Baseline Monitoring Study of Restoration Effectiveness in the Green River (Mile 32): Processes and Habitats in the Channel and Floodplain.

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Abstract

The goal of this study was to characterize baseline conditions at restoration sites on the Green River to support future evaluations of the physical effectiveness of levee setback and removal. The study area encompasses three projects near river mile 32: Auburn Narrows and the Fenster and Pautzke sites from Project MG-18 of the WRIA 9 Salmon Habitat Plan. Explicit hypotheses were proposed in a Before-After design, and linked to quantitative metrics including: (1) channel processes; (2) riparian processes; and (3) aquatic habitat. Metrics were evaluated with a combination of historical photo analysis and field surveys. Conditions were quantified in the pre-levee and flow regulation (baseline) period and compared with conditions in the post-levee and flow regulation (pre-restoration) period. This comparison demonstrates that the river pattern has been converted from a dynamic, multi-thread system to a stable, single thread channel. Lateral migration slowed by approximately 60%, facilitating the expansion of the floodplain forests dominated by willow and cottonwood. Pioneering vegetation covered 45% of the existing bars. Pioneer bars presently contain approximately 190 cottonwood and 12,000 willow stems per hectare, indicating tree regeneration is occurring. Several Douglas-firs established on rocky bars, but naturally-regenerated conifers are otherwise absent. Forests eroded more slowly, with declines ranging from 45 to 81%, depending on patch type. Reductions in bank erosion contributed to a 52% decline in the average recruitment rate of large logs, which provide the essential habitat function of logjam initiation. In spite of this decline, wood loading is presently high (361 pieces km^{-1}), owing to a recent chute cutoff. Aquatic habitat analysis demonstrated that, from the baseline to the pre-restoration period, the mainstem channel narrowed substantially (e.g., from 77 to 39 m) and became more homogeneous. Side channels increased in length though backwater channels retracted. Bar edge and terrace bank edge habitat declined by 47% and 42%, respectively, owing to the expansion of hardened banks and floodplain bank edges. In summary, the channel and riparian processes and aquatic habitat in the study area have been substantially altered from baseline conditions. In the post-restoration period, levee setback and removal may be considered ecologically successful if monitoring hypotheses are confirmed and the river begins to exhibit a shifting mosaic steady state. In such a state, conditions (e.g., the composition of the landscape and biological communities) and processes (e.g., rates of bank erosion, cutoffs, vegetation establishment) fluctuate over time but are relatively predictable and increasingly stable over the long term. The specific distribution, sequencing, and extent of the changes are somewhat uncertain. This uncertainty is in part, the result of the underlying dynamics of a functioning river ecosystem.

Introduction

Reliable protocols and baseline observations are needed to support effectiveness monitoring of restoration projects. Protocols herein are generally applicable to mainstem restoration projects in Middle Green River. This template focuses on quantifying baseline conditions to provide an historical perspective and establish benchmarks for evaluating post-project conditions. This template follows the standard format of a scientific report. Results will be used to determine whether restoration efforts are effective in restoring aquatic and riparian habitats and the biophysical processes that create and maintain them. An additional outcome of this project is to initiate the Adaptive Management Program[1].

This is a case study that can inform future project design and monitoring. Results will increase our understanding of how physical and biological processes respond to modification or removal of levees and revetments in similar contexts, and how multiple restoration projects in close proximity may interact. Findings may later be used in extensive post-treatment (EPT) studies of the effects of levee removal. Results from case studies are somewhat idiosyncratic, as the results cannot be directly extrapolated to

[1] ftp://dnr.metrokc.gov/dnr/library/2005/kcr1876/CHAPTERS/Ch9-AdaptMgt.pdf

other sites. However, findings from this study will be valuable because monitoring of large-scale restoration projects remains rare.

