

Patterns and Controls on Historical Channel Change in the Willamette River, Oregon, USA

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23.1 INTRODUCTION

Distinguishing human impacts on channel morphology from the natural behaviour of fluvial systems is problematic for large river basins. Large river basins, by virtue of their size, typically encompass wide ranges of geology and landforms resulting in diverse controls on channel form. They also inevitably incorporate long and complex histories of overlapping human and natural disturbances. Wide valleys were historically prime locations for human settlement, as immigrants were attracted to relatively flat and fertile floodplain soils and rivers served as conduits of travel and commerce. Over the span of multiple centuries, humans typically modified many aspects of a river's hydraulic and hydrologic behaviour, including streamflow regimes, bank erodibility, and sediment supply. Distinguishing anthropogenic impacts from natural influences in large river basins is therefore difficult because there are so many potential drivers of channel change, and human interventions have occurred over long timescales.

Even where human impacts are minimal, the intrinsic temporal and spatial variability of the flow regime,

sediment supply, bank materials, channel planform, and riparian vegetation interact to create diverse channel morphologies that vary longitudinally. Human activities and interventions are both inset within these natural determinants of channel form, and can affect nearly all of them. Although these interactions are present in all rivers, the broad spatial scale of large rivers provides many opportunities for complex interactions, confounding interpretation of natural from anthropogenic impacts on channel morphology.

Yet distinguishing human impacts from the intrinsic evolution and change of large rivers remains a critical need. Human pressure on large rivers, their valleys and resources is increasing worldwide, while efforts to restore, renaturalize, and re-engineer rivers to meet changing social and ecologic objectives and expectations is also a global enterprise. Efforts to either mitigate human impacts or restore natural functions to rivers requires a clear understanding of how much of the behaviour of rivers is fundamental to their position in the landscape or evolutionary trajectory in time – and therefore difficult to modify – as opposed to the result of one or more human impacts, which may or may not be reversible.

We propose a general framework for distinguishing the relative importance of natural and anthropogenic controls on channel change in large rivers. Our conceptual model describes how channels evolve in complex natural settings amid overlapping anthropogenic activities. We illustrate this framework by interpreting patterns of historical channel change along the Willamette River, a large alluvial river occupying a 28 800 km² basin in western Oregon, USA (Figure 23.1). The Willamette is well-suited to this type of analysis because it has a relatively recent Euro-American history (settlement began in the mid-nineteenth century), and most geomorphically relevant historical events are well documented. Settlement of the Willamette Valley took place in stages, causing anthropogenic impacts to generally follow a well-defined temporal sequence. This timeline of human interaction with the Willamette allows us to better link channel changes with their causes. Our analysis of the Willamette reveals a number of lessons that can be generalized to other larger rivers. In particular, it suggests that although river channels respond to a diverse range of anthropogenic and natural influences,

channel change is typically dominated by a few controlling variables and events.

The Willamette is the thirteenth largest river (by volume) in the conterminous US, similar in size to other well-studied rivers such as the Sacramento in California (Singer and Dunne, 2001, 2004) or the Ain in southern France (Marston *et al.*, 1995). Like other large rivers, the Willamette is composed of a series of geomorphically distinct reaches each of which have evolved uniquely in the century following Euro-American settlement. More than two-thirds of Oregon's population of 3.4 million lives in the Willamette Valley, with most people living in major metropolitan centres situated along the river (e.g. Portland, Eugene), leaving the majority of the Valley in agricultural and forest lands (Hulse *et al.*, 2002). Historical channel change along the Willamette has occurred in response to a range of natural and anthropogenic events, including floods, riparian and valley logging, agricultural development, erosion control and other engineering works, and modification of sediment and flow regimes by dams. Prior to Euro-American settlement, much of the Willamette was a dynamic anastomosing stream flowing through dense riparian forests. Today the modern Willamette is predominantly a single-thread river bordered by agricultural fields and revetments.

The Willamette Valley also faces many challenges common to other large rivers, as there is increasing demand to balance agricultural, urban and industrial demands while protecting endangered species, drinking water, and recreation. As a result, several large-scale restoration projects have been proposed for the Willamette River floodplain and there is large public interest in increasing riparian habitat along the river corridor (Jerrick, 2001). Lessons learned from attempts to interpret and restore the Willamette may therefore have much wider applicability to other larger rivers.

Previous work on the Willamette has emphasized the role of humans on channel change (Benner and Sedell, 1997; Dykaar and Wigington, 2000; Gutowsky, 2000). These earlier studies generally conclude that channel stability has increased following Euro-American settlement, and that this change is largely due to anthropogenic activities, particularly riparian logging, bank stabilization and flow regulation (i.e., Hulse *et al.*, 2002). We believe that this view underemphasizes the role played by floods, bank materials and the overall geologic setting as factors influencing channel change. Here, we seek to develop a more comprehensive model of channel evolution in which we examine the physical setting of the Willamette floodplain, its flood history and the full spectrum of human activities that have influenced channel change.

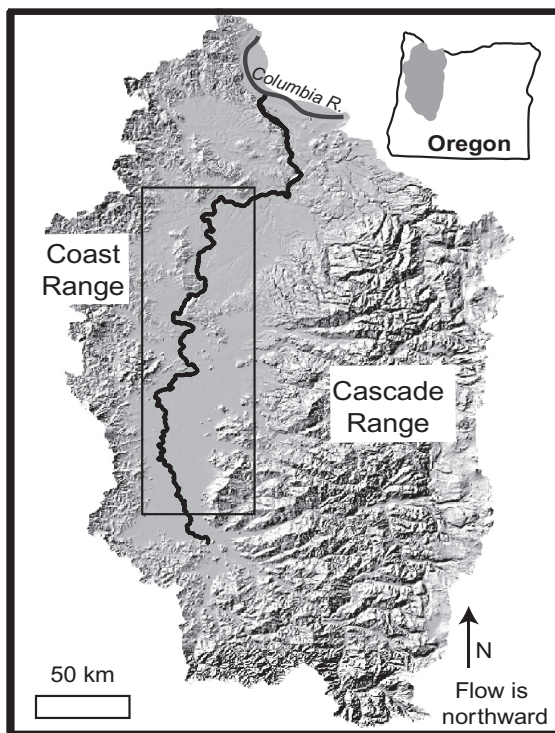


Figure 23.1 Willamette River Basin in northwestern Oregon. Box indicates 200 km study area shown in Figure 23.2

23.2 AN APPROACH FOR INTERPRETING MULTIPLE IMPACTS ON LARGE RIVERS

We aim to interpret the causes of long-term and geographically distributed changes in the form of large rivers. As noted, causal relationships between geomorphic and anthropogenic drivers and channel change can be problematic due to the multiplicity of factors contributing to change, intrinsic river variation in form and processes, long time and large spatial scales over which both drivers and change occur, and the fact that the signature of change may not be unique for specific causal mechanisms. Faced with such difficulties, which are not unique to the Willamette but characteristic of all large rivers, our overarching approach is to build a compelling narrative of change that links plausible drivers with anticipated response patterns in time and space, all subject to the overriding effect of intrinsic geologic controls. This is in contrast to a strict cause-effect approach more suitable to smaller rivers with more limited driving mechanisms. By narrative, we mean a reasonable and logical characterization of driving causal factors and consequent responses, distinguished by their chronology and ranked according to their relative importance.

We first distinguish factors that drive channel change from the response of the channel itself. Drivers of channel change include both natural changes in discharge and sediment regimes, and anthropogenic changes such as bank stabilization and flow regulation. The river's geomorphic response to these drivers is manifested as changes in channel geometry and planform. Disentangling these cause-effect relations is the initial step in identifying whether the dominant impacts in a particular time period is natural or anthropogenic (Table 23.1).

Drivers of channel change are extensive and well known, and involve changes to the discharge regime, bank erodibility, or sediment supply (Schumm and Lichtig, 1965; Lane and Richards, 1997). Along the Willamette, for example, natural drivers of geomorphic change include changing flow and sediment regimes in response to changing climate, particularly glaciation of the headwater basins during the Pleistocene and deglaciation during the Holocene. In addition, singular events such as broad regional floods contribute high volumes of sediment and large wood that, together with high streamflows, act as tools to reshape channels. Human drivers of channel change include navigation improvements by wood snagging, bank protection schemes, flood control dams, and land clearance and conversion.

We define channel response as a change in the physical form of a river channel due to the action of a geomorphic or anthropogenic driver. Channel responses range from one-dimensional changes in channel geometry to transformations in river planform, all of which may occur at different rates. One-dimensional change includes adjustments in width, depth or centreline length. Planform adjustments refer to two-dimensional changes in river morphology; examples include anastomosing channels that become single-thread, or meandering channels that become straight. Each type of river planform displays unique styles of change, and we measure rate of change using metrics best suited for that planform as discussed below. For example we measure migration rates for meandering reaches and avulsion frequency for anastomosing reaches. Because of reach-to-reach variation in channel or floodplain properties, the style and rate of response can vary dramatically along the length of large rivers.

Table 23.1 Predicted channel response to natural and anthropogenic disturbance processes that act as drivers of channel change on the Willamette River

Drivers of channel change		Predicted channel response			
		Channel width	Migration rate	Avulsion rate	Channel length
Natural	Large floods	Increase	Increase	Increase	Decrease due to avulsions
	Moderate floods (bankful)	Increase	Increase	Increase	Increase through migration
Anthropogenic	Loss of riparian vegetation	Increase	Increase	Indeterminate	Increase
	Snag removal	Decrease	Decrease	Decrease	Increase or decrease
	Revetment construction	Decrease	Decrease	Decrease	Stabilize
	Dam construction	Decrease	Decrease	Decrease	Stabilize
	Channel modifications (wing dams, cut-off dykes etc.)	Decrease	Decrease	Decrease	Stabilize

We can draw on the geomorphic literature to make first-order predictions on the likely direction of change in key metrics as a result of specific drivers (Table 23.1). Such predictions constitute hypotheses linking geomorphic and anthropogenic drivers with plausible responses, and provide a reasonable means of interpreting historical patterns of channel change. For example, riparian deforestation generally increases bank erodibility through loss of root strength, leading to increased channel widening and migration (Zimmerman *et al.*, 1967; Rowntree and Dollar, 1999; Murray and Paola, 2003). Large mobile wood accumulations generally redirect flows and obstruct channels, leading to avulsions and multi-thread channels (Tooth and Nanson, 2000; O'Connor *et al.*, 2003). Removal of large wood (through snagging) might therefore be expected to reduce avulsions and promote a wider, single-thread planform (Abbe and Montgomery, 1996, 2002). Bank stabilization structures and flood-control dams decrease bank erodibility and flow erosivity respectively, thus decreasing migration rates and avulsion frequency (Larsen and Greco, 2002). As the channel becomes more stable, relict gravel bars and other formerly active channel surfaces are typically colonized with vegetation and channel width decreases (Nadler and Schumm, 1981). These relationships can be summarized by linking various natural and anthropogenic impacts with their anticipated effects on the channel, hence metrics of channel change.

Table 23.1 summarizes the anticipated effects of different drivers of channel change, and provides a useful framework for linking rates and styles of channel change observed during a particular time period with specific impacts. A key point, however, is that predicted channel responses are not unique to specific drivers, but display equifinality, wherein the same result can be due to multiple causes. To construct a reasonable narrative of causal linkages of channel change, interpretation of change must be constrained by other factors.

