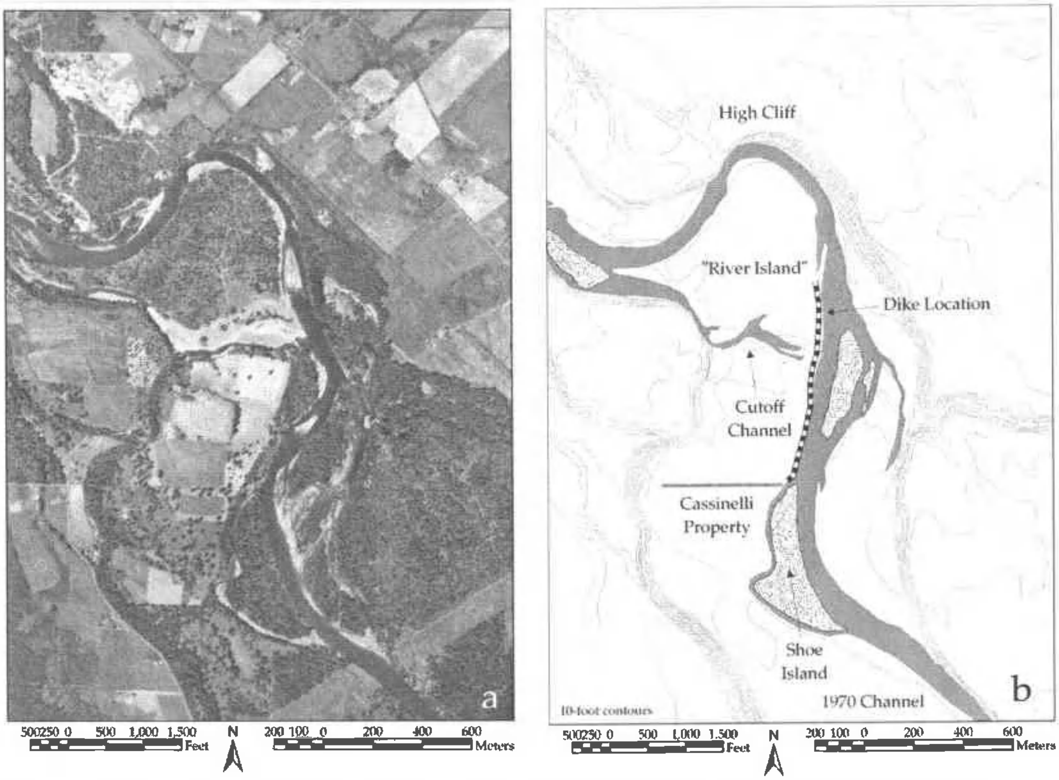

Figure 3.4 a. Aerial photo taken June 17, 1963. b. Detailed site map showing the configuration of the site after dike construction.

In Oregon, zoning and conditional use of land for mining of floodplains is decided by the local land use authority, usually either the city or county planning department. In 1972, the Department of Geology and Mineral Industries (DOGAMI) became the agency responsible for reclamation of floodplain mineral extraction sites. A permit application for floodplain mining at River Island was filed in 1972.

The 1972 mining legislation allowed certain operations, including the River Island site, to remain exempt from regulation and reclamation, and continue site expansion until 1981. From 1979 through 1990, Clackamas County Planning Division regulated the upland mining on behalf of DOGAMI. In 1984, Clackamas County approved a site reclamation plan for 16 of the 160 acres within the 100-year floodplain for the creation of a 4 to 8 m deep pond. The dike, designed to withstand a 100-year flood, ended at the upstream boundary with the Cassinelli property (Figure 3.4b) and no plan or strategy was in place to handle floodwater entry along the upstream property boundary. The Cassinelli property was acquired by the mining operator several years prior to the meander cutoff.

3.5 Methods

Two sets of pre-cutoff channel transect data were available for the River Island reach: Federal Emergency Management Agency (FEMA) flood study transects surveyed in 1979, and a resurvey of selected FEMA transects in 1993. A LEICA 850L total station was used in combination with control points established with a Trimble 4500RTK GPS to resurvey the 1993 and 1979 transects. Gravel bar elevations and pond depths were surveyed periodically to determine transport volumes.

In order to evaluate fish use at the River Island site during the spring, a fish net was deployed between March 6 and June 19, 2002. Portland General Electric (PGE) fisheries biologists set a six-foot Oneida trap net in the northern River Island excavation pond. The trap net was deployed once or twice each month for a sampling period that varied from three to five days. The net was checked every day or every other day and, the trap was removed at the end of the period. Fish captured were identified by species, their length was measured, and then they were released.

During the summer of 2000, seven HOBO temperature recorders were installed at the River Island site. In the main channel, probes were installed upstream and downstream of the meander cutoff in the active mixing zone and secured with concrete blocks. Three recorders were placed on the bottom of the southern pond. In 2001, three additional recorders were added in the northern pond. Complete daily average temperature data for all recorders can be found in Appendix D.

3.6 1996 Flood and Meander Cutoff

In January 1996, Oregon experienced unseasonably cold weather; and snow accumulations of several inches were present on the Willamette Valley floor. Snow pack for the Willamette River drainage was at 112% of average. On February 6th, a warm front, referred to as a "Pineapple Express," brought several days of warm, moist air from the western Pacific Ocean. Heavy rains and warm winds melted snow pack in the mountains to generate a "rain on snow" event, resulting in the flooding of many western Oregon rivers, including the Clackamas River.

The 1964 flood, referred to as the "Christmas Day Flood," is the yardstick by which most floods are measured in Oregon. Peak discharge on the Clackamas River on December 22, 1964, was 2,461 cms (86,900 cfs) at the Estacada gage (14210000), whereas a peak discharge of 1,951 cms (68,900 cfs) was recorded on February 7, 1996, at Estacada (Figure 3.4). Eagle Creek enters the Clackamas River above River Island, so discharge at the site would have been higher than reported at Estacada. Hydrographs for 1965 and 1996 water years at Estacada are plotted in Figure 3.5.

An aerial photo of the River Island site taken February 9, 1996, shows the extent of erosion and channel change that occurred during the peak of the 1996 flood (Figure 3.6). The mean daily discharge at Estacada for February 9, 1996, was 1,025 cms (36,200 cfs). No velocity measurements were made during the flood event; however, valuable information regarding hydraulic conditions during the flood can be derived from the 1996 aerial photo if several simplifying assumptions are made.

Standing waves are prominent in the flood photos taken February 9, 1996 (Figure 3.6: inset). The wavelength of standing waves can be used to estimate average velocity in bedrock channels (Kennedy, 1963; Tinkler, 1997). Portions of the channel at River Island were quickly stripped of alluvium and bedrock was exposed during the flood. The following equation can be used to estimate velocity of reaches where the wavelength of standing waves is known:

$$\lambda = \frac{2\pi \cdot \upsilon^2}{g} \qquad \upsilon = 1.2495 \cdot \sqrt{\lambda}$$

Where λ is the standing wave wavelength in meters; υ is the mean water velocity in m/s; and g is the acceleration due to gravity in m/s^2. The wavelength of standing waves visible in the inset for Figure 3.6 is approximately 15 m. This yields an average velocity of 4.9 m/s through this portion of the reach. This is reasonable, given the discharge 1,025 cms on

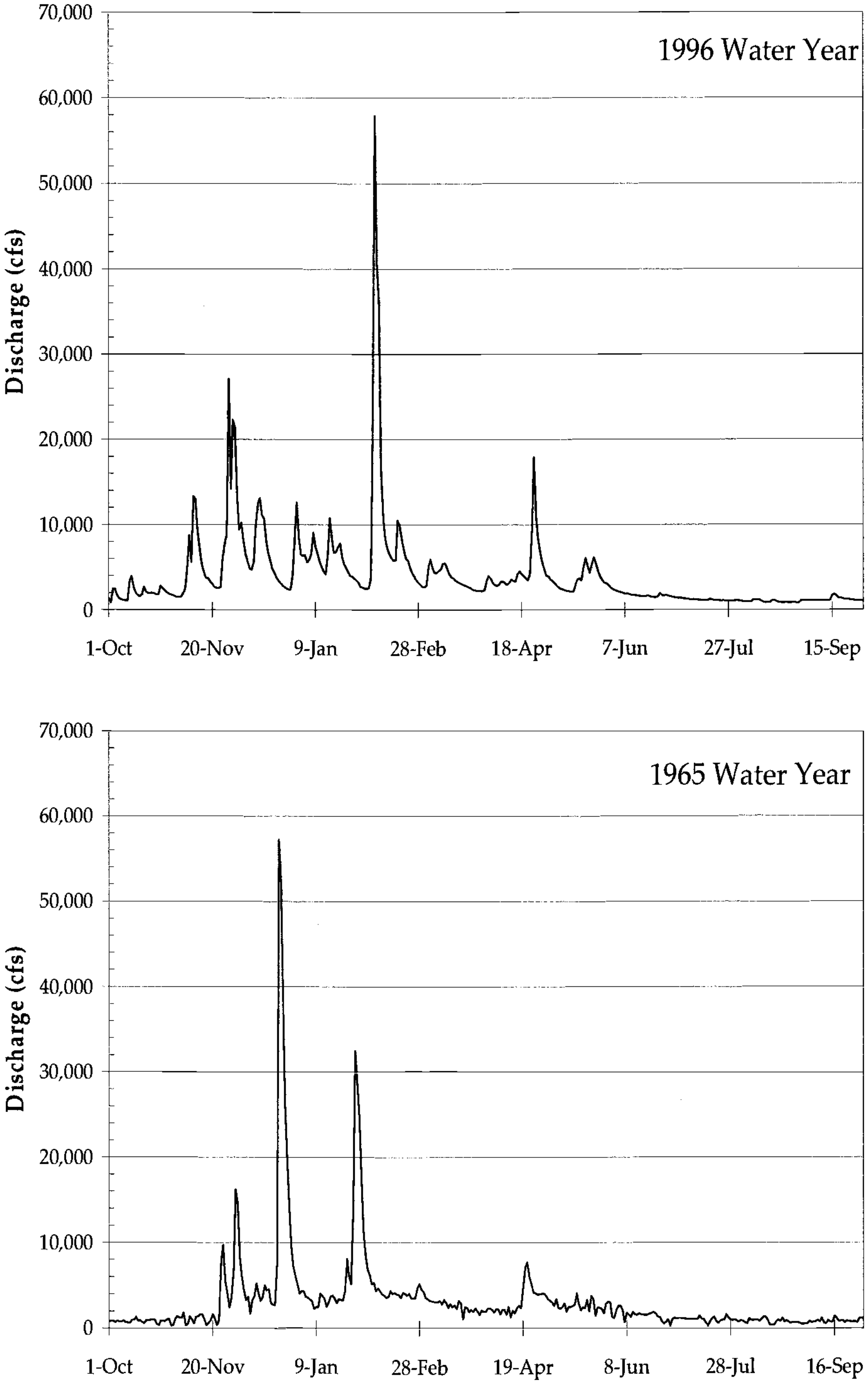

Figure 3.5 Hydrographs for the Estacada gage (14210000) showing mean daily flow for 1965 and 1996 water years.

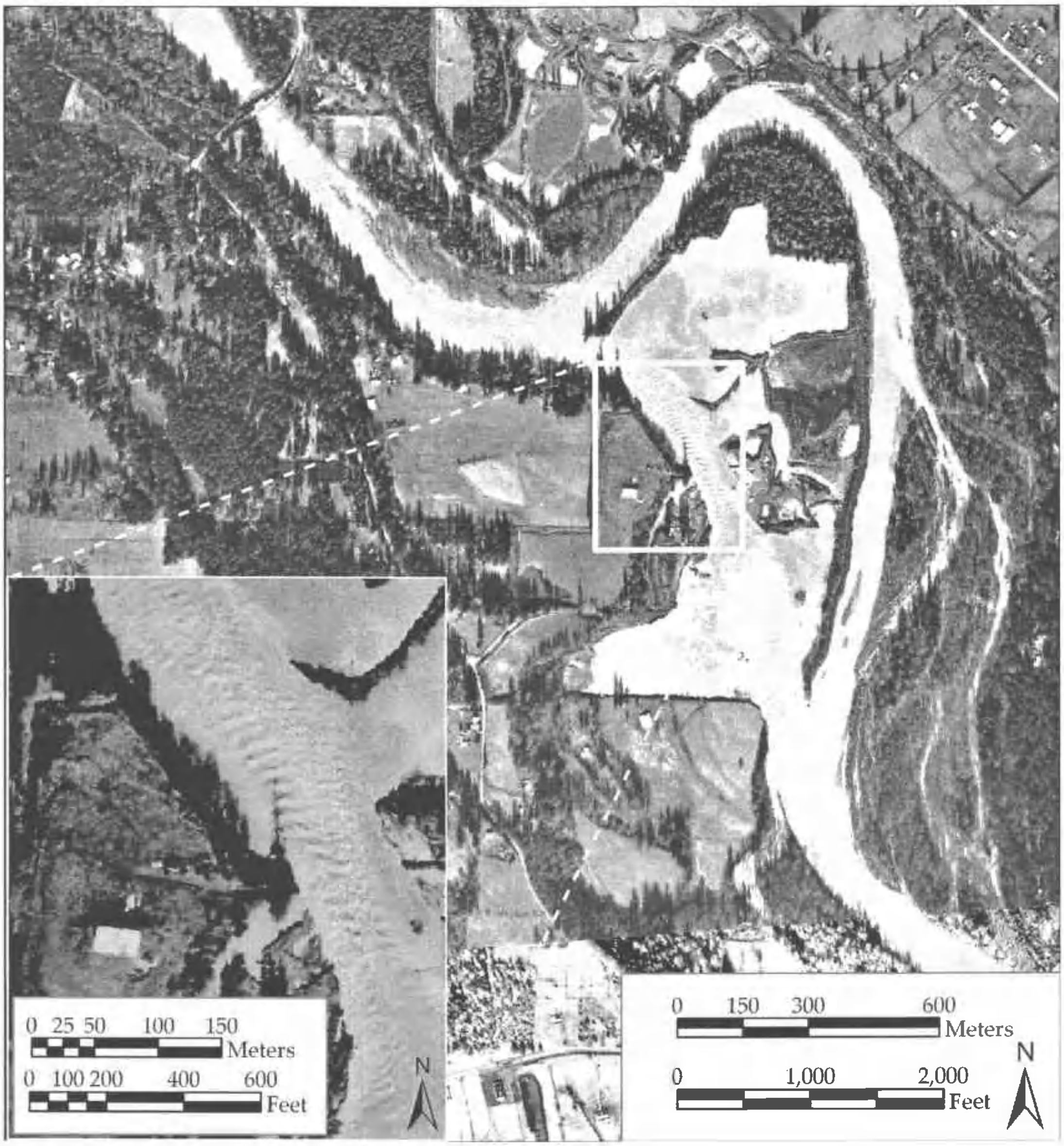

Figure 3.6 Aerial photo taken February 9, 1996. Mean daily discharge at Estacada was 1,025 cms (36,200 cfs). Note standing waves on inset image.

the day the photo was taken. Active channel width is approximately 61 m, channel area and depth can be estimated by:

$$Q = \upsilon \cdot A$$

Water depth of a rectangular channel would be approximately 3.4 m. Shear stress can be estimated in this reach through the equation:

$$\tau = \gamma \cdot R \cdot S$$

Where γ is the specific weight of water in N/m^3; R is the hydraulic radius (area/perimeter) in meters; and S is the energy surface slope (assumed to be roughly parallel to the bed slope). Based on the estimated velocity and depth, shear stress was approximately 10,000 N/m^2 in the location of the standing waves on February 9, 1996. This amount of shear stress is sufficient to mobilize even the largest boulders present in the bed and banks in the River Island reach and the angular boulders used to build the dike.

The river entered the site upstream of the dike (Figure 3.7). It is unclear whether flood waters entered from the Shoe Island channel or another topographic swale further west. As the water rose, a low point between the River Island site and the adjacent Cassinelli property allowed the river to flow around the upstream end of the dike and into the upstream excavation. Once the river began flowing over the 1.5H:1V slopes, it quickly eroded a knick point into the main channel and captured the majority of the flow of the Clackamas River.

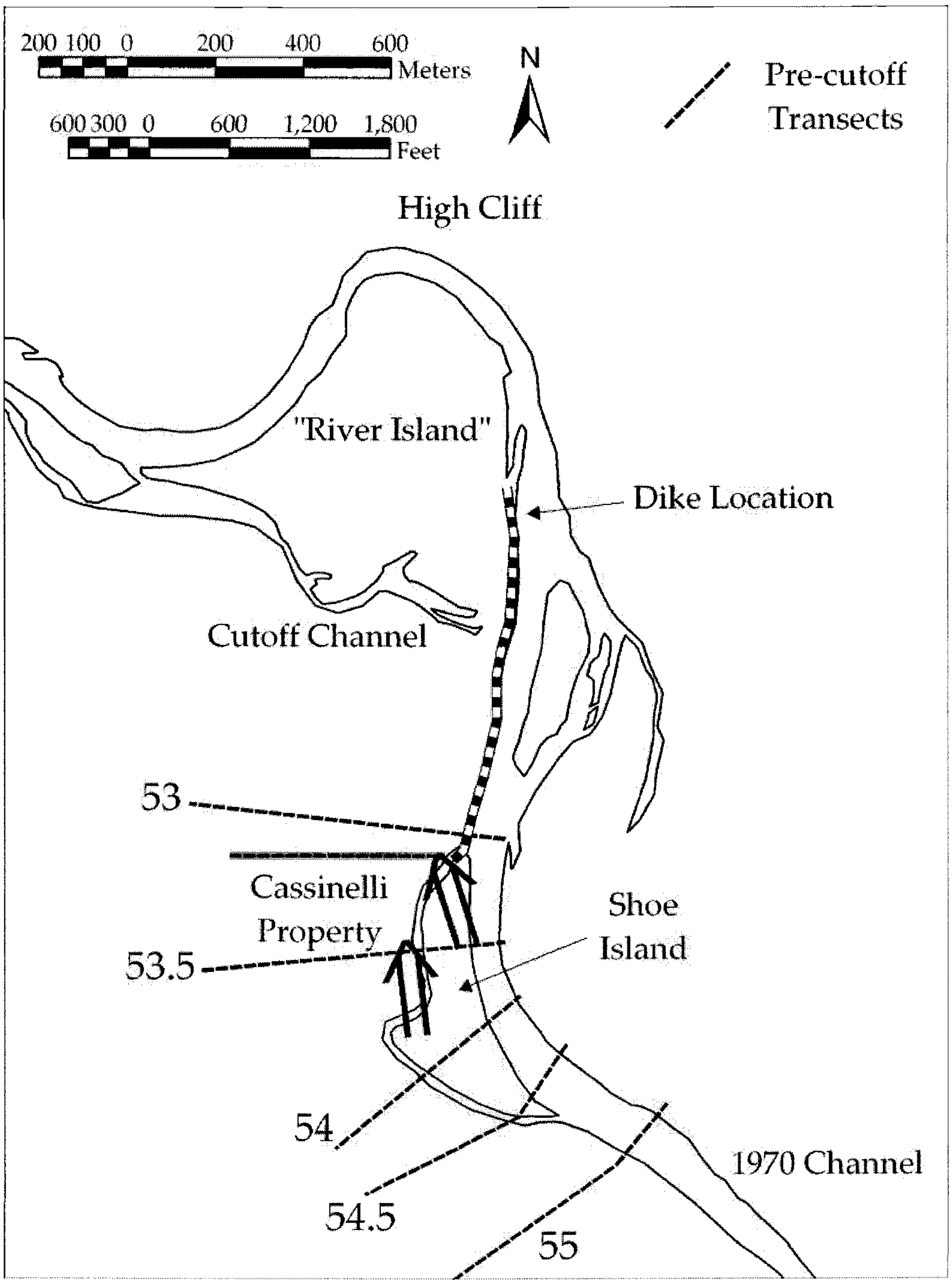

Figure 3.7 Flood routing map. Bold arrows indicate possible flood entry paths. Numbers refer to Section ID #'s found in Table 3.2.

3.7 Channel Geometry Changes

3.7.1 Knick Point Migration

Five channel transects were surveyed in 1993. These same transects were resurveyed in 1998 and subsequent years (Figure 3.7; Table 3.2).

Table 3.2 Transect survey data. Channel thalweg elevations are in feet relative to the 1988 North American Vertical Datum (NAVD88).

Distance Upstream of Barton Bridge (ft) Pre-cutoff	Distance Upstream of Barton Bridge (ft) Post-cutoff	Section ID#	DOGAMI_ID	1970	1979[a]	1993	1998[b]	2000	2001	2002	2003
0	0	47	DGA	138.6	138.6	ND[c]	ND	ND	143.0	142.7	ND
2138	2138	48	DGB	ND	151.5	ND	151.0	ND	151.0	151.4	ND
7506	4368	49	DGC	ND	163.4	ND	160.0	ND	158.5	159.8	ND
10220	6468	53[d]	DGD	ND	172.6	165.7	160.1	160.0	169.7	168.9	168.5
10990	7354	53.5[e]	DGE	ND	ND	174.3	171.4	173.1	173.0	173.7	173.5
11745	7954	54[f]	DGF	ND	177.6	175.8	174.5	173.3	173.3	173.4	173.6
12190	8519	54.5	DGG	ND	177.8	180.3	174.3	174.2	174.0	173.6	174.0
13040	9369	55	DGH	ND	178.1	181.9	175.9	ND	176.5	176.2	176.3
15072	11441	56_Upper	DGI	ND	ND	ND	ND	ND	178.1	178.2	179.1
15603	12001	57_FEMA_BS		ND	178.8	ND	ND	ND	177.6	ND	177.7

[a] FEMA flood study transects selected nearest to transect locations. Elevation is extrapolated where needed.

[b] Surveyed in both 1998 and 1999.

[c] No data available.

[d] Center line of the channel moved laterally ~ 685 feet west.

[e] 193 feet upstream of 1993 data and 2001 data is upstream of 1998-2000 by about 110 feet.

[f] 77 feet downstream from lines surveyed post-1996.

From transect data it is clear that the knick point migrated upstream quite rapidly. Ninety-six percent of the upstream movement of the knick point occurred during the winter of 1997, before the first set of survey data were collected on the transects in 1998. This is reflected in elevation decreases of 1 to 2 m on all transects.

No obvious knick point is visible in aerial photos taken February 9, 1996, just two days after the peak flow. However, the water level and turbidity were sufficiently high to make knick point identification difficult.

The 1998 transect survey shows a general bed lowering of 1 to 2 m; however, 1993 transects only extended approximately 884 m above the cutoff location. Based on aerial photo evidence, it is likely that the knick point had already migrated past all the 1993 sections prior to the 1998 survey. With the exception of the lowermost transect, thalweg elevations have been relatively static since 1998. Transect 53 near the upstream end of the cutoff channel aggraded 3 m between 2000 and 2001. This represents a bed elevation of 1.2 meters higher than was measured in 1993, prior to the meander cutoff. This localized aggradation is probably due to downstream transport and deposition of alluvium in the gravel ponds.

An aerial photo taken July 7, 1996, shows a prominent knick point 274 m upstream of the cutoff location. Upstream of the knick point, channel width increased from 46 to 82 m (Figure 3.8). By April 1997, following a winter with three sizable flood events, an aerial photo showed that the knick point had migrated 2,195 m upstream of the cutoff location (Figure 3.9). The average annual rate of knick point migration is 287 m/year although, as mentioned above, the majority of knick point migration occurred during the winter of 1997.

Riparian vegetation response to the upstream migration of the knick point is striking. Alder trees on the north bank hundreds of feet upstream of the cutoff have died, presumably as a result of rapid lowering of the water table, as the knick point migrated upstream and the bed incised.