Restoration Objectives

Many mainstem river restoration projects in WRIA 9, including the study segment, are intended to restore natural processes of bank erosion, channel migration, floodplain inundation, large wood delivery, logjam formation, and plant succession. These processes – in combination with the natural flow regime - collectively produce complex, productive spawning and rearing habitats for the benefit of threatened fish species and the riverine ecosystem.

Monitoring Objectives

Baseline monitoring – the first step in effectiveness monitoring –provides an historical perspective and establishes benchmarks for evaluating post-restoration conditions. The general goal of effectiveness monitoring is to explain whether a restoration action had the intended effect on habitat conditions and biophysical processes.

In this baseline study, several specific hypotheses are proposed and matched to objectives that measure the outcome of restoration efforts (Table 1). Hypotheses are focused on three categories; river processes, floodplain processes, and aquatic habitat. The goal is to understand how these processes and habitats have changed over time, to provide context for interpreting responses to restoration actions. Understanding changes in process rates yields valuable insights about the effectiveness of restoration actions and the predictability of the outcome. Also, the success of projects depends on the restoration of these processes.

Table 1. Monitoring hypotheses and objectives.
Hypotheses refer to the anticipated results of the restoration efforts at the study site. Some potential mechanisms for the hypothesized response and the rationale for tracking the processes and habitats are also provided. Codes are used later in place of the hypothesis for brevity and for the readers' benefit.

Category	Code	Hypothesis	Objective	Mechanisms	Rationale
River processes	C1	The rate of lateral channel migration will increase, especially meandering.	Use sequential centerline differencing to quantify migration rates from airphotos	Channel constraints have been removed	Channel migration is vital in forming, and maintaining aquatic and riparian habitats
Floodplain processes	R1	Forest erosion will increase	Quantify erosion rates for forest patch types from airphotos	Channel migration will increase	Bank erosion delivers large wood and sediments to the river and creates regeneration sites for the forests
	R2	Increased forest erosion will enhance large wood delivery and alluvium inputs to the river	Measure stand structure and soil depths in forest plots to estimate wood and sediment recruitment potential	The river will be able to undercut forests that were previously inaccessible	Natural wood delivery maintains wood loading in the river by offsetting ongoing losses. Sediments help forests establish in depositional areas.
	R3	Tree regeneration will occur naturally.	Tally tree seedlings in forest plots	Bank erosion and sediment recruitment will create new germination sites	Tree regeneration ensures shade and wood will be provided in the future
	R4	Riparian forest complexity will increase.	Map riparian forest patches and analyze complexity with rank-dominance plots	Formation of new forested areas and erosion of others will create a mosaic pattern	Forest complexity creates a diverse assortment of edge habitats
Aquatic habitat	A1	Channel width, length, area, branching, and associated bar edge habitat will increase.	Quantify channel dimensions, branching, and edge habitat from airphotos and elevation maps	Channel constraints are removed and wood loading should increase	Channel dimensions and characteristics affect the quality and quantity of aquatic habitat, including edge habitats
	A2	Logjams will increase in frequency, size, and longevity.	Tally and map logjams and large wood visible in airphotos	Bank erosion will add wood and channel widening will enhance retention of transported large wood.	Large wood helps to create complex low-velocity habitat and provides cover and shelter.

Methods

Study Area

The Green/Duwamish River currently extends 93 miles from Stampede Pass in the Cascade Mountains to its mouth at Elliott Bay in Puget Sound. Winters are relatively warm and wet. Summers are cool and dry. The channel network, land cover, and streamflow regime reflects a long history of human alterations. Major alterations include re-routing of major tributaries (downstream from the study area), land conversion, water diversion, erosion control, and flood abatement by Howard Hanson Dam. The primary factors affecting ecological conditions at the study area are altered flows of sediment, water, and wood, bank hardening, floodplain fragmentation, and upstream land conversion. Primary natural disturbances are flooding (though now much reduced) and bank erosion.

