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Floodplain Formation and Cottonwood Colonization Patterns on the Willamette River, Oregon, USA

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ABSTRACT / Using a series of aerial photographs taken between 1936 and 1996, we trace coevolution of floodplain and riparian forest on the Willamette River. Within-channel barforms appear to be the predominant incipient floodplain landform and habitat for primary succession. Interlinked development of bar(s) and erosion of near banks, filling of channels, and establishment and growth of cottonwoods and willows results in coalescence with older floodplain. Size and internal structure of riparian forest patches reflect evolution of underlying barforms or channel beds. Floodplain matures as the active channel migrates away by repetition of the bar formation and near-bank erosion process, or is progressively abandoned by infilling and/or constriction with a bar. Other parts of the floodplain are recycled as eroding banks provide the coarse sediment and large woody debris for building new bars. A multichannel planform is maintained as building bars split flow; channels lengthen as bars and islands join into larger assemblages. Avulsion appears to cut new channels only short distances. Given the central role of bars and islands in building new floodplain habitat, we identify their area as a geomorphic indicator of river-floodplain integrity. We measure an 80% decline in bar and island area between 1910 and 1988 within a 22-km section. Dams, riprap, logging, and gravel mining may all be contributing to diminished bar formation rates. Removing obstacles to natural riparian forest creation mechanisms is necessary to regenerate the river-floodplain system and realize its productive potential.

Alluvial rivers form and reform floodplain elements (point bars, islands, oxbows, ridges and swales, etc.) to create physical substrate for riparian forest (Lewin 1978). When pioneer riparian tree species colonize newly emergent landforms, they alter deposition and erosion to influence subsequent geomorphology (Leopold and Wolman 1957, Hickin 1984). Colonization patterns are indicative of interactions between river and emergent floodplain during tree establishment, and these patterns are preserved in the spatial distribution of trees of different ages in mature floodplain forest (Shelford 1954, Johnson and others 1976, Nanson and Beach 1977, Salo and others 1986, Johnson 1992, Hupp and Osterkamp 1996). Effective river-floodplain stewardship requires understanding of how floodplain formation is a basis for pioneer species establishment and growth and for the maintenance of aquatic habitat (Johnson and others 1976, Brinson and others 1981, Asplund and Gooch 1988, Johnson 1994, Ligon and others 1995, Scott and others 1997).

Humans exert a great and growing influence on large river-floodplain systems (Swift 1984, Bravard and others 1986, Rood and Mahoney 1990, Dynesius and Nilsson 1994). An increasing amount of activity is aimed at "restoring" some measure of ecological integrity (National Research Council 1992, Gore and Shields 1995, Rasmussen 1996). Such efforts are often without an adequate foundation in understanding of natural processes and historical context of ecosystem conditions, a clear identification of stewardship goals, and a capability for monitoring and evaluating changes (Kondolf 1995a,b).

In the absence of analysis that provides sufficient basis for accurately predicting consequences, restoration activities have often yielded unwanted—sometimes irreversible—outcomes (Zedler 1988, Nehlsen and others 1991, Beschta and others 1992, Lawson 1993, Ebersole and others 1997). Restoration often fails when underlying abiotic dynamism of river-riparian ecosystems is given too little weight (National Research Council 1992).

KEY WORDS: Cottonwood; Floodplain formation; Primary succession; Stewardship; Willamette River

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Objectives and Definitions

We examine how portions of the Willamette River (Oregon, USA) floodplain have formed and eroded, and how the riparian forests have developed. Using a long-term and extensive aerial photographic record of the Willamette, we develop a descriptive model of these processes from the observed patterns of floodplain formation, channel changes, and riparian forest establishment and growth. We demonstrate the model's applicability by following the evolution of fluvial landforms and riparian forest and interpreting relict floodplain features at specific locations. Our analysis indicates the physical processes underpinning floodplain formation and riparian ecosystem development on the Willamette.

Our objectives are to address the questions: (1) What fluvial landforms suitable for establishment and persistence of pioneer riparian tree species does the river create? (2) How does such habitat become mature floodplain, sufficiently protected from erosion for pioneer tree species to reach reproductive maturity? (3) What spatial distributions of trees result? (4) By what combination of depositional and erosional processes is a multichannel planform maintained? (5) How might cumulative effects of observed fluvial processes and vegetative development account for gross floodplain morphology along 210 km of unconfined river? (6) How might human changes to the fluvial geomorphic regime have impacted floodplain formation mechanisms?

Two terms of central importance are "floodplain" and "riparian." We define floodplain as a fluvial landform adjacent to a channel and built of sediment transported and deposited by the present flow regime of a river (Nanson and Croke 1992). Incipient floodplain is exposed at low flows and submerged at less than mean annual flood, has coarse sediments exposed with fines filling but not covering them, and is covered by vegetation that is less than 50% tree. More developed floodplain is mature. By "riparian" we refer to a zone that extends from recently colonized fluvial landforms exposed at low flow out to the limits of the area wherein biota are adapted to, or characteristic community structures are influenced by, flooding (Junk and others 1989, Streng and others 1989, Gregory and others 1991).

Floodplain morphology is determined by a "fluvial geomorphic regime," which includes (1) relative and absolute amounts and rates of sedimentation and erosion; (2) seasonal and interannual timing, duration, and intensity of flooding, erosion, and sedimentation; (3) types, material composition, and scale of landforms built; and 4) locations at which landforms occur and particularly their spatial relationship to the hydrologic regime. All of these factors can affect establishment and survival of vegetation on incipient and mature floodplain.

Floodplain Formation and Channel Change Mechanisms

The handful of researchers who have performed detailed geomorphological studies on braided or wandering gravel-bed rivers, like the Willamette, show that floodplain morphology and a multichannel pattern are maintained by a wide range and combination of depositional and erosive mechanisms. We review some related studies next to place Willamette processes in perspective and demonstrate the importance of case studies in understanding a particular fluvial geomorphic regime and consequent ecological conditions.

Brierley and Hickin (1992) studied the Squamish River in western Canada, a high-energy gravel-based river that varied from braided through wandering gravel-bed to meandering. Floodplain formation began with compound barforms (mid-channel, bank attached, and point) composed of remnant floodplain and coarse sands deposited by rapidly flowing within-channel water. Coarse sands were often removed by flood flows and floodplain was predominantly composed of fine sands vertically deposited onto basal gravels by slow-flowing water. Brierley and Hickin (1991) showed that floodplain formational mechanisms were independent of river planform type, except that depositional sequences became thicker, and morphological elements more longitudinally extensive and horizontally aligned, as planform changed from braided, through wandering gravel-bed, to meandering.

On the Morice River, a wandering gravel-bed river in western Canada, Gottesfeld and Gottesfeld (1990) found reoccupation of old channels to be the primary mechanism of channel change, with the cutting of new channels and meander migration also contributing. The latter two processes supplied the input of downed trees, which was found to sometimes initiate channel reorganization by log jam formation.

In their study of the Waimakariri River in New Zealand, Reinfelds and Nanson (1993) found that larger floodplains were formed and eroded by lateral migration of the entire braidtrain, yielding a floodplain composed predominantly of gravel bars capped with vertically accreted finer sediment. They deemed reactivation of abandoned channels a secondary erosion mechanism. Warburton and others (1993) discovered braided river planform on the gravel-bed Ashley River in New Zealand was maintained by erosive mechanisms. They found prior flow events responsible for floodplain topography and reported that subsequent bank erosion and reactivation of abandoned channels modified floodplain morphology. Avulsion dominated because channel remnants remained well preserved between floods, indicating little in-filling with gravels.

Wolman and Leopold (1957) briefly mentioned that floodplains of two streams in Wyoming appeared to have been composed of coalesced bars originally deposited within channel. Xu (1996) observed that sediment supplied by bank erosion was used almost exclusively to build within-channel bars and was subsequently returned to floodplain when these merge with banks.

Cottonwood Ecology and Establishment Patterns

Many riparian species are adapted to, even dependent upon, a particular fluvial geomorphic regime and consequent floodplain topography and hydrology. Along the Willamette, a vast majority of remaining stands of riparian forest consist primarily of black cottonwood (*Populus trichocarpa*). Study of cottonwood ecology has yielded a coherent story of cottonwood life history strategy to the floodplain environment (Rood and Mahoney 1990, Scott and others 1996). Black cottonwood pioneers in colonizing bare fluvial landforms (Roe 1958, Burns and Honkala 1990). Its plentiful and very small seeds are dispersed by wind and water from May through June in the Willamette Valley and remain viable for only two to four weeks. Seedlings are shade-intolerant and require bare, moist soils to become established. Germination on suitable seedbeds is rapid, usually occurring within 8–24 h.