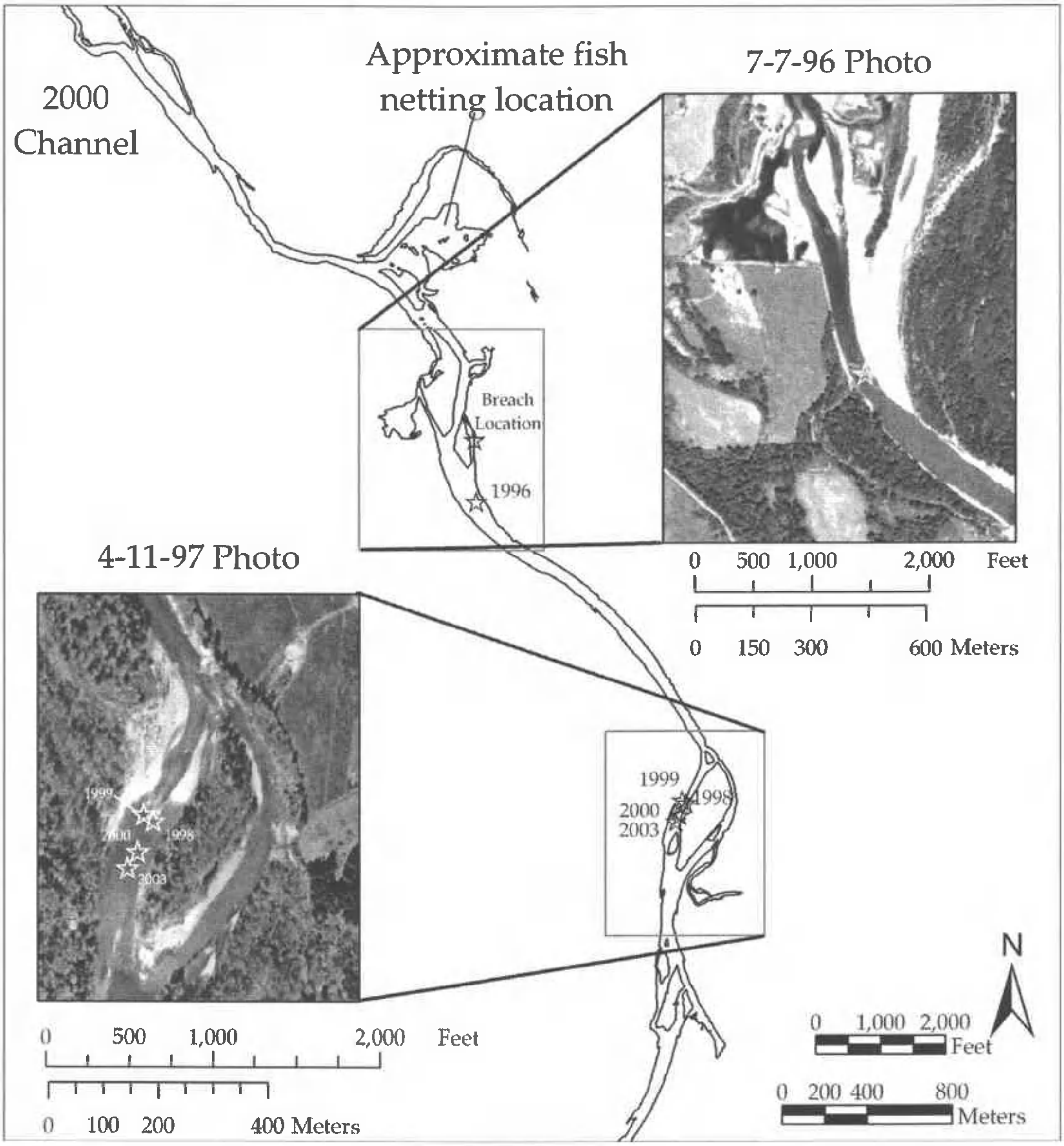

Figure 3.8 Knick point migration between 1996 and 2003. Note the location of fish netting in the northern pit. Stars indicate a measured knick point locations.

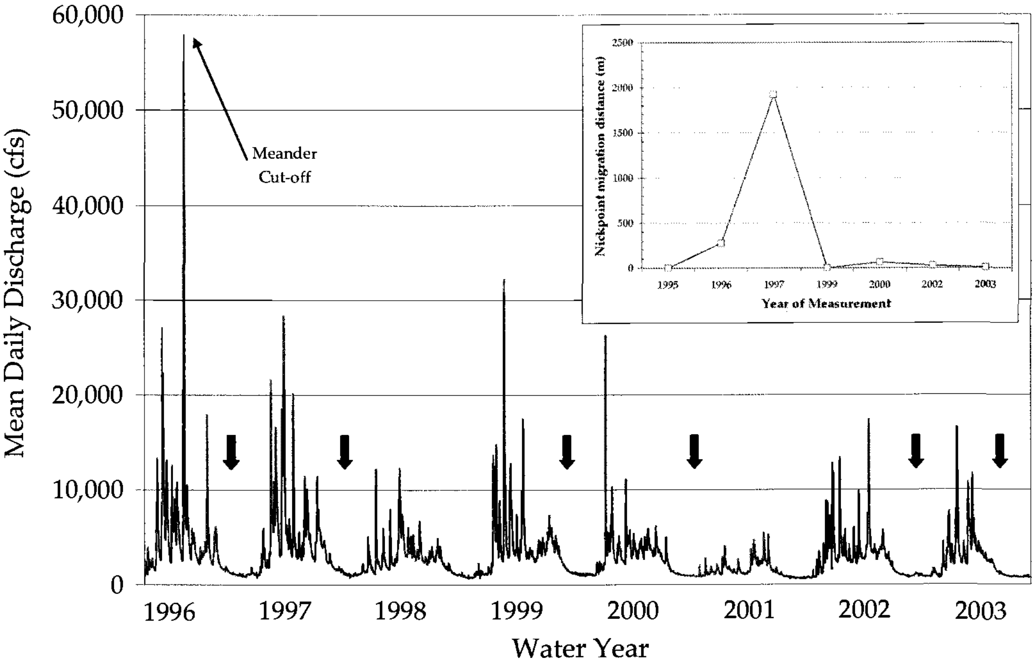

Figure 3.9 Mean daily discharge at Estacada (1421000) 1996-2003. Inset shows knick point migration distance measured upstream of Barton Bridge during the same time period. Arrows indicate approximate timing of knick point measurements from photos and ground survey measurements.

3.7.2 Changes in Channel Gradient

Transect data from 1993 suggests that aggradation was occurring in the main channel upstream and immediately downstream of the cutoff location. Between 1979 and 1993, reach slope increased between transect 53 and 55. Between 1993 and 1988, slope increased at the cutoff location and decreased upstream of the cutoff (Figure 3.10).

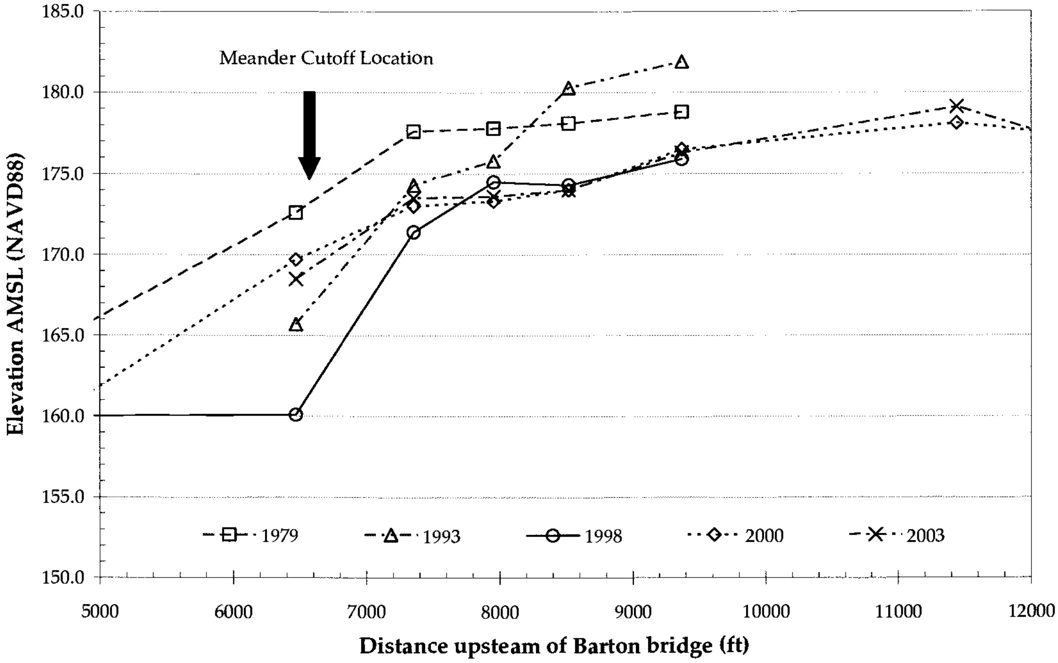

Figure 3.10 Changes in channel gradient 1979 to 2003 based on thalweg elevations from surveyed transects.

3.7.3 Changes in Channel Perimeter

The reach from RM 12 to RM 17 (the reach depicted in Table 3.2 and Figure 3.3) was measured using aerial photos from 1938 to 2000. Channel perimeter length has decreased since 1938, with static to slightly increasing channel perimeter length through the 1950's, 60's and 70's (Figure 3.11). Discharge at Estacada during the photo dates ranged from 27 to 91 cms (960 to 3,220 cfs). No attempt was made to correct for discharge differences. Channel perimeter increased slightly after 1996, due to incorporation of complex shorelines from ponds, but remained well below 1938 perimeter length.

3.7.4 Erosion and Deposition Patterns in Extraction Ponds

Pond area prior to meander cutoff was approximately 28.9 hectares. After the meander cutoff, erosion occurred on the left bank upstream and in the upstream bed; and deposition of gravel occurred in the former extraction ponds, reducing the depth and surface area of ponds (Table 3.3, Figure 3.12).

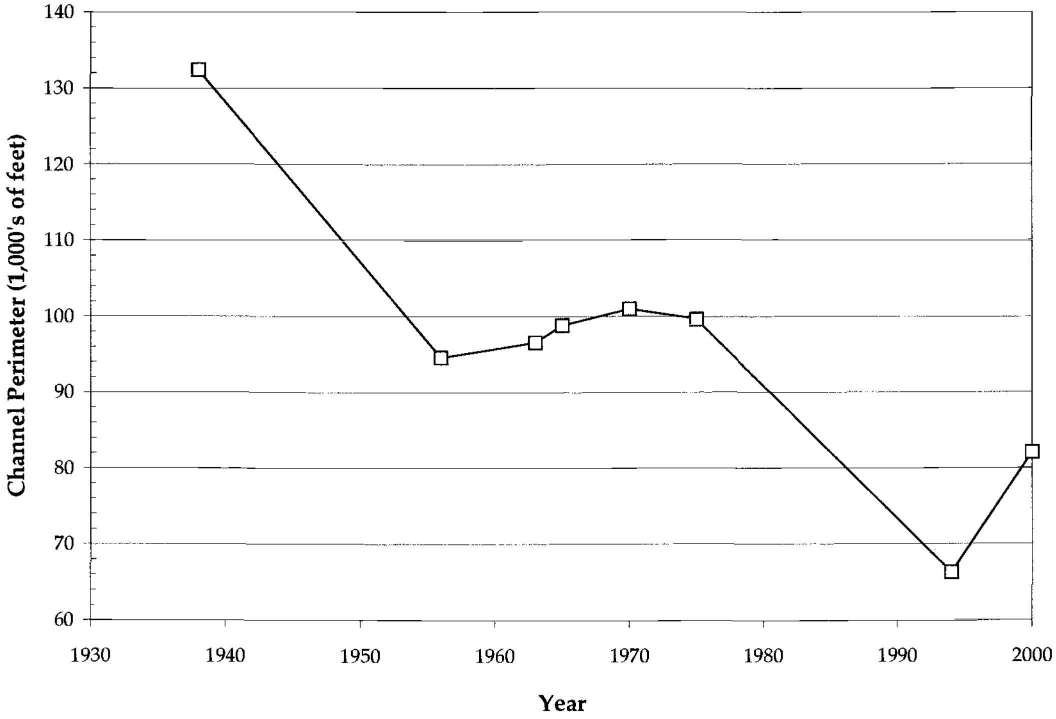

Figure 3.11 Changes in channel perimeter from RM 12 and RM 17 based on 1938 to 2000 on aerial photos. Discharge at Estacada during the photo dates ranged from 27 to 91 cms (960 to 3,220 cfs).

Table 3.3 Deposition and erosion volumes based on ground surveys and aerial photos.

	Amount Eroded[a]		Total Volume in Gravel Bars[b]	
Date of Measurement	Volume (ft^3)	Volume (m^3)	Volume (ft^3)	Volume (m^3)
2/9/1996	3,727,400	105,500	Unkown[c]	Uknown
7/7/1996	363,500	10,300	8,345,100	236,300
7/16/1998	2,103,300	59,600	12,029,700	340,600
10/3/2000[d]	843,800	23,900	12,909,600	365,600
TOTAL	**7,401,500**	**209,600**	**12,909,600**	**365,600**

[a] Average gravel depth was 10 feet.

[b] Bar area was mapped on aerial photos at low water. Bar volumes are cumulative.

[c] Water turbidity and levels were too high to determine deposition amounts.

[d] Bankline surveys in 2002 and 2003 showed virtually no change in bank line since 2000.

The meander cutoff reach is slowly reestablishing channel width as ponds fill with alluvium. Hydraulic connection between the former ponds and the river is generally decreasing as transported gravel is deposited near the opening of the ponds and near the mouth of the former main channel. In July of 1996, the summer after the meander cutoff, channel form through the extraction ponds was braided and gravel deposition was most pronounced in the excavation immediately downstream of the meander cutoff. By the year 2000, the southern pond was connected by only a small downstream outlet at low flows and the downstream mouth of the former channel was completely closed off by a gravel bar.

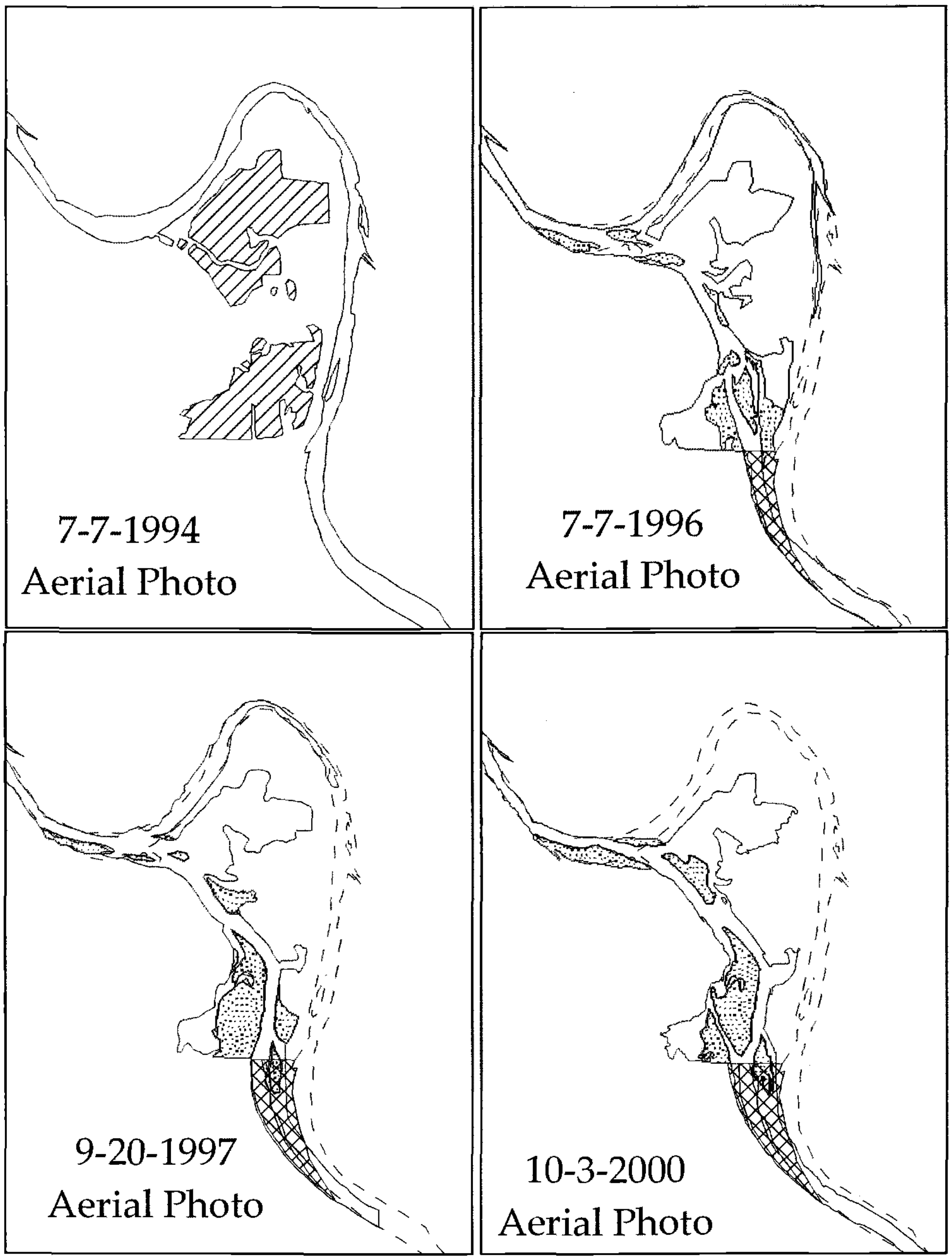

Figure 3.12 Erosion and deposition patterns in the River Island reach 1996-2000. The 1994 channel is shown with a dashed line for reference. Solid lines show the post-1994 channel configuration. Stippled regions are exposed gravel bars. Cross-hatched area is eroded river bank upstream of the cutoff. Hachured area represents the pre-cutoff pond area.

3.8 Thermal and Biological Changes

No studies have been done to evaluate the growth and survival of juvenile salmonids in the lower Clackamas River. However, high summer water temperatures, the prevalence of both native and non-native predators, and the extensive release of hatchery-reared fish have led many biologists to conclude that survival of native juvenile salmonids is low in the lower Clackamas River.

The total number of species caught in the northern River Island pond varied widely among sampling periods (4 to 12), as did the average daily catch (6 to 114). Variation in species count and daily catch did not correspond to changes in flow or time since the beginning of spring (Table 3.4).

Table 3.4 Fish netting data, 2002.

Sample Period	Average Flow (cfs)	# of Native Species	# of Non-native Species	Daily Catch (#/day)
3/5-3/7	3,273	2	2	6
3/18-3/22	3,133	7	1	46
4/1-4/4	3,033	6	2	14
4/23-4/25	3,505	9	2	114
5/29-5/31	4,816	3	2	23
6/17-6/19	2,401	8	3	89

The most numerous species caught during netting at River Island were the native largescale sucker and northern pikeminnow and the non-native brown bullhead. A small number of salmonid smolt and fry were caught, as well as a few adult steelhead. Ten species of native fish and four species of non-native fish were caught during the six sampling periods (Table 3.5). The four salmonid species that were caught (mountain

Table 3.5 Number of fish by species for six sampling periods; spring, 2002.

Period	3/5- 3/7	3/18- 3/22	4/1- 4/4	4/23- 4/25	5/29- 5/31	6/17- 6/19	Combined
Sampling days	3	5	4	3	3	3	21
Largescale sucker	9	128	14	149	8	35	343
Northern pikeminnow	1	17	4	16	41	105	184
Sculpin (various species)	0	9	4	8	7	18	46
Redside shiner	0	4	1	12	0	0	17
Mountain whitefish	0	1	0	2	0	3	6
Bridgelip sucker	0	0	0	0	0	2	2
Longnose dace	0	0	0	1	0	0	1
Chinook salmon							
Wild smolts	0	0	2	4	0	0	6
Hatchery smolts	0	1	2	0	0	0	3
Fingerlings	0	0	0	0	0	46	46
Coho salmon							
Wild smolts	0	0	1	12	0	0	13
Hatchery smolts	0	0	0	10	0	0	10
Fingerlings	0	0	0	0	0	10	10
Steelhead							
Hatchery smolts	0	0	0	5	0	0	5
Winter, adult, wild	0	1	0	0	0	1	2
Winter, adult, hatchery	0	1	0	0	0	0	1
Summer, adult, wild	0	1	0	0	0	0	1
Brown bullhead (non)	7	66	25	116	9	37	260
Common carp (non)	0	0	3	7	3	7	20
Bluegill (non)	2	0	0	0	0	0	2
Largemouth bass (non)	0	0	0	0	0	2	2
Combined	19	229	56	342	68	266	980

non = non-native species

whitefish, chinook salmon, coho salmon, and steelhead) are considered intolerant of warm water temperature. Sampling took place when the water was relatively cool and did not cause a stress to cool-water fishes. During the summer, some of all of these fish will likely leave the pond as water temperatures exceed 21.1 C (70° F).

The stomach contents of five northern pikeminnows were examined; four had salmonid smolt or fry in their stomachs. The number of salmonids in the four northern pikeminnow varied from one to ten. The small salmonids were likely consumed while they were trapped with the pikeminnow in the net and may not reflect the diet of the northern pikeminnow in general.

A summary of smolt sizes is shown in Table 3.6 and indicates a distinct difference in length between wild and hatchery chinook salmon. Hatchery chinook were nearly twice as long as wild chinook.

Table 3.6 Number and lengths of salmonid smolts.

Species	#	Mean Length (mm)	Minimum Length (mm)	Maximum Length (mm)
Chinook salmon				
Wild	6	82	42	128
Hatchery*	3	150	140	159
Coho salmon				
Wild	13	121	110	140
Hatchery*	10	144	128	155
Steelhead				
Hatchery*	5	202	195	210

* Identified by a clipped adipose fin.

Temperature probes were installed during the summers of 2000 and 2001, by Oregon Department of Geology and Mineral Industries (DOGAMI) to evaluate thermal changes resulting from the meander cutoff. Temperature recorders were placed upstream of the ponds (2000-2001), in the southern pond (2000), in the northern and southern ponds (2001), and downstream of ponds (2000-2001) (Table 3.7). Approximate locations of recorders are shown in Figure 3.13.

Table 3.7 Temperature probes installed in 2000 and 2001 at the River Island site.

Year Installed	Location	Serial #	Field_ID	Location Description	Depth (ft)
2000	Upstream of ponds	361281	RISG1	Main Clackamas R. channel adjacent to Shoe Island channel	4-6
2000	Upstream of ponds	361283	RISG2	Main Clackamas R. channel adjacent to Shoe Island channel upstream of RISG1	4-6
2000	Southern pond	361288	RISG6	Southern pit furthest west	7-10
2000	Southern pond	361286	RISG7	Southern pit east side	7-10
2000	Southern pond	361290	RISG8	Southern pit east side	7-10
2000	Downstream of ponds	361287	RISG9	Near large boulder 30 feet upstream of Barton bridge	10-15
2000	Downstream of ponds	361289	RISG10	Next to Barton Bridge abutment 10 feet W. of concrete footing.	6-9
2001	Upstream of ponds	361283	RI1	Main Clackamas R. channel adjacent to Shoe Island channel	4-6
2001	Upstream of ponds	361281	RI2	Main Clackamas R. channel adjacent to Shoe Island channel upstream of RI1	4-6
2001	Northern pond	457166	RI3	Northern pit furthest east	5-7
2001	Northern pond	457165	RI4	Northern pit furthest west	5-7
2001	Northern pond	457164	RI5	Northern pit near bar	5-7
2001	Southern pond	361288	RI6	Southern pit furthest west	7-10
2001	Southern pond	361286	RI7	Southern pit east side	7-10
2001	Southern pond	361290	RI8	Southern pit east side	7-10
2001	Downstream of ponds	361287	RI9	Near large boulder 30 feet upstream of Barton Bridge	6-9
2001	Downstream of ponds	361289	RI10	Next to Barton Bridge abutment 10 feet W. of concrete footing.	10-15

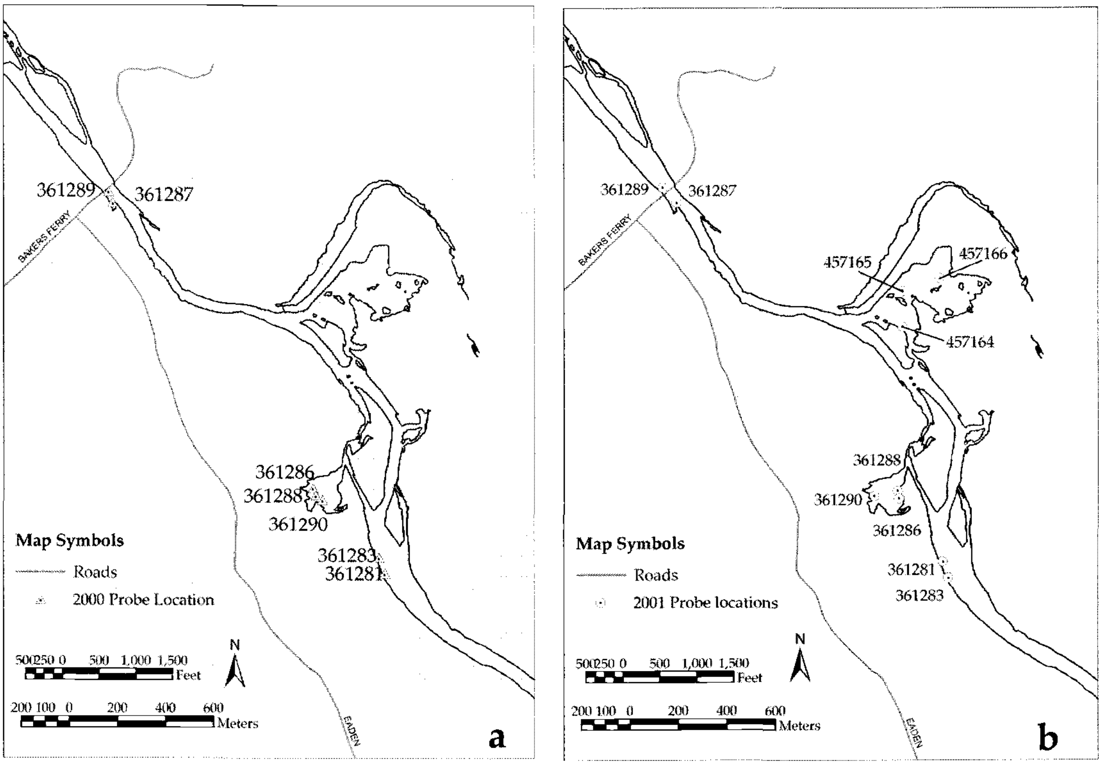

Figure 3.13 a. HOBO temperature recorder locations in 2000. b. in 2001.

Duplicate probes were placed upstream and downstream of the cutoff to insure that continuous data were available in the event of a malfunction. Duplication also allowed an assessment of the variability introduced by recorder placement. The two upstream probes were in very good agreement with each other (R^2_{2000} = 0.9999; R^2_{2001}= 0.9997). However, daily average temperatures for the two downstream probes, located just 10 m apart, differed by as much as 0.62 C in 2000 and 1.65 C in 2001 (R^2_{2000} = 0.9983; R^2_{2001}= 0.9730). This disparity creates a problem in that the observed mean change in daily average temperature between the upstream and downstream probes was only 0.32 C in 2000 and 0.36 C in 2001.