The study area is a historically dynamic valley segment of the Green River approximately 6000 feet long extending upstream from extends from RM 32 on the Green River to the Highway 18 bridge (Fig. 1; also see Appendix A for a comprehensive time series of aerial photos). This valley segment includes the sites of three adjoining restoration projects: the Fenster, Pautzke, and Auburn Narrows sites. This segment was selected because of the large scope of restoration, the advanced state of implementation, and the projects' priority status in the WRIA 9 Salmon Habitat Plan[2]. The sites are aggregated for the purpose of this study because they are linked by shared hydrology, geomorphology, and forest dynamics.

The boundaries of the study area correspond to the extent of the restoration activities and the location of persistent constraints on channel dynamics. Specifically, the upstream boundary corresponds with a persistent embankment created to support the Highway 18 bridge. The downstream boundary corresponds to the approximate boundary of the Fenster project site, which coincides with a point at which the river exhibits a low level of lateral migration in historical records. The lateral extent of the study area corresponds to the mapped 100-year floodplain. Flooding and channel migration are confined on the north side by a steep bluff and by a railroad prism on the south side. The railroad was built in 1887 greatly pre-dating the earliest airphotos.

Restoration projects are ongoing in the study area. In 2004, King County DNRP relocated a segment of the Fenster Levee and thus reconnected the mouth of Pautzke Slough to the mainstem. The remainder of the levee will be relocated away from the channel in 2008. The north bank and area upstream of the project site is owned and managed by the Washington State Departments of Fish and Wildlife, and Parks. The Auburn Narrows Natural Area owned and managed by King County is immediately upstream. One of the largest habitat restoration projects ever constructed in King County was completed within the Auburn Narrows Natural Area in the summer of 2007. Following the implementation of the Pauztke project, all levees in the study area will have been removed or relocated, or destabilized (e.g., through notching).

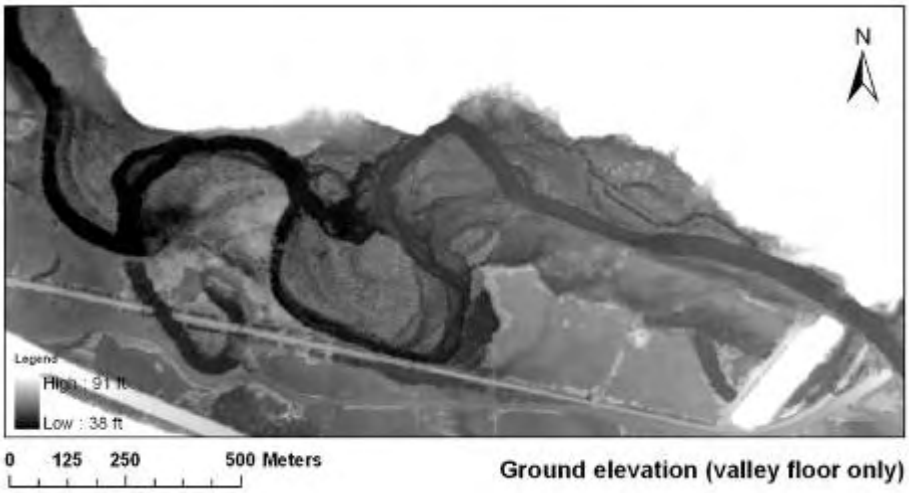
[2] http://dnr.metrokc.gov/Wrias/9/HabitatPlan.htm

Figure 1. Site map of the study area.
Panels show the site in 1936 (A) and 2007 (B), and ground elevations (C).

