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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.

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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 km^2 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.

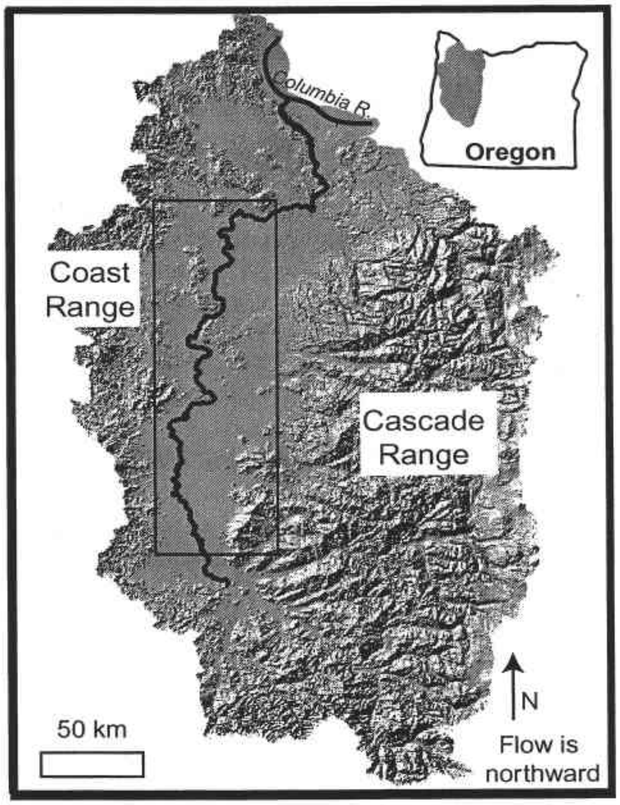


Figure 23.1 Willamette River Basin in northwestern Oregon. Box indicates 200 km study area shown in Figure 23.2

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.

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 Lichty, 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 cutoffs, 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

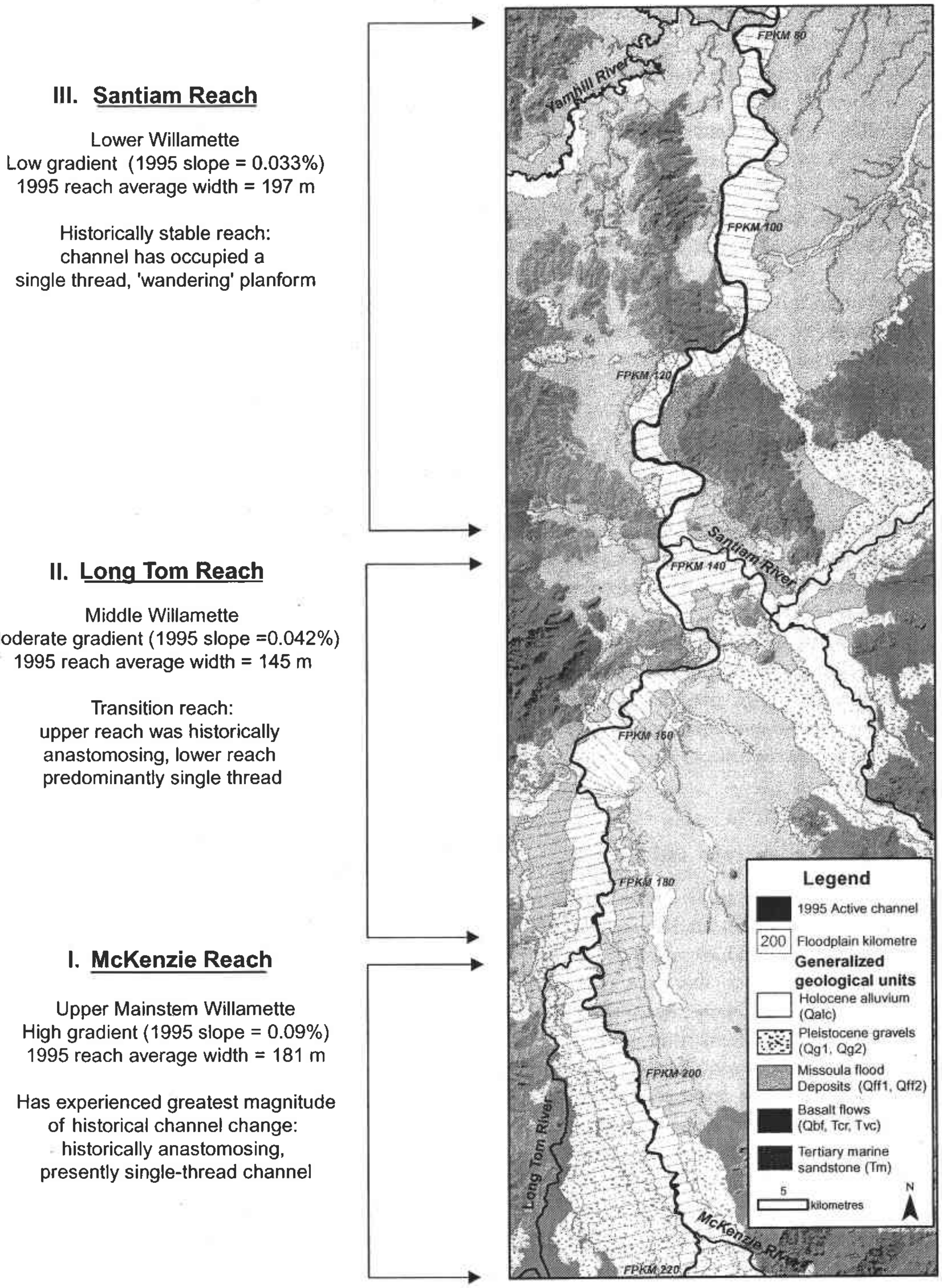
The Willamette Valley is situated between two rugged and deeply dissected mountain landscapes, the volcanic Cascade Range to the east and the uplifted marine sandstones of the Coast Range to the west (Figure 23.1). Although heading in the mountains, the Willamette River itself is a relatively low-gradient 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 rainfall 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).