Fortunately, PGE had independently installed a probe within 100 m of the downstream location in 2001. Temperature data from the PGE probe was in good agreement with one of the two probes installed for this study (Figure 3.14).

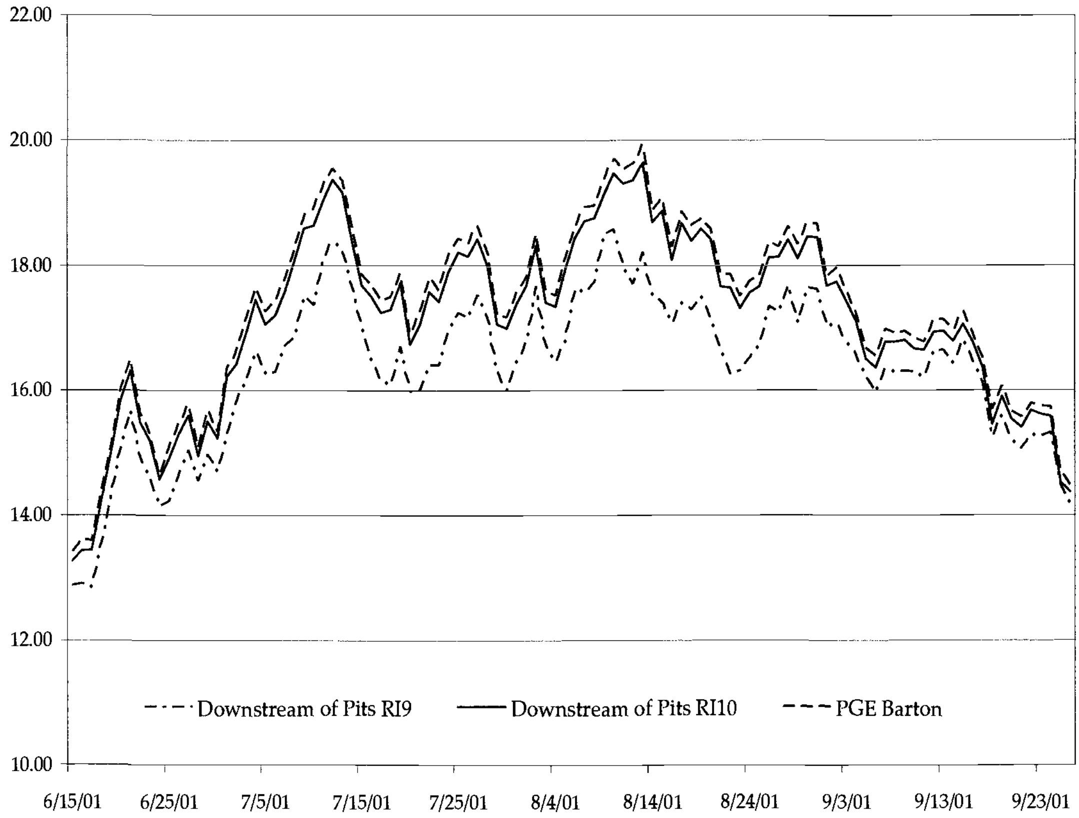

Figure 3.14 Temperature data differences between downstream recorders showing the agreement between the PGE recorder and RI10.

Since the PGE probe and RI10 are in good agreement, Probes RI10 and RISG10 were used for analysis of upstream and downstream changes in water temperature. Data from RI9 and RISG9 were not used in the analysis.

Temperature increase between the upstream probes in the main channel and probes below the meander cutoff at Barton Bridge was 0.32 C in 2000 and 0.36 C in 2001 (Figure 3.15, Figure 3.16, and Table 3.7). Average temperature over the entire summer was 0.32 to 2.76 degrees Celsius higher in the ponds than in the main channel upstream of the ponds. Pond temperatures were more variable than main channel temperatures. Vertical thermoclines were evident in the ponds due to local input of hyporheic (intragravel) flow and lack of water movement.

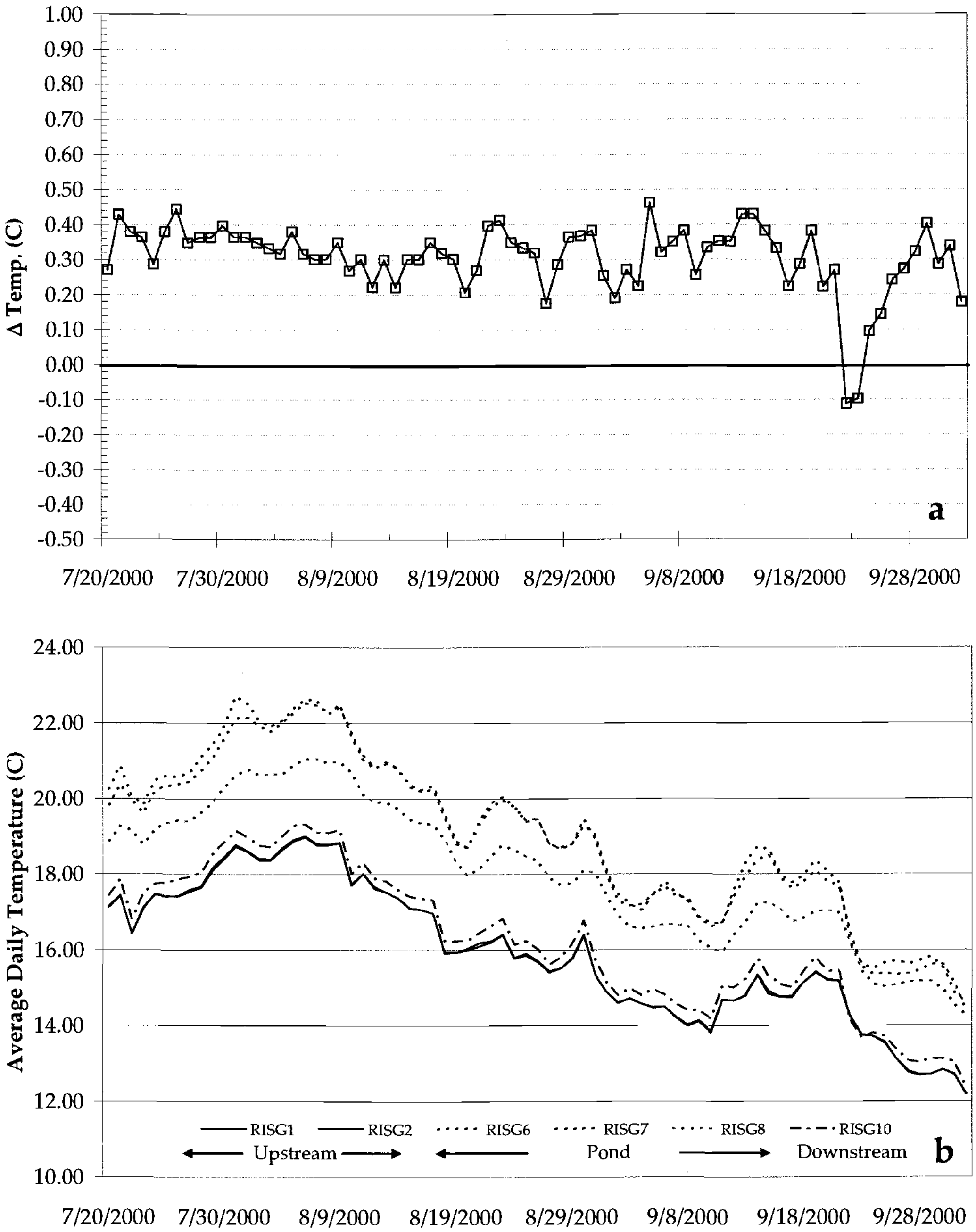

Figure 3.15 a. Change in temperature between the upstream and downstream probes. b. Average daily temperature data from six recorders during 2000.

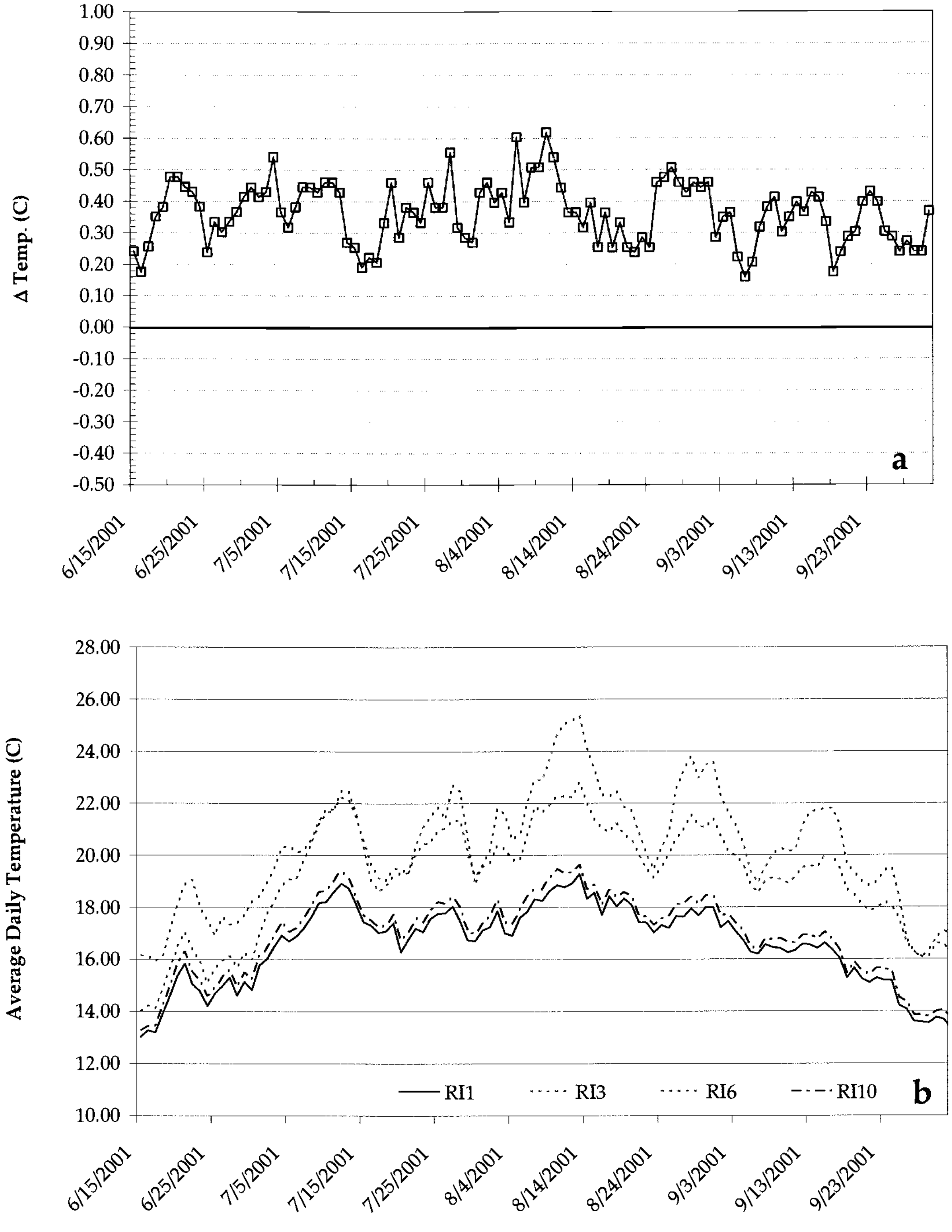

Figure 3.16 a. Change in temperature between the upstream and downstream probes. b. Average daily temperature data from four recorders in 2001.

3.9 Discussion

The Clackamas River dike construction adjacent to River Island resulted in channel simplification and may have resulted in increased bed load transport adjacent to the dike. Gravel aggradation in the main channel, combined with the path of low flow resistance provided by the excavations, contributed to the relocation of the river into the meander cutoff channel.

Diking at the River Island meander temporarily halted the process of pattern shift that was occurring. The dike adjacent to the site was stable from an engineering perspective, but because it was not extended onto adjacent land, it was ineffective at preventing a meander cutoff. The river exploited the path of least resistance onto the adjacent land. Had the dike not been built, it is likely that the river would have continued to use the cutoff channel during floods and may have eventually shifted into this channel permanently. It appears that mining activity in the presence of the dike accelerated this natural trajectory of change into a single flood event.

Since the gravel ponds became an efficient trap for sediment once incorporated into the river, they can be used as a means to estimate bed load transport in this reach. If the assumption is made that bed load transport downstream of ponds is essentially zero ($L_{out} = 0$), then the total amount of deposition in bars (D_b) within the extraction ponds provides an estimate of total sediment transport from three upstream sources: 1) E_b, erosion of upstream banks; 3) E_d, erosion of the bed through incision and degradation; and 4) L_{in}, bed load transport into the reach from upstream sources.

$$E_b + E_d + L_{in} = D_b - (L_{out} = 0)$$

$$L_{in} = D_b - (E_b + E_d)$$

E_b and D_b can be estimated from aerial photos and ground surveying. The total amount eroded from upstream bank, E_b is approximately 210,000 m^3 and the total amount deposited D_b is 366,000 m^3 (Table 3.3). E_d can be estimated by the bed degradation for surveyed transects (Figure 3.17). The volume eroded due to be degradation, E_d, is estimated to be 57,300 m^3. Therefore, bed load transport into the reach was approximately 98,700 m^3, between 1996 and 2000, or about 24,700 m^3/yr. This result is consistent with the bed load transport rate of 22,800 m^3/yr determined from reservoir trap data at River Mill Dam (Wampler, 2004).

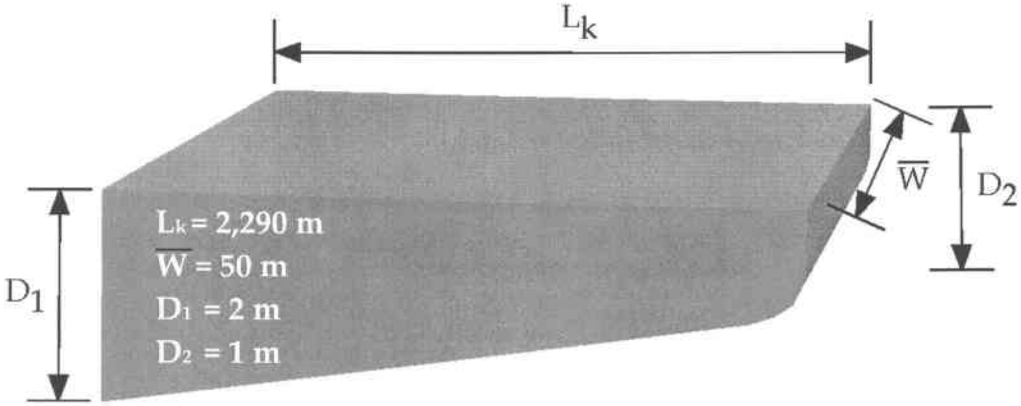

Figure 3.17 Conceptual diagram for estimating sediment volumes displaced by bed degradation.

Biologic changes resulting from the meander cutoff are both positive and negative. During the summer months, warming of river water temperatures and predation of salmonids occurs as a result of the connection between the ponds and the river. The magnitude of warming is not large relative to the warming trend in the entire lower Clackamas River. Salmonids clearly use the pond into the summer, but so do many predators, potentially offsetting any habitat gains through increased predation. It is not possible to evaluate whether predation is more prevalent in the ponds than it is in the main river.

Off-channel ponds and alcoves, such as the River Island ponds, can provide winter refuge and feeding areas for juvenile salmonids (Bustard and Narver, 1975b; McMahon and Hartman, 1989; Swales and Levings, 1989; Moser et al., 1991; Giannico and Healy, 1998; Sommer et al., 2001). However, no netting or electro-shocking was done during the winter to evaluate the usage of the ponds as refuge. Data from other Willamette Valley gravel extraction ponds and alcoves connected to rivers, suggest that usage of side-channels may be important, especially at night when avian predators are less active (Bayley et al., 2001) Chip Andrus, personal communication, 2000).

3.10 Implications for Floodplain Mining

The River Island site represents a site that fell through jurisdictional cracks. The DSL clearly understood that mining in the cutoff was fundamentally in-stream mining. However, after the dike was constructed, it was determined that the mining was above the ordinary high water mark and mining at the site was regulated as floodplain mining.

Jurisdictional boundaries at River Island site were not sensitive to geomorphic processes occurring in the river. The dike, constructed to prevent floodwater from entering the meander cutoff, delayed an ongoing process of meander cutoff that was taking place over several decades.

Floodplain mine regulators in Washington state have adopted the concept of a channel migration zone (CMZ) (Rapp and Abbe, 2003). This type of delineation results in a boundary which implicitly considers the dynamism of a given river through historic analysis of river migration. CMZ delineation methodology removes areas termed disconnected migration areas (DMA). DMA's are areas isolated from the CMZ by human structures built to prevent channel migration. At River Island this methodology may have resulted in the removal of the area behind the dike from the CMZ. It is not clear whether the proposed CMZ methodology evaluates the stability of structures relative to the river slope and stream power for a given river. Such evaluation would insure that structures intended to isolate the river from meander areas could in fact do so under the full range of expected flows.

The meander cutoff at River Island was somewhat unique in that channel transect data had been collected only a short time before the cutoff occurred. Pre-cutoff transect data extended only 880 m above the cutoff location; not far enough to record the rapid upstream progression of the knick point. In order to capture the scale of migration that occurred at River Island, pre-cutoff transects would need to have extended at least 3 km, and perhaps as much as 5 km upstream of the cutoff location. Baseline data which extends far enough upstream to capture geomorphic changes of the magnitude that occurred is crucial to improving our understanding of the impacts from gravel pit avulsions. Sediment transport modeling should be done in reaches where mining or other floodplain modifications are planned to determine if the channel is aggrading or degrading. Sediment transport modeling upstream and downstream would provide reach-scale aggradation and degradation patterns so that changes in sedimentation patterns could be identified.

The gravel pit capture at River Island highlights the potential risks of mining near a large gravel-bed river. Mine depth in excess of the thalweg of the adjacent channel increases the risk and potential off-site impacts. In locations where multiple gravel excavations are present within the CMZ, a comprehensive reclamation and restoration plan should be developed which provides long-term channel stability within the natural variability of the entire river reach.

3.11 Acknowledgements

Data collection and the study plan for River Island site was initiated by Frank Schnitzer, Oregon Department of Geology. Field assistance was provided by Rick Maxwell, Clackamas County Surveyor, Ben Mundie, Dawn Marshall, Bob Houston, Bud Stone and volunteers from the staffs of Lidstone and Associates and David Newton and Associates. Portland General Electric provided surveying assistance and equipment. Jim Morgan and the Metro Regional Government provided access to the site. A special thanks to Darrel Burnum, Clackamas County for surveying assistance and overall project support. Thanks to Chip Andrus, who reviewed fish usage data and provided helpful wording suggestions.

4 GEOMORPHIC CHANGES RESULTING FROM RIVER MILL DAM OPERATIONS, CLACKAMAS RIVER OREGON

P.J. Wampler[†], G.E. Grant[§]

[†]Department of Geosciences,

Oregon State University, Corvallis, OR 97331

[§]USDA Forest Service, Pacific Northwest Research Station

Oregon State University, Corvallis, OR 97331

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4.1 Abstract

River Mill Dam on the Clackamas River was completed in 1911 to provide hydroelectric power to the burgeoning city of Portland, Oregon. It is one of the oldest dams of its size in the western United States. Hydrologic changes from the dam are minimal, but a set of dam-induced geomorphic changes resulting from sediment supply changes has been documented. Incision immediately below the dam is minor due to erosion-resistant bedrock. Regularly spaced bedrock pools up to 10 m deep have been eroded into bedrock for 3 km below the dam. Average pool spacing is 250 m or approximately 3.6 channel widths. Deep pool formation may be related to sediment supply reduction and channel degradation below the dam.

Measurable geomorphic changes below the dam also include: 1) increase in surface grain-size; 2) reduction in side channel area; 3) stripping of bar alluvium; 4) exposure of bedrock; and 5) lowering of water surface elevations.

Sediment input sources for 13 km below the dam are limited to mass wasting and lateral erosion of Holocene terraces and islands. For about 3 km below the dam, there is approximately 300,000 m^3 of sediment stored in islands, bars, and in the channel. This represents 13 years of bed load transport based on reservoir trap data for River Mill Dam.

Between 1908 and 2000, water surface elevations of the Clackamas River dropped an average of 0.8 m for 17 km below River Mill Dam; remained unchanged for the next 6.4 km; rose 1 m for the next 11.3 km; and

dropped 1.2 m for the last 3 km. Surface grain D_{50} is 2 to 3 times higher for approximately 2 to 3 km below the dam.

4.2 Introduction

Dam construction changes the way water and sediment move through river systems (Williams and Wolman, 1984). Changes to water flow depend on the hydrology of the watershed, storage capacity of the reservoirs, and operating procedures for the dams. Large dams operated for flood control and water storage purposes generally reduce the frequency and magnitude of geomorphically effective flows (Gregory and Park, 1974; Andrews, 1986; Knighton, 1988; Webb, 1999; Warner, 2000). Peak flow reduction is also common (Biedenharn, 1983; Inbar, 1990; Stevens, 1995; Erskine et al., 1999). Flow modification can result in a variety of channel responses including: 1) channel narrowing and incision (Gregory and Park, 1974; Warner, 2000; Gilvear, 2004) or channel widening (Andrews, 1986; Assani and Petit, 2004); 2) invasion of non-native vegetation (Erskine et al., 1999; Webb, 1999); 3) aggradation and reduced ability to process tributary sediment input (Parker, 1981; Biedenharn, 1983; Petts and Thoms, 1986; Knighton, 1988); 4) temperature changes including warming or cooling of downstream reaches (Baxter, 1977; Webb, 1999); and 5) impacts to biota and vegetation (Nilsson et al., 1991; Power et al., 1996; Ponton and Vauchel, 1998; Greenwood et al., 1999).

Physical and ecologic changes also result from sediment trapping and clear water release below the dam. Virtually all dams trap the downstream movement of sediment to some degree. Trap efficiency, the percentage of total sediment transport intercepted by a dam, is related to watershed characteristics, water and sediment inflow, reservoir residence time, and water and sediment outflow (Graf, 1984).

Downstream impacts from sediment trapping include: 1) incision (Galay, 1983; Williams and Wolman, 1984; Galay et al., 1985; Hadley and Emmett, 1998); 2) surface grain-size increase (Sear, 1992) or surface grain size decrease (Biedenharn, 1983); 3) decrease in lateral migration rates, floodplain dynamism, and sinuosity (Shields et al., 2000; Assani and Petit, 2004); 4) reductions in juvenile fish refuge due to side channel loss (Ponton and Vauchel, 1998); and 5) beach erosion and increased bedrock exposure (Webb, 1999; Assani and Petit, 2004).

Downstream changes resulting from flow and sediment transport modification are generally most pronounced near the dam. These decrease with distance downstream of the dam, as sediment is replaced from downstream sources. Impacts also migrate downstream with time. The rate of migration is a function of several variables, including channel geometry, bed characteristics, and sediment availability below the dam. The length of degradation downstream varies considerably. Bed degradation extended for 150 km below Possum Kingdom Reservoir on the Brazos River in Texas (Stanford et al., 1996). However, this amount of degradation is more common for sand-bed rivers (Williams and Wolman, 1984). Gravel-bed rivers typically show a more modest amount of degradation (Grant et al., 1999). Degradation often results in a decrease in slope below the dam (Petts, 1984), and can be rapid following dam construction. Bed armoring may or may not be limited by degradation, depending on the dam operations, sediment characteristics, and grain-size distribution (Parker, 1981).

Incision in most gravel-bed rivers tends to be a self-regulating process. As incision into alluvium progresses, bed material typically becomes coarser. This has the effect of making the bed more difficult to erode, reducing the frequency of flows large enough to mobilize the bed. When alluvium is thin and bedrock is exposed through incision, erosion is controlled by the resistance of the bedrock to erosion and increased lateral erosion would be predicted.

Many regulated rivers experience a combination of changes resulting from flow and sediment transport modification (Warner, 2000), while other rivers experience little or no geomorphic change due to river regulation (Grant et al., 1999; Phillips, 2003).

Physical changes in flow, channel form, and bed characteristics downstream of dams often result in changes to the river ecosystem. Uniform post-dam water temperature in the Colorado River below Glen Canyon Dam resulted in increased aquatic productivity below the dam (Webb, 1999). However, native species were displaced by cold-tolerant trout species. Reduced flood frequency and river regulation of the Colorado River in the Grand Canyon increased the area of fluvial marshes (Stevens, 1995). Dam impacts on biota tend to be rapid (Power et al., 1996), while geomorphic changes tend to occur more slowly, at a rate proportional to the changes in the frequency of bed-mobilizing flows and sediment availability below the dam (Grant et al., 2003).

In recognition of the vital role that geology and geomorphic setting play in determining the magnitude and trajectory of downstream effects from dams, an analytical framework for predicting downstream effects based on flow frequency and sediment availability has been developed (Grant et al., 2003). This model uses two dimensionless variables T* and S*. T* is the fractional change in the frequency of bed mobilizing flows and S* is the ratio of sediment supply below the dam to sediment supply above the dam (Figure 4.1).