A

B

C



Monitoring Design

This study employs a Before-After (BA) experimental design at the valley segment scale. This is a case study where strictly speaking, inferential power is limited to a single valley segment (the experimental unit). Measurement units vary among response variables, but are generally line and belt transects. Samples (measurements) are replicated across years in remote sensing analyses and across plots in field surveys. The BA design compares three periods:

- Baseline (Pre-levee, pre-flow regulation) (1936-1970)
- Pre-restoration (Post-levee, post-flow regulation) (1970-2006)
- Post-restoration (Levee-removed, ongoing flow regulation) (2007-2017)

True reference conditions are unavailable because human activities (land clearing, for example) in the Middle Green River predate the earliest land surveys (1867) and large wood was removed from most of the Middle Green River flood control efforts of the early 1900's. However, early surveys and historical airphotos provide valuable insight on conditions existing prior to steep declines in salmonid populations, and before the proximate causes of habitat degradation in the study area (levees, bank hardening, and flow regulation) were initiated. Similarly, airphotos taken during the pre-restoration period can be used to quantify the large-scale response (presuming a cause-and-effect relationship) to factors of degradation. Baseline conditions can, in some cases, provide targets for restoration; 'baselines' against which improvements resulting from restoration can be compared. Pre-restoration conditions are useful for determining whether site conditions are on a positive trajectory (improving).

Sampling intervals during the baseline and pre-restoration periods are mostly limited by the availability of orthorectified historical airphotos. Baseline sampling is limited to 1936, 1959, 1961, and 1970. The latter actually portrays conditions immediately after levees were built and flows were regulated, but has been included on the assumption that the biophysical response at the study area was lagged by several years. Pre-restoration period sampling intervals include 1978, 1990, 1996, and 2006. Restoration at the study site began in earnest in the latter half of 2007. Field sampling was conducted in a single year (2007).

Channel Processes

(C1) Channel Migration

Channel migration rates and mechanisms were quantified using sequential analysis of channel centerlines (i.e., sequential centerline differencing or SCD; see Appendix B for example). This analysis relies on measurements of the distances between channel centerlines from sequential digital orthorectified photos. This technique generates relatively unbiased, directional and mechanistic estimates of average channel movement rates within fixed belt transects extending across the 100 year floodplain.

Channel centerlines (polyline shapefiles) were manually delineated by following the center of the low flow channel in each photo year. In multi-thread reaches, the centerline followed the channel with the widest wetted width. Each centerline was split into 200 ft segments ending in a visible endpoint (dot). Channel movement between photo years was quantified by manually delineating vectors (shapefile) extending from the endpoint of each segment to the point of intersection with the centerline from the initial (t_0) and subsequent (t_1) photo year. Vectors were extended in a direction roughly perpendicular to the t_0 centerline. Vector lengths were calculated in ArcMap. The annual movement rate at each vector was estimated (annualized) by dividing vector length by the number of years elapsed between t_0 and t_1

(O'Connor et al. 2003, Latterell et al. 2006). For example, if vector length was 100 ft over at 10 year interval, the annual movement rate was estimated as 10 ft yr^{-1}. Each vector was attributed with the mechanism of channel change (i.e., switching, meandering, cutoff) and direction of movement (i.e., river left, river right) from t_0 to t_1. Herein lays the sequential aspect of this technique. This process was repeated over each photo interval. For example, t_1 was substituted for t_0 and the difference between channel centerlines between t_1 and t_2 was compared.

Parallel belt transects were then established systematically at 300 ft intervals over the entire study area. Transects were oriented perpendicular to the main axis of the study area (a straight line between the center of the wetted channel at the upstream and downstream reach boundaries). These belt transects were used as sampling units for summarizing longitudinal variation in the rate, direction, and mechanism of channel movement. Average annual channel movement rates were calculated separately for each mechanism and direction based on all vectors within each belt transect and photo year. Averages were then calculated across photo years to estimate values during baseline and pre-restoration periods. Sampling grids were used to quantify habitat dynamics, including two alternative approaches.

Riparian Processes

Riparian habitat characteristics were measured from airphotos and in the field. Baseline and pre-restoration conditions were measured from sequential orthocorrected digital airphotos using cartographic tools in ArcMap. Forest plots were surveyed in the field because estimates of stand structure were needed to characterize variability in forest characteristics, to determine the extent of natural tree regeneration, and to quantify wood delivery rates to the channel.