The most obvious factors that influence the interpretation of channel are the timescales and locations of change relative to the timing and location of drivers. For example, an action or event that directly modifies the channel (e.g. bank protection or dredging) has a higher likelihood of directly effecting channel change than activities occurring on the adjacent floodplain. Furthermore, human actions that directly impact discharge or sediment transport (such as dams) would have a greater influence than activities that indirectly influence runoff and sediment generation (such as timber harvest and other land uses conducted away from the channel). The scale of any activity is also critical, as large flood control dams, lengthy revetments or widespread riparian deforestation would clearly have a greater effect than smaller-scale versions of similar

impacts. Another important constraint for interpreting complex patterns of channel change is imposed by the geological setting of the channel itself. Variations in intrinsic erodibility of bed and bank materials, including location of erosion-resistant valley walls and bedrock, can be used to interpret spatial variations in response due to other drivers.

Floods play a unique role as mechanisms for initiating and promoting accelerated channel changes that may or may not have other primary causes or for shifting trajectories of channel adjustment. In particular, floods can catalyze or galvanize impacts that have been latent or hidden up to that point, as thresholds are exceeded (Grant *et al.*, 1984). Through lateral migration, for example, small to moderate-sized floods (e.g. 2- to 10-year events) can set the stage for abrupt planform shifts during large floods due to avulsions and scour of secondary channels. Floods typically elicit planform changes and can thereby cause the river to adopt a dramatically different style of evolution. For instance, a highly sinuous, meandering channel may experience a series of avulsions and meander cut-offs, causing the channel to adopt a low-sinuosity planform with higher gradient. Depending on sediment supply, bank erodibility and the ensuing discharge regime, such planform changes could initiate further channel changes, such as incision. Floods can therefore be seen as the triggers to disturbance cascades (*sensu* Nakamura *et al.*, 2000) wherein one impact can trigger a series of subsequent adjustments. Within a cascade, the magnitude and style of sequential adjustments steers the overall direction of channel change in some direction until another large impact resets the trajectory of channel change. These adjustments and their net outcome are highly contingent upon the pre-existing channel planform, distribution of resistant bank materials, floodplain physiography and other floodplain characteristics.

On the Willamette and other large rivers, the channel that we observe today is inevitably a function of the order in which various impacts occurred. Large river basins are contingent systems whereby the channel response to a particular impact in a given time period is contingent upon all previous events. This contingency inevitably limits reliance on precise cause-and-effect models to explain observed phenomena, but lends itself to a plausible and quantitatively supported historical narrative that accounts for the sequence of events as well as the events themselves. In this sense, river evolution mimics biological evolution (Gould, 1989),

In the following sections, we use these concepts of plausible hypotheses, disturbance cascades and a quantitatively supported narrative to examine natural and anthropogenic impacts on the Willamette River. We do this by

relating channel planform and trajectories of change to both geological controls and impacts to the channel and floodplain. We set the stage for our analysis by briefly describing the physical setting and human history of the Willamette Valley, and illustrate inherent controls on channel change by focusing on how the geological history of the Willamette Valley helps define floodplain physiography, bank materials, sediment supply and other aspects. What emerges is a reasonably compelling and heretofore unreported narrative ordering the relative importance of natural and anthropogenic impacts on the last 150 years of channel evolution. We conclude with considerations of how this type of analysis can be generalized to other large rivers.

23.3 GEOLOGIC SETTING, HUMAN AND FLOOD HISTORY OF THE WILLAMETTE

Some geographic and historical context for the Willamette River is required in order to properly interpret both our study and the patterns of channel evolution. Here we consider some of the most important physical factors that set the geomorphic constraints on channel pattern, describe our reach-scale delineations with respect to those factors, briefly discuss the history of human settlement of the Willamette Valley and its consequences for the channel, and summarize what is known about the flood history over the past 150 years.

23.3.1 Watershed Physiography and Climate

The Willamette Valley is situated between two rugged and deeply dissected mountain landscapes, the volcanic Cascade Range to the east and the uplifted marine sandstones of the Coast Range to the west (Figure 23.1). Although heading in the mountains, the Willamette River itself is a relatively low-gradient river, with an average slope of 0.0005 over its lowermost 250 km, and a planform that ranges from braided and anastomosing in its upper reaches to wandering and meandering in its lower reaches, all within a broad valley floor ranging in width from 10 to 50 km. The mainstem Willamette begins at the confluence of the Coast and Middle Forks of the Willamette in the southern valley, and flows northward through alluvium and lacustrine deposits for more than 200 km. In the northern valley, the Willamette River incises a gorge through Tertiary basalt flows and passes over the 15 m high Willamette Falls. Below Willamette Falls, the river is tidally influenced for 20 km to its confluence with the Columbia River near Portland.

The Willamette Valley is characterized by a Mediterranean climate with cool, wet winters and warm, dry

summers. Average precipitation in the valley floor is approximately 1200 mm year⁻¹, which falls mainly as rain-fall during the winter. Headwater reaches receive as much as 2500 mm, which falls as both rain and snow (Oregon Climate Service, 2006). Major Willamette floods typically result from basin-wide rain-on-snow events (Harr, 1981).

23.3.2 Geological Setting of the Willamette in Relation to Channel Stability

The floodplain physiography that we observe today in the Willamette Valley results from a geological history of constructional volcanism, uplift and deformation, incision, and an unusual depositional sequence from catastrophic Pleistocene outbreak floods on the Columbia that resulted in backwater flooding of the Willamette River. The Willamette Valley is a fore-arc basin that formed in response to subduction of the Pacific Plate beneath the North American Plate. Tertiary marine sandstones (unit Tm, Figure 23.2) form the basement of the Willamette Valley, which was separated from the Pacific Ocean approximately 20–16 Ma when submarine volcanic rocks were uplifted, forming the Coast Range. About 15 Ma, subareal flood basalts of the Columbia River Basalt Group (CRBG) flowed westward from eastern Oregon, covering large portions of the northern Willamette Valley (Hooper, 1997). Structural deformation has created local uplands of CRBG flows in the middle Willamette Valley that locally restrict valley width while the lower 25 km of the Willamette is incised through CRBG flows (Yeats *et al.*, 1996; O'Connor *et al.*, 2001).

During the Pleistocene, volcanic construction of the High Cascades on the eastern boundary of the Willamette Valley coincided with a cooler, moister climate to cause enhanced sediment production. Sands and gravels generated by glacial and periglacial processes fed a vast network of braided rivers that extended across the valley floor, depositing valley fill sediments and alluvial fans primarily along the eastern margin of the basin (Qg2 unit, Figure 23.2), and displacing the river to the west (O'Connor *et al.*, 2001). Between 15 and 12.7 Ka, dozens of catastrophic glacial dam outbreak floods originating in Glacial Lake Missoula swept across southeastern Washington and flowed down the Columbia River (Waite, 1985; Benito and O'Connor, 2003). The Missoula Floods back-filled the Willamette Valley from its confluence with the Columbia and blanketed the valley with fine-grained silts and clays. These Missoula Flood deposits (unit Qff, Figure 23.2) form the surface of the main valley floor and range in thickness from 35 m in the northern valley to less than 5 m in the southern valley (O'Connor *et al.*, 2001).

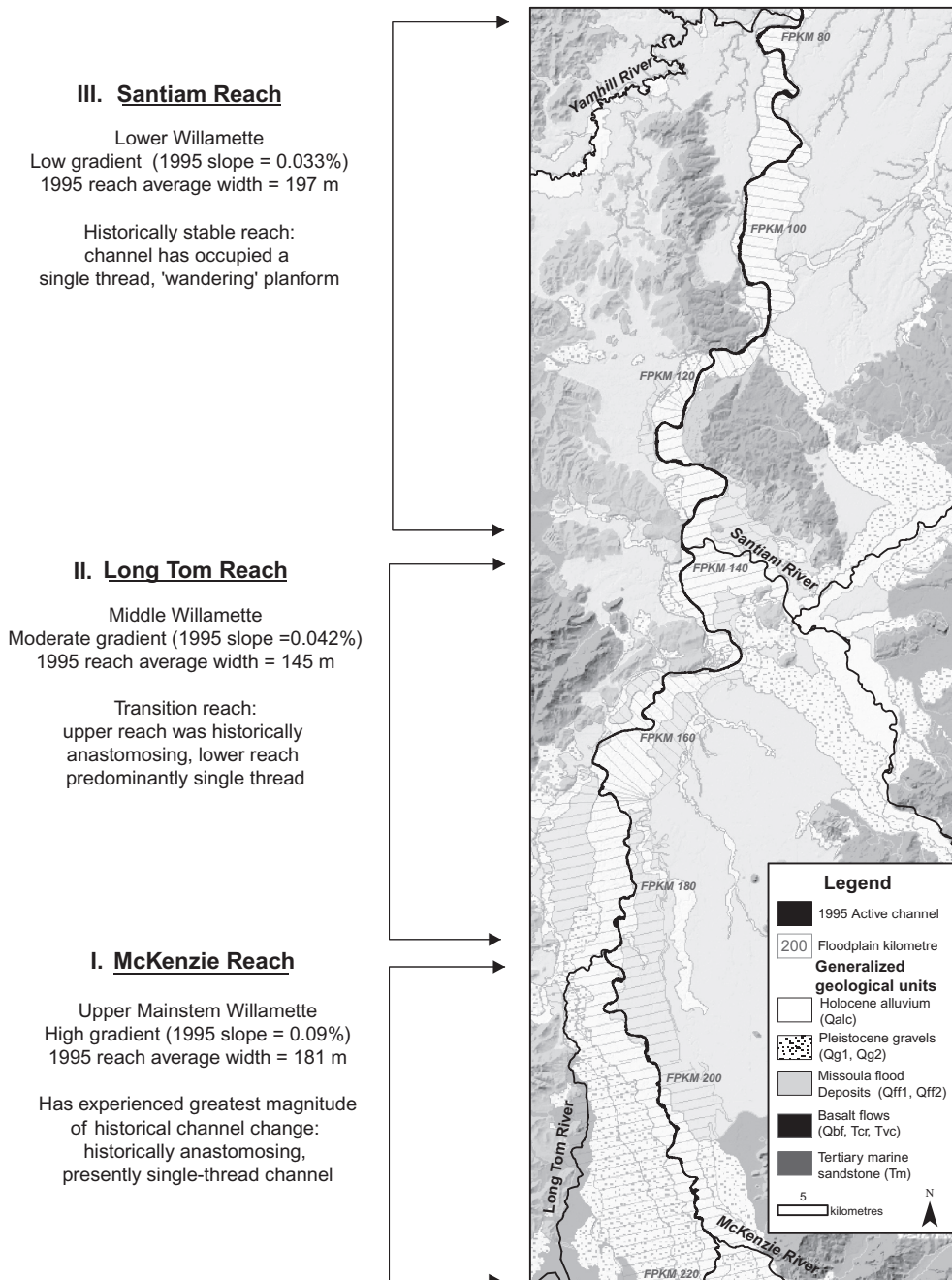


Figure 23.2 Geologic and physiographic setting of Willamette River study area. The 220 km long study area was divided into three reaches on the basis of planform, discharge and tributary influence. (Geological map from O'Connor *et al.*, 2001. Willamette River active channel and floodplain transect maps from Hulse *et al.*, 2002)

The warmer, drier Holocene climate triggered a wave of regional incision, and Pleistocene braid plains were replaced by the inset anastomosing planform of the modern Willamette. In historical documents, the Holocene floodplain is frequently termed the valley bottom as it is situated 3–35 m below the surfaces of the terraces comprising the main valley floor (Figure 23.3). Holocene floodplain surfaces (unit Qalc, Figure 23.2) range from recent point-bar and active-channel deposits to forested floodplains, and form a 1–2 km wide swath of silts, sands and gravels, deposited less than 12 000 years ago.