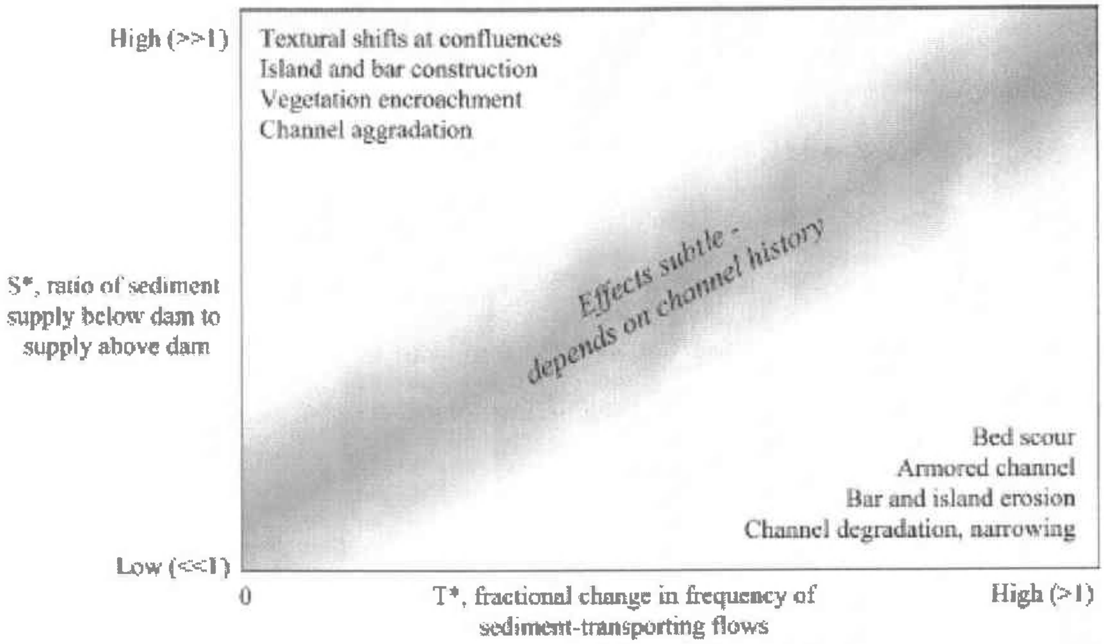


Figure 4.1 Conceptual framework for downstream effects of dams (Grant et al., 2003).

River Mill Dam, completed in 1911, is operated by Portland General Electric (PGE) primarily for power generation. The Clackamas River is regulated by six dams built between 1905 and 1993, with a combined generating capacity of about 155 megawatts. River regulation on the Clackamas River began in 1905, with the construction of Cazadero Dam, located approximately 5 km upstream of River Mill Dam. North Fork Dam, completed in 1958, has the largest storage reservoir, storing 18,630 acre-feet at full pool. Appendix E contains details on Clackamas River hydroelectric projects.

North Fork Dam has the only reservoir large enough to potentially alter peak flows. However, frequency and duration of peak flows are largely unchanged during the period of record (Figure 4.2). Impacts due to flow regime changes are expected to be negligible below River Mill Dam because it is operated as a "run of river" dam, spilling all flows greater than 113 cms (4,000 cfs). However, the frequency and duration of bed-mobilizing flows may have changed due to grain-size changes below the dam.

Longitudinal and temporal changes can be predicted if sediment supply and hydraulic data are known. Evaluating the downstream effects of a dam as old as River Mill Dam is complicated by a lack of pre-dam topographic and grain size data. One approach to address this paucity of data would be to compare grain size and geometry trends for a similar river, not affected by river regulation. For example, in order to address a paucity of pre-dam data, researchers compared vegetation differences between regulated and unregulated rivers in Sweden (Nilsson et al., 1991). A similar approach was used to examine riparian vegetation response to river regulation along the Green River in Colorado (Merritt and Cooper, 2000). This approach was not followed on the Clackamas River because an

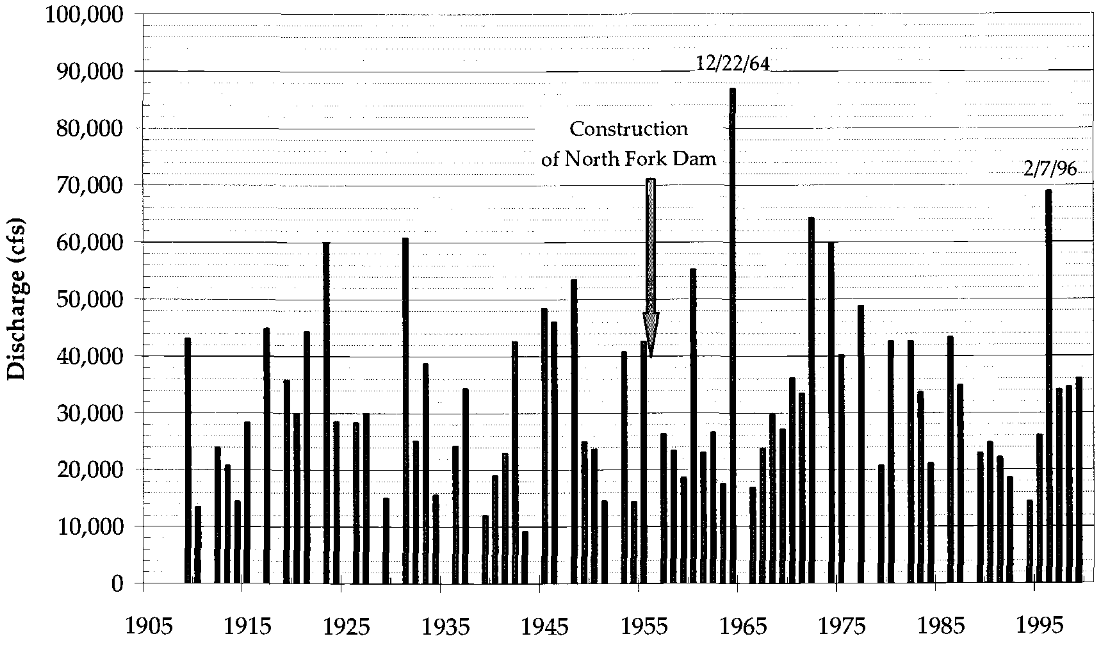


Figure 4.2 Peak flow at Estacada, 1909 to 1999.

adequate unregulated river with a similar geomorphic and geologic setting could not be found.

River Mill Dam operations have created minor hydrograph changes during the summer months when low flows vary due to maintenance and regulation of upstream dams. Generally the cumulative change in mean daily flow has decreased from the 1920's until approximately 1945, at which time flows generally increased to return to the long term mean (Figure 4.3).

Potential effects below River Mill Dam can be divided into three main categories: 1) geomorphic effects, such as the frequency of avulsions and lateral erosion rates driven by changes in sediment supply; 2) bed elevation changes (incision/aggradation) and decreases in water surface elevations in side channels, due to entrenchment and channel narrowing;

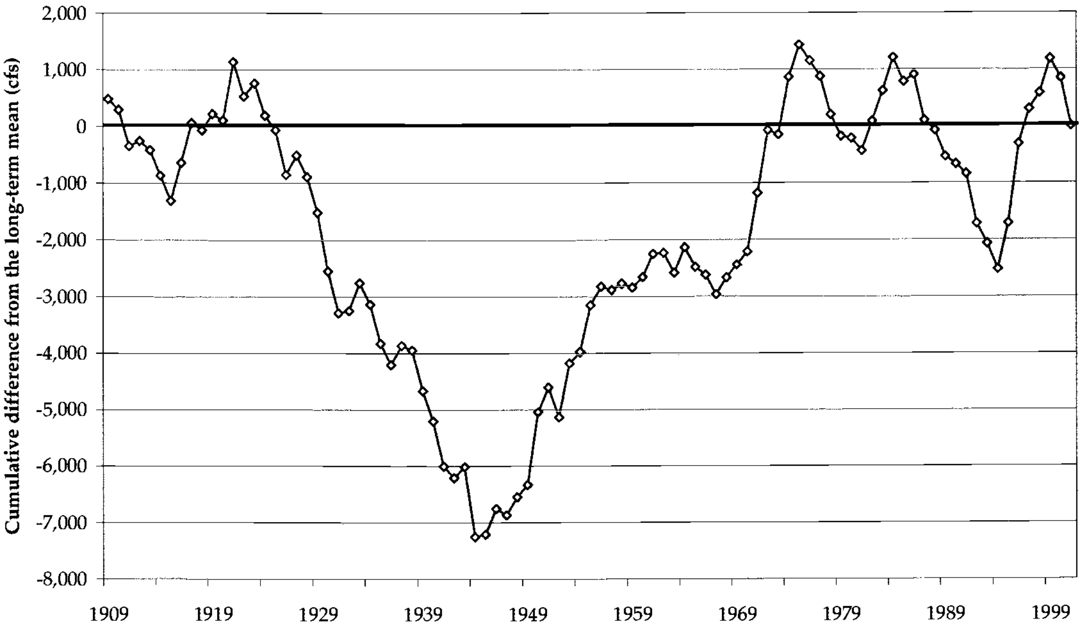


Figure 4.3 Long term cumulative variability in mean flow, Clackamas River at Estacada.

and 3) sediment grain-size changes, which result from "winnowing" of fines and bed armoring.

This study uses a combination of historic maps, aerial photos, historic surveys, gage records, and grain size analysis to evaluate the downstream effects of River Mill Dam. Bed load transport is estimated using reservoir trap data and two different GIS methods. Bed load estimates are compared with gravel storage below the dam.

4.3 Study Area and Geologic Setting

The Clackamas River, a large gravel-bed river located in northwestern Oregon, is part of the Clackamas watershed, comprised of six major sub-basins draining a total area of approximately 243,560 hectares

(Figure 4.4). The present study examined geomorphic changes in the lower Clackamas River below River Mill Dam (RM 23.5 to 0).

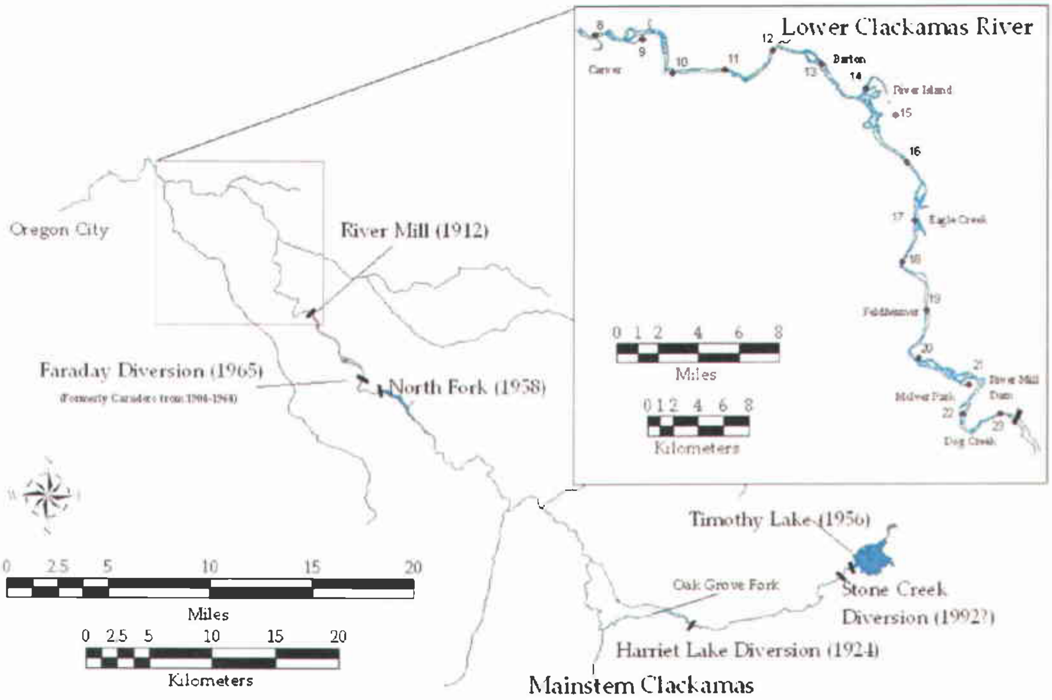


Figure 4.4 Map of the Clackamas basin with dams. Inset shows a portion of the lower Clackamas River with USGS river miles.

The geologic setting in which a dam is located is critical to evaluating geomorphic changes, and understanding how long-term geologic trends relate to short-term patterns of change (Grant et al., 2003). Geologic and geomorphic transitions occur at the location where River Mill Dam was constructed.

Alluvium within the modern floodplain of the Clackamas River occurs as a relatively thin layer (< 3 m) resting on bedrock of either Sandy

River Mudstone (SRM) or Sardine Formation. When the sediment is mobilized during flood events, erosion of the thin layer of alluvium can expose bedrock. Once exposed, bedrock tends to become sculpted by hydraulic forces into grooves (flutes), potholes, and deep pools. Bedrock exposure within the active channel, although present along the entire river, is more abundant in the 3 km reach below River Mill Dam than in the river downstream.

Since it began operation, approximately 3.9 million m^3 of sediment has been trapped behind River Mill Dam. Sediment trapping has resulted in measurable geomorphic changes for at least 16 km downstream, and perhaps to the mouth of the Clackamas River (38 km).

Three sources of anthropogenic gravel introduction which were identified immediately below River Mill Dam are: 1) River Mill Dam construction "spoils"; 2) gravel discarded by Estacada Rock products (~RM 22.9); and 3) materials used to maintain the Upper McIver boat launch. Of the three sources, the first is by far the most volumetrically significant.

Decades of in-stream and floodplain gravel mining, construction of extensive bank protection structures, land use practices both in the upper watershed and on the terraces above the river, and climate oscillations during the Holocene have also changed the geomorphology and channel characteristics of the lower Clackamas River (Wampler, 2004). The present study is part of an ongoing Federal Energy Regulatory Commission (FERC) license renewal process for several Clackamas River projects by PGE.

The Clackamas River traverses three distinct physiographic provinces in its 97 km course from its headwaters to the Willamette River.

The headwaters in the High Cascades provide the river with a relatively constant supply of cold, clean water throughout the year. As the river enters the Western Cascades, it encounters a deeply eroded landscape with abundant landslides and high sediment yield. Near Estacada, the river emerges from a confined canyon into a broad valley, which is part of the Willamette Valley physiographic province. As it travels, river processes and form are affected by the unique geology and physical characteristics of each physiographic province (Figure 4.5).

The High Cascades contain very young basalt flows, as well as the tall, well-known peaks in Oregon, such as Mount Hood and Crater Lake (Mount Mazama). High Cascades volcanoes generate large volumes of ash and mudflows near volcanic peaks, but also have very low sediment yield where highly porous basalt flows allow precipitation to infiltrate without forming surface drainages. Porous rocks and abundant groundwater flow provide significant flow to the Clackamas River during the summer months.

The Western Cascades are an ancient, inactive, volcanic chain (~10 to 40 million years old), once similar to the modern High Cascades. Rocks in the Western Cascades province are deeply weathered, eroded, and prone to mass wasting. Volcanic activity in the Western Cascades contributed extensive volcanic mudflows, ash-deposits, and lava to the Willamette Valley Province. Approximately 10 to 14 million years ago, volcanic ash, sediment, and debris flowed from the Western Cascade Mountains westward, depositing an extensive layer of volcanic breccia, locally referred to as the Sardine Formation. This cemented mixture of fine-grained ash

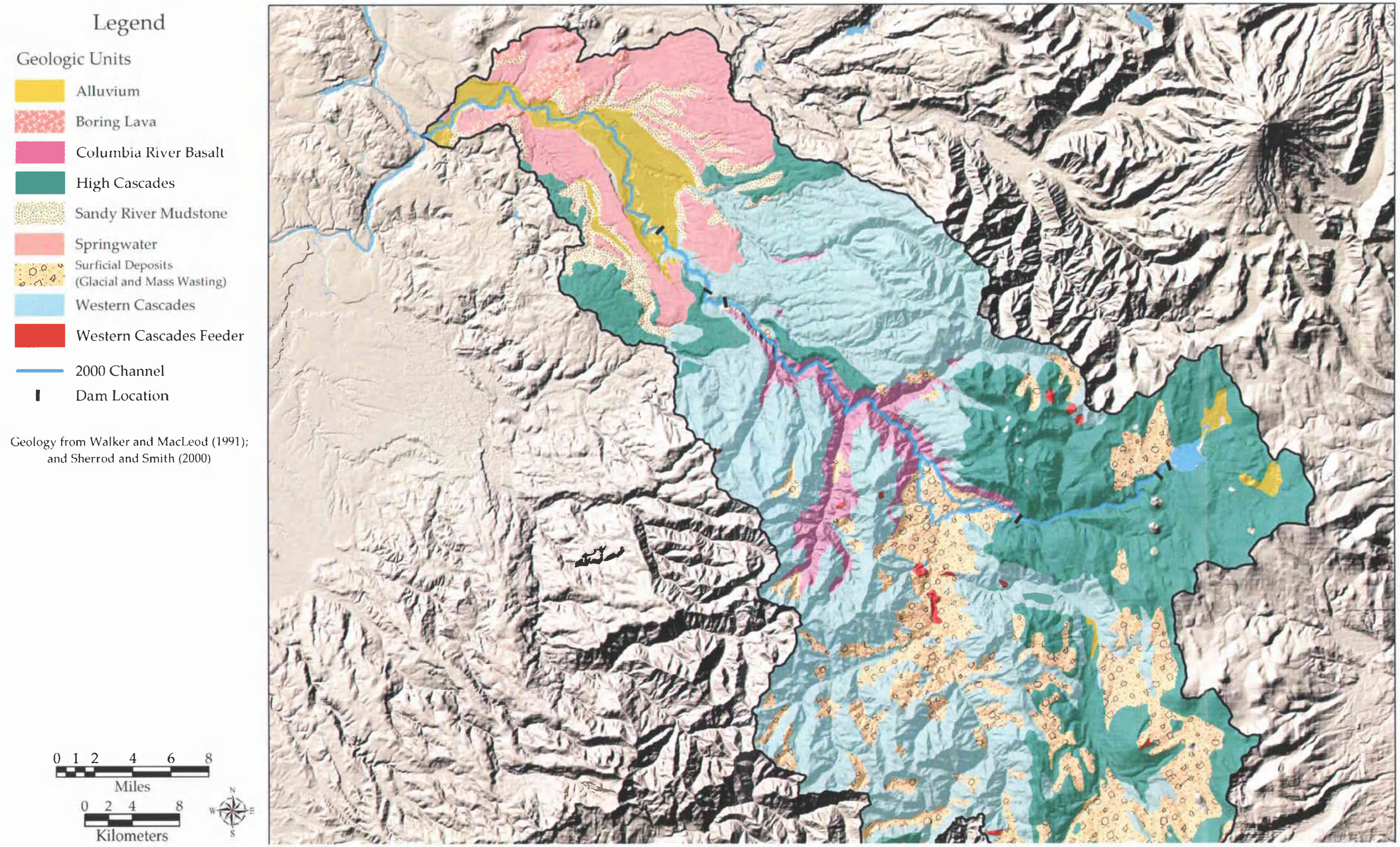


Figure 4.5 Simplified Clackamas watershed geology.

and clay contains large rock fragments (up to 1.4 m in diameter), and forms the bedrock beneath River Mill Dam and for approximately 3 km downstream (Figure 4.6).

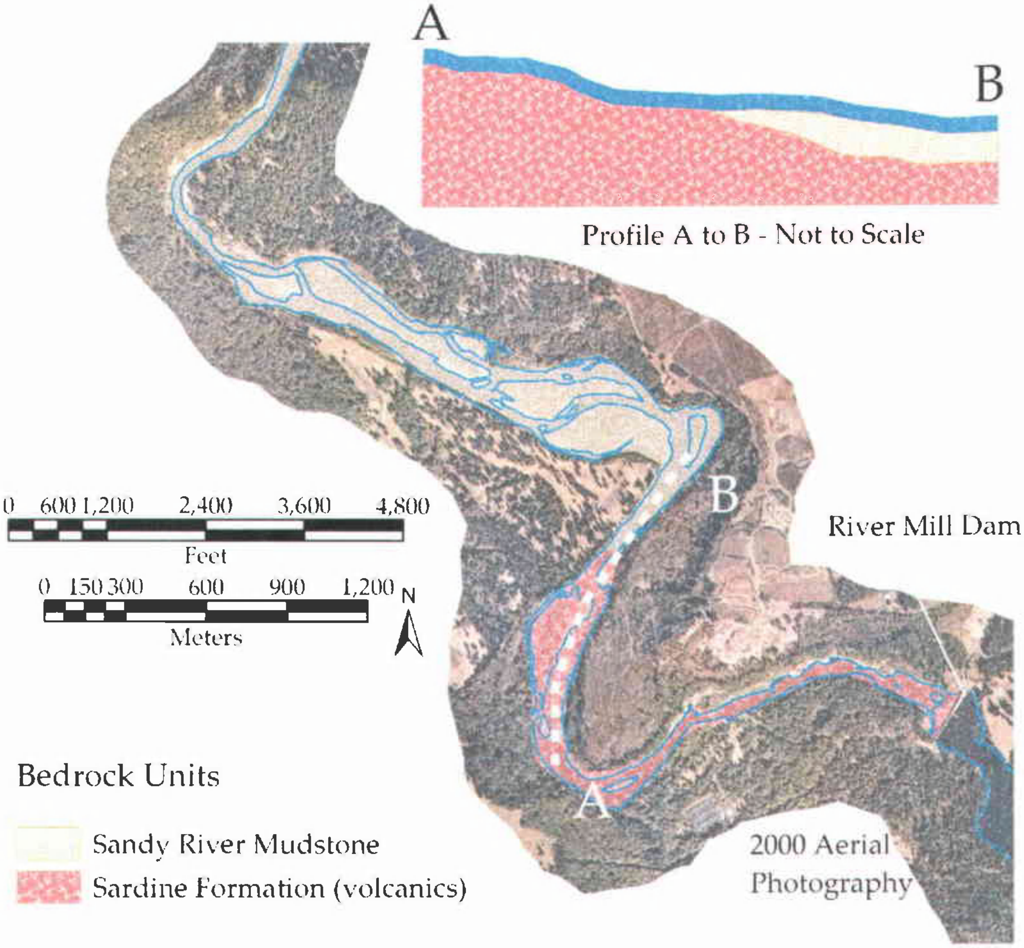


Figure 4.6 Bedrock geology below River Mill Dam.

Bedrock in the lower Clackamas River Basin is a geologic unit called the Sandy River Mudstone (SRM). The SRM, a silty, volcanic, mudstone, was deposited in a lake environment on top of the Sardine Formation. Unlike the Sardine Formation, the SRM does not contain large rock fragments and is much more easily eroded. This contrast in erodibility affects the form and gradient of the Clackamas River. The geologic contact between the SRM and the Sardine Formation occurs just below River Mill Dam, complicating interpretations of geomorphic changes attributable to the dam.

The Willamette Valley physiographic province has collected sediment generated in the Western and High Cascades, including glacial outwash from Cascade glaciers. The last 1.8 million years have been a time of dramatic changes in climate and fluctuations in glacial ice in the Cascade Mountains. Ice fluctuations were likely accompanied by dramatic changes in sediment yield from the Upper Clackamas Basin. Aggradation and valley widening would have occurred during times of high sediment yield; and incision and valley narrowing would be predicted when sediment supply from the upper basin decreased.

Some of the most cataclysmic, climate-driven events in the Willamette Valley Province were a series of glacial outburst floods called the Missoula, or Spokane floods. These huge floods began near Missoula, Montana, traveled across eastern Washington, down the Columbia Gorge, and backed up into the Willamette and Clackamas valleys (Bretz, 1969). In the vicinity of Portland, these floods reached an elevation of approximately 120 to 130 m. As many as 10 to 120 floods carried huge volumes of silt, sand, gravel, cobbles, and large boulders known as glacial erratics. Glacial erratics were rafted into the valley embedded in ice chunks floating on the floodwaters. The floods blanketed many river floodplains in the Willamette Valley with silt several 10's of meters thick.

4.3.1 *Geomorphic History and Historic Changes to Channel Plan Form*

The geomorphic history of the Clackamas River is influenced by geology, geographic position, and regional climate change. The Clackamas River, as well as other large rivers draining the Cascade Mountains, deposited expansive gravel approximately 10,000 to 12,000 years ago. These deposits are younger than the Missoula flood deposits (O'Connor et al., 2001). In the Clackamas River Basin, these deposits are referred to as the Estacada Formation or the Estacada Surface (Qt$_3$). This cut-fill terrace, a gently sloping alluvial surface underlain by bedrock in many locations, contains 3 to 20 m of river sediments. It is one of many prominent straths along the lower river, which are generally < 10,000 years old (Figure 4.7).