(R1) Forest Erosion

The first step in quantifying forest erosion rates was to map riparian habitat units from aerial photos (Table 2; also see Appendix C for classified land cover maps). Units were mapped in three zones: (1) parafluvial zone; (2) orthofluvial zone; and (3) terraces (Stanford 2006). Generally, the parafluvial zone is the area within the bankfull channel where sediments are annually deposited and scoured by floods and usually contains early successional vegetation. The orthofluvial zone contains patchy developing floodplain forests that are frequently or occasionally inundated but reworked only by big floods, rapidly enlarging over time with well-drained thin soils lacking organic matter, ridge and swale topography dissected by flood channels with scour pools or spring brooks. This zone also contains perennially flowing springbrooks and oxbow lakes (Stanford 2006). Planform maps of units were manually delineated for each photo year. Units were designated based on airphoto interpretation of visual texture, color, position, and other indicators.

Cumulative forest erosion rates were empirically estimated for select habitat unit types; pioneer bars, developing floodplains, established floodplains, and terraces. Fields and second growth were also evaluated. Erosion rates were estimated by establishing a fixed dot grid (100 ft. spacing) across the entire study area along vectors oriented perpendicular to the valley axis of the valley. These points were classified according to the patch type they fell within. Two ‘cohorts’ of points were tracked through subsequent airphotos. Cohorts were named for the initial photo of reference. The initial 1936 cohort was tracked through 1970 to quantify patch-specific erosion rates for the baseline period (specifically, 1959, 1961, 1970). Points were reclassified from the 1970 photos (1970 cohort, hereafter) and then tracked through 2007 to quantify erosion rates for each patch type during the pre-restoration period (specifically, 1978, 1990, 1996, 2007).

Unit specific erosion rates were quantified for each cohort by plotting the proportion of the initial points in a single patch type remaining undisturbed by the river against the number of years elapsed since the initial observation (1936 or 1970). An exponential decay model was fit to each habitat unit type (Latterell et al. 2006). The form of the model is

$$p_{l,t} = e^{-kt}$$

where $p_{l,t}$ is the proportion (ranging from 1.0 to 0.0) of the points in patch type l remaining intact (not eroded) at time t in years (p at t_o is 1.0), k is the calculated erosion rate constant, and t is time in years. Each model was used to calculate the erosion rates of each habitat unit type (half-life; $t_{0.50} = 0.693/k$, 95% life, $t_{0.95} = 3/k$).

Table 2. Riparian habitat units.
Units and descriptions are based on Latterell et al. (2006) and Stanford (2006).

Zone	Unit name	Description	Inundation
Parafluvial	Unvegetated bar	Unvegetated alluvial depositional feature exposed at summer low flow	Annually
	Pioneer bars	Depositional feature covered by young, native pioneering (shrubby) vegetation, often less than 100% canopy closure, occurring anywhere in floodplain but often on point bar margins	Annually
Orthofluvial	Developing floodplain patches-	Rapidly expanding patches of native pioneering woody species undergoing rapid natural thinning and alluvial deposition	Frequent
	Established floodplain patches	Mature hardwood stands dominated by original pioneer cohort, with relatively thick alluvial deposits and moderate stem densities, well established herb layer	Intermittent
Terrace or bench	Terrace	Alluvial landforms elevated at least one to several meters above the elevation of the active channel with well-established, mature forests and deep alluvial soils.	Infrequent
	Anthropogenic features	Agricultural fields, roads, buildings, pastures	Infrequent

(R2) Large Wood and Alluvium Delivery

Forest erosion rates were used to estimate wood delivery rates from each unit type during the baseline and pre-restoration periods. First, the average area of a given unit type during the baseline period was multiplied by the erosion rate (i.e., $p_{l,t}$) for that unit (where $t = 1$) to estimate the annually eroded area. This value was then multiplied by the average number and/or volume of trees > 10 cm dbh per unit area to estimate wood delivery rates to the channel. Next, this was repeated using values from the pre-restoration period. Alluvium (fine sediment) delivery rates resulting from forest erosion were estimated in the same fashion, by multiplying average unit area and erosion rate by the average soil depth in the given patch type. Wood delivery estimates from all natural unit types (Table 2) were then summed to estimate the average annual wood delivery rate.