The location of the Willamette River with respect to the Holocene floodplain and adjacent older terraces has implications for bank stability and channel change. Along much of its length, the river is flanked on both sides by Holocene alluvium, whereas in other areas, the Willamette flows against older, more indurated bank materials along the floodplain margins (Figure 23.2). The most extensive of these more resistant bank materials include partially cemented Pleistocene gravels (Qg2) that underlay Missoula Flood sediments. Other resistant geological units are locally important and include Tertiary marine sandstones (Tm) that crop out near Albany at floodplain km 110 (FPKM 110) and Tertiary volcanic deposits (Tvc and Tcr) that border the channel near Salem (FPKM 70). Although not strictly speaking a geological control, the Army Corps of Engineers have stabilized large portions of the Willamette River with large, angular boulders (revetments) that form a resistant bank material.

Geological factors also control bank height along the Willamette. Bank height steadily increases downstream as the river becomes increasingly entrenched within both Holocene and Pleistocene surfaces. In the southern valley, elevations of terrace surfaces typically rise 2–5 m above low-water stage, whereas surfaces in the northern valley are up to 15 m higher than low-water stage (O'Connor *et al.*, 2001). Banks are highest where the river flows against Pleistocene terraces composed of indurated Qg2 gravels

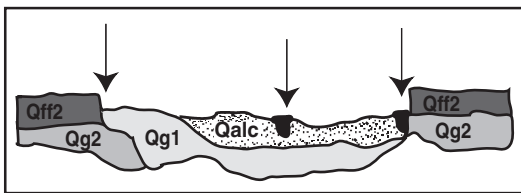


Figure 23.3 Generalized cross-section of Willamette floodplain. Geological units are same as those shown in Figure 23.2. Arrows indicate typical locations of Willamette River within Holocene floodplain. (Geological units are from O'Connor *et al.*, 2001)

and overlying Missoula Flood deposits. Along the upper reaches, Qg2 gravels typically comprise the lower 1–2 m of banks, while along the lower river these same gravels comprise the lower 5–10 m (O'Connor *et al.*, 2001).

23.3.3 Study Length Delineation

The changing geological setting of the river as it proceeds northward requires that different units be delineated within the study length in order to compare channel responses to various geomorphic drivers. These reaches provide the spatial template for our analysis. The Willamette can be broadly delineated into three alluvial reaches on the basis of valley slope, planform, bankful discharge and location of major tributary junctions (Figure 23.2). The uppermost reach (McKenzie Reach) spans the relatively steep and historically anastomosing Willamette River between the confluences of the McKenzie and Long Tom Rivers. The Long Tom Reach includes portions of both the upper and middle Willamette Valley between the confluences of the Long Tom and Santiam Rivers with the Willamette. The Santiam Reach is the lowest-gradient reach, as it begins at the Willamette's confluence with the Santiam River and continues to the Yamhill River confluence in the northern valley.

Much of the McKenzie Reach was historically bordered by erodible Holocene alluvium and flow in the main channel was divided by large (2–4 km) semi-stable forested islands. Voluminous inputs of large wood and sediment combined with floods led to frequent avulsions and high rates of bank erosion. An extensive network of side channels bordered the main channel and were frequently abandoned, eroded or re-occupied following avulsions and channel migration. This dynamic channel system provided many obstacles to early navigation and nineteenth century channel improvement efforts were focused on maintaining a stable, single-channel on the upper Willamette (including the upstream portion of the Long Tom Reach).

In the Long Tom Reach (Reach II), the channel transitions from an anastomosing planform to a single-thread, wandering planform. Like the McKenzie Reach, the flow in the upper Long Tom Reach was historically divided among multiple channels separated by large islands. Beginning near Corvallis at FPKM 165, the channel adopts a single-channel planform with fewer islands and side channels. While the multi-threaded sections of the Long Tom Reach historically experienced frequent channel shifting, the single-thread areas have been more stable.

The Willamette along the Santiam Reach is generally contained within a single-channel that wanders between

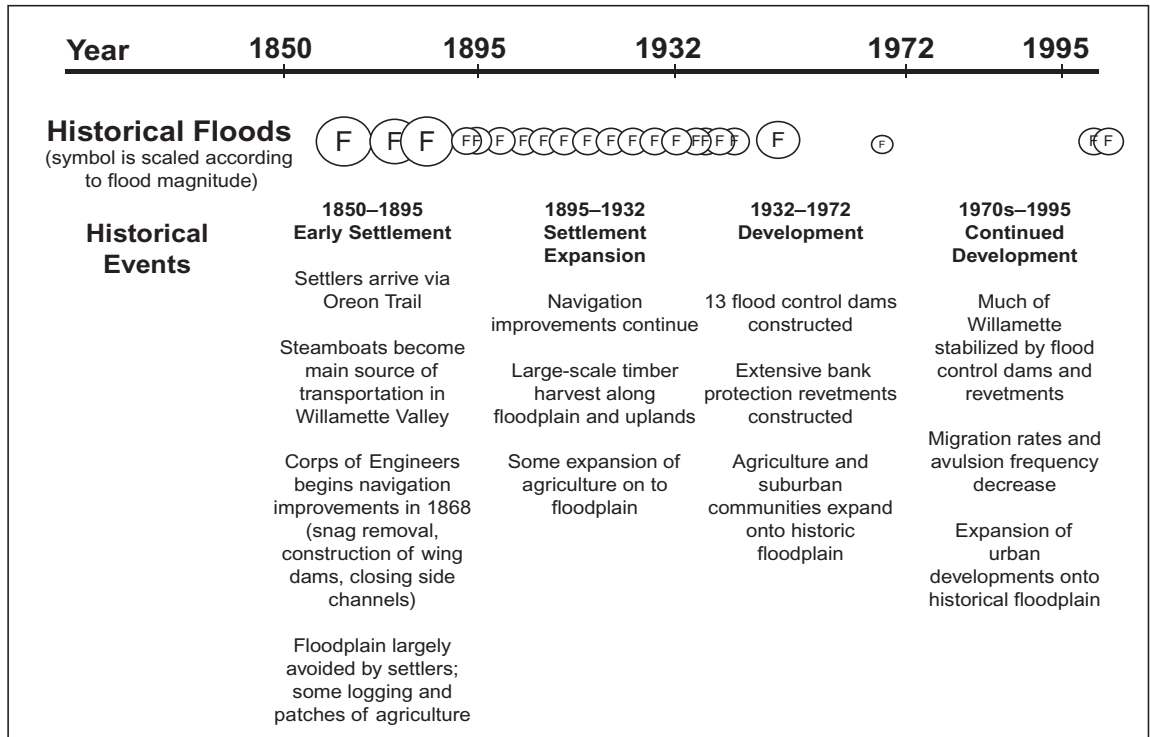


Figure 23.4 Timeline of geomorphically relevant historical events in Willamette Valley. Prior to Euro-American settlement in the late 1840s, the Willamette River and its floodplain were largely unaffected by human activities. The first Euro-Americans to enter the Willamette Valley were Lewis and Clark in 1805, and the region remained largely unsettled until the late 1840s following the development of the Oregon Trail

paired terraces formed of Pleistocene and Holocene alluvium and bedrock. Along the floodplain margins, the Willamette forms 3–5 km long bends which impinge upon Qg2 gravels. Low-sinuosity bends alternate with fairly straight reaches creating a ‘wandering’ planform (*sensu* Church, 1983). The low gradient Santiam Reach ends at the Newburg Pool, a 40 km long backwater area created by ponding above Willamette Falls.

23.3.4 Timeline and Consequences of Euro-American Interaction with Willamette River

Humans have lived in the Willamette Valley for 9000 years (Cheatham, 1988), but the Willamette River and its floodplain were largely unaffected by anthropogenic activities until the mid-nineteenth century following the arrival of Euro-Americans. Although Lewis and Clark were the first Euro-Americans to enter the Willamette Valley in 1805, settlement of the Willamette Valley did not fully begin until the late 1840s following the develop-

ment of the Oregon Trail. We therefore focus our attention on major human modifications since 1850 that may have directly impacted channel planform, style of adjustment, or overall channel behaviour (Figure 23.4).

Early Settlement 1850–1895

Early settlers to the Willamette Valley generally avoided the floodplain, preferring to homestead along the outer margins of the main valley floor, a location which provided safety from floods, while granting access to both prairie and upland timber (Bowen, 1978; Towle, 1982). General Land Office (GLO) maps of the Willamette floodplain from 1851 to 1853 show that much of the floodplain was densely forested and depict the lower reaches of the Willamette as primarily confined to a single channel, while the upper Willamette was divided among multiple channels containing numerous gravel bars, and large wood rafts. GLO maps also show that in each township (9324 ha in area), only a few claims, fields or houses appear to have

been situated on the floodplain. In the following decades floodplain lands were increasingly utilized for agriculture while riparian logging spread through the Willamette Valley (Nash, 1904; Towle, 1982). By 1895, approximately 23% of the middle and lower Willamette and only 11% of the upper Willamette was bordered by agriculture, leaving the remaining floodplain lands in either original riparian forest or logged areas (Gregory *et al.*, 2002a).

Steamboats became the main form of transportation along the Willamette Valley in the mid-1850s, which required that a navigable channel be maintained between agricultural towns along the upper Willamette and trading centres downstream (Anderson, 1974). In 1868, the Corps of Engineers began removing downed trees (snags) from the Willamette (Sedell and Froggatt, 1984). Yearly snagging records show that about 1000 downed and streamside trees were removed annually from the mainstem Willamette between 1868 and 1935 (Figure 23.5) (USACE, 1867–1892; Sedell and Froggatt, 1984). In the 1870s the Corps began channelizing the Willamette (Figure 23.4) by eliminating side channels and narrowing the main channel (Benner and Sedell, 1997). The 1895 navigational survey conducted by the Corps shows that approximately 18 km of man-made structures (including wing dams, check dams, retaining walls, bridges and revetments) bordered the Willamette (USACE, 1895). In addition to the structures, the Corps filled secondary channels with downed trees, blocked the heads of side channels with logs, and deepened the main channel by scraping shoal bars (USACE 1875: 765; Benner and Sedell, 1997). Whereas most of the channelization occurred along lower reaches where the river was largely confined to a single channel, snagging predominantly occurred on the upper Willamette where large wood rafts were more common.

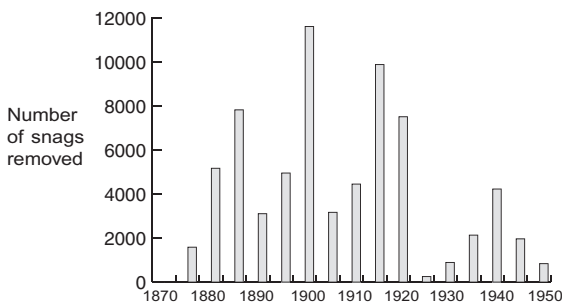


Figure 23.5 Snag removal 1870–1950 along upper Willamette. Plot shows total number of snags removed per 5-year interval between Albany and Eugene (FPKMs 150–220). Logs removed include harvested streamside trees and downed trees (snags). (Adapted from data provided by Sedell and Froggatt, 1984)

First-hand accounts by the Corps of Engineers in the Annual Reports to the Chief of Engineers provide telling statements on the efficacy of channel improvements in the late nineteenth century. In 1875 after 7 years of channel improvements, the Corps claimed that the upper Willamette underwent such frequent changes that ‘it would be impossible to confine its waters into one main and permanent bed’ (USACE 1875: 765). In 1881 another author wrote that, the upper Willamette remained ‘exceedingly troublesome’ while the middle and lower reaches of the Willamette were ‘free from material obstructions’ (USACE, 1882: 2655–2659). In the early 1890s, one author described a particularly laborious season of channel maintenance then concluded his passage by writing, ‘this work, however is but temporary, and in the nature of things much of it may have to be done over again’ (USACE, 1892: 2836). Such statements suggest that even after several decades of channel improvements, the upper Willamette remained prone to frequent channel change, whereas the lower reaches were more easily coaxed into a stable planform.