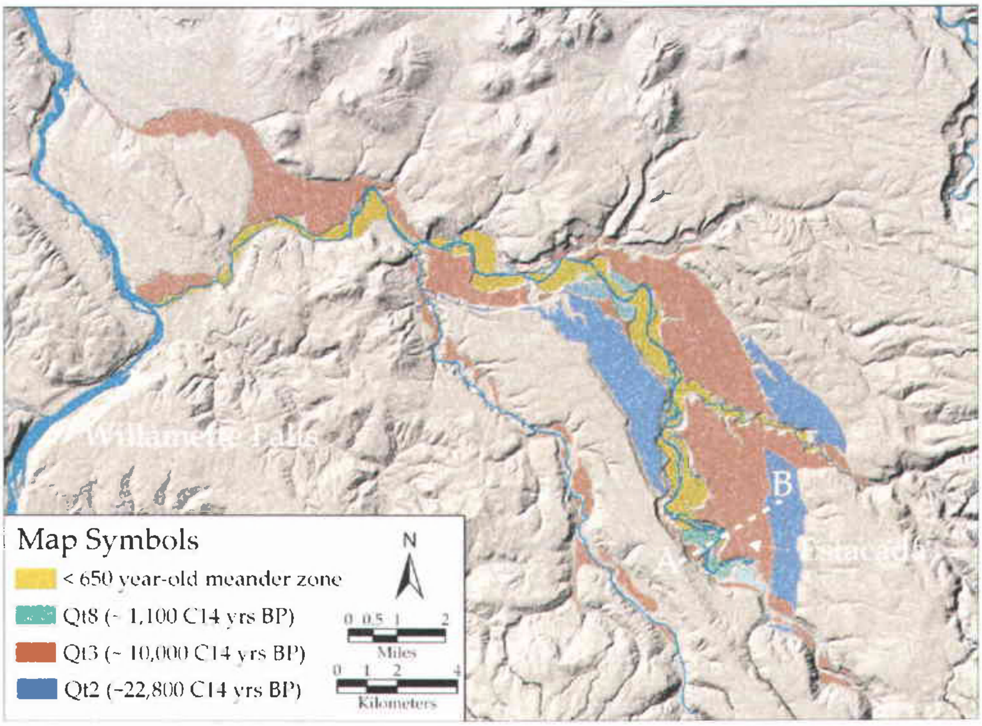


Figure 4.7 Map of geomorphic surfaces along the Clackamas River.

Terraces, such as the Estacada Surface and Holocene strath terraces below River Mill Dam, provide a record of alternating periods of abundant sediment supply during which aggradation, meandering, braiding, and valley widening occurred; followed by periods of reduced sediment supply, during which the river degraded and incised into its floodplain and the underlying bedrock. Terrace ages and elevation differences between the modern and historic floodplains indicate that the Clackamas River has experienced rapid incision over the last 10,000 years (4.3 mm/year). Incision based on a 22,800 year-old terrace is approximately 2.4 mm/year. This suggests the rate of incision has increased in the last 10,000 years. Elevation differences between the top of the 10,000 year-old Estacada Surface and the current river bed suggest long-term incision is greatest near the present location of River Mill Dam and decreases downstream (Figure 4.8).

The Clackamas River exhibits a combination of channel forms including meandering, anabranching, and braiding. Meandering rivers are sinuous and prone to channel meander cutoffs as lateral migration occurs, while anabranching rivers have several channels separated by relatively stable islands. Some meandering reaches of the Clackamas River are relatively fixed in their position due to high mudstone cliffs (SRM) that impede lateral movement.

The channel at these locations is entrenched against the mudstone cliff and does not easily migrate out of the "rut" in which it flows. This somewhat unique channel form has resulted in entrenched reaches that are

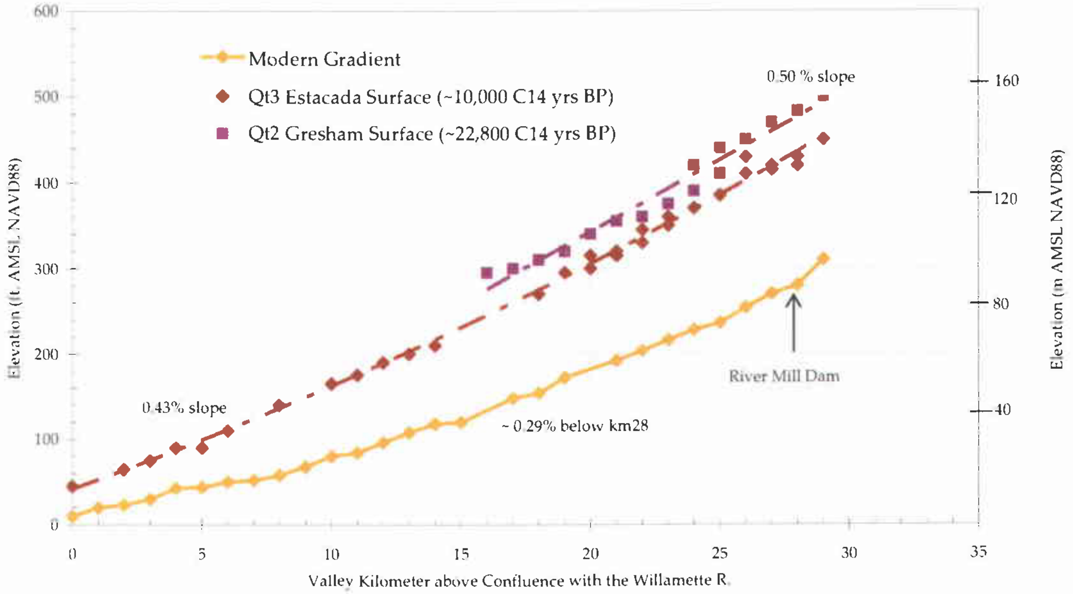


Figure 4.8 Longitudinal profile of selected Clackamas River terraces.

relatively stable for long periods of time (>150 years), and reaches that are not entrenched which exhibit dynamic channel migration behavior (Figure 4.9).

Bank erosion occurs in some locations on an annual basis, but major channel change typically occurs during large floods such as occurred in 1964 and 1996. Channel change events and meander cutoffs have resulted in channel length decrease since the earliest mapping in the 1850's.

Identification of dam-related effects with distance below the dam becomes more difficult due to the similarity between incision related to channel change events, and incision resulting from dam construction. At the reach near the former location of River Island Sand and Gravel Co.,

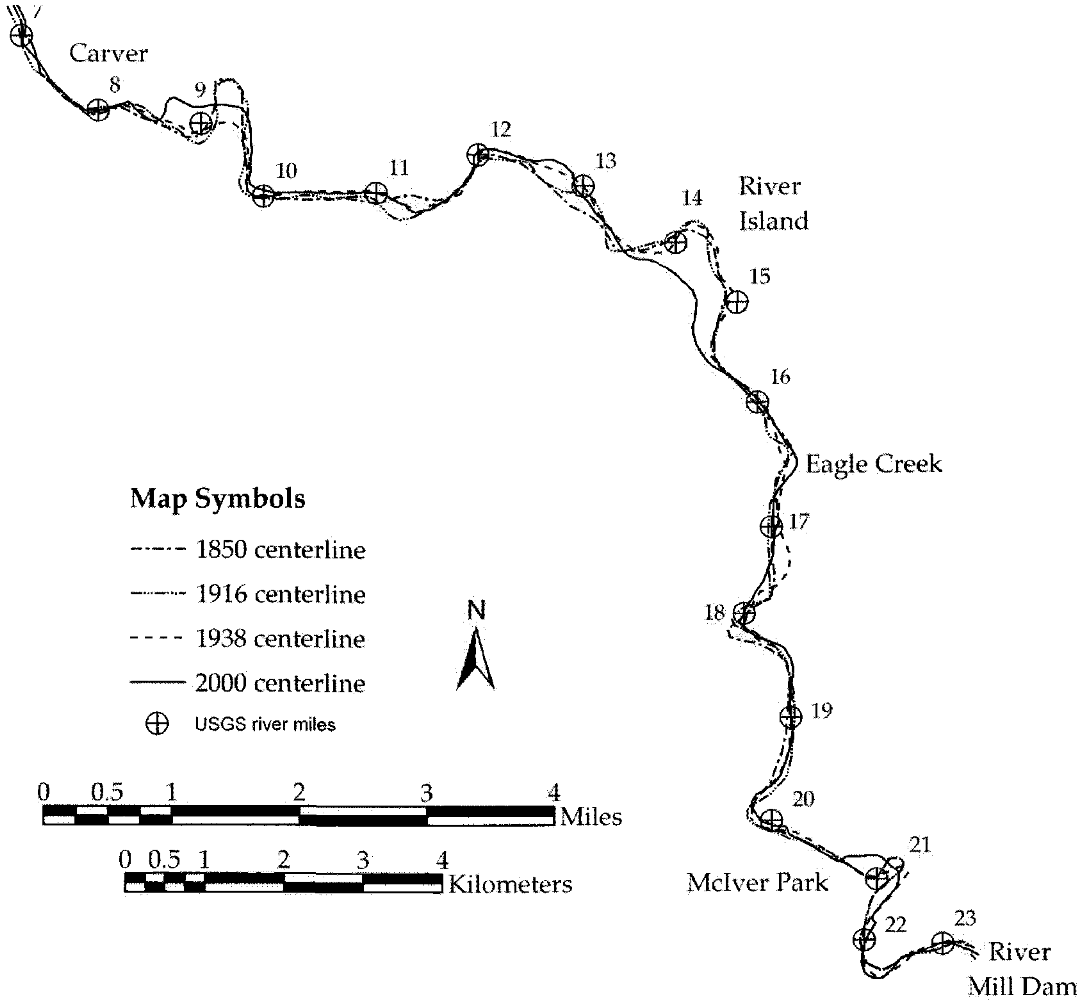


Figure 4.9. Lateral channel change 1853-present in study area, based on aerial photos and historic maps.

rapid channel change occurred during February 1996, at approximately RM 14.5. In a matter of hours, the river cut off a meander and began flowing through a series of gravel pits located on the inside of the meander bend. The avulsion resulted in a reduction in reach length of 1,100 meters. Reach slope increased from 0.0022, to approximately 0.0035. The slope change, or knick point, from the meander cutoff has migrated upstream 2,290 m, resulting in increased bed load transport, 2 m of incision, and rapid lowering of the water table.

In contrast to the rapid channel change experienced at River Island, several reaches of the lower Clackamas River are meandering at a slower rate. Some meanders have remained in the same location for 100's to 1,000's of years, based on radiocarbon dates and terrace mapping. The result is steep cliffs on the outside of bends, deep pools, terrace preservation on the inside of bends, and large active landslides, such as the one located downstream of McIver Park (RM 20). A series of strath terraces along the inside of the bend suggest lateral migration in a northeasterly direction over the last 1,600 years (Figure 4.10). The presence of gravel deposits on the terraces also suggests significant variability in depositional regime over the same period. The bend is migrating laterally at a rate of 1,100 m in 10,000 ^{14}C yrs B.P. or about 0.11 m/yr. A strath terrace 6 m above the modern channel, referred to as the McIver Surface (Qt_8), reveals the position of this meander roughly 960 ^{14}C yrs B.P. The meander is migrating downstream as well as laterally.

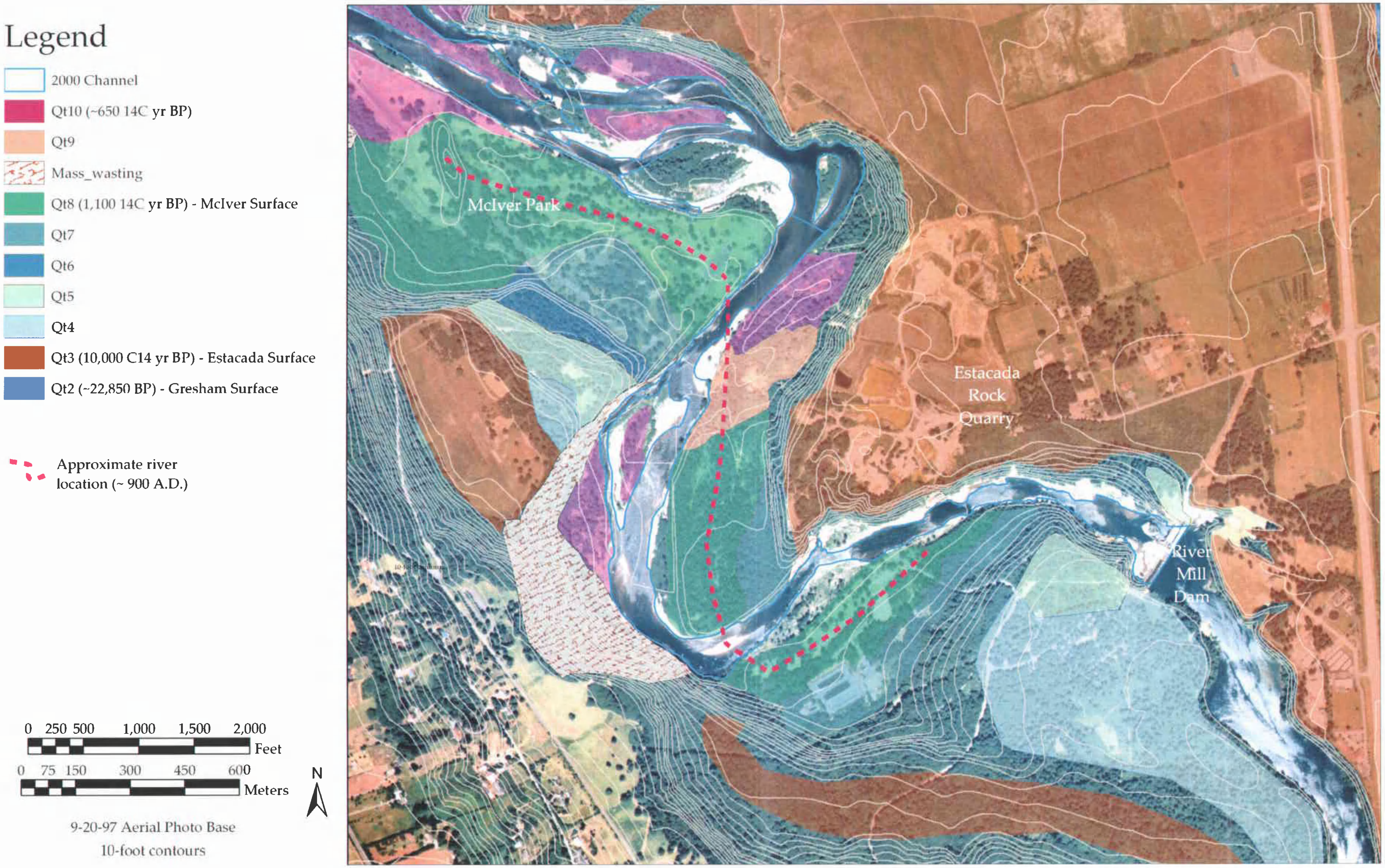


Figure 4.10 McIver Surface below River Mill Dam.

4.3.2 *Reservoir Trap Data*

Each dam on the Clackamas River has trapped a portion of sediment transported from the watershed upstream. Since the dams were constructed at different times, they have captured sediment from different time periods and different fractions of the catchment upstream (Table 4.1).

Table 4.1 Summary of sediment trapped by dams along the Clackamas River.[a]

	River Mill (Washington Infrastructure Services Inc., 2001)	**North Fork**	**Combined N. Fork and River Mill**	**Harriet**			
				1924-1948 (Soil Conservation Service)	**1924-1956**	**1957-1985**	**1924-1985**
Year dam completed	1912	1958		1924	1924	1924	1924
Beginning year of accumulation	1905	1958	1905	1924	1924	1956	1924
Ending year of capture	1956	2000	2000	1948	1956	1985	1985
Years of accumulation	51	42	95	24	32	29	61
Total Sediment[b] (yds^3)	5,080,404	10,443,100	15,523,504	6,453	92,013	83,387	175,400
Sediment Load (yds^3)/Year	99,616	248,645	163,405	269	2875	2875	2875
Sediment Load (ft^3)/ Year	2,689,632	6,713,415	4,411,943	7,260	77,636	77,636	77,636
Tons[c]/ Year	107,585	268,537	176,478	290	3,105	3,105	3,105
Drainage Area (mi^2)	671	526	671	131.5	131.5	77.5	131.5
Drainage Area (km^2)	1738	1362	1738	341	341	201	341
Yield ($T/mi^2/yr$)	160	511	263	2.2	23.6	40.1	23.6
Yield ($T/km^2/yr$)	62	197	102	0.9	9.1	15.5	9.1

[a] Data from McBain & Trush (2002) unless otherwise noted.

[b] River Mill Reservoir estimated as 30% gravel/cobble, 70% sand-sized and smaller.

[c] Rock density assumed to be 80 lbs/ft^3.

River regulation of the lower Clackamas River began in 1905, with the construction of Cazadero Diversion Dam, located approximately 3 river miles upstream of River Mill Dam. Cazadero Dam intercepted coarse bed load between 1905 and 1964. A large flood in December 1964, resulted in the failure of Cazadero Dam. It is assumed that most of the sediment trapped by Cazadero Dam was washed into the River Mill Reservoir which was completed in 1911. Thus, sediment trapped behind River Mill Dam represents intercepted bed load transport from the upper Clackamas watershed from 1905 until North Fork Dam was completed in 1958. Harriet Lake Diversion Dam (1924) and Timothy Lake Dam (1956) may have intercepted some sediment; however, the volumes trapped are probably minor compared to the total volume in River Mill and North Fork reservoirs (Figure 4.4).

PGE estimates that approximately 3.8 million m^3 (5 million yds^3) of sediment are trapped behind River Mill Dam. Trapped sediment is comprised of approximately 70% fine sediment (< 2 mm) and 30% course-grained (> 2 mm) sediment (Washington Infrastructure Services Inc., 2001).

4.4 Methods

4.4.1 Surveying

Both LEICA 850L total station surveying and Trimble 4500 RTK GPS surveying utilized the State Plane Coordinate system (NAD 1983 Oregon North State plane projection) and the NAVD88 vertical datum. A total of 9,521 survey points were collected during the 2001, 2002, and 2003 field seasons (Appendix F).

For approximately 3 km below River Mill Dam, detailed bathymetry data were collected in 2003, using a combination of total station surveying techniques and an Acoustic Doppler Profiler (ADP) with an integrated real-time kinematic (RTK) GPS unit for horizontal and vertical position. There were no major flood events during the three years of surveying that would significantly change bed geometry.

Original notes were recovered for approximately 25 transects from approximately 150 m to approximately 396 m below the River Mill Dam (Lanahan, 1910). According to the survey notes, depths were determined by sounding rod or chain. The vertical datum for the survey is not specified; however, the "fit" of bank lines appears good in most cases, suggesting that there is not a large vertical offset between the 1910 datum and NAVD88 datum used for the 2001-2003 surveying. It is likely that elevations reported in the survey notes are in the same vertical datum as surveying done in 1908. If this is true, then adding 0.73 m (2.4 feet) to the sounding elevations will place them in the NAVD88 vertical datum. The magnitude of the difference between the 1908 and 2003 transects makes height differences due to datum shifts less of an issue than if differences were minor.

Thirty-two transects by the Federal Emergency Management Agency (FEMA) in 1979 were georeferenced, located, and resurveyed using GPS control points and total station surveying.

4.4.2 GIS Analysis

Historic aerial photos and maps were georeferenced using ArcView 3.2 Image Analysis Suite and ArcMAP 8.2 georeferencing tools. All aerial photos were georeferenced to a set of 2000 orthophotos provided by PGE. A minimum of 6 points were used to reference each photo. Short-term channel migration was analyzed using maps and aerial photos dating back to 1853. Photos were compared to determine erosion and channel migration rates.

Two different GIS methods were used to estimate sediment storage changes below River Mill Dam: 1) Digital Elevation Model (DEM) difference; and 2) 3D polygon.

The DEM difference method required the construction of a 1938 DEM based on the 1938 aerial photo and extrapolation of known topography from 2000 photogrammetry and topographic surveys performed during 2001-2003. For example, the elevation of an island that was eroded was extended to its pre-erosion position in order to create the topography of the island prior to erosion. The most significant source of error in this method is the assumptions made during creation of the 1938 DEM. The modern DEM was compiled from extensive surveying and bathymetry collected from 2001 to 2003; and 2000 photogrammetry. Since bathymetry is not available for 1938, it is not possible to determine whether significant changes to in-water channel geometry have occurred.

The 3D polygon method outlines areas of erosion and deposition on the 1938 and 2000 aerial photos. Each polygon is assigned an average depth from which volumes of erosion and deposition can then be calculated. Elevations used to derive depth were from total station ground surveying.

4.4.3 Tracer Experiments

In order to evaluate the mobility of bed load and surface grain size below the dam, painted particles and tracer rocks were used. Approximately 140 particles were painted and fitted with passive

Integrated Transponders for identification (Figure 4.11). In addition, eight 1-meter squares of in-situ gravel bed were painted and surveyed.

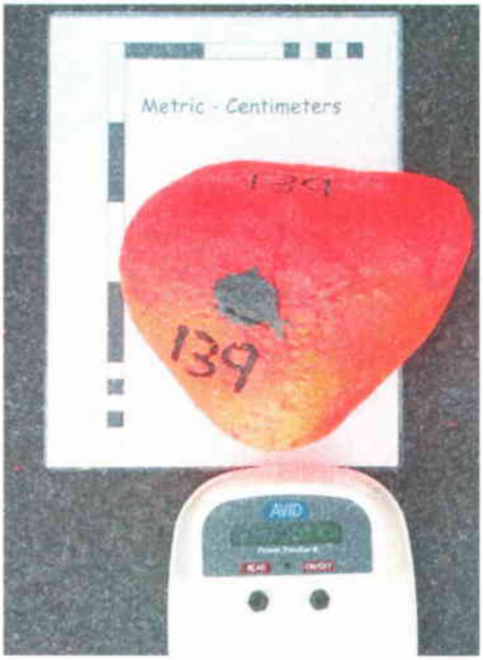


Figure 4.11 Painted tracer rock with Passive Integrated Transponder (PIT) tag reader.

Tracers and painted squares of surface sediment were surveyed after a discharge event of 273 cms, which occurred January 4, 2003. Many tracers less than 32 mm were not recovered, indicating that they were moved during the event. This result is consistent with 676 individual particles that were mobilized from the painted squares at RM 22.7 below the dam.

4.4.4 Sediment Storage below River Mill Dam

In order to evaluate downstream impacts to the Clackamas River below River Mill Dam, it is necessary to estimate historic and modern bed load transport rates and determine what sediment sources are available below the dam to replace trapped sediment. Reservoir trap data provides a time-integrated estimate of bed load transport. Sediment storage for 3 km below River Mill Dam was evaluated using aerial photos, digital elevation models, and GIS techniques to calculate: 1) storage in the active meander belt; and 2) Holocene terrace storage. Sediment introduced by anthropogenic means was also estimated using historic elevation photos and documents.

In order to evaluate whether bed load transport recorded by dam trapping is significant relative to storage below River Mill Dam, volumes were calculated based on topographic data collected during the 2001, 2002, and 2003 field seasons. Deep pool bathymetry was collected during the summer of 2003, using Real Time Kinematic GPS and an Acoustic Doppler Profiler. Sediment volume analysis encompassed the active meander belt, defined as the area below Holocene terraces (> 650 years old), subject to inundation and erosion over a time span of centuries.

Since the base of the stored gravel was not visible in many cases, the assumption was made that bedrock elevation immediately adjacent to a gravel bar represented the bedrock base for volumetric calculations. The bedrock base is likely to be irregular and may contain paleo-channels. Therefore, gravel storage estimates should be considered minimum values.

4.4.5 *Grain Size Analysis*

Evaluating grain-size changes that result from dam construction was hampered by a lack of grain-size data collected prior to dam construction. Several indirect methods were used to quantify changes to sediment size, including: 1) detailed identification of current grain-size distributions both below and above River Mill Dam; 2) comparison of modern grain-size data to Holocene terraces; 3) rock tracer experiments to predict bed load mobility within the reach below River Mill Dam; and 4) examination of historic ground photos.

Approximately thirty sites were selected from River Mill Dam (RM 23.9) to Carver (RM 8) for the collection of surface and sub-surface grain-size data. Sample locations were chosen to provide good spatial coverage; and, when possible, and similar geomorphic settings were chosen (i.e., bar heads). Surface grain-size analysis consisted of Wolman pebble counts of 50 to 200 particles. Surface particles were measured using an aluminum gravelometer template with ½ ϕ-size intervals.

Subsurface samples were collected from a one-meter square in the same location as surface Wolman pebble counts. Surface armor typically was 1 to 2 grain diameters thick and was removed prior to subsurface sampling. Subsurface samples were field-sieved to reduce sample size. Final sieving was done in the lab. An additional 10 surface Wolman pebble counts were obtained near and above River Mill Dam in 2002. The samples upstream of River Mill Dam were taken to evaluate whether the observed coarsening below the dam was different than the coarsening trend above the dams (River Mill, Faraday, and North Fork) (Appendix G).

4.4.6 Bed Elevation Changes (Incision/Aggradation)

Evaluating short-term incision trends resulting from dam operations is complicated by rapid Holocene incision near the River Mill Dam location.

Radiocarbon dating of the Estacada Surface, located 43 m above the present river, yields an incision rate of 43 m/10,000 years, or approximately 4.3 mm/year. This rate of incision is an order of magnitude greater than that reported for other incising valley systems (Schumm and Ethridge, 1994). The anomalously high incision rate may be the result of a catastrophic event downstream such as a landslide dam or other transitory obstruction. Specific gage analysis was done for the Estacada gage (1421000). Estimates of root crown height above the modern water surface were made for roughly 1 km below the dam, using a clinometer and measuring tape.

4.5 Results

4.5.1 Sediment Storage Estimates

Alluvium is stored in two main areas adjacent to the Clackamas River below River Mill Dam: 1) in the active meander belt (< 650 years old); and 2) in Holocene terraces (> 650 years old). The river can more easily access sediment stored in the active meander belt; however, the volume stored in this location is minor immediately below River Mill Dam. Some input from terraces occurs due to mass wasting, but is likely volumetrically minor based on field observations. Modest sediment volumes have been introduced through anthropogenic inputs.