A permanent forest plot (belt transect) was established in the following unit types: pioneer bar, developing floodplain, established floodplain, and terrace (young and old) (Table 3; See map in Appendix D). Survey methods followed Van Pelt et al. (2006). Plots were placed within stands deemed to be representative of a given unit type and near the 2007 channel. Plots were 2h long where h is the approximate height of the dominant trees in the unit type. Plot width was also scaled to h, so that plot area was roughly $1.5h^2$ (Van Pelt et al. 2006). For example, stand dominant cottonwood trees on terraces are approximately 50 m tall. The terrace plot was therefore 100 m long and 38 m wide totaling 3,800 m^2. Plots were oriented at azimuths perpendicular to the channel (excluding the young terrace) and placed so that they fit within existing stand boundaries. All plots were located in stands on river left (south side) to

permit year-round access. Steel re-bar posts were centered at both ends of the plot and a fiberglass tape was stretched between them, functioning as a central transect line. Plots were not replicated in multiple patches.

Table 3. Forest plot dimensions.

Forest Unit	Plot	Est. age (years)	Length (m)	Tree Plot		Seedling Plot	
				Width (m)	Area (ha)	Width (m)	Area (ha)
Pioneer bar	4	9	26	14	0.036	4	0.0104
Developing floodplain	2	15	50	18	0.090	8	0.04
Established floodplain	3	27	60	22	0.132	9	0.054
Young Terrace	5	~70	80	30	0.240	12	0.096
Old Terrace	1	~100	100	38	0.380	15	0.15

At each plot, the following variables were quantified: live and dead stem density, stand basal area, stem diameter and height distributions, species compositions, and seedling density. Stem maps were created by measuring the X coordinate of each qualifying stem from the central tape and the Y-coordinate from the distance to the stem as measured by a TruPulse laser rangefinder (Laser Technologies, Inc., Centennial, Colorado, USA) (See Appendix D for stem maps). Laser accuracy was ± 1 ft for horizontal distances. All standing stems >5 cm in DBH were measured for species, status (live or dead), diameter at breast height (DBH), height (using the TruPulse laser), and crown height. Stand age was estimated from historical airphotos (Table 3). Tree stem volume was estimated from allometric equations (Table 4).

Table 4. Allometric equations for tree stem volume (in m^3).
Predictor variables are on stem diameter (DBH in cm) and stem height (HT in m). Adapted from Van Pelt et al. (2006).

Species	Equation	Intended Use
Acer macrophyllum	$(0.0001074*DBH^{2.543})+(0.0002033*HT^{2.512})$	*Acer macrophyllum*
Alnus rubra *Salix spp.* *Prunus emarginata*	$(0.000336*DBH^{2.181})+(0.0005764*HT^{2.163})$	*Alnus rubra*
Picea sitchensis *Thuja plicata*	$(0.0002596*DBH^{2.30})+(0.000178*HT^{2.697})$	*Picea sitchensis*
Populus trichocarpa	$(0.000364*DBH^{2.205})+(0.00001757*HT^{3.203})$	*Populus trichocarpa*

Soils and topography were also measured at each plot. Soil depth – the depth from soil surface to refusal at cobble layer-was measured at 1 m intervals along the centerline with a steel soil probe. Plot profiles were constructed using a level and stadia rod, collecting elevations (to 1 cm) at 1-m intervals along the center transect. The elevation of the river water surface at the time of survey was also recorded. The spatial coordinates of the starting point were measured with a GPS and the ground elevation of the landward end of the transect (starting point) was measured in ArcMap from King County's lidar ground surface elevation model (2 x 2 m grid cells).