Cottonwood is a phreatophyte, obtaining water directly from the water table. Summer precipitation throughout its range is typically meager, so root growth must keep pace with a falling water table. If a seedbed is too high, seedlings fail to establish for want of moisture; if too low, scour from floods, constant flood-training, or excessive inundation may prove fatal (Mahoney and Rood 1993, Scott and others 1993). Cottonwood recruitment is cyclically episodic (Stromberg and others 1991), depending on convergence of favorable conditions (Baker 1990).

Black cottonwood reaches reproductive maturity in about 10 years (Burns and Honkala 1990). Mature forests do not reseed in place because cottonwood requires full sun to establish and grow. Typically, more mesic and xeric tree species succeed decadent stands of black cottonwood (Johnson 1992).

Black cottonwood reproduce vegetatively, sprouting vigorously from roots and stumps (Roe 1958). It has also been observed to reproduce by physiological abscission of twigs (cladoptosis), although proportionately few trees originate this way (Galloway and Worrall 1979). In general, asexual reproductive mechanisms have limited capacity for dispersal and are unlikely to give rise to extensive forest.

Spatial distributions of riparian cottonwoods reflect underlying fluvial landforms. A well-known example is occurrence of even-aged arcuate bands of poplars along laterally migrating point bars in unconstrained river reaches (Everitt 1968, Leopold and others 1964, Johnson and others 1976, Nanson and Beach 1977, Noble 1979, Bradley and Smith 1986). These bands establish on newly emergent point bars, and their age increases with distance inland from the convex shoreline. Opposite a point bar, the bank erodes, sometimes undercutting trees established in a similar fashion when an active channel was in a different position. Everitt (1968) made use of this predictable relationship between channel meandering and tree establishment and growth to map floodplain age and infer gross rates of channel migration and sediment transport of the Little Missouri River in North Dakota.

Scott and others (1996) synthesized results of their own and others' studies of spatiotemporal cottonwood community patterns and identified three floodplain-forming processes that guide establishment patterns: (1) lateral point bar migration (described above); (2) flooding, which creates localized areas of overbank vertically deposited sediment, resulting in a small number of even-aged linear stands (Scott and others 1997); and (3) channel narrowing and avulsion, which leave behind abandoned channel beds and yield no regular spatial or temporal cottonwood pattern (Johnson 1994, Friedman and others 1996).

Other researchers have shown that additional fluvial landforms can support establishment and survival of cottonwood in specific hydrogeomorphic and climatic contexts. Asplund and Gooch (1988) found that in a stream of the arid Southwest cottonwood recruitment was most common in aggrading zones along abandoned secondary and tertiary channels, which provide reliable water supply and protection from flood scour. McBride and Strahan (1984) reported that gravel bars afforded primary successional habitat for cottonwood in an intermittent stream in northern California. On the braided Platte, North Platte, and South Platte rivers, Johnson (1994) found bars composed of relatively coarse sands were primary successional sites for cottonwood and willow.

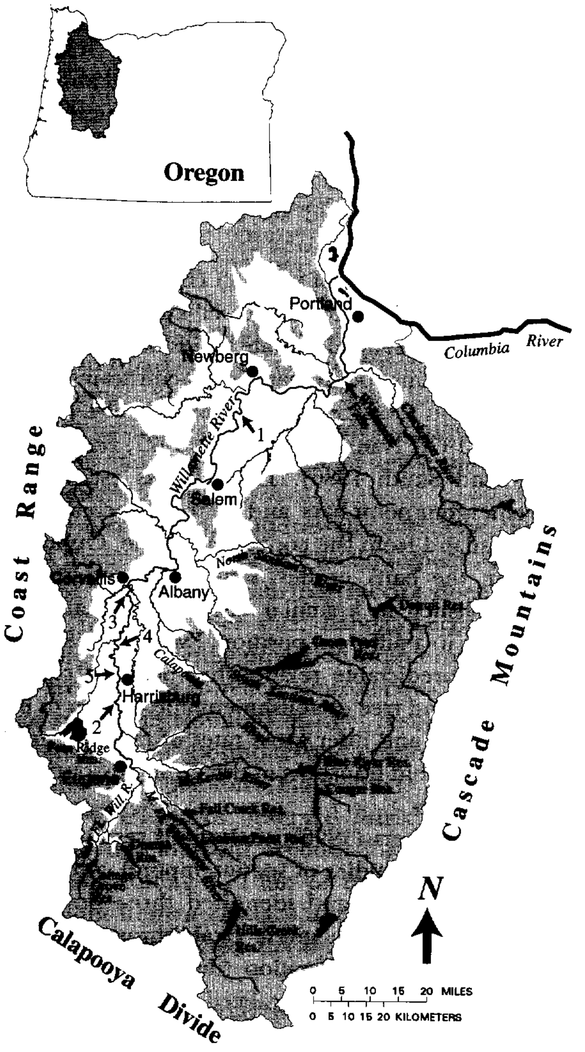


Figure 1. The Willamette River watershed showing major tributaries, Army Corps reservoirs, and cities. The central white region is the Willamette Valley. Numbered arrows refer to the five examples in the results section.

Study Area

The Willamette is a large, mostly gravel-bed river (Hughes and Gammon 1987), which drains a humid alluvial valley with extensive active and relict floodplains (Parsons and others 1970). For much of its length, including the portion under study, the river occupies a dominant meandering main channel that sometimes splits around multiple bars and vegetated islands of varying stability and size, perennial secondary channels, seasonally active side channels, and backwater areas.

Physiography and Geology

The Willamette generally flows northward from its origin at the confluence of the Middle Fork and Coast Fork Willamette Rivers just south of Eugene to its junction with the Columbia River, 301 river km away (Figure 1). It drains 29,800 km^2 bounded by the relatively high and rugged Cascade Range on the east and the Coast Range on the west.

The valley is an area of low relief. The upper two thirds of the river, south of Newberg, flows on unconsolidated fluvial deposits. The lower third has incised a channel through basalt bedrock (Sedell and Froggatt 1984). Elevation of the Willamette declines gradually from 134 m at its origin above Eugene to nominal sea level at its mouth. A basaltic intrusion creates a 15-m falls at river km 42.6.

Slope and lithological controls result in three distinctive morphologic and hydrologic sections, previously described by Rickert and Hines (1975). From mouth to falls, the river is tidally influenced, but remains nonsaline. From above the falls to about river km 84 is the Newberg pool. Tidal and Newberg pool sections are characterized by deep, slow-moving water, narrow floodplains, and a channel constrained by bedrock.

Examples in this study are drawn from the unconfined section above the Newberg pool. The unconfined river has broad floodplains, a main channel that is relatively wide and shallow, and bed material that is mostly gravel and cobble (Hughes and Gammon 1987). This section fits the class of alluvial rivers known as wandering gravel-bed rivers, exhibiting a combination of meandering, braided, and anastomosing channel patterns (Desloges and Church 1989, Nanson and Croke 1992). Within this section there are three breaks in channel slope: between Eugene and Harrisburg average slope is 0.98 m/km, between Harrisburg and Corvallis average slope is 0.62 m/km, and between Corvallis and Newberg average slope is 0.35 m/km. Channel planform varies with slope from more to less multichannel; the portion below Corvallis appears as a mostly single thread meandering river with few secondary channels.

Climate and Hydrology

The Willamette Valley lies roughly 80 km from the Pacific Ocean, and prevailing westerly marine winds are a primary determinant of its Mediterranean climate (Taylor and others 1994). Winters are cool and wet; summers, warm and dry. Most runoff and flooding is caused by winter rains, with winter rainfall on melting snow the primary mechanism for generation of major flood flows (Waananen and others 1971; Hubbard and others 1993). Melting snow at higher elevations of the Cascade Range adds a seasonal runoff component during April and May.

Mean daily discharge records were obtained for US Geological Survey gaging stations at Albany and Salem (US Geological Survey 1996). These are the only gaging stations on the Willamette with records covering the 60-year study period. Summary stream flow statistics at the Albany gage (Table 1) show some gross effects of dams on hydrologic regime. Drainage area above the Albany gage is 12,536 km^2 and 43% of that area drains into reservoirs. The predam period is from water years 1895 to 1949, before significant reservoir construction began, while the postdam era is from 1964 to 1996, after essentially all reservoirs above Albany were operating.

Floodplain Morphology and Vegetation

The Holocene stratigraphy of the Willamette floodplain has been little studied (McDowell 1991). Parsons and others (1970), in an effort to understand soil development, used high-altitude aerial photography to map geomorphic surfaces, each of which represented an episode of landscape development. They identified three depositional geomorphic surfaces, which they concluded were alluvial deposits from the present drainage system during the Holocene. These surfaces, with their approximate age of formation in years before present, are: Winkle 12,000–5000; Ingram <5000; and Horseshoe, <300 (Parsons and others 1970, McDowell 1991). Although Parsons and others (1970) concluded that the lowest and most recent floodplain (Horseshoe Unit) continues to be built by lateral migration of meanders, cutting of new channels, and abandonment of old channels, we present data pointing to some different processes.