4.5.1.1 Active Meander Belt Sediment Storage

A detailed sediment storage analysis was completed for a 3 km reach below River Mill Dam (Figure 4.12).

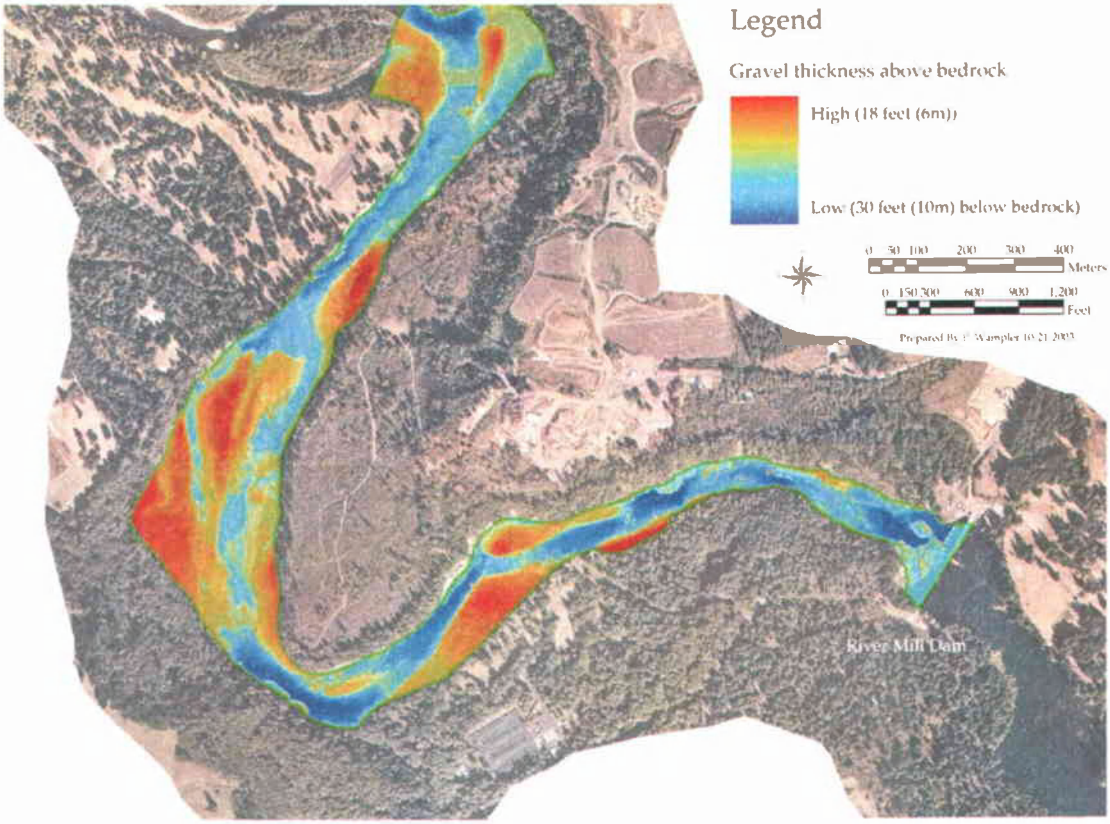


Figure 4.12 Gravel thickness below River Mill Dam. Bedrock elevations were surveyed and used to calculate sediment thickness.

Gravel storage volumes and the volume of gravel needed to fill the reach to various gravel depths were calculated using ArcGIS 3D Analyst (Table 4.2). Gravel storage estimates are somewhat low due to in channel transport not accounted for by the GIS analysis.

Table 4.2 Gravel storage volumes below River Mill Dam[a]

Storage Location	yd^3	m^3
Gravel present above bedrock[b] in active meander belt	391,228	299,115
Volume of gravel needed to fill deep pools to bedrock level	228,443	174,657
Total volume of gravel needed to fill deep pools and active channel to:		
30 cm above bedrock	303,372	231,945
1.5 m above bedrock	775,771	593,119
3 m above bedrock	1,552,236	1,186,770

[a] Volumes are for the active meander belt (<650 years) for 3,091 m (10,140 ft) below River Mill Dam.

[b] Bedrock elevations were determined from total station survey and photogrammetric methods. Bedrock elevations beneath gravel bars and islands were assumed to be roughly the same elevation as adjacent bedrock shelves. The 3D bedrock surface was created using ARCGIS 3D analyst. Volumes above and below the bedrock surface were calculated by subtracting the bedrock 3D surface from the 2003 bathymetry surface using ArcGIS spatial analyst.

4.5.1.2 Holocene Terraces

The primary sources of spawning-size gravel (10-100 mm) immediately below River Mill Dam are terrace gravels within Holocene terraces. A thickness of approximately 6 m of gravel is present above the mudstone on this terrace. If all of the available surface were eroded into the river, the total volume introduced would be approximately 2,860,000 m^3 of sediment. This volume represents 70% of the sediment trapped behind River Mill Dam (Washington Infrastructure Services Inc., 2001). Grain size analysis of terrace gravel indicates that roughly 61.6% is sand-size (< 2mm), and 38.4% is gravel- and cobble-sized material (> 2mm). This is comparable to the grain size proportions for sediment trapped by River Mill Reservoir; 70% fine-grained (< 2mm), 30% course-grained (> 2mm).

Other terraces downstream of McIver Park provide additional resources from which the river can replenish sediment load. But many of these terraces are isolated from erosion by bank protection structures. For example, an additional 6,970,000 m^3 of sediment are present in a 3.7-meter-thick terrace near Paradise Park (RM 20) and Feldheimer (RM 19). However, roughly 60-70% of this sediment source is isolated from erosion and incorporation into the river by bank protection structures.

4.5.1.3 Anthropogenic Gravel Introduction

During the construction of River Mill Dam, rock and gravel were excavated. Excavated material is quantified in daily construction reports as being on the order of 57,000 m^3 (75,000 yds^3) (unpublished construction reports, 1910). Rock and gravel was transported by steam engine on a small rail line below the dam, and stockpiled in a "spoil pile." A comparison of recent photos with historic photos taken at the spoil pile shortly after dam construction shows that virtually all the spoils have been eroded (Figure 4.13). It is unclear how far the material moved; although 1910 river soundings suggest that some of it may have moved only a short distance downstream to fill a deep pool that was present in a 1910 survey.

Estacada Rock Products, Inc., located just downstream of River Mill Dam is another potential source of anthropogenic sediment introduction. This mining area has been in operation since 1948. According to workers at the quarry, significant amounts of what was considered worthless rock (20 to 50 mm (1- to 2-inch) drain rock) was pushed over the riverbank into the river at approximately RM 22.9. The exact volumes introduced in this way are unknown; however, large stockpiles of this material are present on the site today, suggesting volumes may have been in the 100's to 1,000's of

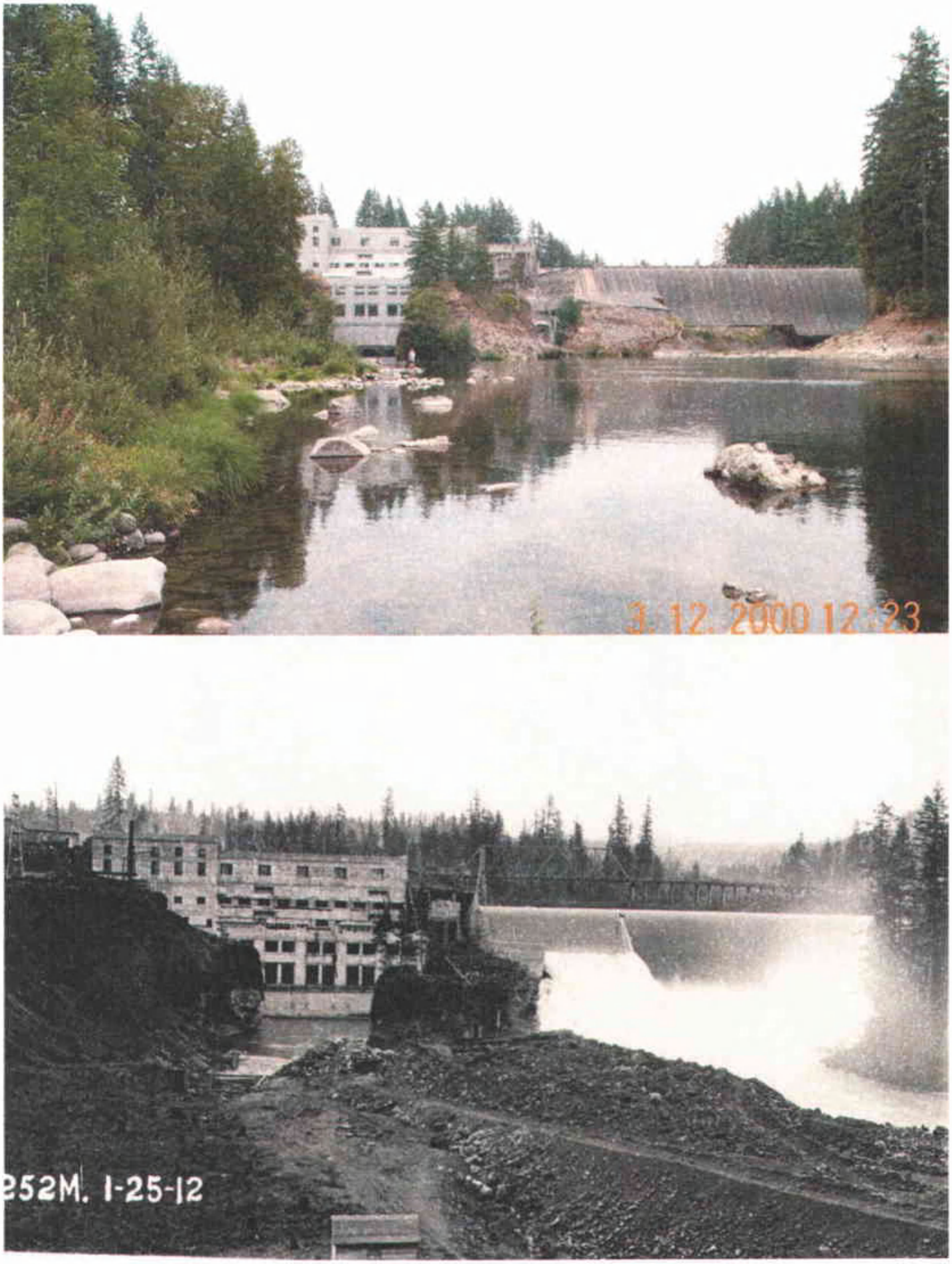


Figure 4.13 Spoil pile below River Mill Dam 2003 and 1912.

cubic meters. Smaller grain sizes along the downstream end of a gravel bar on the right bank may have been derived from this source.

Lastly, several years of repair and reconstruction of the upper McIver boat launch (RM 22.7) has introduced relatively minor quantities of gravel, on the order of 10's of cubic meters. This rock is visible in a trail along the left bank below the current location of the boat launch. This rock is easily distinguished from river rock in that it is not rounded.

4.5.2 Bed Load Transport below River Mill Dam

Bed load transport was estimated by two different geographic information system methods and from reservoir trapping.

4.5.2.1 Sediment Mobility Thresholds

Sediment entrainment studies were conducted during winter 2003, using painted particles with grain sizes ranging from 2 to 256 mm. Results indicate that spawning-size gravels (up to 128 mm) are mobile during even moderate flood events (~1-year recurrence interval) on the Clackamas River below River Mill Dam. Mobile clasts ranged from < 2 mm to 128 mm, with an overall D_{50} (median grain size) of 11 mm for recovered clasts (Table 4.3).

Salmonid spawning was observed in several areas in the 3 km reach below River Mill Dam in 2002 and 2003, suggesting that suitable substrates are available in pockets within the reach. Locations of observed spawning activity were often downstream of actively eroding Holocene terraces.

Table 4.3 Mobile sediment particles measured after January 4, 2003 flood.

Square Number	Location	Mobile Clasts		
		Number	D_{50} (mm)	D_{max} (mm)
1	Upper McIver (~RM 22.7)	402	8.7	32
2	Upper McIver (~RM 22.7)	71	26.0	64
3	Below Feldheimer (~RM 18.5)	39	44.0	64
4	Below Feldheimer (~RM 18.5)	7	28.9	45
5	Below Feldheimer (~RM 18.5)	110	35.8	128

Terraces appear to provide a local source of suitable substrate that remains available as flood flows decrease.

4.5.2.2 Bed Load Transport based on Reservoir Trap Data

One of the best means of estimating long-term bed load transport is the trapping of sediment which has been occurring for 93 years behind River Mill Dam (much of the trap occurred during the first 51 years). This record provides a time-integrated estimate of bed load transport (Table 4.4).

The trapping rate for North Fork Reservoir was over 3 times greater than the River Mill trap rate. The difference is probably due, at least in part, to the fact that North Fork Dam captured bed load during both the 1996 and 1964 floods.

Table 4.4 Reservoir trap data for coarse bed load (from (McBain and Trush, 2002); and (Washington Infrastructure Services Inc., 2001).

	yd^3	m^3
River Mill Dam (51 years)	5,080,404	3,884,248
River Mill Dam Bedload[a]	1,524,121	1,165,274
Annual volume of coarse bedload trapped	**29,885**	**22,849**
North Fork Dam (42 years)	15,523,504	11,868,570
North Fork Dam Bedload[a]	4,657,051	3,560,571
Annual volume of coarse bedload trapped	**91,315**	**69,815**
Combined (93 years)	20,603,908	15,752,818
Combined Bedload[a]	6,181,172	4,725,845
Annual volume of coarse bedload trapped	**66,464**	**50,816**

[a] Bedload defined as > sand-size (assumed 30% of total sediment trapped).

4.5.2.3 Geographic Information System Bed Load Transport Estimates

In order to compare modern bed load transport rates below River Mill Dam to trap-derived rates, bed load transport below the dam was estimated by comparing aerial photos from 1938 and 2000. Discharge was comparable during the two photo dates (1938 $Q_{Estacada}$ = 24 cms; 2000 $Q_{Estacada}$= 27 cms). Two different GIS-based methods were used to estimate bed load transport rate based on the photos: 1) the DEM differencing method (Table 4.5); and 2) the 3D polygon method (Table 4.6).

4.5.3 Bed Elevation Changes (Incision/Aggradation)

The Clackamas River exhibits incision, both in response to short-term changes such as avulsion events and dam construction; and long-term incision related to climate oscillations and large changes in the sediment flux from the upper watershed. In order to directly evaluate short-term changes in channel geometry and bed elevation, it is necessary to have historic bed elevations.

Table 4.5 Bed load transport based on 1938 aerial photos and 2003 bathymetry.

	DEM Difference Method[a]	Volume		Annual Rates
		yd^3	m^3	
Deep-pool geometry assumed to be comparable in 1938	65 years from 1938 to present lost to erosion	207,242	158,448	
	65 years from 1938 to present gained in bars	71,732	54,843	
	Net Transport out of reach	135,510	103,605	
	Annual Bedload Transport (m^3/year)			1,594
	Tons[b]/ Year			2,710
Deep pools assumed to be a largely post-1938 feature	65 years from 1938 to present lost to erosion	463,122	354,082	
	65 years from 1938 to present gained in bars	61,039	46,668	
	Net Transport out of reach	402,083	307,414	
	Annual Bedload Transport (m^3/year)			4,729
	Tons[b]/ Year			8,042

[a] Volumes were calculated by creating a TIN based on the 1938 aerial photography and reconstruction of 1938 topography. The difference between the reconstructed 1938 3D surface and the 2003 3D bathymetry was used to calculate volumes of sediment loss or gain.

[b] Gravel density assumed to be 1.7 tons/m^3.

Note: This method does not account for in-channel bedload transport; not visible on aerial photos.

Table 4.6 Bed load transport based on aerial photos between 1938 and 2000.

Polygon and Average Depth Method[a]	Volume		Annual Rates
	yd^3	m^3	
65 years from 1938 to present lost to erosion[b]	296,664	226,816	
65 years from 1938 to present gained in bars	59,971	45,851	
Net Transport out of reach	236,693	180,965	
Annual Bedload Transport (m^3/year)			2,784
Tons[c]/ Year			4,734

[a] Volumes were calculated based on delineating polygons of erosion and depostion between the 1938 and 2000 aerial photos, assuming an average depth of gravel for each polygon area.

[b] No attempt to account for deep pool excavation is included in this volume.

[c] Gravel density assumed to be 1.7 tons/m^3.

Note: This method does not account for in-channel bedload transport; not visible on aerial photos.

Pre-dam topographic data were obtained from two sources: 1) a report on power possibilities on the lower Clackamas River (Sellers and Rippey Consulting Engineers, 1908c); and 2) river soundings from Portland Railway and Light Company surveys done as part of the site investigation for the construction of River Mill Dam (Lanahan, 1910). The 1910 soundings extend for a distance of approximately 396 meters below the current dam location and the Sellers and Rippey data extend from above River Mill Dam to the mouth of the Clackamas River.

In addition to the pre-dam topographic data, several indirect approaches were used to evaluate bed elevation changes, including: 1) qualitative water surface elevation changes based on 1938 and 2000 aerial photos; and 2) gage-analysis of the Estacada United States Geologic Survey (USGS) gage.

4.5.3.1 2003 River Bathymetry Data

Detailed 2003 river bathymetry data revealed regularly spaced deep pools for 3 km below River Mill Dam. Prominent both in the shaded relief map and the longitudinal profile of the 2003 topographic data, is the presence of several deep pools in the reach below River Mill Dam (Figure 4.14 and Figure 4.15). Pools are spaced approximately 240 to 370 m apart or roughly 3.6 channel widths. Pool depth during summer low flow ranges from 3 to 9 m. Underwater camera examination of Dog Creek Pool (RM 22.4) revealed a bottom dominated by exposed bedrock with occasional large boulders, either derived from the bed or from eroding cliffs adjacent to the pools. Almost no alluvial storage was observed in this pool.

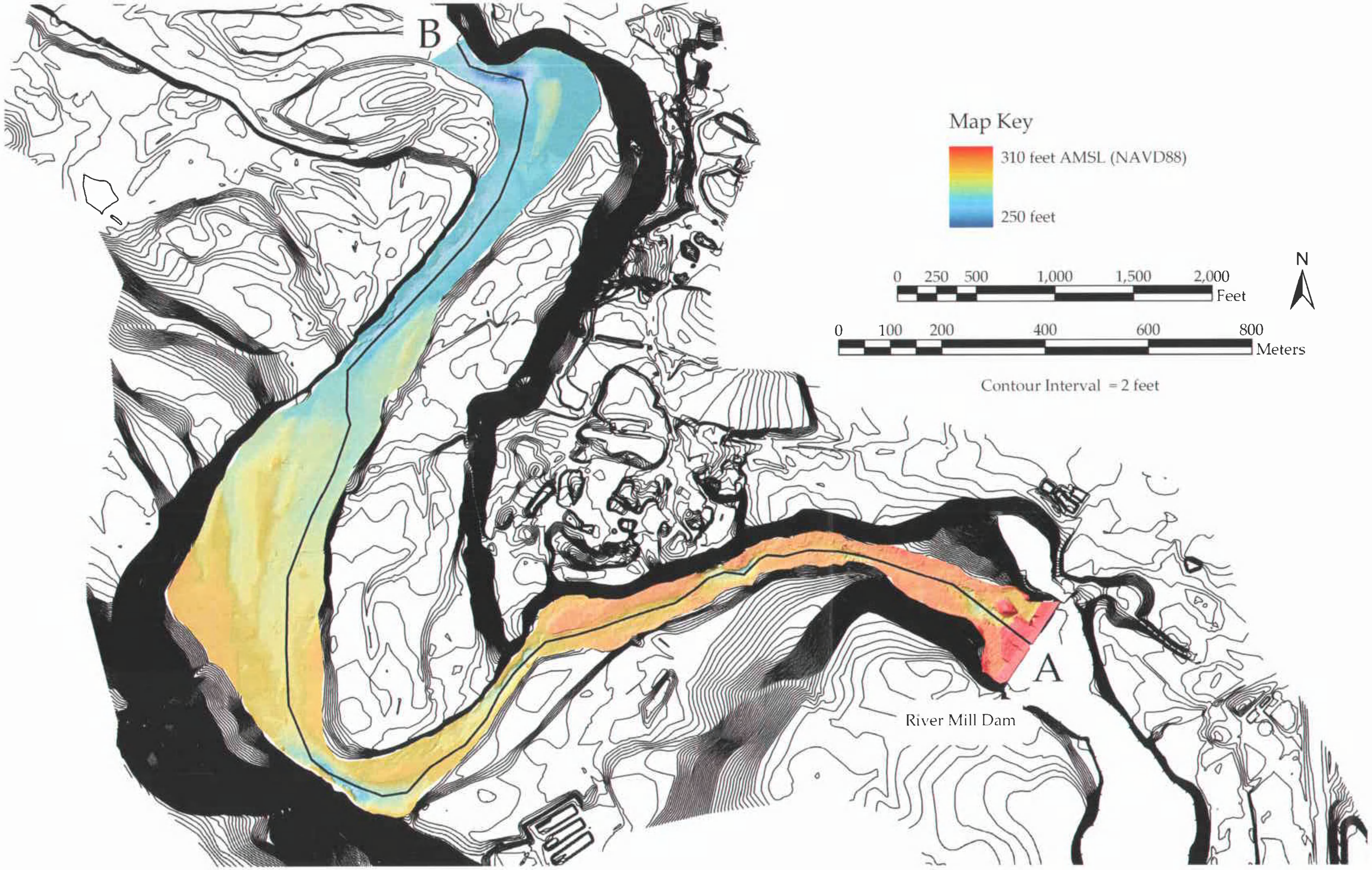


Figure 4.14 2003 Clackamas River bathymetry.

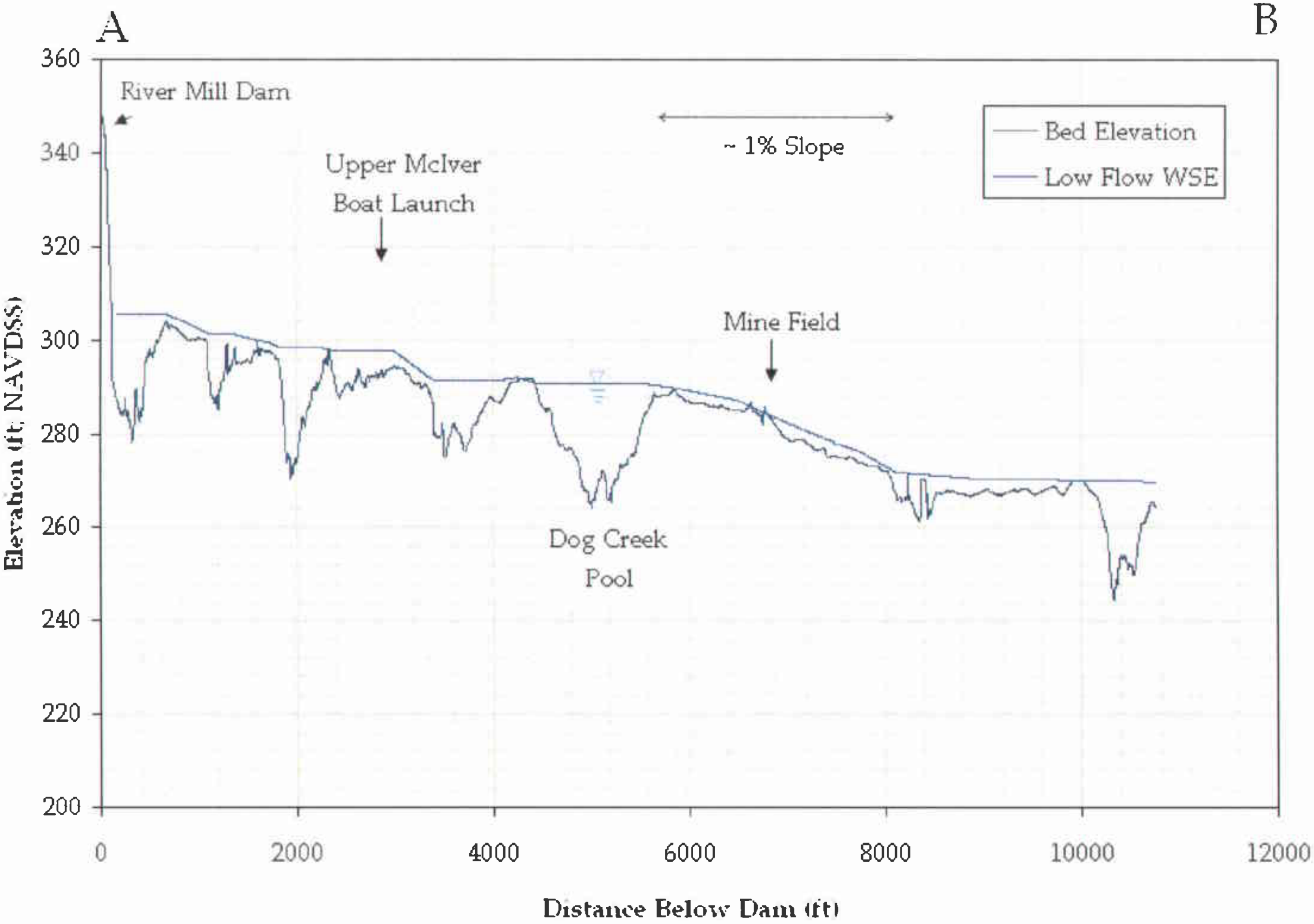


Figure 4.15 Longitudinal profile of A-B from Figure 4.14.