III. Santiam Reach

Lower Willamette
Low gradient (1995 slope = 0.033%)
1995 reach average width = 197 m

Historically stable reach:
channel has occupied a
single thread, 'wandering' planform

II. Long Tom Reach

Middle Willamette
Moderate gradient (1995 slope =0.042%)
1995 reach average width = 145 m

Transition reach:
upper reach was historically
anastomosing, lower reach
predominantly single thread

I. McKenzie Reach

Upper Mainstem Willamette
High gradient (1995 slope = 0.09%)
1995 reach average width = 181 m

Has experienced greatest magnitude
of historical channel change:
historically anastomosing,
presently single-thread channel

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 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).

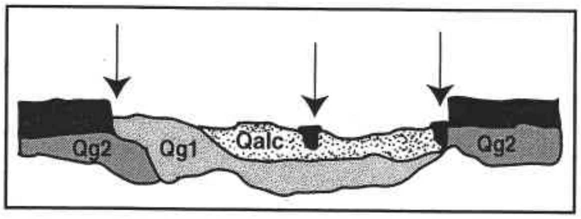


Figure 23.3 Generalized cross-section of Willamette floodplain. Geological units are same as those shown in Figure 23.2. Arrows indicate typical locations of Willamette River within Holocence floodplain. (Geological units are from O'Connor *et al.*, 2001)

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

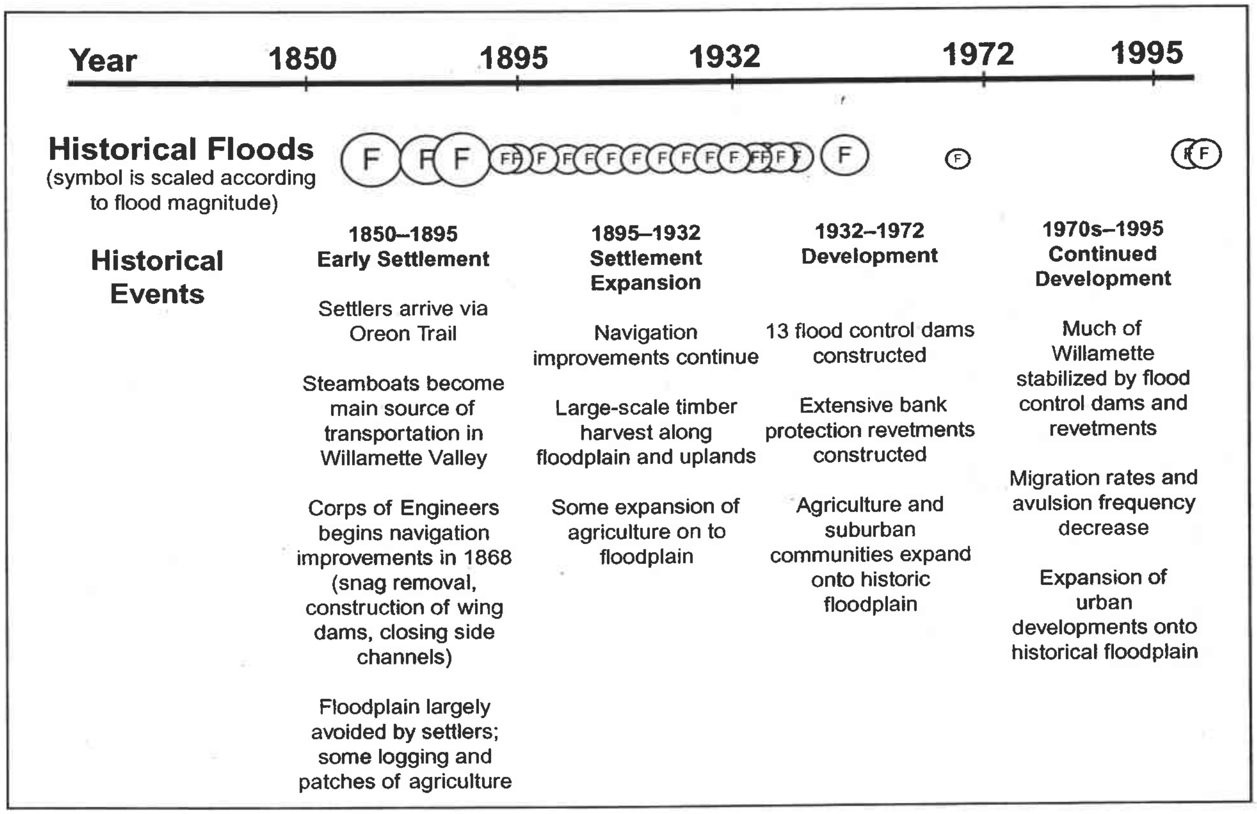


Figure 23.4 Timeline of geomorphically relevant historical events in Willamette Valley. Prior to Euro-American settlement in the late 1840s, the Willamette River and its floodplain were largely unaffected by human activities. The first Euro-Americans to enter the Willamette Valley were Lewis and Clark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