Land surveyors in the 1850s found an extensive floodplain forest composed of black cottonwood, willow (*Salix* spp.), Oregon ash (*Fraxinus latifolia*), red alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*), and Douglas fir (*Pseudotsuga menziesii*) (Johannessen and others 1971, Towle 1982). Reports by the US Army Corps of Engineers (US ACE) at roughly the time of Euro-American settlement described river and floodplain forest between Eugene and Harrisburg: "... the river bottom is from one to two miles in width.... The timber, consisting of cottonwood, or Balm of Gilead, maple, ash, alder, and willows, is dense, and ... is traversed by sloughs and bayous, large and small, and in times of floods is covered by swiftly-running water to a depth of from five to ten feet" (Report of the Chief of Engineers, US Army, 1875).

Human Alterations to Natural Fluvial Geomorphic Regime and Floodplain Vegetation

Over the past 150 years, humans have altered principal factors governing the fluvial geomorphic regime of the Willamette. These include discharge, sediment supply and character, and bank erodibility. In turn, theses changes have affected how the river builds and modifies sedimentary landforms and incorporates these into floodplain, and thus the amount and suitability of primary successional habitat to native species. Among noteworthy human modifications to the river-floodplain system are dam and reservoir construction on major tributaries, channel-bank stabilization structures, in-stream dredging and snag removal, side channel cutoff dams, wing dams to direct flow towards channel center, in-stream and floodplain gravel mining, and clearing floodplain forest for agriculture and human settlements (Sedell and Froggatt 1984, Benner and Sedell 1997).

Table 1. Summary streamflow statistics for the USGS Albany gage (river km 192)[a]

Period	Mean annual flow (m^3/sec)	Mean annual maximum flow (m^3/sec)	Mean peak timing	Mean summer low flow (m^3/sec)	Seasonal flow range (−)
Predam	387	3,128	22 January	110	8.1
Postdam	397	1,996	21 January	165	5.0

[a]The seasonal flow range is defined as the ratio of mean annual maximum discharge to mean annual discharge.

During the period considered in this study, construction of a US ACE flood-control reservoir system and emplacement of boulder revetments (riprap) to stabilize channel banks have had large effects on the fluvial geomorphic regime. Between November 1941 and October 1968, ten major flood control reservoirs were constructed (Shearman 1975). This system regulates many major tributaries from the Cascades above Salem; however, there are no dams on the mainstem (Figure 1). Approximately 43% of the area above Albany drains into reservoirs (US Army Corps of Engineers 1989). About 76 km of channel bank has been stabilized with riprap between river km 88 and 301 (US ACE 1984). Figure 2 shows cumulative construction of reservoirs and riprap.

Reservoirs reduce peak flows and variation in seasonal flows (Table 1). The magnitude of these effects depends upon downstream distance from dams and operating policy. Flow at Albany is only indicative. Actual effects are different at each study site shown below in aerial photographic series. Seasonal timing of peak flows remains essentially unchanged since reservoirs serve primarily as short-term (days) floodwater storage and only secondarily as longer-term (months) water storage. Table 1 shows that the summer low flows have been augmented by releasing reservoir water (to dilute pollution).

Effects of human changes to the natural fluvial

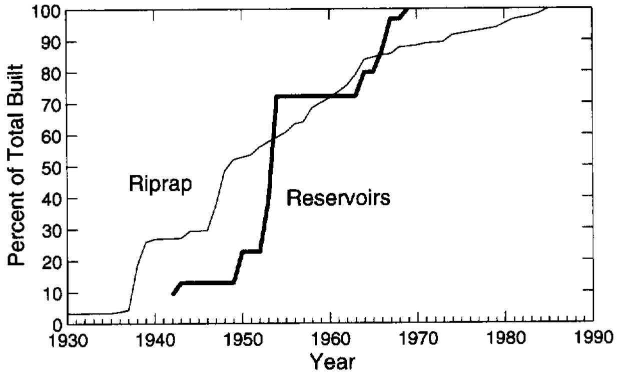


Figure 2. Cumulative totals of US Army Corps flood-control reservoirs and riprap construction over time. For reservoirs, "percent of total built" refers to the flood-control capacity based on the drainage area above the dams.

geomorphic regime have been particularly evident on channel pattern. Since Euro-American settlement in the 1800s, the multichannel section of the river between Eugene and Albany has been simplified towards single channel. Approximately 45%–50% of original channel length from the McKenzie River confluence to Albany was lost between 1854 and 1975 (Sedell and Froggatt 1984, Benner and Sedell 1997).

Removal of floodplain forest was at first gradual and then rapid as commercial demand for trees grew. Large-scale exploitation began shortly before 1900, when trees were towed to a paper mill at Willamette Falls (Towle 1982). As early as 1893 people attempted "reforestation" by planting black cottonwood cuttings (Roe 1958), probably with the intention of supplying pulpwood to the mill. In the mid-1930s a large portion of lower floodplain was still wooded (Towle 1982). Conversion of floodplain area to intensive agriculture began with expansion of irrigation and implementation of a flood-control reservoir system.

Most of the area covered by floodplain forest only a century ago is now used for agriculture (Johannessen and others 1971, Towle 1982, Benner and Sedell 1997). Remaining forest continues to be removed to make way for development (Frenkel and others 1984), and only relatively small, fragmented patches persist (Frenkel and others 1984, Benner and Sedell 1997). Current rates of black cottonwood establishment and growth appear inadequate to sustain even today's modest area of mature forest. During informal (qualitative) surveys of the entire river during 1995 and 1996, we found few sapling-size trees.

Methods

Using time sequences of aerial photographs we observe creation and evolution of fluvial landforms and concomitant development of riparian cottonwood forests. With US Geological Survey (USGS) maps and a Landsat-TM image we compute island areas.

We obtained photographs showing the river from near the start of the mainstem just north of Eugene (river km 290) to Corvallis (river km 210) for the years 1936, 1944, 1959, 1972, 1986, and 1993. We also acquired several photographs of this region taken in 1996, as well as an historical series of photographs at river km 103 where ground observations indicated recent geomorphic activity.

Examples of floodplain formation and riparian ecosystem development were identified. For each: (1) a series of photographs was scanned and imported into an image-editing program; (2) using features that remained geographically fixed from oldest to most recent photograph (e.g. road intersections, buildings, isolated trees), the same geographic area was clipped from each image; and (3) all images were converted to a common scale.

River flow shown in the photographic record varies between 69 and 767 m^3/sec at the Albany gage, about a 3-m range in stage, sufficient for bars and islands to become submerged or exposed and for channels to become connected or disconnected. Reservoirs and riprap built during the observation period influence river dynamics. The 60-year photographic record may be divided into three periods defined approximately by reservoir and riprap construction: (1) before, 1936–1950; (2) during, 1950–1967; and (3) after, from 1967 onward. Riprap location is shown on the aerial photographs (Figure 2).

USGS maps covering the Willamette from Eugene to Harrisburg were digitized and analyzed using a geographical information software package. Map dates and scales are: 1910, 1:31,680; 1940, 1:62,500; 1946, 1:62,500; 1967, 1:24,000. We also acquired a Landsat-TM image of the same section of river taken on 31 August, 1988. The TM image was processed with a tasseled cap transformation and had 25-m cell resolution (Cohen and others 1995). Using a geographical information software package and comparison with 1993 aerial photographs, we extracted active river channels from the TM image.

Results

We now present five examples of floodplain formation, with accompanying riparian forest establishment and development, and one example showing floodplain architecture of four reaches with different planform types. Examples represent a range of bed slopes from about 0.37 m/km to 1.11 m/km. Each example is identified by river kilometer upstream from mouth. For a 22.4-km section of river, we describe changes in island area over nearly 80 years.

Our convention for interpreting aerial photographs taken at a range of river stages is to use "bars" and "islands" as follows. Bars are raised gravel landforms exposed at lower flows. They are either bare or support only annual vegetation and/or flood-trained woody vegetation. Islands are surrounded by water at lower flows. Their land surface is sufficiently elevated to support woody vegetation with a developed crown. Islands have been stable long enough to allow for development of cottonwoods to, or near, reproductive age.

Example 1: Multiple Barforms

This example is shown in Figure 3 and illustrates the formation, colonization, and coalescence of several barforms. Of the five examples we present, it has the shallowest gradient and is furthest downstream (Figure 1).