Agricultural development 1895–1932

The period 1895–1932 was marked by increased development of the Willamette River floodplain, as channel improvements, riparian logging, and expansion of floodplain agriculture continued. Dredging was authorized by Congress in the 1896 River and Harbor Dredging Act, and from 1908 to 1929, approximately 78 000 m³ of material were removed annually from the middle and lower Willamette (USACE, 1969b; Willingham, 1983; Benner and Sedell, 1997). The Corps also continued to improve navigation through snag removal and construction of various structures so that by 1932, approximately 16 km of wing-dams and other structures (bridges, dikes, retaining walls, revetments, etc.) bordered the Willamette (USACE, 1932).

Logging of riparian forests for paper production and timber export increased greatly during the early twentieth century and caused the percentage of forested lands bordering the river to decrease by more than 50% along much of the Willamette (Gregory *et al.*, 2002a). Although logging led to increases in cleared floodplain lands, much of the floodplain was still avoided because bottomlands were plagued by frequent floods, high erosion rates, and poor drainage (Anderson, 1974). Despite these problems, floodplain agriculture continued to increase so that by 1932, 40–50% of the Willamette was bordered by agriculture, with the most substantial increases occurring along the upper Willamette, where there was a four-fold increase in the length of channel bordered by cultivated crops (Gregory *et al.*, 2002a).

Urbanization, development, and dam construction 1932–1972

The interval 1932–1972 was marked by rapid development of the Willamette River floodplain. Within the span of several decades, dams, revetments, and drainage-control and irrigation projects were constructed that enabled agriculture and suburban development to expand onto the historic floodplain.

Although bank protection had begun in the late nineteenth century, the extent and rate of bank stabilization efforts increased dramatically in the mid-1930s (Figure 23.6). Revetment construction by the Corps and private individuals continued through the late twentieth century (Fig. 23.6), and by the 1970s, 90% of all present-day revetments were constructed (Gregory *et al.*, 2002c).

Dam building quickly followed authorization of the Willamette Valley Project in 1938, which entailed the construction of a series of multiple-purpose projects (Oregon State Planning Board, 1938; USACE, 1969a). By 1970, every major tributary of the Willamette had at least one flood control project, so that the entire Willamette Basin was regulated by a total of 13 reservoirs. Of these reservoirs, 11 are major flood control projects and two are primarily re-regulating reservoirs (Willingham, 1983). The multiple-purpose projects reduce flood peaks, support higher summer flows, and in some cases, provide hydro-power (USACE, 1969a).

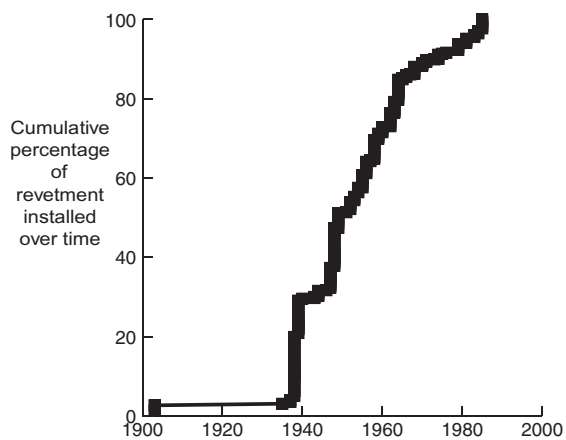


Figure 23.6 Cumulative percentage of revetment constructed along Willamette River, 1900–1985. Percentage is computed from lengths of revetment that have a known construction date (about 45% of total revetments). (Adapted from data provided by Gregory *et al.*, 2002c)

Post-development and continued change 1972–1995

Development of floodplain lands slowed in the late twentieth century as many farms were converted to rural residences (Towle, 1982). Although the majority of revetment had been constructed by the early 1970s, the Corps of Engineers and private agencies continued to maintain and extend existing bank stabilization projects (Gregory *et al.*, 2002c). Major actions undertaken during the period 1972–1995 that affected channel change involved dredging, gravel mining and management of riparian lands. In addition, several large cities have developed their waterfronts, requiring extensive bank stabilization to protect nearby developments. Channel improvements for navigation were limited to the lowermost reaches of the Willamette River (primarily downstream of Willamette Falls, near the confluence with the Columbia) whereas instream gravel mining occurs at many locations along the mainstem channel.

23.3.5 Flood History of the Willamette River

The Willamette River has historically experienced a wide range of floods of different magnitudes (Figures 23.4 and 23.7). Peak flows generally occur in the rainy season between November and March, and are typically associated with rain-on-snow events involving warm, moist subtropical air masses. Infrequent, extreme events (which we refer to as ‘large floods’) arise when these extra-tropical excursions result in intense rainfall accompanied by warm air temperatures over a period of several days, rapidly melting pre-existing deep and extensive snow packs in the Cascade Mountains and foothills. Such conditions led to the largest historic floods, which occurred in 1861, 1881, and 1890, though several other large floods may have also occurred earlier in the nineteenth century before the advent of gauged records (Figure 23.7). Many communities were wholly or partly destroyed in the 1861 flood (approximately $14\,160\text{ m}^3\text{ s}^{-1}$ at Salem) as floodwaters filled the Holocene floodplain and in some areas, overtopped the Pleistocene terraces (Miller, 1999; Gregory *et al.*, 2002b). The large floods of 1881 ($12\,120\text{ m}^3\text{ s}^{-1}$ at Salem) and 1890 ($12\,690\text{ m}^3\text{ s}^{-1}$) also heavily damaged several towns and caused extensive erosion (USACE, 1881; Brands, 1947; Anderson, 1974).

Prior to construction of flood-control dams in the 1940s, the Willamette also experienced many moderate magnitude floods that were two to three times greater than modern bankful flow (Figure 23.7). Corps of Engineer reports from the late nineteenth century state that, even during these more common ‘freshets’, the floodplain was inundated to a depth of several metres and logs would fill the Willamette and adjacent sloughs (USACE, 1875).

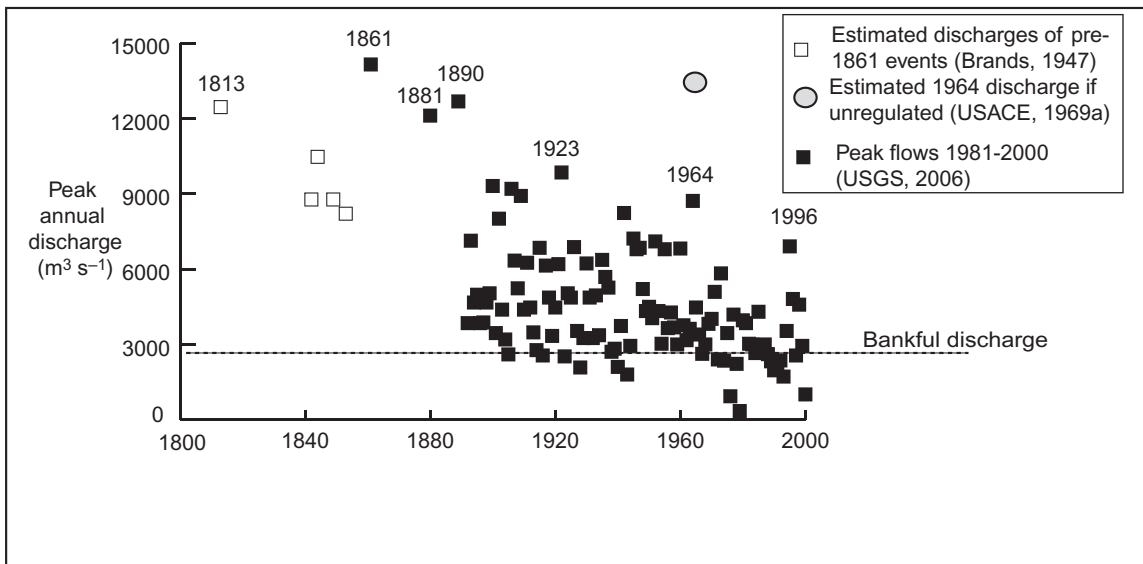


Figure 23.7 Peak discharge 1813–2000 for Willamette River at Salem. Peak flows have decreased steadily following construction of 11 major flood control reservoirs. Discharge for pre-1861 events was estimated from historic highwater marks (Brands, 1947)

During the moderate floods of 1951 and 1955, soil was stripped from fields situated atop Holocene alluvium, and erosion isolated several fields on newly created islands (Anderson, 1974).

Flood magnitudes began to decrease in the 1950s as increasing numbers of flood control dams were completed (Figure 23.4). The largest flood of the regulated era occurred on Christmas Eve of 1964 (peak discharge at Salem of $8700 \text{ m}^3 \text{ s}^{-1}$) and that flood may have been similar in magnitude to the 1861 flood of record (Figure 23.7) if seven flood control dams had not reduced peak discharge (USACE, 1969a). The February 1996 flood was the largest post-dam event, though its discharge was similar in magnitude to ‘moderate’ floods experienced every few years prior to flow regulation ($6900 \text{ m}^3 \text{ s}^{-1}$ at Salem). Although many low-lying areas were inundated, channel change was relatively minor compared with previous floods.

23.4 DATA AND METHODS FOR MEASURING HISTORICAL CHANNEL CHANGE

23.4.1 Historical Channel Maps

We calculate rates and styles of channel change using digital maps of the Willamette River compiled from historical maps and aerial photographs from 1850, 1895, 1932, 1972 and 1995 (Table 23.2). For 1850, 1895 and

1932, we used maps of the active channel produced by the Pacific Northwest Ecosystem Research Consortium (PNWERC) from surveys conducted by the General Land Office in 1850 and USACE in 1895 and 1932 (Hulse *et al.*, 2002). The PNWERC also produced the 1995 channel map from aerial photographs provided by the USACE (Hulse *et al.*, 2002). For the Long Tom and Santiam Reaches, this set of maps allows us to measure channel change for three time periods: 1850–1895, 1895–1932 and 1932–1995.

Inspection of the 1932 and 1995 channel maps for the Long Tom and Santiam Reaches reveals that the lower and middle Willamette did not experience significant channel change over the 1932–1995 period (an interval marked by widespread revetment and dam construction). In contrast, the McKenzie Reach contained numerous bends that initially migrated rapidly in the 1930–1950s and were subsequently stabilized with revetment by 1972. Averaging migration over the interval 1932–1995 would therefore provide inaccurate results for areas that experienced channel shifting followed by several decades of stability. We thus exclude the period of rapid development (1932–1972) from our analysis of the McKenzie Reach and calculate channel change for the three periods: 1850–1895, 1895–1932 and 1972–1995. We digitized the 1972 channel along the McKenzie Reach from aerial photographs produced by the USACE (USACE, 1972).

Table 23.2 Channel maps used to quantify historical channel change

Map date	Original survey or photo source	Map description	Source for georeferencing and digitizing	Precision
1850	General Land Office (GLO) Cadastral Surveys	Cadastral survey of townships and sections. Most of study area surveyed 1851–1853	Hulse <i>et al.</i> , 2002 ^a	±10 m
1895	Army Corps of Engineers (USACE)	Navigational blue-line survey. Study area surveyed October–November of 1894	Hulse <i>et al.</i> , 2002	Unknown
1932	USACE	Navigational survey of study area conducted 1931–1932	Hulse <i>et al.</i> , 2002	±5 m
1972	USACE	Main channel and active channel ^b digitized from mosaic of orthophotographs in 1972 Willamette River and Tributaries Map Book. Photography flown May 2, 1972 at ~300 m ³ s ⁻¹	These authors	±10 m
1995	USACE	Main channel and active channel digitized from orthophotographs flown August 1994 and September 1995 (~150–200 m ³ s ⁻¹)	Spencer Gross Photography, PNWERC	±5 m

^aPacific Northwest Ecosystem Research Consortium (PNWERC) presented in Hulse *et al.* (2002).