It is unclear whether deep pools were a prominent feature of the Clackamas River prior to River Mill Dam construction. Pre-dam topographic data and anecdotal data suggest that although present, pools were likely less abundant, perhaps shallower, and may have been a transitory feature.

In the summer of 1908, Sellers and Rippey Consulting Engineers (SR), a Philadelphia firm, hired surveyors to collect topographic data from North Fork (~RM 32) to the mouth of the Clackamas River. The primary purpose of the survey was to evaluate potential power production sites below Cazadero Dam, the only power plant present at the time. The survey was started August 27, 1908, and was completed late October, 1908 (Sellers and Rippey Consulting Engineers, 1908c).

The average discharge during the surveying between North Fork and Barton was approximately 22.8 cms (August 27 to September 24, 1908). Surveying from the mouth of the Clackamas River to Barton was carried out between September 30th and October 28th, during which time the discharge at Estacada averaged approximately 36.87 cms. The 2000 aerial photos and photogrammetry was 27 cms at Estacada. Water surface elevation differences between 1908 and 2000 would not likely be dramatically affected by a difference in stage between the 2000 and 1908 surveys.

The SR report included numerous original photos, complete with descriptions of photo locations as well as discharge estimates for all major tributaries. An example of these photos compared to photos taken of the same area in 2003 can be found in Figure 4.16 and Figure 4.17. Though

Figure 4.16 Photograph from Sellers and Rippey site report 1908c. $Q_{Estacada}$ = ~39.6 cms.

Figure 4.17 Photograph taken in August 2003 from River Mill Dam looking downstream. $Q_{Estacada}$ = ~24 cms.

many of the photos have descriptions, only three could be confidently located based on the descriptions. It is possible that there are errors in the photo descriptions, or that the river has changed such that reoccupation of the original photo locations is not possible.

Gravel is visible in several of the photos taken below River Mill Dam. Although gravel size analysis is not possible, qualitative analysis of the photos taken below the dam suggest that grain size was smaller than modern gravel deposits, and bars with spawning-size gravel were more abundant in 1908 than at present. The reach immediately below River Mill Dam (< 1 km) appears to have been a bedrock reach when the dam was constructed.

The narrative of the river in the SR report provides several informative observations including: 1) detailed descriptions of bank heights and composition (gravel or clay); 2) description of gravel bars and gravel extraction activity; 3) bedrock exposure and composition; and 4) discharge estimates for all tributaries. Key observations, by 1908 river mile, are summarized in Table 4.7.

Bedrock exposure is mentioned at Clear Creek, but is not recorded again until RM 23.5. The bed of the stream between RM 23.5 and roughly RM 8 is described as "clean gravel." The river is said to form "clay bluffs" on the outside of bends and "low, gradually rising land" on the inside of curves.

Table 4.7 Summary of observations, (Sellers and Rippey Consulting Engineers, 1908b).

1908 River Mile	Observation
2 to 8	River bed and shores are small gravel being extracted for building purposes.
8	Clear Creek enters the Clackamas R. ~ 700 feet above Baker's Bridge.
~ 8.5	High rock bluff on right bank is about 67 feet above the water surface.
10	Barton USGS gage.
17.25	Eagle Creek enters and the Clackamas both banks of Eagle Creek are cultivated.
23.5 to 24.5	Gravel and clay banks give way to "cemented gravel or conglomerate" (Sardine Formation).
24	River is narrower than at any other point between the mouth and Estacada (future River Mill Dam site).
24-27.5	River flows through a gorge or canyon.
25	USGS cableway location (Estacada gage, former location).
26.75	Cazadero Station location.

4.5.3.1.1 1908 Map and Longitudinal Profile, North Fork to Mouth of the Clackamas River

Accompanying the SR report was a detailed map (Map C.R. #205). The original map, obtained from the PGE engineering archives, is 6 m long and was prepared at a scale of 1 inch=500 feet (1:6,000). A longitudinal water surface profile obtained from 325 survey stations is inset on the map. The vertical datum used for the longitudinal profile is described as the "O.W.P. datum as now used for the Cazadero station records." The water surface elevation at the mouth, in terms of the above datum, was +2.4 ft on October 3, 1908 (Q ~24.5 cms at Estacada). According to another SR report (Sellers and Rippey Consulting Engineers, 1908a), the Cazadero Powerhouse floor was 122.6 m (402.1 ft) based on the "railway" or "U.S.G.S.

sea level datum" (also referred to as the O.W.P. datum). When the powerhouse floor was surveyed in 2003, the elevation obtained was 404.5 ft (NAVD88) (Gary Reynolds, personal communication). This results in a difference of +2.4 ft (NAVD88-O.W.P. = ~2.4 ft). Based on these data, it is assumed that adding 2.4 ft to the elevations obtained in 1908 will place them in the NAVD88 vertical datum and allow a comparison of water surface elevations from the 1908 survey.

The water surface elevation comparison suggests that the Clackamas River, over the last 92 years (1908 to 2000), degraded an average of 82 cm from about RM_{1908} 24 to RM_{1908} 14 (Figure 4.18). Water surface elevation is largely unchanged from RM_{1908} 14 to RM_{1908} 10 (average change = 20 cm), at which point the river aggraded an average of 98 cm until RM_{1908} 2, below which it degraded 110 cm. Since the 1908 survey recorded only water surface elevations, it is not possible to determine whether there have been significant changes to the geometry of the channel from these data; for example, whether deep pools and exposed bedrock were present in 1908. Geometry data are available from soundings taken below the dam in 1910.

Anecdotal evidence of degradation near the mouth of the Clackamas River is consistent with the 1908 mapping data. A comparison of 2003 photos with historic photos taken prior to 1899, suggest a lowering of the water surface elevation of 1 to 2 m (Figure 4.19 and Figure 4.20).

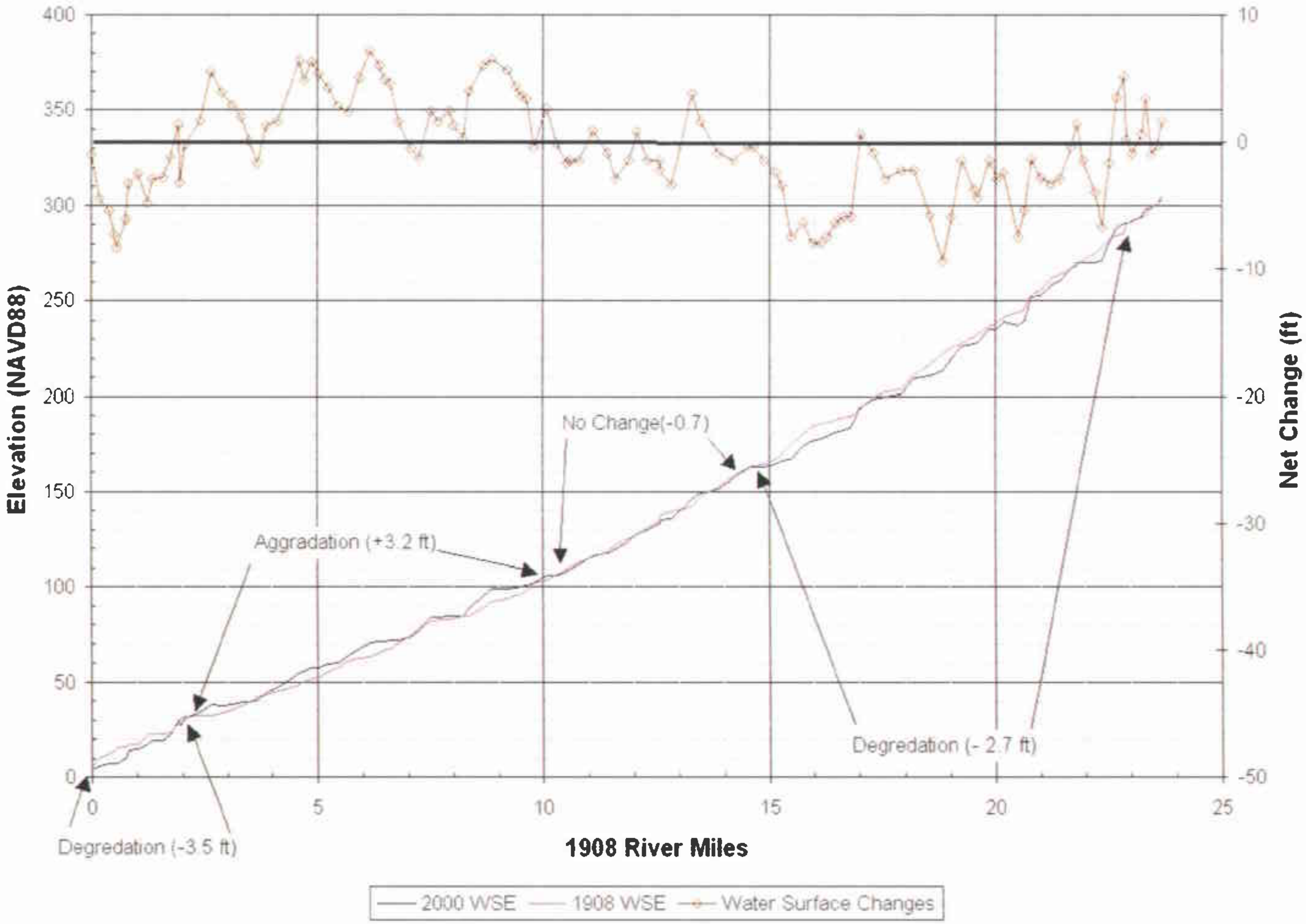


Figure 4.18 Comparison of water surface elevations, 1908 and 2000. The upper line is change in water surface elevation during the same period.

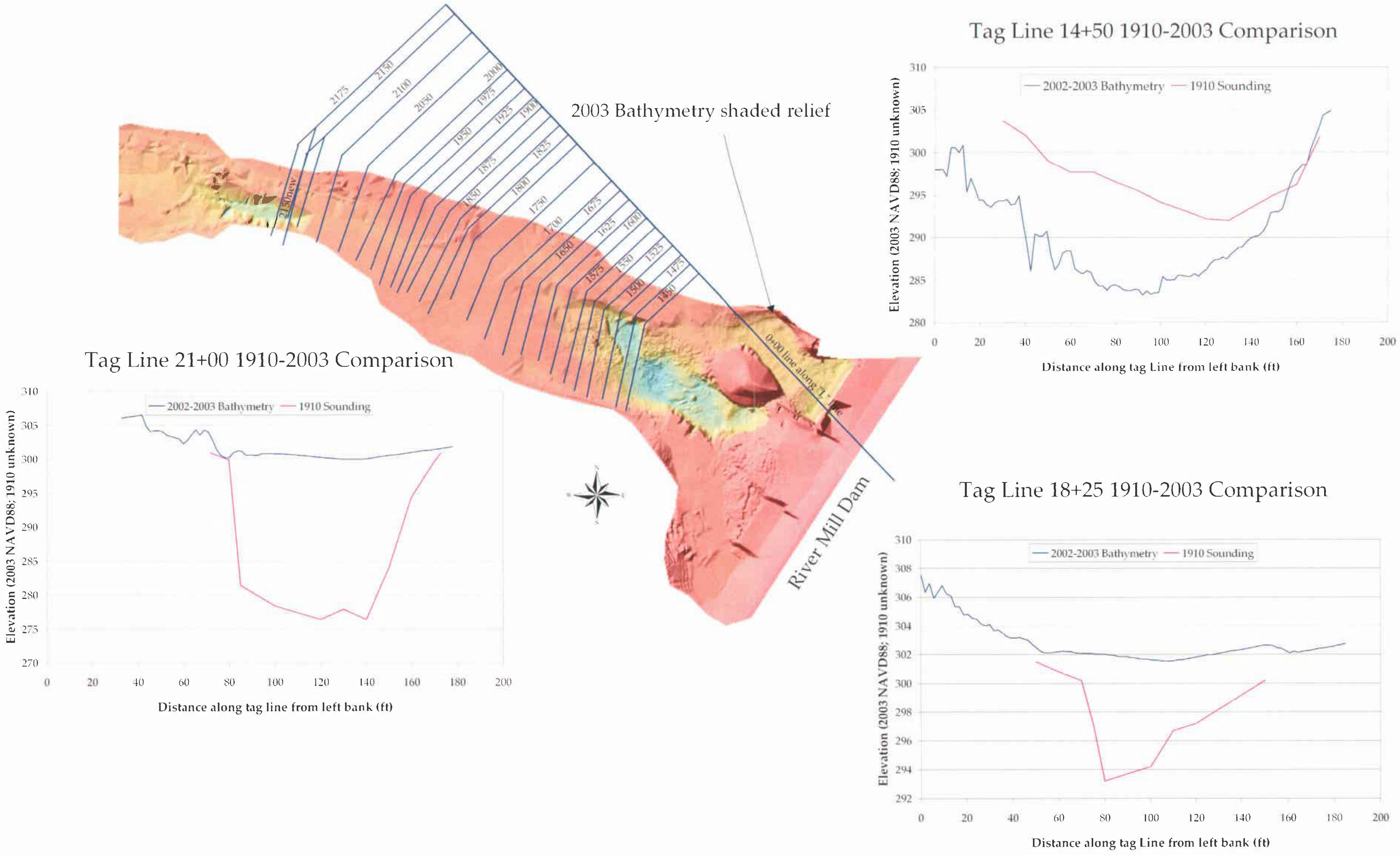
Figure 4.19 1899 Photo taken near the mouth of the Clackamas River (~RM 1.3).

Figure 4.20 2003 photo taken at ~RM 1.3 looking downstream. Q=24 cms at Estacada. Note the difference in water level, suggesting significant downcutting since the pre-1900 photo was taken.

4.5.3.1.2 1910 River Soundings

In 1910, transects were surveyed on or about September 12, 1910 (Figure 4.21). Discharge measured at the Estacada gage remained 24 cms (840 cfs) from September 12 until September 19, 1910. The average discharge for the month of September was 24 cms (850 cfs). This discharge is comparable to the summer low flow for most of the modern surveying done between 2001 and 2003 (~20 to 25 cms).

Soundings from 1910 provide compelling evidence for the presence of deep pools prior to dam construction, although the limited extent of the survey leaves uncertainty as to whether deep pools extended as far downstream as they do at present. At least two deep pools were documented by the 1910 survey. Although pools were essentially the same depth in 1908, it is clear from a comparison of 1910 bathymetry with 2003 bathymetry that the location of deep pools has changed. A deep pool originally located approximately 329 m below the dam appears to have filled with sediment. Since most of the filling would have occurred during or after the construction of River Mill Dam, the source would have to have been a relatively short reach below the dam. There are two possible sediment sources: 1) the river bed immediately below the dam (which is largely exposed bedrock at present); and 2) material excavated from the dam site during construction. Daily construction notes indicate that approximately 57,000 m^3 were stored in a "spoil" pile located just below the small island below the dam (Figure 4.13). The material excavated was described as a mixture of rock and gravel.



Tag Line 14+50 1910-2003 Comparison

Tag Line 21+00 1910-2003 Comparison

Tag Line 18+25 1910-2003 Comparison

2003 Bathymetry shaded relief

Figure 4.21 1910 transect locations and comparisons to 2003 bathymetry.

There is no record of this material being removed after it was placed in this pile. Presumably the material was eroded by river flows after the dam was constructed, and likely accounts for the filling of the pool documented by the 1910 soundings.

4.5.3.2 *Qualitative Comparison of Aerial Photos*

The 3 km reach below the dam is characterized by deep narrow slots and pools carved into bedrock, lateral erosion, and stripping of alluvium from bedrock surfaces. This may be due, in part, to the durability of the Sardine Formation, which forms the bedrock in much of the reach below the dam. Large angular clasts exposed by erosion often remain cemented in the matrix for many years after exposure, suggesting that erosion rates are low. Persistent bed features, such as the "Mine Field" below Dog Creek (RM 22), are created by boulders that remain embedded in the bedrock, creating an effective grade-control and energy dissipation structure. Figure 4.22 shows a sketch of the pattern of bed degradation observed for approximately 3 km below River Mill Dam. Degradation is characterized by lower water surface elevations; deep pools, up to 9 m deep; bedrock surfaces stripped of sediment; and bedrock shelf formation where lateral erosion of mudstone cliffs has occurred. The result is an overall decrease of low flow in side channels, and an increase in exposed bedrock.

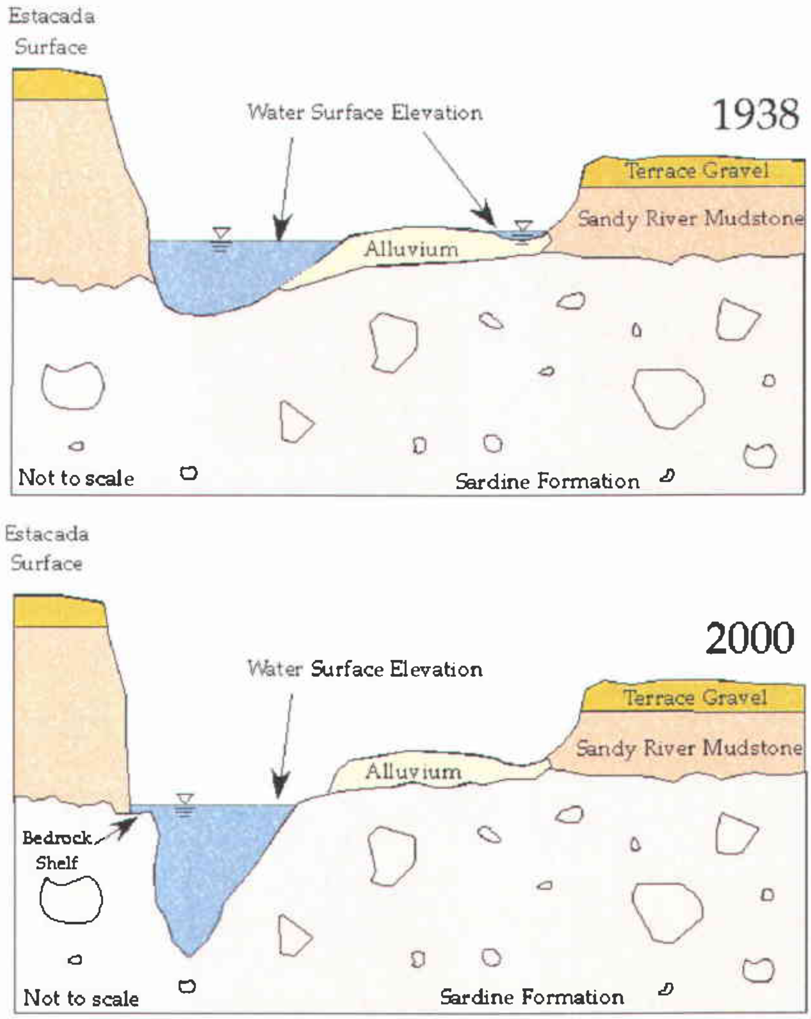


Figure 4.22 Schematic diagram of bed degradation pattern below River Mill Dam. The diagram is based on 1938 and 2000 aerial photos.

4.5.3.3 Specific Gage Analysis of Estacada Gage

Historic discharge measurements made at the cableway for the USGS Estacada gage (#14210000; ~RM 22.8) suggest that the water surface elevations for a given discharge have decreased by approximately 0.30 m since the gage was installed at its present location in 1958 (Figure 4.23 and Figure 4.24). A drop in water surface can result from incision of the bed or

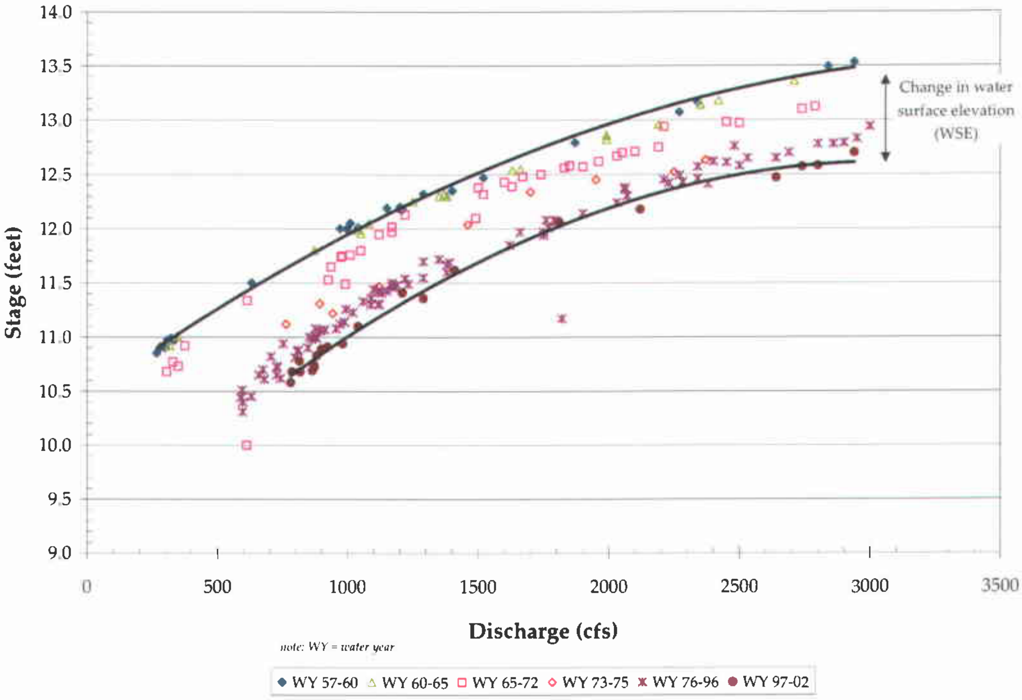


Figure 4.23 Stage/discharge for the Estacada USGS gage (14210000).

a lowering of the downstream control, which determines water surface elevations at the measurement location. Based on field observations and bedrock surveying, it is likely that as the channel erodes laterally toward the right bank near the upper McIver boat launch, water surface elevation at the USGS cableway is decreasing due to a bedrock surface which slopes downward toward the right bank. Gage measurements are summarized in Appendix H.

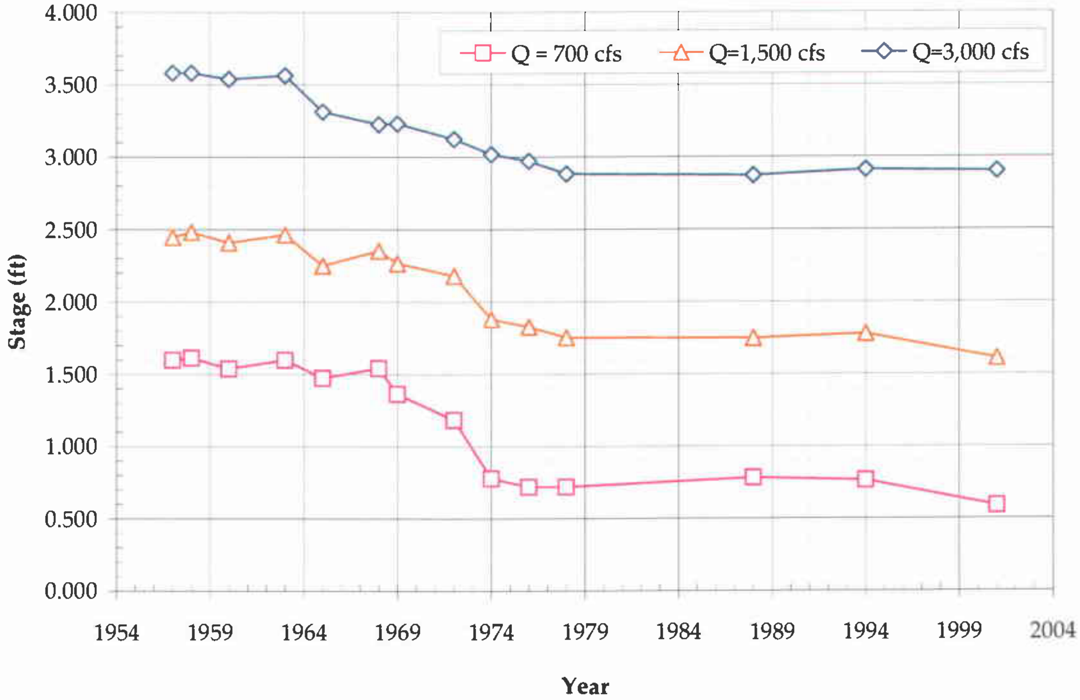


Figure 4.24 Stage height (1957 datum) at Estacada gage (14210000) at a discharge of 20 cms (700 cfs), 42 cms (1,500 cfs), and 85 cms (3,000 cfs), 1954-2004.

4.5.3.4 Root Crown Measurements

An examination of the left bank below River Mill Dam provides anecdotal evidence for incision, or at least removal of lateral gravel storage in bars. Numerous examples of exposed tree root crowns are present below River Mill Dam. An example of the type of relationships observed can be found in (Figure 4.25).

Generally root crowns are 2 to 3 m above the summer low flow water surface. It is assumed that gravel surrounded the roots while the trees were growing and has since been eroded away. This is consistent

Figure 4.25 Photo of exposed tree roots.

with general erosion of marginal gravel deposits below River Mill Dam. Although the original extent of channel margin deposits is difficult to quantify due to lack of pre-dam data, it appears that some amount of stripping has occurred to expose the tree roots along channel margins.