Frame 1936. The sequence begins in 1936 with a well-forested island labeled 1 and a newly emerging unvegetated gravel bar labeled 2 adjacent. Channel maps from 1852 show that the secondary channel occupied by this bar was then the main channel (Hoerauf 1970).

Frame 1944. The coalescent process progresses rapidly from 1936 to this frame where the secondary channel is filling with smaller barforms. Bar 2 has grown in size and acquired some vegetation at its downstream end. A new bar labeled 3 has formed and begun to block the entrance to the secondary channel.

Frame 1953. Bar 2, almost fully vegetated and with tree crowns evident, is now an island. It has joined both mature floodplain and island 1, creating a backwater habitat (a) during summer low flow. The upstream portion of the side channel has practically filled with gravel. Bar 3 has coalesced with adjacent landforms; only a narrow, sinuous channel remains at this highest flow shown in the photographic sequence.

Frame 1963. Environmental conditions on what was once bar 3 have become suitable for colonization. The shape of the patch of vegetation now present reflects that of the original bare bar visible in 1944. Some small trees are evident on bar 3. The side channel upstream from island 2 is now completely filled with vegetation, much of it cottonwoods with discernible crowns. The backwater has narrowed as island 1 has continued to grow. Island 2 is now uniformly covered with cottonwoods, adding a patch of riparian forest characteristic of the Willamette floodplain.

Frame 1983. The bar formation process begins anew with central bars 4 and 5, and lateral bar 6 emergent at this river stage. Until this frame, depositional processes were most evident. Now the river margin at b has been eroded into a scallop shape by water apparently redirected around building gravel bar 4. Bar 3, now more thoroughly merged with the adjacent floodplain, has visible crowns of cottonwoods. A single arcuate band of trees can be seen at the tip of arrow c. (A similar arcuate band was observed directly in 1996. In that case one or a few established trees were molded into this pattern by constant flood training and downstream sprouting of root suckers.)

Frame 1996. Bar 4 has built laterally, deepening the scallop-shaped notch into older floodplain and filling the area once occupied by retreating bar 6. There is a narrow band of vegetation at the head of bar 4 and isolated plants are visible elsewhere on the bar. Bar 5 has grown and acquired some centrally located plants, and is joined to bars 1 and 6 by a higher flow chute. Fluvial landforms 1, 2, and 3 have joined older floodplain, adding patches of cottonwood forest to the riparian ecosystem. In 1996, the genesis of those patches is not readily visible. The backwater area (a in 1953) is blocked upstream and will not fill with gravel. If closed downstream, as appears to be occurring, it will form a crescentric lake. This feature, a result of incomplete island coalescence, is common in older Willamette floodplain.

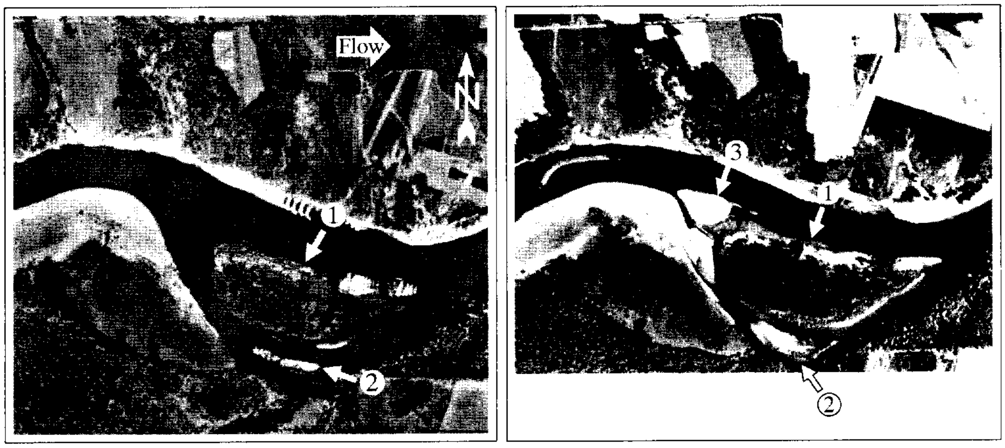
Example 2: Multiple Barforms

Figure 4 shows development and incorporation of 14 gravel barforms into floodplain. We follow several from bare gravel to forested floodplain. Shoreline revetments are noted. Channel maps from 1852 show this region braided, with several secondary channels (Hoerauf 1970).

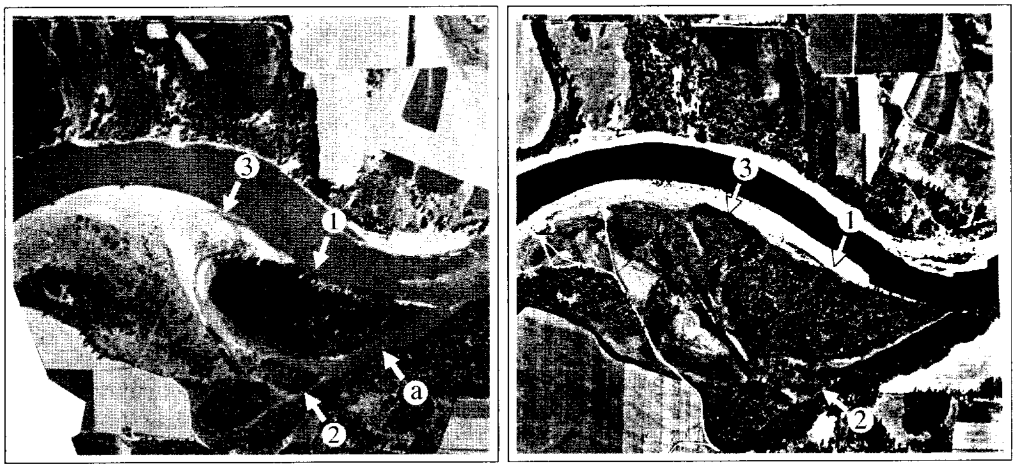
Frame 1936. A scalloped out notch is evident in the right bank adjacent to mostly bare mid-channel bar 1 (upstream third possibly vegetated). Bar 2, likely a former central bar, has acquired some vegetation and has been overwhelmed by the outward growth of lateral bar 4. Bar 3 is partly vegetated, and a secondary high-water channel separates it from older floodplain. Lateral bar 4 is noteworthy for its lack of vegetation.

Frame 1944. Mid-channel bar 1 has grown larger and acquired vegetation, while the upstream end of a secondary channel is closing as it joins lateral bar 4. Bar 2 is now completely vegetated with tree crowns visible. Bar 3 remains unchanged in size, but mature cottonwoods signify that it has become an island. Newly emergent bars 5 and 6 appear, and the river margin has eroded opposite each. Lateral bar 4 acquires some scattered trees. Riprap is added to the outside edge of the main channel bend.

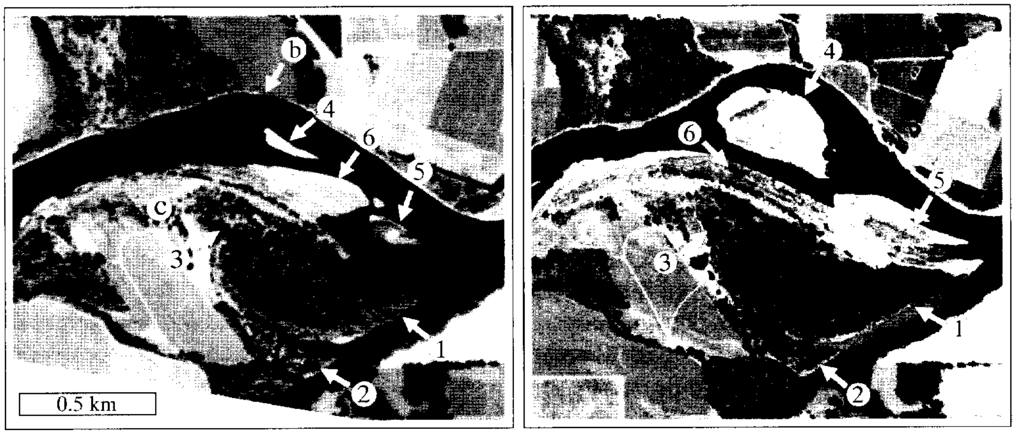
Frame 1959. What began as bar 1 now supports mature cottonwoods. Here attached to lateral bar 4, creating a backwater area, it may still be an island at



(a) August, 1936 (113 m^3/s) (b) August, 1944 (88 m^3/s)