^bFor 1972 we digitized the active channel from aerial photographs. Although discharge at the time the 1972 photos were taken is about twice that of flow during the 1995 photos, there is only about 1 m difference in stage, and reach-averaged channel width for the low-water channel varies by less than 2% between the photo series.

For the historic maps and the aerial photos, the active channel was defined as the area within the boundaries of the annual high water (1–2 year flow) mark, although definition of these boundaries was sometimes subjective. Gravel bars, small side channels, and surfaces vegetated with annual species (e.g. small shrubs, grasses, and willows) were included within the active channel, and channel-adjacent areas and islands containing larger woody vegetation were excluded (Hulse *et al.*, 2002). Where present, steep banks clearly demarcated active channel boundaries.

23.4.2 Measuring Rates and Styles of Channel Change

We focused our analysis on several metrics that best describe adjustments in planform, erosion style and erosion rates. Channel width was measured by digitizing transects orthogonal to the channel centreline for each time interval. Transects were drawn at the intersection of the active channel with each floodplain kilometre boundary for kilometres 18–223. We digitized channel centrelines at a scale of 1:5000 to compute centreline length and sinuosity for each time period. In areas with multiple channels, the centreline was drawn for the largest channel, and in instances where wide bends (e.g. width >500 m) appeared to contain backwater areas, the centreline was drawn to reflect the assumed position of the thalweg. We determined the length of channel bordered by

resistant banks by overlaying the channel maps and digitized centrelines from each time period with the surficial geology map of O'Connor *et al.* (2001). For each time period, the centrelines are divided into bend-sized sections, and each section is classified according to the type of bank material being eroded. Resistant banks include areas stabilized with revetments or any geological unit more indurated (and older) than Holocene alluvium including Pleistocene gravels, Tertiary marine sandstones and Tertiary volcanics.

To measure the rate and style of channel change between two time periods, we calculated migration rates, avulsion frequency and several other metrics to describe the relative dominance of each process. Digitized channel centrelines from sequential time periods were overlain, and we calculated the change in area of channel polygons. Stable areas are characterized by nearly congruent centrelines or very thin flow-parallel polygons; larger channel change polygons indicate areas where the channel either migrated or avulsed away from its original position. Each polygon was then classified according to the style of erosion (lateral migration versus avulsion). Lateral-migration polygons were further classified according to whether the centreline shifted towards the inside of the bend (straightening) or whether the centreline shifted towards the outside of the bend (normal migration). Because meander migration frequently involves both straightening and normal migration as bends elongate and migrate downstream, we restricted our classification of straighten-

ing to polygons where the centreline clearly moved to the inside of the bend, resulting in significant (e.g. >15 m) erosion.

Channel migration was measured as distance travelled orthogonal to the centreline for a particular time interval. Following the methodology of Micheli and Kirchner (2002), polygon width serves as a proxy for average distance travelled orthogonal to the centreline and was calculated by dividing polygon area by one-half of the polygon perimeter. Migration rates for each polygon were then calculated by dividing polygon width by the number of years in the time interval. We calculated reach-average migration rates for three styles of erosion: normal migration, straightening, and lateral migration (an average of both normal migration and straightening). Avulsion frequency was easily computed by summing the number of avulsion-related polygons in each reach, for each time period.

The relative dominance of each type of erosion was assessed by computing the percentage of centreline length subject to avulsion, straightening, and lateral migration. We also computed the annual area eroded per length of channel for lateral migration and avulsion. This latter analysis avoids the bias introduced by averaging migration rates derived from various-sized polygons, and provides a better indication of the area of floodplain reworked by different styles of erosion.

23.4.3 Development of a Two-Dimensional Flood Model for Willamette River

In order to better understand how different magnitude floods influenced avulsions, migration rates and widening, we relied upon the two-dimensional flood models of Denlinger (2002) and DHI (2005) to examine stream power generated during different-sized floods. We used these models to compute the magnitude and distribution of stream power for the 1861 and November 1996 flood along 10 km of the upper Willamette near FPKM 206. This allows us to compare patterns of erosion and deposition from large-scale versus moderate floods.

The flow models are both two-dimensional, finite difference models that solve the shallow-water flow equations on a two-dimensional grid of any surface. We built the grid from a digital elevation model giving spatial coordinates of the ground surface for the upper Willamette, and forming a rectangular mesh with square cells 10 m on each side. The inflow hydrograph for the 1996 flood is constructed from stage and discharge records at Harrisburg (USGS Station 1416600). Because time-series data for the 1861 flood are not available, the 1861 hydrograph is estimated by scaling the 1996 hydrograph according to

estimated stage at the Harrisburg. A single value for bed friction is used to parameterize velocity gradient with depth, and this resistance combined with the forcing of the topography determines the three-dimensional variation of stage throughout the reach.

By comparing modelled stage with observed high-water marks over the three-dimensional terrain we can constrain both the average value for bed friction and discharge. Along the upper Willamette, there are few well-defined highwater marks for the 1861 and 1996 floods and we therefore rely upon digital inundation maps compiled by the PNWERC to constrain our modelled stage (Gregory *et al.*, 2002b). The variation of stream power, which is the product of bed friction and depth-averaged velocity then provides a means to compare where erosion and deposition will occur for a flood with the modelled discharge.

23.5 RESULTS: PATTERNS AND CONTROLS ON HISTORICAL CHANNEL CHANGES

Each of our three reaches changed in the century following Euro-American settlement. For each reach, we summarize both the net changes that occurred during 1850–1995 and the dominant styles of adjustment that occurred in each time period.

23.5.1 McKenzie Reach, 1850–1995

In 1850, the Willamette River along the McKenzie Reach was a narrow, sinuous anastomosing channel dominated by avulsions and rapid migration. By 1995, the channel width had increased by 13% and flow was primarily contained within a single channel that evolved primarily through lateral migration (Figure 23.8). This transition occurred in three stages. Between 1850 and 1895, the McKenzie Reach experienced 46% increase in channel width and 11 large avulsions while lateral migration was limited to less than half of the channel length. Many of the avulsions involved the re-occupation of 1–4-km-long side-channels spanning large-amplitude bends (Figures 23.8 and 23.9) and resulted in a 20% decrease in centreline length between 1850 and 1895.

After experiencing a general widening and straightening during 1850–1895, the McKenzie reach narrowed by 15% as lateral migration became dominant during 1895–1932 (Figures 23.8 and 23.10). Although migration rates more than doubled and the length of channel subject to migration increased by 20%, centreline length only increased slightly. The overall style of migration was quite dynamic as several low-sinuosity portions of the 1895 channel developed into bends that subsequently migrated downstream (Figure 23.10).

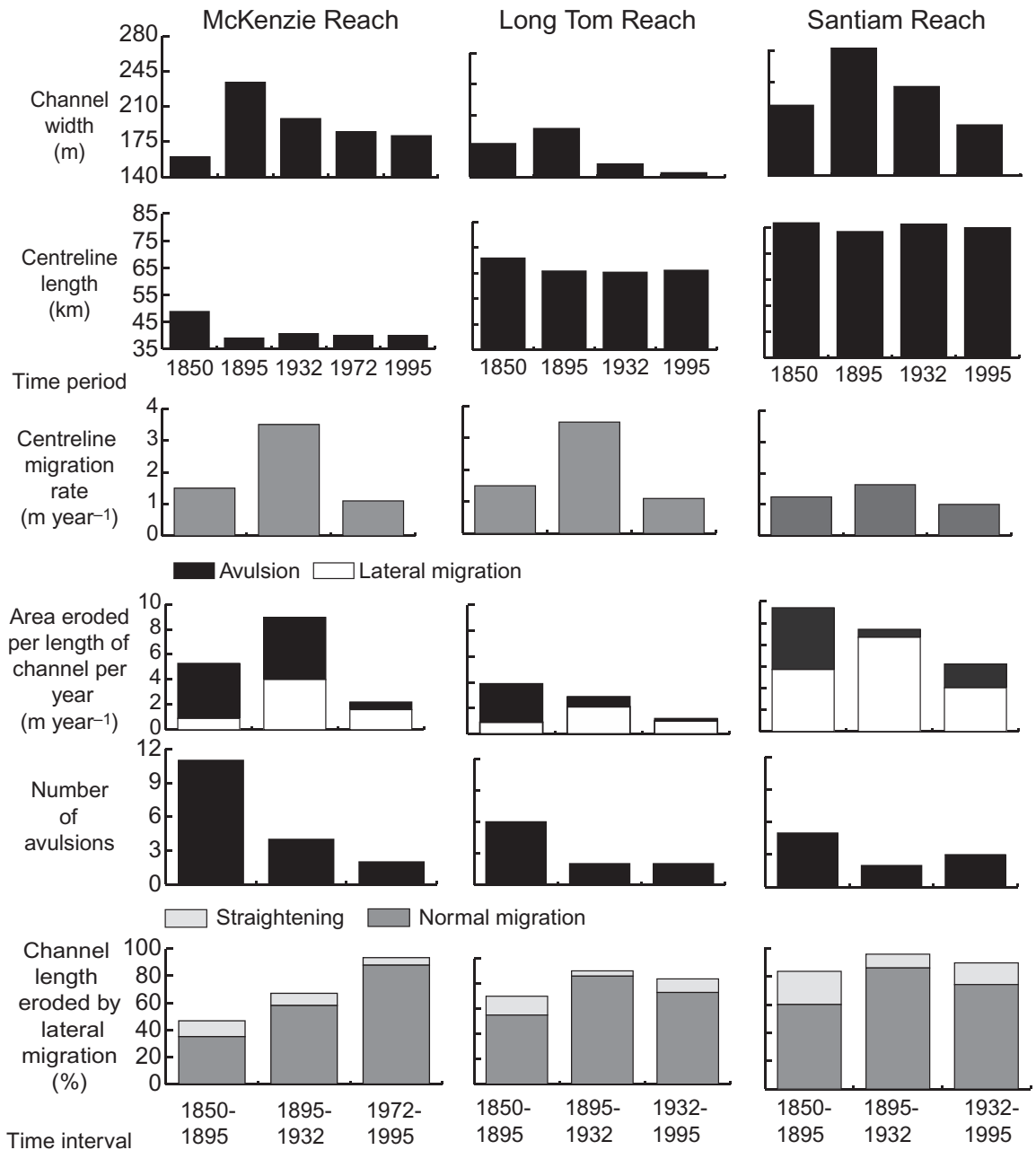


Figure 23.8 Patterns of channel change for mainstem Willamette River, 1850–1995



Figure 23.9 Example of avulsions 1850–1895 along upper Willamette River. Similar large-scale avulsions occurred along the entire Willamette River during this time period. In many cases, the 1895 channel avulsed into former side channels (e.g. FPKM 165–170) or carved cut-off channels (e.g. FPKM 169). (Geological map from O'Connor *et al.*, 2001. Historical Willamette River channel maps and floodplain transect maps from Hulse *et al.*, 2002)