4.5.4 *Surface and Sub-surface Grain-size Analysis*

Analysis of grain size data indicates a discernable increase in surface grain-size, which appears to deviate from the trend observed upstream of Faraday and North Fork dams (Figure 4.26). Median grain size also appears to deviate from trends typical for other gravel-bed rivers. Elevated grain-sizes are discernable for approximately 3 km below the dam. Other areas of grain-size increase are observed below this point. However, these are likely related to avulsion events further downstream (i.e., River Island Sand and Gravel site). Another grain-size anomaly was observed in the

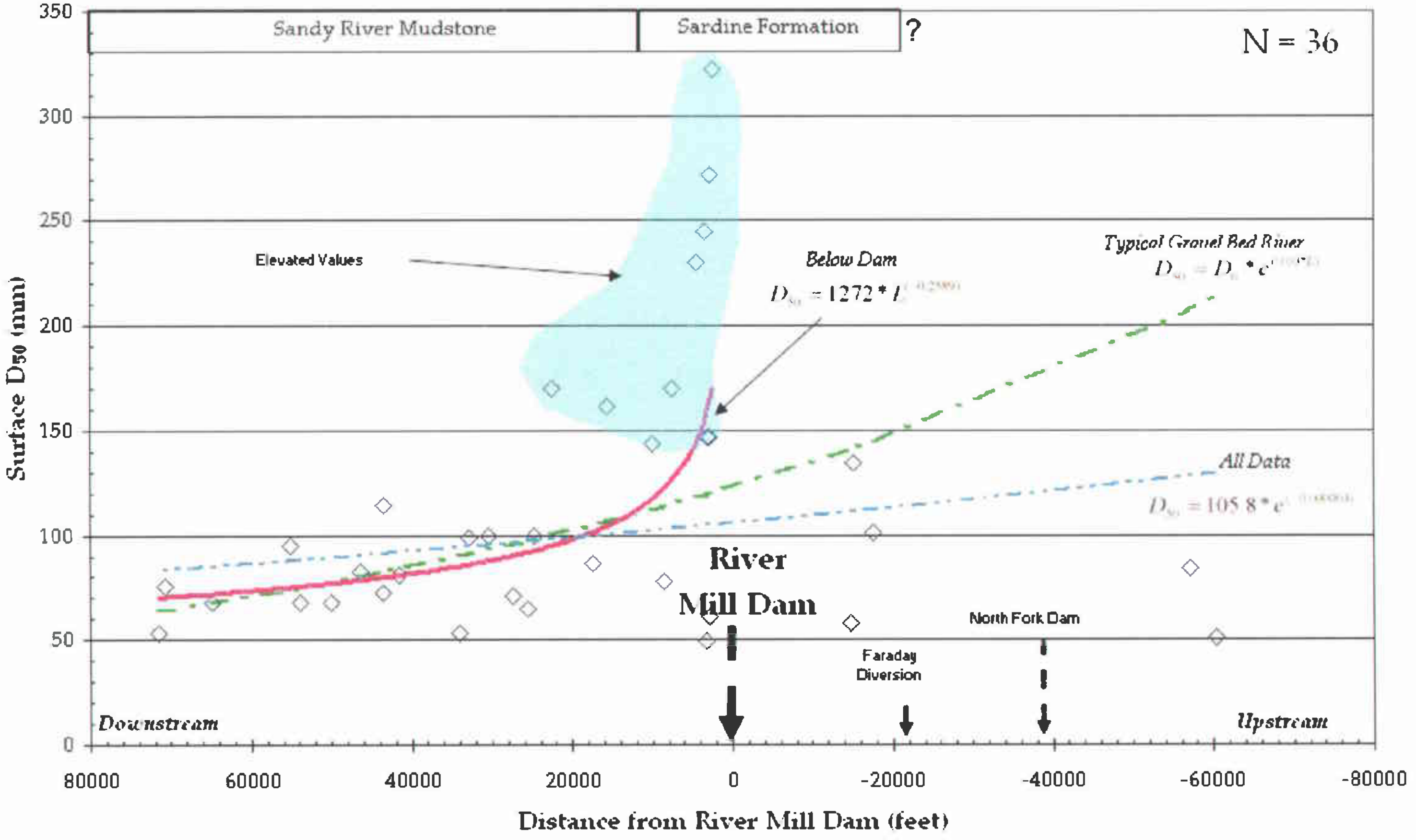


Figure 4.26 Surface grain-size in the lower Clackamas River.

area referred to as Boulder Garden, upstream of Faraday Diversion Dam. This concentration of large boulders is likely the result of either the introduction of a more resistant rock unit nearby, a historic landslide that carried large boulders into the reach, or a paleoflood. Subsurface grain size data did not reveal any systematic longitudinal trends.

4.5.5 Channel Width Changes

Width changes below River Mill Dam were evaluated using historical aerial photos with similar discharges (1938 $Q_{Estacada}$ = 24 cms (860 cfs); 2000 $Q_{Estacada}$= 27 cms (960 cfs)). Between 1938 and 2000, channel width decreased an average of 16.2 m for a distance of approximately 2,400 m below River Mill Dam. Over the next 1,500 m, the channel splits into multiple channels resulting in a net channel widening with an average width increase of 32.3 m (Figure 4.27). Below this point, width changes become less systematic and are likely affected by avulsion events, which result in local areas of width increase and decrease.

4.6 Discussion

The present study suggests there have been measurable impacts to the Clackamas River for at least 3 km below River Mill Dam which can be attributable to Clackamas project operations. Similar but more subtle impacts may be present for up to 14 km below the dam. Impacts include changes to the channel geometry, grain-size, and bed elevation. All of these must be viewed in the context of the natural climate variation and other

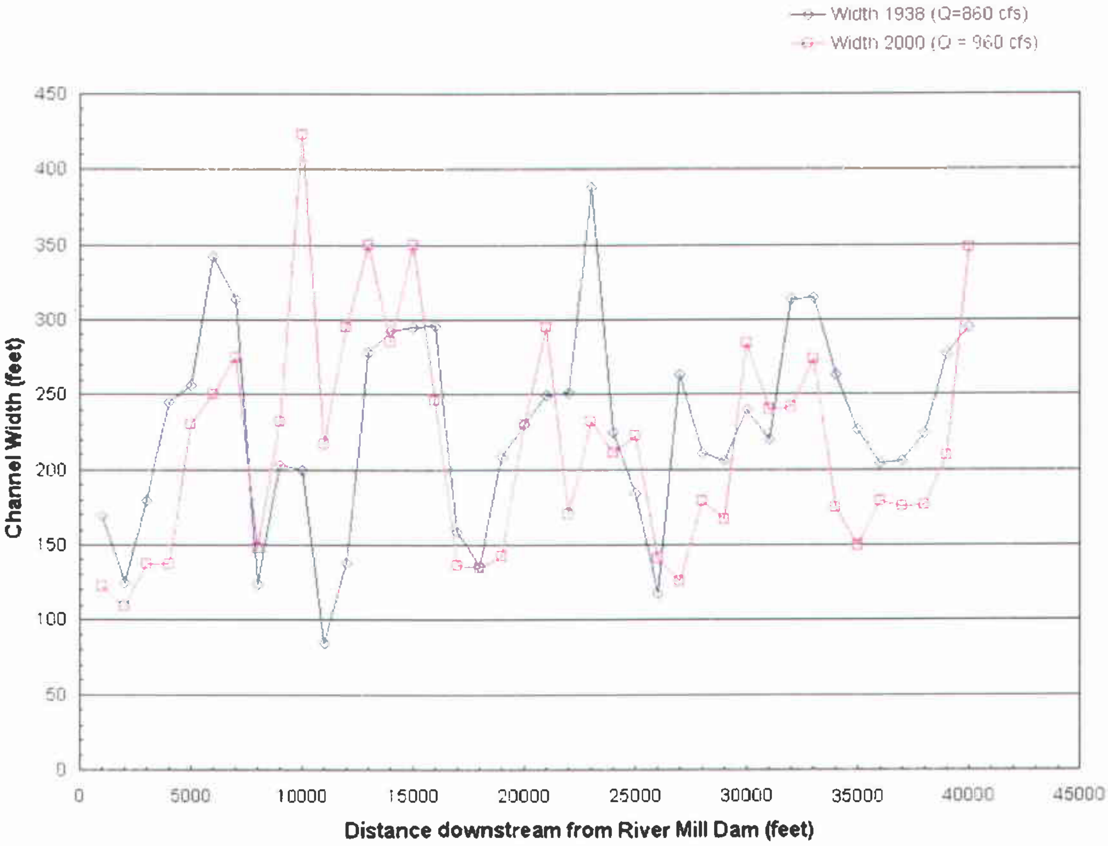


Figure 4.27 Changes in channel width below River Mill Dam, 1938-2000.

anthropogenic changes to the system. Impacts due to the dam operations below 14 km may be present; however, it is not possible at this time to isolate them from natural river processes and other anthropogenic impacts such as gravel mining and bank protection.

Channel migration and lateral erosion are common on the lower Clackamas River. Easily eroded mudstone allows the river to cut deep pools and channels at river bends. These "ruts" in the channel profile tend to occupy the same location for hundreds to thousands of years. Movement out of these "ruts" may be linked to large influxes of sediment (aggradation), which are sufficient to fill the channel and allow the river to move to other locations on the floodplain. Changes in sediment supply resulting from dam closure, isolation of the floodplain by bank protection structures, and in-stream gravel mining may affect the formation and persistence of deep pools, meander bends, and rapid channel relocations.

Sources of gravel between 10 mm and 100 mm below River Mill Dam are limited to islands, gravel bars, and Holocene terraces immediately below River Mill Dam. Input from older terraces above the river is limited to localized landslides which are volumetrically minor. The volumes available below the dam, the sediment motion data from winter 2003, and a comparison of the sediment trapping volumes, suggest that the amount and aerial extent of spawning-size gravel have been reduced as a result of River Mill Dam operations. Replacing sediment trapped behind upstream dams would require introducing large volumes of gravel before widespread aggradation below River Mill Dam is likely to occur. The high frequency of mobility for small particles below the dam suggests that material introduced may not be retained in the reach below the dam.

In order to replace bed load trapped by River Mill and North Fork dams, a minimum of 1,594 to 4,730 m^3 of gravel per year would need to be added, based on GIS bed load transport estimates. Actual quantities needed may be much higher depending on in-channel transport and flow conditions.

In November 2003, approximately 76 m^3 of gravel was added near RM 22.7 as part of an augmentation pilot project to better understand the fate and transport of gravel in this reach. Monitoring throughout 2003-2004 has provided valuable data on bed load transport of spawning-size gravel (10-76 mm) in the reach below River Mill Dam. Data from the pilot project may be used to make more accurate estimates of gravel volume needed to achieve gravel management goals below River Mill Dam.

4.6.1 Reservoir Trap Data

It is likely that erosion rates for both the active meander belt and Holocene terraces are insufficient to offset sediment volume trapped by reservoirs. Determining the amount of gravel that would offset trapped sediment is complicated by what is clearly a long-term trend (since the early Holocene) of periodic reductions in sediment supply. The Clackamas River may have been sediment supply limited prior to dam construction. Isolation of sediment sources by bank protection has likely made geomorphic responses to reduced sediment supply more pronounced below River Mill Dam.

4.6.2 Bed Load Transport below River Mill Dam

Neither the DEM differencing method nor the 3D polygon method can account for in-channel transport, which does not result in erosion or deposition visible on the photos. As a result, both methods would be expected to underestimate the actual bed load transport rate. Bed load transport on the Clackamas River at the Clackamas gage (RM 1.7) was estimated using the modified Einstein method (Laenen, 1995). Twenty-three percent of the total load was bed load and the total load during a 2-

year 1-day flood event was 15,800 tons/day, or 3,634 tons of bed load/day. This is comparable to the annual bed load transport numbers derived from the GIS bed load transport methods.

Bed load transport rates based on reservoir trapping are an order of magnitude greater than those calculated from the 65-year aerial photo comparison. There are several possible explanations for this difference: 1) a reduction in transport rate due to bed coarsening; 2) isolation of stored sediment by incision and exposure of bedrock; 3) insufficient accounting for in-channel transport by GIS methods; and 4) trap volumes biased by higher bed load transport rates due to channel constriction and slope above River Mill and North Fork dams.

Many studies, including the present study, have documented bed coarsening below dams (Collier et al., 2000). Bed coarsening tends to increase with time since dam construction, but approaches a limit as the bed becomes too coarse to transport under the most frequent flows. As the median size of available bed load increases, the frequency of bed load transport would be predicted to decrease (Grant et al., 2003), resulting in a net decrease in bed load transport over time. It is possible that the observed low transport rate below River Mill Dam is the result of an armored bed that may have developed only decades after River Mill Dam was constructed, prior to 1938 photography.

In addition to bed coarsening, incision and exposure of bedrock below River Mill Dam has increased since dam construction. This would result in more energy being dissipated by bedrock erosion, creating complex bedrock morphology such as potholes, flutes, and perhaps deep pools.

4.6.3 *Bed Elevation Changes (Incision/Aggradation)*

Pre-dam topographic data, gage analysis, and root crown observations all suggest that there has been bed degradation and erosion of channel margin deposits below River Mill Dam. Bed degradation is most prominent in the 3 km immediately below the dam, and may be present in a more subtle form for as much as 14 km below the dam. Deep pools and bedrock exposure below River Mill Dam appear to have increased since dam construction.

The regularity of the deep pools is striking and suggests some feedback between river form and dominant flows. What is not clear from any of the data obtained to-date is whether deep pools were a prominent feature below River Mill Dam prior to dam construction. Deep pools were not documented in the 1908 survey of the river, suggesting they were not prominent enough to warrant a comment in the report. The 1910 soundings prove there were at least some deep pools present immediately below the dam; however, the limited extent of the 1910 survey does not shed any light on the presence or absence of deep pools more than 400 m below the dam.

The pattern of change immediately below River Mill Dam is relatively minor incision, channel margin erosion, and bedrock exposure until the first major flow divergence (~RM 22.7). At this point, channel incision is characterized by isolation of existing gravel bars and bank erosion resulting in bedrock shelves. Below the first flow divergence (at the upper McIver boat launch), it is likely that prior to dam construction deep pools were periodically filled with alluvium transported during flood events and more alluvium was present within the active channel and at channel margins. The rate at which meanders "heal" and begin to increase sinuosity may be affected by changes in sediment supply.

4.6.4 Controls on Grain Size

The threshold of motion for particles with a D_{50} of approximately 22.6 mm is 240 to 270 cms based on particle motion experiments across from the upper McIver boat launch. Since there is very limited source of this size material below the dam, bed coarsening would be predicted as smaller particles are evacuated from the reach below the dam by relatively frequent flows.

Observed deviations in grain-size trends are likely produced by either selective transport of fine-grained sediment out of the surface sediments below River Mill Dam, or large sediment bias introduced by the presence of residual boulders from the Sardine Formation. The Sardine Formation contains very large clast sizes (up to 1.4 m) which are likely too large to be transported by flows which have occurred since dam construction. Thus, over time, the surface grain size in this area may become biased toward larger grain sizes due to local introduction of large clasts.

4.7 Conclusions

Effects from River Mill Dam are complex, but measurable from the dam downstream for 3 km, and include:

1) Surface grain size D_{50} has increased by 2 to 3 times.
2) Channel bedrock exposure and bedrock pool numbers and depths have likely increased from pre-dam conditions.
3) Bed degradation of approximately 0.3 m in 93 years has occurred.
4) Channel width has decreased and water surface elevations have dropped in side channels.

Below 3 km downstream, impacts are more subtle and are combined with anthropogenic and climate changes. Sediment reduction may have resulted in reduced lateral channel migration and bed degradation for about 17 km downstream of River Mill Dam.

Downstream effects from River Mill Dam fall somewhere between the prominent effects observed for the Green River in Colorado (Andrews, 1986), and the very subtle effects described below Pelton-Round Butte Dam on the Deschutes River in Oregon (Grant et al., 1999). As predicted, the dam effects are most prominent immediately below the dam and become more subtle downstream.

5 CONCLUSIONS

The original motivation for this study was to evaluate the downstream effects of River Mill Dam. Dam effects were interpreted within the context of current climatic trajectories and with reference to a human modification of the floodplain which resulted in a meander cutoff. Interpretations and evaluations of river modifications must consider the geologic and geomorphic context and other mechanisms of change which may be altering river form and process over different spatial and temporal scales.

River response to climate change, dam construction and meander cutoff are interdependent on the Clackamas River. It is difficult to accurately attribute river response to one of these mechanisms without considering the relative contribution of the others. Furthermore, separating or determining the relative contribution of each mechanism is challenging because: 1) dam effects are progressively more subtle downstream; 2) the meander cutoff at River Island took place in the context of a river system already changed by sediment reduction below River Mill Dam; 3) temporal and spatial scales are very different for the three mechanisms examined; and 4) there are numerous other factors driving change in the river, such as bank protection, gravel mining, and floodplain development which were not evaluated.

Holocene terraces along the lower Clackamas River are consistent with a warmer and dryer climate since the last global cold period, referred to as the Little Ice Age (LIA) which began around 1450 and ended about

1850. Sediment flux reduction, bed degradation, and a reduction in lateral migration activity has likely occurred since the end of the LIA.

Trajectories of change discussed in the preceding three chapters are generally operating in the same direction, toward channel degradation or incision, causing more pronounced change than might be observed if the processes were operating in isolation (Figure 5.1).

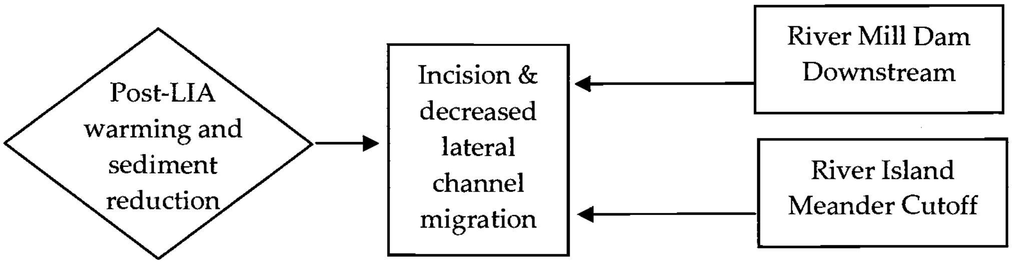


Figure 5.1 Multiple driving mechanisms for degradation and reduction in channel migration activity for the lower Clackamas River.

Incision along the Clackamas River represents the combined effects of anthropogenic and natural trajectories of change. Part of the observed incision rates below River Mill Dam are a result of climate change and degradation affecting the entire watershed; and part of the incision rates at River Island meander cutoff are due to climate and dam-induced incision. (Figure 5.2).

Short term changes, resulting from River Mill Dam operations and meander cutoff, are not independent of each other or the long term pattern of climate change. For example, the River Island meander cutoff increased the incision rate already imposed on the river by River Mill Dam and climate-change. Futhermore, downstream effects of River Mill Dam

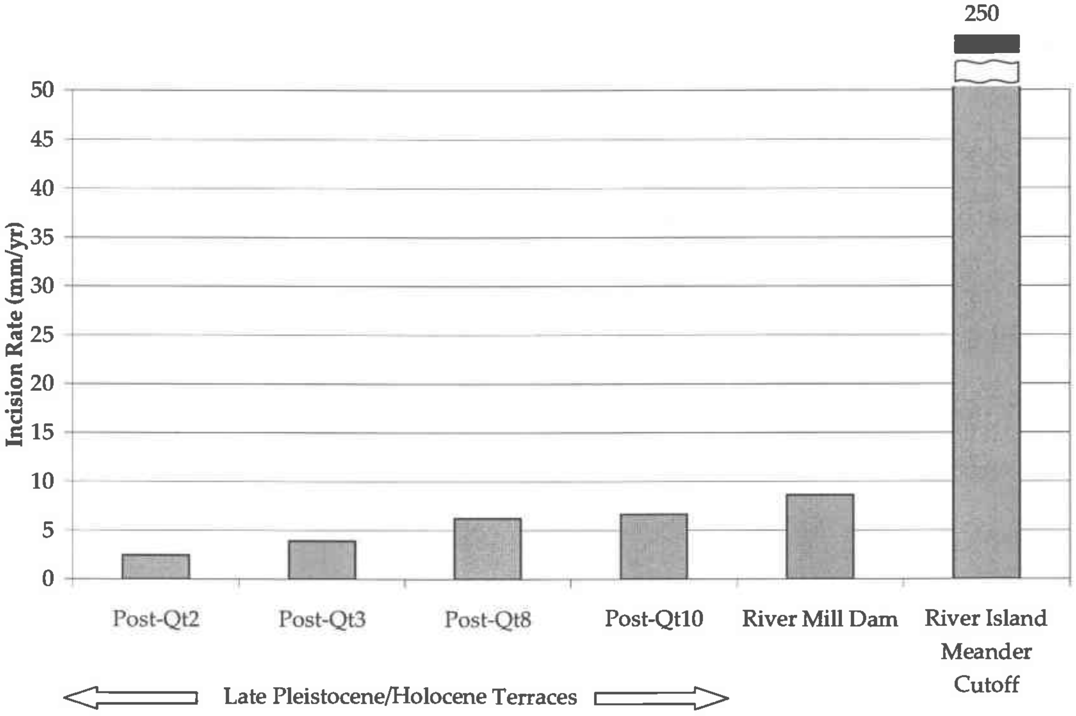


Figure 5.2 Incision rates based on different temporal scales of change for the Lower Clackamas River.

operations are superimposed upon incision already taking place due to late Pleistocene/ Holocene fluvial reponse to climate variability.

Response time, or the amount of time it take the river to return to a stable configuration after a disturbance or change, may also be affected by the combined effects of anthropogenic and natural influences. For example, River Island gravel extraction ponds are filling with eroded sediment and bed load transported in the channel. The rate at which gravel deposition is occurring in the ponds is likely affected by the reduction in sediment supply due to dam construction and climate change.

Watershed-scale changes on the Clackamas River are currently characterized by slow change, which is occurring in one direction (degradation) with episodic trend reversals (aggradation). Downstream effects from both River Mill Dam and the meander cutoff at River Island represent discrete events causing the channel form adjust to changing sediment load, slope, and prevailing climatic mode (Table 5.1).

Table 5.1 Summary of changes in channel forming variables. Arrows indicate direction of change. A = aggradation, I = incision, L_s = sediment load, D = grain size, Q = discharge, and S= slope.

	L_s	D	Q	S	Channel Response
Watershed Scale (Chapt. 2)					
Aggradation Phases	↑	↓	↑	↑	A
Degradation Phases	↓	↑	↓	↓	I
Downstream of River Mill Dam (Chapt. 4)	↓	↑	↔	↓	I
River Island Meander Cutoff (Chapt. 3)					
Upstream	↓	↑	↔	↓	I
In Ponds	↑	↓	↔	↓	A
Downstream	↓	↑	↔	↔	A, I

Modern values of bankfull discharge and slope place the Clackamas River near the boundary between meandering and braided channel forms (Figure 5.3).

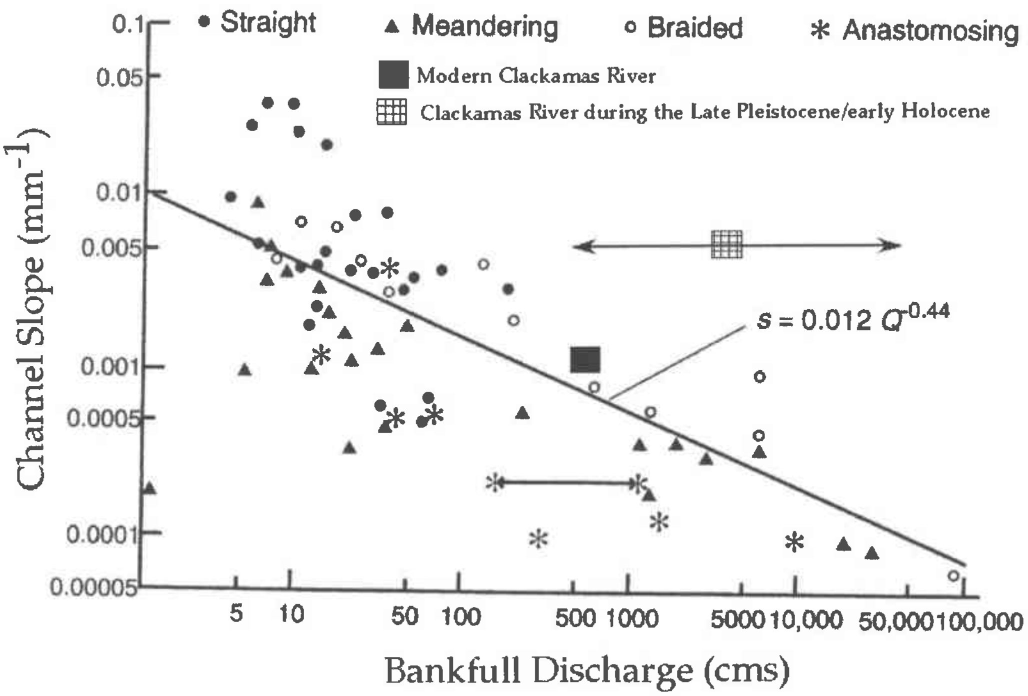


Figure 5.3 Modern and historic channel slope and bankfull discharge for the Clackamas River (from (Leopold and Wolman, 1957).

During the late Pleistocene and early Holocene, the Clackamas River likely had a braided channel form with a bankfull discharge and sediment flux greater than modern times. Since that time, bankfull discharge and slope have decreased, favoring a meandering channel form. Since the start of the Little Ice Age (LIA, ~1450 A.D.) the Clackamas River has experienced reduced sediment load and probably a significant reduction in bankfull discharge.

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