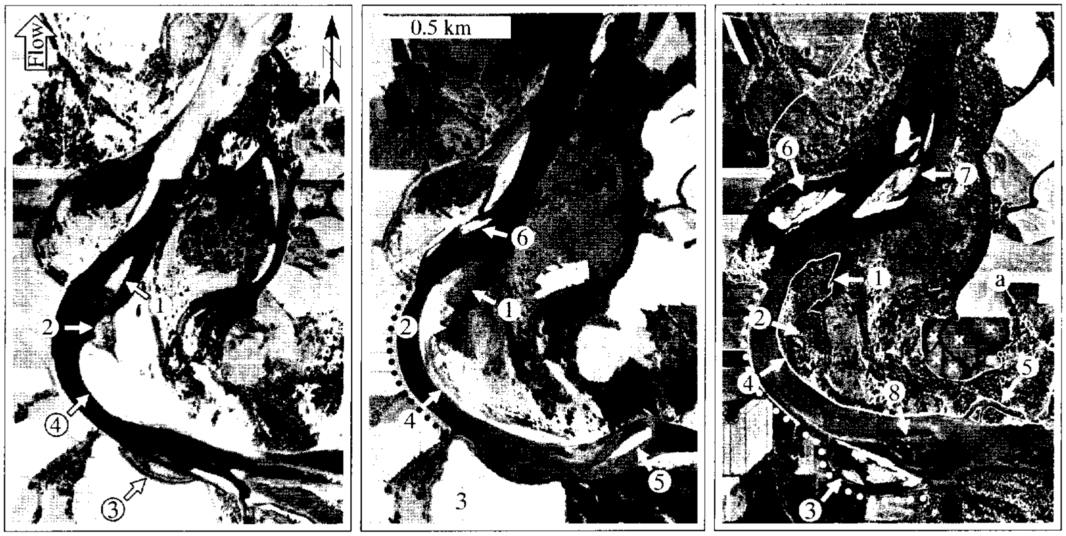
(c) May, 1953 (750 m^3/s) (d) September, 1963 (248 m^3/s)



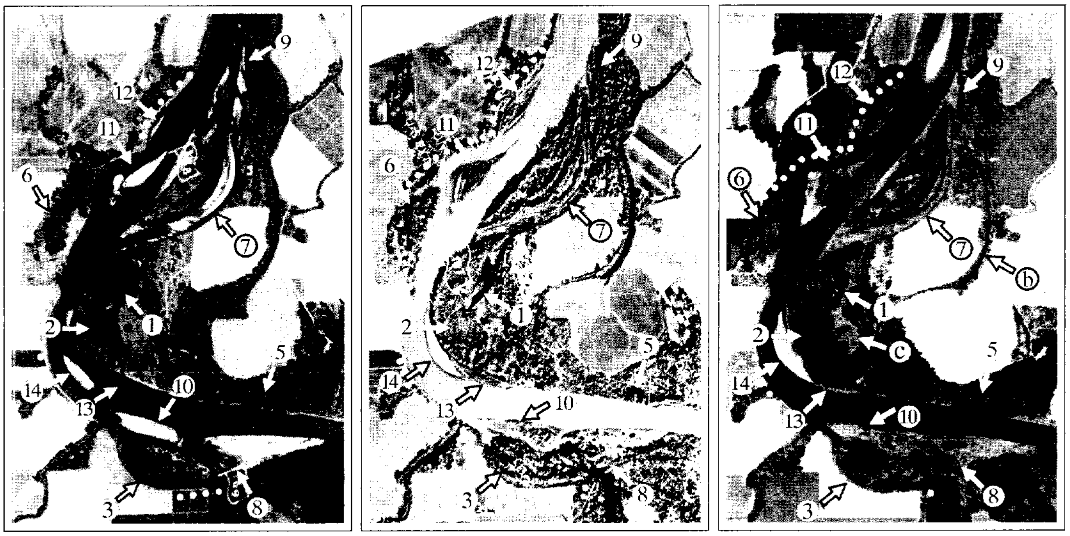
(e) September, 1983 (360 m^3/s) (f) July, 1996 (229 m^3/s)

Figure 3. Historical series at river km 103, with calendar year and flow at the Salem gage given below each photograph. Scale bar is shown in the 1983 frame.

higher river stages. Bar 2 has mature cottonwoods. Bar 3 has grown laterally, while riprap has been added to prevent the secondary channel from eroding further into older floodplain. Mid-channel bar 5 has been reworked substantially and become a small island. Bar 6 has grown significantly, replacing the eroded landform that supported a patch of forest in 1944. Dissected central bar 7 emerges. Incipient bar 8 remains sub-



(a) August, 1936 (86 m^3/s) (b) May, 1944 (326 m^3/s) (c) April, 1959 (767 m^3/s)



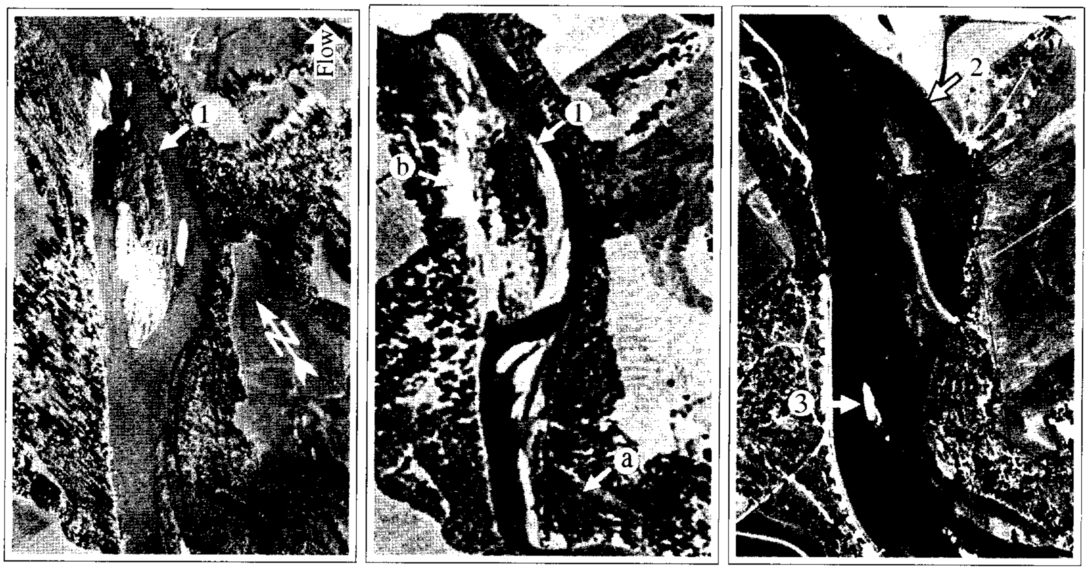
(d) May, 1972 (394 m^3/s) (e) March, 1986 (703 m^3/s) (f) May, 1993 (436 m^3/s)

Figure 4. Historical series at river km 269, with calendar year and flow at the Albany gage given below each photograph. Scale bar is shown in the 1944 frame. Dotted lines, black or white, show location of shoreline revetments.

merged at this relatively high stage but has caused some erosion into lateral bar 4. Label a points toward six coalesced islands, each marked by a white x, composing mature floodplain. Some combination of factors in this agricultural field has revealed the pattern of bars formed from coarse gravel and channels filled with finer sediment.

Frame 1972. A fluvial landform derived from bar 1 has joined older floodplain to close the downstream end of the former secondary channel. The crescentric lake thus formed is more clearly evident in 1986 at the tip of arrow 1. Bar 3 has been colonized and now has mature cottonwoods. Island 5 has merged with older floodplain. Barform 6 has joined mature floodplain and been colonized by cottonwoods. The dissected barform 7 has coalesced into one contiguous forested island with, among other patterns, three arcuate bands of trees. The secondary channel adjacent to 7 has filled with multiple bars of smaller scale, one of which is identified as 9. Gravel bar 8 is now emergent with vegetation at its downstream end. Gravel bars 10, 11, 12, and 14 are newly emergent, while the presence of submergent bar 13 is evidenced by erosion into lateral bar 4. Riprap has been placed along the river margin near bar 12.

Frame 1986. The previously emergent bars 9–12 have all been colonized, with some tree crowns evident. More riprap has been added to stop further erosion opposite



(a) August, 1936 (86 m^3/s) (b) August, 1944 (69 m^3/s) (c) May, 1959 (767 m^3/s)

(d) May, 1972 (394 m^3/s) (e) March, 1986 (703 m^3/s) (f) July, 1996 (159 m^3/s)

Figure 5. Historical series at river km 216, with calendar year and flow at the Albany gage given below each photograph. Scale bar is shown in the 1972 frame. Dotted lines, black or white, show location of shoreline revetments.

bar 11. Bar 13 has emerged and been colonized. While the evolution of central bar 14 is uncertain, we label the renewed deposition attached to bar 4 as 14.