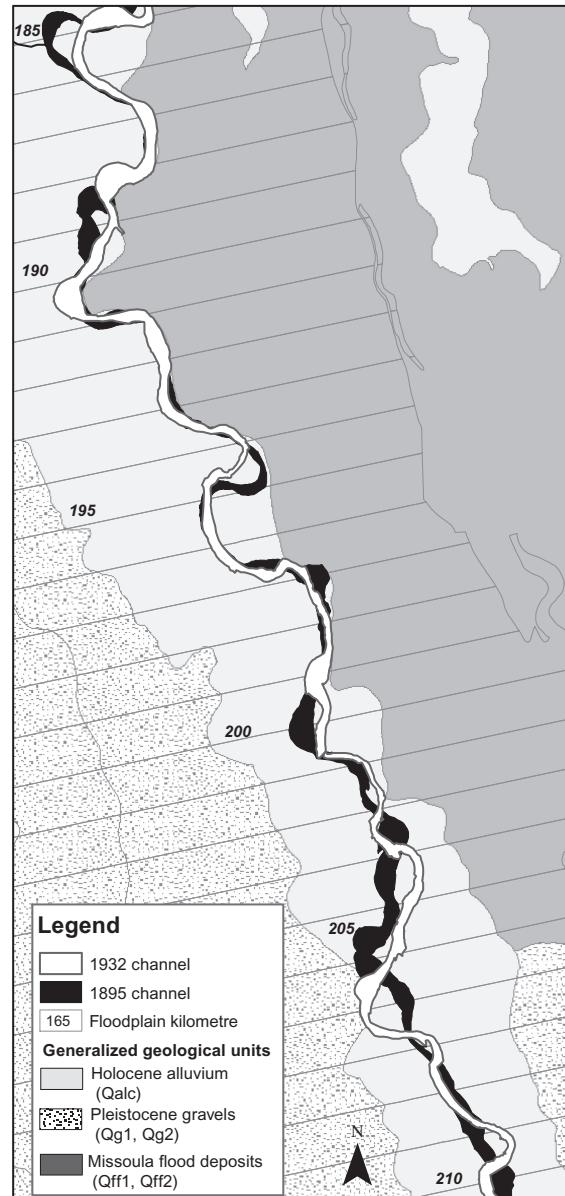


Figure 23.10 Example of rapid meander migration 1895–1932 along upper Willamette River. Along much of the Willamette River, small initial bends in the 1895 channel developed into larger bends which subsequently migrated downstream by 1932 (e.g. FPKM 200–205). As sinuosity increased, channel width also narrowed during the 1895–1932 time period. (Geological map from O'Connor *et al.*, 2001. Historical Willamette River channel maps and floodplain transect maps from Hulse *et al.*, 2002)

Channel change during 1972–1995 was more subtle than during earlier periods as migration and avulsions were limited to areas of the floodplain where revetments did not restrict channel movement (Figure 23.8). Migration rates decreased by 60% from those experienced during 1895–1932, avulsion frequency decreased and the channel narrowed slightly. Although much of the centreline experienced some movement during the late twentieth century, in many areas of floodplain, channel narrowing caused the centreline to appear to shift laterally though actual bank erosion was minimal.

23.5.2 Long Tom Reach, 1850–1995

Historical channel change along the Long Tom Reach reflects its position as a transition zone as the upstream portion of the reach has transformed from a dynamic, anastomosing channel towards a more stable channel, whereas the lower reach has maintained its more stable single-thread planform. Over our 150-year study period from 1850 to 1995, the Long Tom Reach experienced an 18% net decrease in channel width and a 7% decrease in channel length (Figure 23.8). Whereas the McKenzie and Santiam Reaches experienced large increases in width during 1850–1895, the Long Tom only widened by about 10% and appears more prone to narrowing, as channel width decreased by 20% between 1895 and 1932 and an additional 6% from 1932 to 1995. Like the McKenzie Reach, much of the net decrease in sinuosity was accomplished during 1850–1895 by avulsions along the upper sections of the Long Tom Reach that were historically anastomosing (Figure 23.8).

The Long Tom Reach is unique in that while avulsions between 1850 and 1895 influenced a large portion of the floodplain, lateral migration has influenced a greater portion of the total channel length during all time periods. Migration rates were greatest during the interval 1895–1932 when several low-sinuosity sections of the upper Long Tom Reach developed small initial bends while other existing bends migrated downstream (similar to the example shown in Figure 23.10 for the McKenzie Reach).

Although reach-average channel change trends for 1932–1995 indicate that erosion due to avulsions and meander migration decreased during the twentieth century, the entire Long Tom Reach did not immediately become more stable. Aerial photographs of the upper Long Tom Reach show that several bends migrated rapidly from 1932 to 1972 so that local migration rates exceeded 10 m annually in some areas. Nearly all of these rapidly eroding bends were stabilized with revetments by 1972 and bank erosion from 1972 to 1995 was generally limited to areas

unprotected by revetments. In contrast, the channel downstream of Corvallis (FPKM 165) experienced little net change over the entire 1932–1995 interval.

23.5.3 Santiam Reach, 1850–1995

Although the Santiam Reach has generally been much more stable than the upper reaches, this lower study reach has followed similar trends to the others. Similar to the Long Tom Reach, the Santiam Reach experienced a net decrease in channel width and slight decreases in channel length over the entire study interval of 1850–1995 (Figure 23.8). Much of the loss in centreline length was accomplished through several large avulsions during 1850–1895 though subsequent migrations during 1895–1932 nearly recovered much of the 1850 sinuosity. Like the McKenzie Reach, the Santiam Reach initially experienced large (~30%) increases in channel width between 1850 and 1895. However, during the intervals 1895–1932 and 1932–1995, channel width decreased by 15% and 18%, resulting in a 10% net decrease in reach-average width by 1995.

In all time periods, the Santiam Reach has been dominated by lateral migration. The overall annual rate of migration has fluctuated slightly (1–1.6 m) and most lateral migration has occurred in Holocene alluvium along the lower portion of the reach downstream of Salem (FPKM 110). Bends situated adjacent to Qg2 gravels appear to remain locked in place and have only migrated slowly outward against the terrace. Like the other reaches, during the period 1895–1932 the river experienced the greatest lateral migration rates, but along the Santiam Reach, migration was dominated by lateral shifting of large (>5 km) bends, rather than the development and subsequent downstream migration of small bends as seen on upper reaches.

Twentieth century channel change along the Santiam Reach was marked by channel narrowing and an overall decrease in floodplain erosion (Figure 23.8). Although three avulsions occurred, they generally bypassed smaller portions of the floodplain compared with larger, historic avulsions. Migration rates were similar to rates experienced during the mid-late nineteenth century, but the area affected by migration is much less than for historic periods. Decreased migration, fewer avulsions and continued channel narrowing cause much of the 1995 channel to be positioned within the boundaries of the 1932 channel.

23.5.4 Summary of Willamette River Channel Change, 1850–1995

Our results revealed that, between 1850 and 1895, all reaches experienced numerous avulsions, increases in

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

Along all reaches, the percentage of channel bordered by resistant banks has increased substantially over the 150-year study interval (Figure 23.11). Moreover, we see that some bends situated adjacent to naturally resistant bank materials (e.g. the Qg2 located along floodplain margins) were historically able to migrate or avulse away from resistant banks, causing the percentage of channel bordered by resistant banks to fluctuate slightly over time (Figure 23.11). However, bank stabilization in the mid-twentieth century apparently causes many of these bends

to remain locked in place, as key sections of revetment prevent the channel from avulsing or migrating back towards the Holocene floodplain.

23.5.5 Flood Model Results

On the upper Willamette, large-magnitude floods such as the 1861 event ($\sim 7930 \text{ m}^3 \text{ s}^{-1}$ at Harrisburg) inundate the entire Holocene floodplain and generate erosive overbank flows (Figure 23.12a). In many areas, flow follows the regional (floodplain) topography rather than the river, causing streampower to be concentrated in areas outside the main channel. Power is typically highest along inside, rather than the outside, of meander bends. Such patterns of erosive flows could have led to scouring of point bars, and may have caused widening of the channel or migration towards inside of bend (straightening). Streampower is also high at the downstream end of bends, but on the outside of the channel where chute formation and avulsions are likely to occur. Overbank flows in areas not adjacent to the channel could have carved new side-channels, or triggered migration and avulsions along existing secondary channels.

Moderate sized floods such as the 1996 event ($\sim 2100 \text{ m}^3 \text{ s}^{-1}$ at Harrisburg) and those experienced every few years in the early twentieth century may inundate the floodplain but do not produce erosive overbank flows (Figure 23.12b). Stream power from modern, post-dam floods is generally greatest in the channel and more likely leads to within-channel scouring and local bank erosion rather than chute formation. Overbank stream power for moderate-sized floods is much lower than power generated by large-scale floods (typically $< 10 \text{ W m}^{-2}$ versus $> 40 \text{ W m}^{-2}$ for large floods). These streampower patterns indicate that avulsions may have only been possible in areas with high erodibility, e.g. sparsely vegetated point bars or along multi-thread reaches. Model results are consistent with post-1996 channel changes, which indicate bank erosion was greatest in areas where the active channel is relatively wide and characterized by gravel bars and side channels.

23.6 DISCUSSION, NARRATIVE OF HISTORICAL CHANNEL CHANGE

Our results reveal the inherent complexities in interpreting causative mechanisms for channel changes in large rivers. Against an ever-changing backdrop of flood history, evolving land uses, flow regulation, and engineering interventions in the channel itself, patterns and rates of channel change vary by both reach and time period. Interpretation of factors forcing or controlling river evolution at the scale

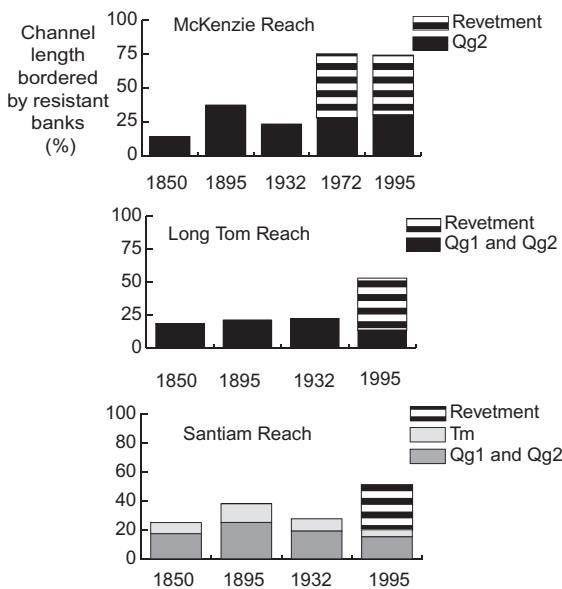


Figure 23.11 Length of channel bordered by resistant bank materials. Revetment installed in the 1930s–1970 stabilizes large areas of the Willamette River, while naturally resistant banks have historically bordered an additional 13–40% of each reach. (Geological units from O'Connor *et al.*, 2001)

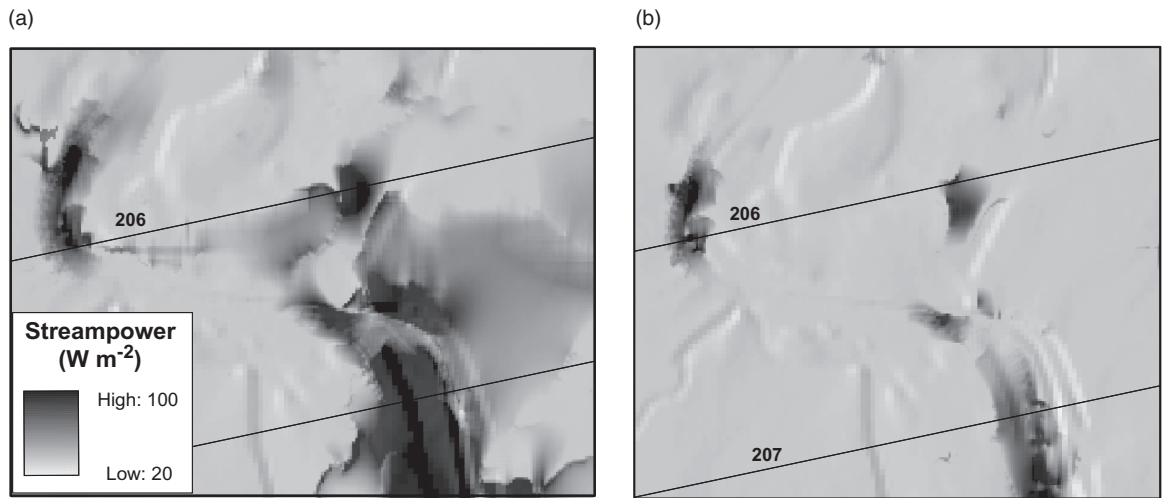


Figure 23.12 Comparison of streampower for large floods and moderate floods. Streampower was calculated as the product of shear stress and velocity using MIKE 21, a two-dimensional hydrodynamic model. Area shown spans FPKM 205–208 along the upper Willamette upstream of Harrisburg. (a) Streampower at $7930\text{ m}^3\text{ s}^{-1}$, estimated peak discharge for the 1861 flood of record at Harrisburg. (b) Streampower at $2100\text{ m}^3\text{ s}^{-1}$, approximate peak discharge for the 1996 flood at Harrisburg. The 1996 flood was similar in magnitude to the ‘moderate’ floods that occurred frequently in the early twentieth century

of the entire river must therefore rely more on a plausible narrative supported by multiple lines of evidence rather than simple cause-and-effect type models. Here we discuss some salient aspects of that narrative for the Willamette, interpret the history of channel changes, and consider how this one case study informs interpretation of processes of channel change in other large rivers.