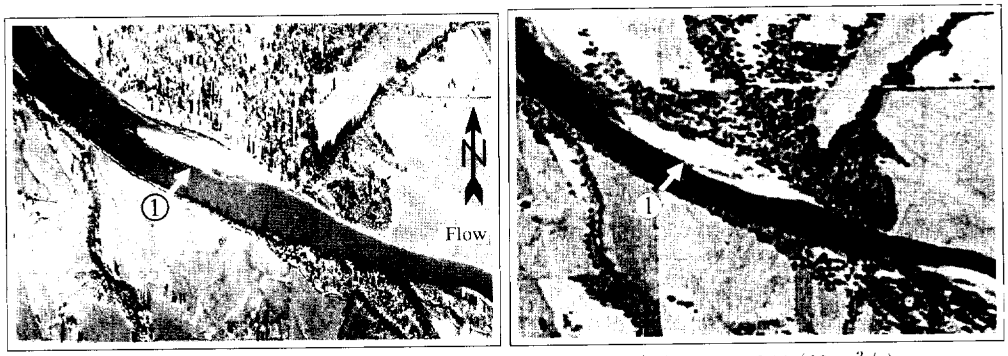
Frame 1993. Modest change has occurred. Almost all bars identified have evolved into fluvial landforms supporting riparian forest and are now attached to older floodplain. Island 11 has yet to join mature floodplain, now lined with riprap. Label b identifies an older crescentric lake, formed prior to 1936. Label c points to a naturally occurring gap in riparian forest structure on lateral bar 4.

Example 3: Central Bars

Figure 5 shows evolution of two central bars in a portion of the river that historically has been just downstream from where the multichannel becomes predominantly a single channel (Hoerauf 1970).

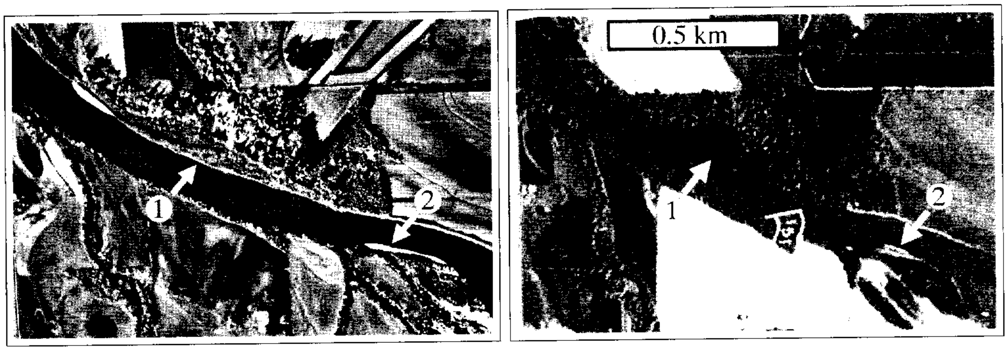
Frame 1936. Island 1, its downstream half densely vegetated, has diverted flow to scallop both right and left river banks.

Frame 1944. At this river stage, lowest shown in the sequence, island 1 appears attached to the left bank by bare gravel b.



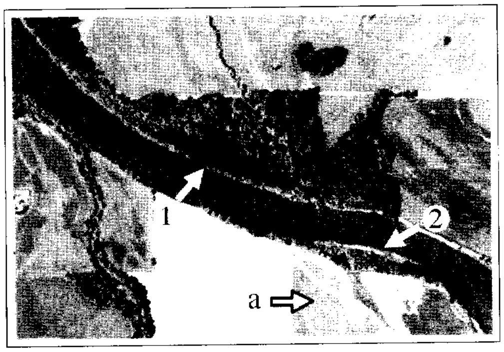
(a) August, 1936 (86 m^3/s)

(b) August, 1944 (69 m^3/s)



(c) March, 1959 (286 m^3/s)

(d) May, 1972 (394 m^3/s)



(e) May, 1993 (436 m^3/s)

Figure 6. Historical series at river km 241, with calendar year and flow at the Albany gage given below each photograph. Scale bar is shown in the 1972 frame.

Frame 1959. Bar 2 has formed and attached to older floodplain. Island 1 and its associated vegetation appear to have been removed by flooding. What portion of bar 2 material derives from Island 1 is unclear. Bar 3 is emergent, and riprap has been constructed along the left bank. Young riparian forest labeled a in the 1944 frame has been eroded away.

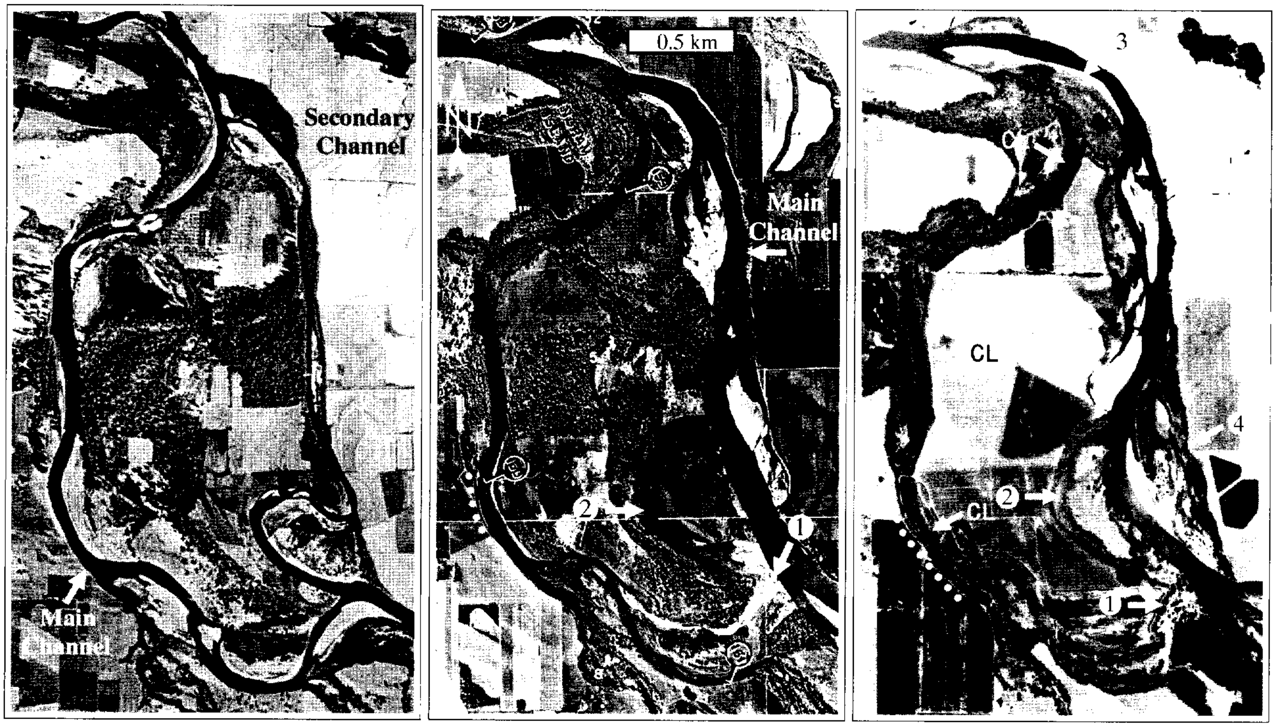
Frame 1972. Bar 2 has become an island with cottonwood crowns visible. A large downstream section has disappeared, leaving only a few small gravel mounds protruding above the water surface. Bar 3 has built laterally and appears as a dissected central bar still devoid of vegetation. Hardening of the left bank from riprap is likely affecting development of bar 3.

Frame 1986. The downstream section of island 2 has refilled. Ground inspection confirmed that trees on this low-lying area are willows. Bar 3 has been colonized.

Frame 1996. Landform 2 shows a complex spatial distribution of cottonwoods, willows, and gaps, which attests to its dynamic fluvial geomorphic history. Dissected bar 3 has become a single island with centrally positioned trees.

Example 4: Side Bar

Figure 6 shows formation, colonization, and incorporation of a side bar into older floodplain. Historical channel maps show this segment of channel to have



(a) August, 1944 (69 m^3/s)
(b) April. 1959 (767 m^3/s)
(c) July. 1996 (159 m^3/s)

Figure 7. Historical series at river km 255, with calendar year and flow at the Albany gage given below each photograph. Scale bar is shown in the 1959 frame. White dotted lines show location of shoreline revetment built in 1947.

remained straight and to have shifted little laterally since 1852 (Hoerauf 1970).

Frame 1936. Bare gravel side bar 1 is emergent.

Frame 1944. Side bar 1 has built more longitudinally than laterally. A single arcuate band of trees (probably) can be seen.

Frame 1959. Side bar 1 is entirely covered with young trees. Smaller side bar 2 is forming.

Frames 1972 and 1993. Side bar 1 has seamlessly joined older floodplain. Younger cottonwoods, which established on the side bar, create a readily distinguishable patch of forest. Side bar 2 has grown and trees have matured. By 1993 three relict islands (labeled a and each marked with an x) in the floodplain have been revealed by removal of trees from the filled channel. Geomorphic origins of these islands are clear from the 1936 frame and support the interpretation of relict island features in Figure 4.

Example 5: Channel Abandonment and Large Island Coalescence

Figure 7 shows the coalescence of a large bar and island assemblage and a third-order avulsion. Channel maps from 1852 show an island about a third the size at this location (Hoerauf 1970).

Frame 1944. The main and secondary channels surrounding a large bar and island assemblage are identified. Multiple barforms are visible in the main channel. Aerial photographs from 1936 show that, at a flow slightly greater than that in the 1944 photograph, the secondary channel is disconnected from the main.

Frame 1959. The main channel has been abandoned and the secondary channel widened and straightened to become the main (third-order avulsion). The head of the old main channel is filled with gravel at 1. Bars constrict the old main channel at several locations, and some have built sufficiently to support cottonwoods. Point bar 2 was cut off and the channel filled at its head. This bar is being incorporated into the large bar and island assemblage.

Frame 1996. The coarse sediment blocking the old main channel at 1 now supports scattered trees. Point bar 2 has fully joined the large bar and island assemblage. Bar 3 has built downstream, blocking the exit of the old main channel to create a crescentric lake. Two more crescentric lakes are visible and appear destined to persist as the current main channel is now about 1 km away. Bar 4, although similar in outline to a point bar, is composed of several coalesced bars and islands.

Floodplain Geomorphic Elements

We now examine mesoscale floodplain morphology of four reaches (Figure 8), representing different planform types and a range of gradients in light of floodplain formational mechanisms observed in examples 1–5. These diverse sections of river contain important similarities with respect to geomorphic floodplain elements—abandoned channels and islands, oxbows, ridges and swales—which are signatures of the sedimentary and erosional environment (Lewin 1978, Brierley and Hickin 1991). We rely upon three characteristic elements as primary indicators of floodplain origin. The first, abandoned channel fill, forms as islands merge into one another and mature floodplain. The second, a crescentric lake, results from incomplete island coalescence. The third, an abandoned island or island assemblage, is visible where bounding relict channels can be discerned.

Historical Island Area

Because islands are important to ongoing formation of floodplains and maintenance of riparian forest, we calculated changes in island area between the confluence with the McKenzie River and Harrisburg (22.4 river km) from 1910 to 1988. For map interpretation, islands were defined as land areas completely surrounded by perennially flowing water and the result is shown in Figure 9. Table 2 shows island area statistics. Island area declined dramatically from 1946 to 1967, almost to one tenth of what it was in 1910, while average island size fell to about one quarter of what it had been in 1910. By 1988 island area rebounded somewhat to roughly one fifth the 1910 reference value.

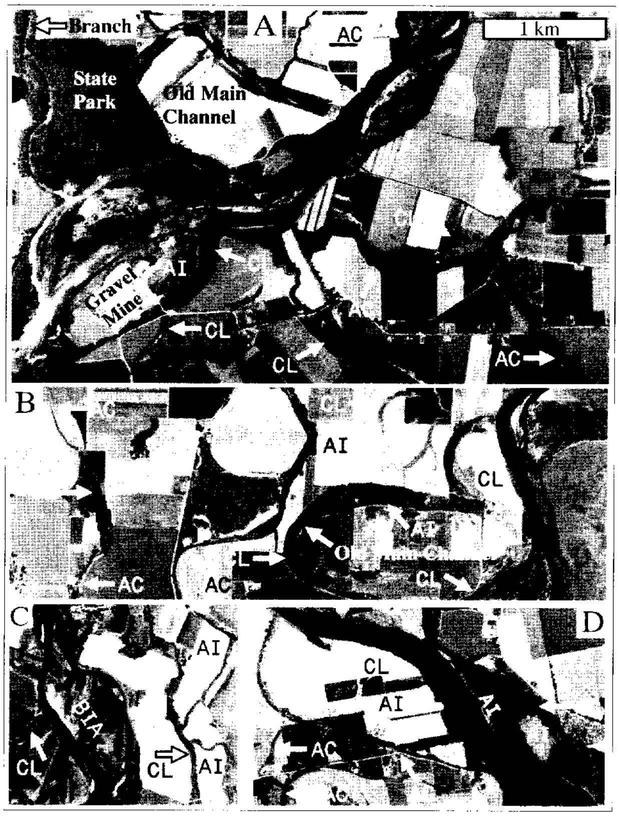


Figure 8. Common floodplain geomorphic elements associated with different channel planform types. Examples A and D are from the predominantly single-thread reach below Corvallis at river km 113 and river km 107, respectively. Examples B and C are from the more multi-channel reach above Corvallis at river km 244 and river km 263, respectively. Geomorphic element abbreviations: CL = crescentric lake, AC = abandoned channel, AI = abandoned island, and BIA = bar and island assemblage. Note: for all frames river flows upward, common scale bar shown in frame A; photographs taken in May or June 1993.

Discussion

Data Quality

Our data show a consistent pattern of floodplain and cottonwood forest development through a range of spatial scales. Because we have a 60-year photographic record, we are able to follow small areas (on the order of 0.7 km^2) through the entire sequence of bare gravel bar formation, vegetative colonization, concomitant bar and vegetation growth, and coalescence with older floodplain. Although 60 years is insufficient to follow larger areas through this entire sequence, complete coverage of 80 river kms enables us to view large floodplain areas at various stages of development in different locations.

Floodplain Formation: Deposition

The large-scale morphology of the Willamette floodplain appears to be a result of coalesced gravel bars and islands originally deposited by within-channel processes. Incipient floodplain is composed predominantly of barforms, alone or in combination. These include lateral point bars, side bars, and central bars (Leopold and Wolman 1957, Leopold and others 1964, Lewin 1978). The last of these, including its dissected forms, is ubiquitous and may be the likely origin of most floodplain.

As channels gradually fill, barforms and islands merge with each other and with river margins. Overbank flow deposits finer-textured sediment upon this mosaic, covering underlying structure and moderating

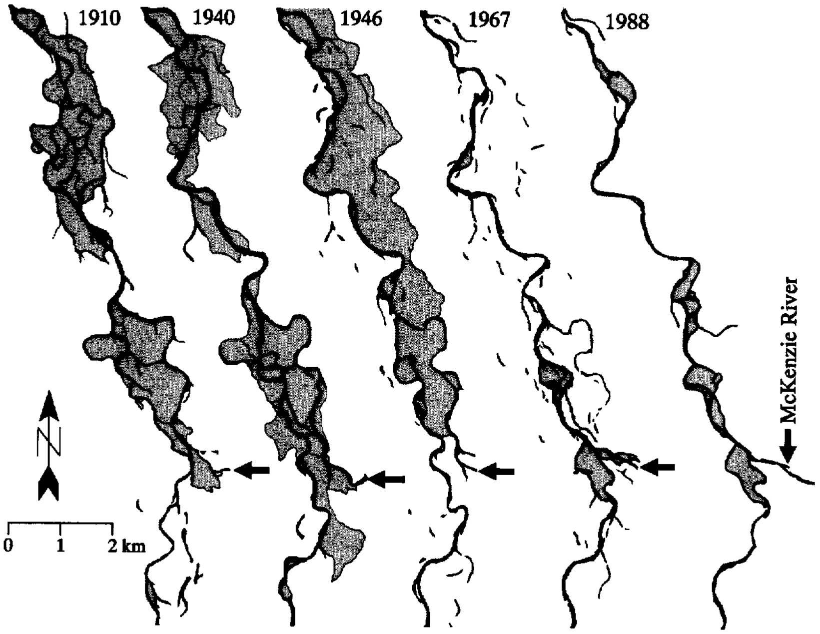


Figure 9. Historical USGS channel maps from 1910, 1940, 1946, and 1967, and 1988 channel map derived from a Landsat-TM image. River section shown is from Eugene to Harrisburg. Black is active channel and gray is island. Arrow points to the McKenzie River.

its topography. This process can account for even large islands and their merger with mature nonisland floodplain as well as for all relict geomorphic elements in mature floodplain. Over a length of 80 river km we find small- and moderate-sized islands merging and large islands incorporating into mature floodplain, as channel sections ($\approx$5 km) blocked by barforms and debris fill with sediment (Figure 7). Interestingly, although rates of floodplain formation and qualitative features such as barform size may differ with planform type and slope, formation mechanisms appear consistent over the entire unconfined river.