23.6.1 Interpreting Historical Channel Change, 1850–1995

In order to determine why the Willamette has displayed varying rates and styles of channel change over the 150-year study interval, we compared our results against the list of natural and anthropogenic impacts in Table 23.1 that may have triggered the observed patterns of channel change. This analysis suggests that large floods, smaller floods and the full spectrum of human modifications to the channel and floodplain each have had distinct effects on channel planform and behaviour, but that the impact of these different causative factors varies in magnitude and timing.

Large magnitude floods appear to have had a profound impact on the entire Willamette River system in the mid-late nineteenth century, in particular the avulsions, channel widening and decreased sinuosity that occurred during 1850–1895. This interpretation is consistent with: (1)

gauge records indicating that the three largest historical floods in 1861, 1880 and 1891 occurred during this time period (Figure 23.7); (2) flood model results showing stream power during the largest floods is concentrated in overbank areas and therefore more likely than smaller floods to cause channel widening and avulsions (Fig. 23.12); (3) the observation that the 1850–1895 period was marked by numerous avulsions whereas subsequent time periods with fewer large floods had substantially fewer avulsions (Figure 23.8); (4) historical records during this early period (e.g. Brands, 1947) that describe large, channel-spanning, wood rafts that, once mobilized during exceptional floods, could readily have served as tools for stripping surfaces and eroding banks, thereby facilitating channel widening (Johnson *et al.*, 2000); (5) aerial photographs of the Willamette floodplain that reveal many examples of large-amplitude bends having been abandoned through avulsions, with few examples of meander bends that have evolved entirely through lateral migration (Figure 23.13).

Periods of frequent, more moderate magnitude floods appear to result in accelerated lateral migration as opposed to avulsive ‘hopping’, as evidenced by channel changes during the period 1895–1932 (Figure 23.10). Over this time, at least 25 flood events (Figure 23.7) occurred that were twice or greater the magnitude of the modern bankful flood (USGS, 2006). This coincided with an increase in

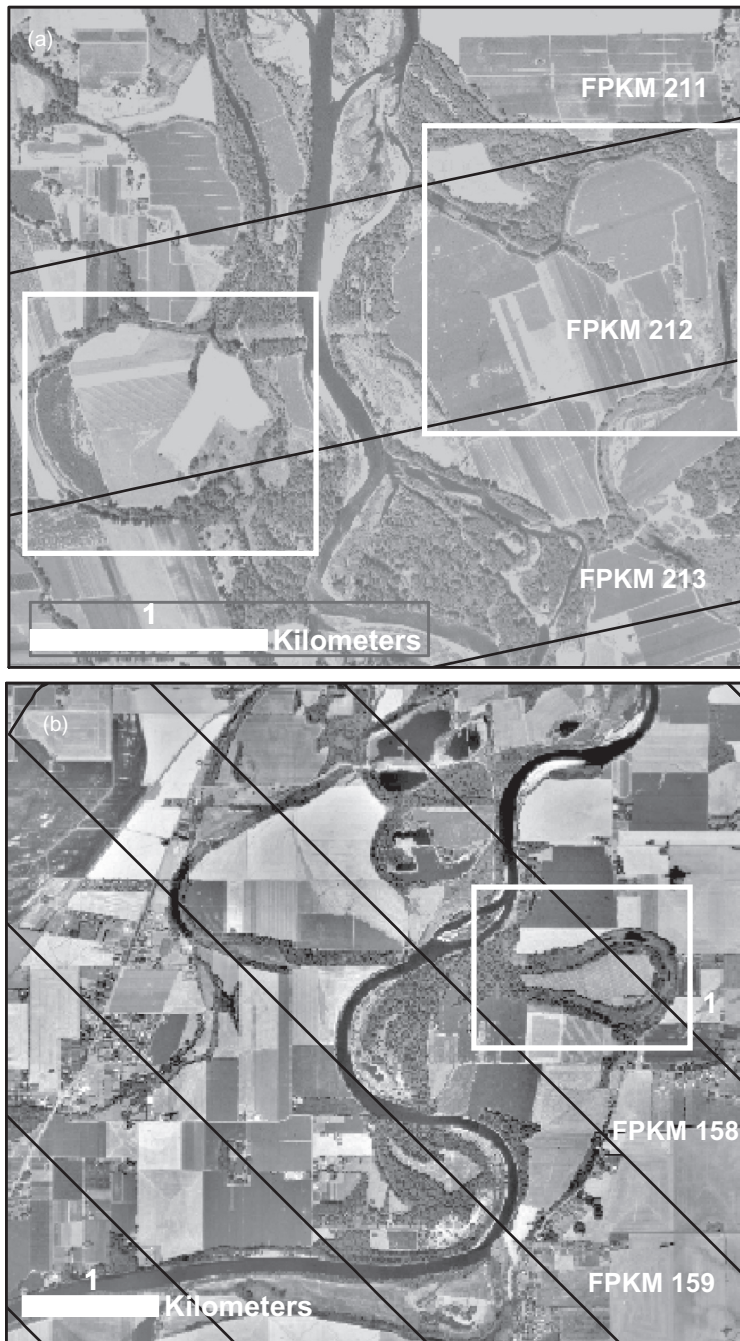


Figure 23.13 Examples of avulsions and meander migration recorded in remnant floodplain features. (a) Examples of abandoned large-amplitude bends as recorded in aerial photographs of Willamette River floodplain. These bends were probably active in the nineteenth century. Similar features are found in many other areas of the southern Willamette Valley. (b) Example of meander bend that evolved entirely through lateral migration. Such bends are rare in the Willamette Valley floodplain. This bend is located between Corvallis and Albany and probably formed along a side channel in the early twentieth century

migration rates of 50–300% and greater sinuosity. Our stream power modelling demonstrates that during moderate-sized floods (such as the 1996 flood and those experienced every few years prior to flood control), stream power is concentrated in the channel rather than on the floodplain, thereby promoting lateral migration (Hickin and Nanson, 1984). Aerial photographs from 1995 to 2000, for example, show that annual local migration rates in areas of the McKenzie Reach without artificial revetments (e.g. FPKM 210–212) exceeded 20m, a rate that is much higher than reach-averaged migration rates for the interval 1972–1995. Such rapid channel change is likely due to moderate magnitude floods that occurred within a year of each other in February and November 1996. Floodplain inundation during such moderate floods is typically not deep or swift enough to carve cut-off channels or trigger avulsions except in highly erodible areas or former low-lying channels.

In addition to the frequency of moderate floods, another factor promoting the rapid migration rates observed from 1895 to 1932 was the prevalence of erodible banks. At the beginning of the twentieth century and prior to the erosion-control engineering that took place mid-century, most of the Willamette River was bordered by erodible Holocene alluvium (Figure 23.11) (Wallick *et al.*, 2006). Again using the 1996 floods as an example of the style of channel changes that were common early in the last century, most lateral erosion that occurred during those floods was concentrated in areas where the active channel was fairly wide and both banks were flanked by Holocene alluvium.

Human activities do not appear to have had a major influence on rates and styles of channel change until the mid–late twentieth century. Although some previous work has suggested that the Willamette became increasingly stable following Euro-American settlement in the mid-nineteenth century (i.e. Benner and Sedell, 1997; Hulse *et al.*, 2002), our results clearly demonstrate that the Willamette was an active and dynamic river subject to avulsions and rapid migration well into the first third of the twentieth century. The timing of human settlement of the valley (Figure 23.4) does correspond to the previously discussed shift from avulsion to lateral migration, but we interpret this shift as being more due to flood history than direct human impacts on the river and its environs, which were modest until the mid-1900s. Navigation improvements by the Corps of Engineers in the nineteenth century targeted only a small percentage of the entire channel (<10% of total river length), and historical records indicate that many of the wing-dams and other structures were swept away or disrupted by channel shifting following floods (USACE, 1875, 1882, 1891). Land conversion and riparian deforestation may have accelerated bank erosion

locally, but we do not believe this was a major driver of channel change because very few settlements were located along the Willamette floodplain in the nineteenth and early twentieth centuries (General Land Office, 1851–1853; USACE, 1895; Bowen, 1978; Towle, 1982). Even by 1932, less than half of the entire mainstem Willamette was bordered by farm lands, and most agriculture occurred along the more stable lower reaches. The upper Willamette, which had the highest migration rates, experienced very little floodplain agriculture until the mid–late twentieth century (Anderson, 1974; Gregory *et al.*, 2002a).

Similarly wood snagging, which has been interpreted as a major factor contributing to reduced channel migration (e.g. Sedell and Froggatt, 1984), removed only a small portion of the total volume of large wood available in the historical Willamette floodplain. Many historical records indicate that sloughs and side channels were frequently filled with downed trees following ‘freshets’ throughout the late 1800s (USACE, 1875: 763). On average, approximately 1000 snags were removed annually from the upper Willamette roughly between 1870 and 1920 (Sedell and Froggatt, 1984). Assuming that these logs were taken from a 50km area extending upstream of Corvallis (FPKM 165), this resulted in approximately 20 logs removed per kilometre of floodplain per year. Without minimizing the cumulative impact of large wood removal, it is important to recognize that the upper Willamette floodplain extended laterally for several kilometres and was still densely forested in many areas until the 1930s. We therefore suggest that snagging by itself did not have a significant impact on channel change. Rather, it was snagging in combination with the widespread conversion of floodplain forests to agriculture (which diminished local availability, hence recruitment of large wood) and dam construction (which limited the transport of wood from tributary channels to the mainstem Willamette) that reduced the in-channel abundance of wood. With both wood supply and flood peaks reduced, the channel was less prone to avulsions due to wood clogging of channels. Clearly disentangling the specific effects of woody debris removal on channel morphology from other concurrent changes to the channel regime is difficult, but on balance we suggest that it played a secondary role to flow regime changes.

Another interpretation of decreased migration rates and channel narrowing that occurred from the 1930s onward is that they are broadly consistent with predicted patterns of increased channel stability and incision following dam construction and bank stabilization (Williams and Wolman, 1984; Shields and Cooper *et al.*, 2000). Migration rates decreased by 40–70% along the entire Willamette during this period, while avulsion frequency

diminished by 50% on the upper Willamette. From 1932 to 1995, channel width decreased slightly on the upper and lower reaches of the Willamette, while the Santiam reach narrowed by nearly 20%. At the same time, aerial photographs from 1939 to 1996 show maturation of riparian vegetation and decreases in the number of bare gravel bars adjacent to the main channel (Gutowsky, 2000). Distinguishing between dam construction versus bank stabilization as driving these changes is problematic, however, since both activities occurred concurrently. The rapid development of bank stabilization measures from the 1930s onward, however, has to be seen as having a primary control on channel migration rates (Figure 23.6), as it represents a direct intervention in the channel designed specifically for the purpose of reducing bank erosion, hence lateral migration. By 1995, nearly 50–75% of the Willamette was bordered by either naturally resistant bank materials (e.g. cemented Pleistocene gravels, Tertiary marine sandstones, or basalts) or revetments (Figure 23.9). Many areas that were not stabilized with revetments or had intrinsically resistant banks were nonetheless ‘inherently stable’ (and predominantly straight) reaches that had experienced little net change over the 150-year study period. The modern Willamette River is highly constrained, with lateral adjustments possible on only a few reaches.