Fluvial Landform Erosion

Predominant erosional mechanisms maintaining multichannel planform and floodplain geomorphology and accretional mechanisms forming bars occur proximally. We find: (1) cut-bank erosion on outside curves opposite point bars, (2) bank scalloping adjacent to building within channel bars, (3) short lengths of channel cut across point bars, and (4) rapid expansion of a secondary channel as a main channel becomes blocked.

Channels migrate by repetition of the bar formation and near-bank erosion process. Floodplain matures as the active channel migrates away or is abandoned, becoming more protected from erosion. Other parts of the floodplain are recycled as eroding banks provide the coarse sediment and large woody debris for building new bars.

Examples of either a sudden and major shift of a channel to a new location (first-order avulsion) or of reactivation of abandoned channels (second-order avulsion) are absent (Nanson and Knighton 1996). Our observations are inconsistent with the assertion that the Willamette's multichannel planform results from erosional processes, in particular, flood flows excising channels from existing floodplain (Parsons and others 1970).

Fluvial Landforms Suitable for Cottonwood Recruitment

Several incipient floodplain landforms, and in particular, many barforms, can satisfy the requisites for cottonwood establishment and growth to reproductive maturity, but favorable patterns of landform evolution—including protection from intense erosional forces—and hydroclimatic regime over a period of at least a decade are necessary.

Fluvial landforms on the Willamette that can support cottonwood recruitment are: (1) multiple barforms, including central bars, side bars, and point bars; and (2) Channels abandoned as they fill: (a) with a coarse sediment lobe, and (b) when bars and smaller islands gradually coalesce with one another and river margins.

Fluvial Landforms and Spatial Pattern of Cottonwoods

Associated with each landform above is a typical spatial pattern of cottonwoods and willows. Barforms are nucleation sites for nascent riparian forest, and coevolution of barform and cottonwood stand adds a patch of nearly even-aged trees to mature floodplain forest. Within such a patch we find no regular spatial pattern of trees. Typical examples are shown by Figure 3 landform 1 and Figure 6 landform 1.

Although point bars are common on the Willamette, distinctive multiple arcuate bands of trees associated elsewhere with lateral point bar formation are seldom seen here. The photographic evidence suggests that the dominant mode of point bar formation is the accretion of relatively featureless broad gravel sheets (see Figure 4a, bar 4), rather than incremental accretion of arcuate slivers of sediment forming series of ridges and swales. Some of these point bars may be composite landforms containing central bars. For example Figure 3c shows coalescence of central bar 3 within a point bar. Such imbricated landforms support unique spatial distributions of trees.

Abandoned channels support forest patches characteristic of barforms as well as linear stands, which become established as areas between bars and other small channel segments fill with finer sediments. Crescentric lakes may be interspersed, as happened to the old main channel in Figure 7. Channels at junctions may fill with coarse substrate and support scattered trees as in Figure 7, landform 1.

Cumulative Human Impacts on Floodplain Formation

As mentioned earlier, young black cottonwoods currently appear insufficient to replace existing mature stands. Possibly, cottonwood recruitment is periodically episodic on time scales greater than 20 years, or perhaps young cottonwood forests are now more than before being cleared as islands become incorporated into mature floodplain. We suggest that a combination of human impacts is limiting riparian forest renewal. By building dams and riprap, mining gravel, clearing forest, and expanding agriculture, humans have rapidly and substantially altered a fluvial geomorphic regime to which cottonwoods are adapted, and in the absence of which, they are regenerating at a small fraction of historic levels (Table 2).

Cumulative human impacts upon the fluvial geomorphic regime have tended to reduce the multichannel river to a more single-thread configuration (Figure 9). The multi-channel river becomes a single channel river as secondary channels continue to fill and fewer new channels are created through formation of large bar and island assemblages.

River-Floodplain Stewardship

Identifying stressors interfering with regulatory processes critical to ecosystem function and structure (i.e., productivity and food webs) and developing strategies for mitigating or altogether removing these is central to effective stewardship. By disrupting the fluvial geomorphic regime—the principal organizing force creating and maintaining floodplain and riverine habitats—we pose a major, perhaps the single most important, impediment to riparian forest regeneration.

Table 2. Summary of island area statistics derived from Figure 9

	Year				
	1910	1940	1946	1967	1988
Total island area (km^2)	15.29	18.73	18.64	1.76	3.11
% Change from 1910 area	0	+23	+22	−89	−80
Number of islands	36	46	26	15	17
Average island area (km^2)	0.43	0.41	0.72	0.12	0.18

Cottonwoods can play an important role in evaluating and monitoring stewardship. We and others have noted that cottonwoods maintain and create habitats by altering the riverine environment with large woody debris that creates jams and aquatic habitat (Sedell and Froggatt 1984), changing the depositional energy environment of incipient floodplain landforms to increase accumulation of finer sediments and make fluvial landforms more resistant to erosion, and adding organic matter to newly deposited and nutrient-poor primary substrate through annual leaf litter. This central role in river-floodplain system function and structure, combined with the previously noted sensitivity to disruption of fluvial geomorphic regime, makes cottonwoods an excellent indicator of ecosystem integrity.

Integrity of the river-floodplain system relies upon ongoing processes which: (1) maintain riparian forests in different locales in a spectrum of developmental stages, and (2) support biological succession on the floodplain and, near the river, retain the potential for return to bare fluvial landform. These processes are generated by phenomena occurring from headwaters to river mouth. Because integrity entails capacity for ongoing renewal, it cannot be maintained by simply recreating aspects of its appearance at particular locations and times.

Addressing symptoms of a disrupted fluvial geomorphic regime by planting trees to mitigate impacts of diminished forest regeneration or by reconnecting old channels or dredging backwater areas to enhance aquatic habitat will not remove underlying obstacles to ecosystem integrity. The example of tree-planting illustrates this convincingly. Mature floodplain, where trees are typically planted, is rarely, if ever, suitable habitat for cottonwood establishment. Maintaining artificial plantings until they become self-sufficient requires ongoing human intervention for many years and still too often results in stunted trees. Planting on sites other than those where cottonwoods naturally establish sacrifices important tree "services" such as root binding of sediments and contribution of woody debris to within-channel processes. Under normal conditions, only one in a billion cottonwood seeds becomes a reproductively mature tree, and planting cuttings, or even collected seed, interferes with natural selection, with unknown and unknowable consequences. Since cottonwoods do not reseed in situ, planting programs do not result in a self-sustaining population and must continue indefinitely. Finally, and perhaps most importantly, people ignorant of the limited benefits of tree-planting may be lulled into a false sense that forest is being "restored" and may fail to undertake or support stewardship activities that address more fundamental aspects of ecosystem degradation.

Over the past 150 years, humans have transformed the Willamette river-floodplain system. Once there was a several kilometers-wide riparian forest along a multichannel river that frequently flooded, rapidly recycled floodplain material, was fed by free-flowing tributaries, and supported two chinook salmon races (Nehlsen and others 1991). Now there are scattered patches of trees, eroding croplands, an increasingly single-channel river, diminished hydrological connection between river and floodplain, dams on major tributaries, one extinct salmon race, and another of "special concern." If we are to look forward 150 years with positivity and confidence, what will we do now?

Substantially increasing regeneration rates of cottonwood—currently a small fraction of historic levels—entails retreat from practices that have been common for generations. Some reforms, such as refraining from cutting recently formed patches of forest and mining those landforms for gravel, leaving woody debris in the river, and ceasing public subsidy of bank stabilization projects may be realizable in the near-term. Others, such as purchasing recently formed riparian lands and intact relict floodplain habitat, buying development rights and conservation easements on mature floodplain, experimental removal of riprap, and altering dam operation to enhance habitat formation may take longer to gain the necessary support.

The quality of our stewardship depends upon learning to better predict the consequences of our acts and recognizing limits in our ability to do so. Foresight, always difficult when working with complex systems, has been made even more so by factors such as the introduction of exotic species and anthropogenic global climate change. Given these facts, we will proceed cautiously, with frequent reevaluation. We can further enhance our chances for success by maintaining a watershed-scale and long-term (decades) perspective, commensurate with the temporal and spatial scales of the processes with which we are interacting.

People in the watershed, like our fellow humans elsewhere, are, at best, underinformed and, at worst, sorely misinformed about what is possible. Only an ecologically informed populace will understand that present investment in the actions listed above will pay handsome future returns. By shaping a stewardship plan that integrates the aspirations of diverse stakeholders and does not violate boundaries imposed by physical laws, we can more fully realize the river's potential value.

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