Dam construction from the 1930s onward was highly effective in limiting the sizes of most winter floods. By 1970, 13 major flood control reservoirs had been constructed, and the largest peak flow of the post-dam era was the 1996 flood, which as noted above, was similar in magnitude to the ‘moderate’ sized floods that occurred every few years in the early twentieth century (Figure 23.7). Reduced peak flows limited opportunities for lateral change, although the tendency for the channel to incise would also have been limited by reduced stream power (Grant *et al.*, 2003). Reduction in sediment supply due to upstream dams was probably not much of a factor driving channel changes in the Willamette, since other studies have shown no change in sediment rating curves following dam construction (Klingeman, unpublished data; Laenen, 1995). Abundant sediment supply in tributaries below dams and on the valley floor apparently compensates for sediment deposited in reservoirs upstream of dams.

Our estimates of rates of channel change are limited by the long time intervals between sequential aerial photos and maps. A more accurate picture of the timescales of changes relative to specific flood events and human activities might have emerged had the inter-photo intervals been less. For example, on the McKenzie Reach, we were able to discriminate channel changes that occurred in the post-

dam and revetment era of 1972–1995 from changes that occurred during 1932–1972. Because rates of channel change during the 1972–1995 period are significantly lower than for previous time periods, we hypothesize that migration rates calculated for the period 1932–1995 along the Long Tom and Santiam Reaches may underestimate rates of channel change from 1932 to 1972 while overestimating channel changes from 1972 to 1995. Along all reaches, our use of centreline migration rates probably overestimates actual bank erosion during the twentieth century, because during periods of channel narrowing, the centreline may appear to shift laterally though actual bank erosion is negligible (Wallick, 2004). Thus, while our calculated migration rates for all reaches during the twentieth century were lower than for previous intervals, we suspect that actual bank erosion may be even lower than our the migration rates reported here.

23.6.2 Extending Lessons learned on the Willamette to Other Large Rivers

What can we learn from this detailed examination of historical channel changes on the Willamette that is applicable to other large rivers? Several key lessons emerge from this analysis that provide insight into factors controlling the intrinsic evolution of large rivers and disentangling how human activities modify and shape channel behaviour. In particular, this study gives some confidence that the complex history of large rivers can be deciphered using historical records, and a general explanatory narrative can be developed.

For rivers where the human history is relatively recent (i.e. last one to two centuries), it is still possible to interpret patterns and controls on intrinsic channel behaviour prior to any human interventions or modifications. What emerges from our examination of the Willamette is that there exists a hierarchy of factors controlling the pattern and evolution of the river. This is not a new concept (Schumm and Lichty, 1965), and we need to be cautious in extending conclusions from our particular case study to other rivers. Nevertheless, the patterns, timing and longitudinal trends of channel changes experienced by the Willamette from 1850 to 1900 suggest that in the absence of human impacts, channel evolution is inevitably steered by spatial variations in channel morphology and temporal variations in basin disturbances such as floods.

In particular, spatial variation in channel gradient, valley geometry, and bed and bank erodibility provide first-order controls on channel form, particularly planform and determine the sensitivity with which a given reach will respond to drivers of channel change. Of these, channel gradient and valley geometry appear to be overarching

controls on channel form, with variation in erodibility introducing a factor that can locally trump these broader scale controls. We find it noteworthy that the overall style of channel change in a given time period was remarkably similar across the entire study area, but the magnitude of change (e.g. the increase in migration rates or magnitude of channel widening) varied widely according to study reach. For example, the higher-gradient McKenzie Reach responded quite sensitively to the flood-rich period 1895–1932 through rapid migration of numerous bends, whereas the lower gradient Santiam Reach experienced a more dampened version of ‘rapid migration’ regarding both observed erosion rates and the number of bends that experienced this style of change.

This finding is consistent with the general longitudinal transition of the Willamette from an anastomosing to a more meandering or wandering system, and accords with other findings on both mountain (Ferguson and Ashworth, 1991; Grant and Swanson, 1995) and lowland rivers (Leopold and Wolman, 1957; Knighton and Nanson, 1993).

Along with the physical setting of the channel, a key factor influencing the channel condition at any particular time is the magnitude, recency and sequence of flood flows. Large scale differences in Willamette River morphology and processes – for example, the predominance of avulsions versus lateral migration as a mechanism of channel change – appear to result from whether particular periods of time include large or more moderate floods. During flood-rich periods, more of the valley bottom is maintained as active channels whereas during flood-poor periods, the channel tends to wander laterally. The time period between flows doing significant geomorphic work has been identified as an important factor on par with the magnitudes of floods themselves in terms of shaping the channel (Wolman and Gerson, 1978). Not only the interval between floods, but also the sequence of flows may also play a role in determining channel condition at any given point in time, particularly where vegetation and woody debris are present (Tal *et al.*, 2004). Vegetation in particular, and the cohesion it provides for bank sediments, is emerging as a first-order control on channel pattern, and its presence or absence can determine whether the channel is braided or meandering (Gran and Paola, 2001; Murray and Paola, 2003). With floods acting as vegetation-resetting events, an important time-scaling factor for interpreting channel behaviour is the magnitude and frequency of floods relative to the timescale of recolonization and growth of vegetation.

Turning now to what the Willamette study reveals about the role of human activities on geomorphic evolution of large rivers, we observe that human impacts are

invariably overlain onto a river system with certain intrinsic controls, as discussed above. This suggests that any attempt to interpret human impacts requires that those intrinsic controls be accounted for first, a daunting task where human modifications to the channel span multiple centuries. Because of the recency of human modifications to the channel, rivers such as the Willamette can provide a useful reference point for more disturbed rivers elsewhere. But even where the human history is relatively short and decipherable, interpreting the river’s response is quite complex, particularly since human actions occur in concert with each other and with external drivers such as floods.

The Willamette study highlights that both the sequence and timing of human interventions in rivers has important implications for interpreting long-term channel behaviour. Sequence involves the order in which interventions occur, while timing reflects when they occur in relation to other channel-shaping events, particularly floods. Our results suggest that the sequential order of disturbances can have important effects on rates and styles of channel change in subsequent time periods. On the Willamette, periods of moderate floods enhance lateral migration which causes the channel to develop a more sinuous planform. Bends created by migration are then susceptible to avulsions and straightening by large-magnitude floods. In the absence of anthropogenic activities, flooding patterns along the densely forested historic floodplain probably caused the Willamette to alternate between a narrow, sinuous planform (e.g. the 1850 planform) and a wider, straighter planform (e.g. the 1895 planform) over the scale of multiple decades. However, it seems that the upper Willamette never recovered its pre-large flood planform because closure of side channels, bank stabilization and other Euro-American activities forced greater amounts of flow into a larger, single channel while also suppressing lateral migration. Thus, a century after the large-magnitude floods of the 1800s, the upper Willamette still maintains a wider, straighter planform than was observed in 1850.

It is interesting to speculate whether the channel planform evolution would have been markedly different had the first half of the twentieth century included more large floods similar to the 1861 event. Would the loss of riparian forests and concomitant reduction in large wood stored within the channel as agricultural use of the valley bottom expanded have increased (because of reduced vegetation and bank cohesion) or decreased (because of lower concentrations of potentially mobile wood) the erosive power of a large flood? These kinds of speculations underscore the contingent nature of channel response. Although he was writing about biological evolution, Gould (1989: 283) could have been describing channel evolution:

‘I am not speaking of randomness, but of the central principle of all history – contingency. A historical explanation does not rest on direct deductions from laws of nature, but on an unpredictable sequence of antecedent states, where any major change in any step of the sequence would have altered the final result. This final result is therefore dependent, or contingent, upon everything that came before – the unerasable and determining signature of history.’

Although clearly obeying physical laws and constrained by both physical setting and process dynamics, channel evolution in large (and, to a lesser extent, smaller) rivers is inevitably contingent – it cannot be interpreted solely on the basis of physics. The history of channel changes, whether due to natural or anthropogenic actors, sets the river’s evolutionary course and predisposes it to respond to subsequent actors or events in a way different than had those initial changes not transpired. Simple cause-and-effect models can be used to explain some aspects of this behaviour, for example why a particular bank failed under a particular flow regime. The overall trajectory of changes requires that these direct causal linkages be supplemented by a broader narrative that weaves the sequence and timing of factors driving change and consequent responses. This narrative can be developed using historical information and relatively simple metrics, and while it does not constitute proof of why certain changes occurred when they did, it can provide a plausible and rational explanation for complex fluvial phenomena.

23.7 CONCLUSION

Our study of the Willamette River reveals that geologic controls, flooding and human activities have all exerted large influences on channel change, but that the relative importance of these variables has shifted over time. Prior to flow regulation and bank stabilization, the Willamette was an anastomosing river flowing through a densely forested floodplain. During periods of moderate floods, meander migration led to the development of bends along both the mainstem Willamette and side channels. Large-scale floods led to avulsions and extensive increases in channel width and decreases in sinuosity. In the periods following these large floods, meander migration probably led to the redevelopment of bends with migration occurring rapidly along reaches flanked by Holocene alluvium. Anthropogenic activities had no clear effect on planform or erosion rates until the 1930s when widespread bank stabilization and dam construction resulted in diminished migration rates, fewer avulsions and channel narrowing. By the late twentieth century, more than 30% of the

Willamette was stabilized with revetments, while naturally resistant bank materials bordered an additional 13–30% of the three study reaches. Large-scale geological controls in combination with bank materials determine the magnitude of channel response to anthropogenic and natural impacts: more intrinsically stable reaches (e.g. the lower Willamette and those bordered by resistant banks) required little to no effort to maintain a navigable channel. In contrast, steeper reaches along the upper Willamette required substantial maintenance and were not fully stabilized until flood control dams and extensive revetments were constructed.

The approach we employed here was successful in providing a framework for understanding how large rivers evolve over time amid overlapping drivers of channel change. This framework leads to a narrative of historical channel changes that provides some basis for assessing how large rivers may respond to future anthropogenic or natural impacts.

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

The analyses applied here are applicable to other large rivers because nearly all large rivers are influenced by a myriad of spatially and temporally varying impacts. However, assembling a narrative of historical channel change is an ambitious task because it requires a wide range of historical, geomorphic, geologic and hydraulic analyses. The datasets that support these analyses are necessarily extensive and must encompass broad spatial and temporal timeframes. On the Willamette, historical channel maps, and geological maps are readily available while records of landuse and human activities required more in-depth analyses of historical documents. In addition, our approach relied heavily on previous work, especially the data collection and compilation efforts by the PNWERC (Hulse *et al.*, 2002).

Despite the extensive analytical effort required for such a large-scale study, such an approach is important because it avoids the bias introduced by smaller-scale studies wherein only a single driver of channel change is analyzed. For example, had we limited our analyses to the impact of large floods on channel morphology, the various

roles geology plays in dampening flood-related channel change might have been neglected. Moreover, by studying large rivers over broad spatial and temporal timescales in light of a full range of natural and anthropogenic impacts, a much more comprehensive picture of channel evolution in large rivers emerges.

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