(R3) Tree Regeneration

Tree regeneration was quantified with field surveys in forest plots. Tree seedlings less than 5 cm DBH were tallied and species identified within a smaller belt transect 0.3*h* in width co-located on the central transect (Table 3).

A technique similar to that used for R1 was used to quantify the cumulative rate of vegetation establishment on unvegetated areas including gravel bars and the wetted channel. In this analysis, the y-

axis of the plot $p_{l,t}$ represents the proportion of points in patch type l (gravel bars, for example) that remained unvegetated t years after the initial observation (1936 or 1970). Thus, k is indicative of the vegetation colonization rate or the loss of unvegetated surfaces.

(R4) Riparian forest complexity

Riparian habitat (planform) complexity was characterized with rank-abundance graphs (or Whittaker curves) which quantify temporal changes in the patterns of relative abundance of unit types in the study area (using the same subset of unit types as above). The area of each qualifying unit was summed to estimate the total 'habitat area' in a given year based on planform landcover maps. The proportion of the total habitat area comprised by each patch type was calculated for each photo year. The unit types were rank-ordered within each year from highest (largest proportion of total habitat area) to lowest. The natural log of the proportion of the total habitat area was then calculated for each unit type and year. Resulting values were plotted against the rank order (1-10, for example) regardless of unit type and a linear regression model is fit to the values from a single photo year. Unit types that were not present in a given photo year were assigned 'no data' rather than zero to permit models to be fit to log-transformed data. These steps were repeated for each photo year.

The estimated slopes of the lines were used as indicators of unit heterogeneity and were compared among years. For example, a slope of zero indicates that units are present in equal proportions and that the study area is relatively heterogeneous in composition. As the slope increases (becomes more negative), this indicates that the study area is dominated by one or several unit types interspersed with smaller units of a different type.

Aquatic Habitat

Airphoto analyses were used to map baseline aquatic habitat conditions. Baseline and pre-restoration conditions were measured from sequential orthocorrected digital airphotos using cartographic tools in ArcMap (ESRI, Redlands, California). High flow conditions prevented the measurement of channel thalweg profiles, width-depth ratios, and the average and residual pool depth, though these metrics may be surveyed in the post-restoration phase.

(A1) Channel Dimensions, Branching, and Edge Habitat

Active channel width was measured in each sampling (airphoto) year at 60 regularly spaced (100') line transects oriented perpendicular to the main valley axis. Channel width measurements were perpendicular to the channel axis at the point of intersection with the line transect. Channel lengths were measured by type: primary mainstem, secondary mainstem, side channels, backwater channels, and engineered channels. The wetted channel area was estimated by delineating the wetted channel in each photo year as a polygon. Additionally, the wetted edges (Table 5) of the channel were classified and measured in each photo year (Beechie et al. 2005).

Table 5. Edge habitat at the study site
Categories and descriptions modified from Beechie et al. 2005.

Category	Type	Description
Bar edge		Shallow, low-gradient interface with shore
	Point	Bar located between the river and an unvegetated point bar or a point bar with pioneering vegetation
	Mid-channel	Bar located between the river and an mid-channel bar (island)
Bank edge		Vertical or nearly vertical shore, either natural or hardened
	Floodplain	Bank located between the river and a developing or established floodplain patch
	Terrace	Bank located between the river and a terrace patch
Hardened edge		Artificially hardened bank such as railroad prism, levee, or revetment

(A2) Logjams

Logjams were surveyed to quantify the trapping and retention of large wood and provide a mechanistic link for observed changes in habitat complexity. Large wood and logjams visible in historical airphotos were mapped and measured in ArcMap. Logs were assigned to individual logjams for estimating logjam size and the total number of jams present.

Results

Channel Processes

(C1) Channel migration

The channel was very dynamic during the baseline period (Fig. 2). Channel switching was common in the upper half of the study reach (Table 6). Relatively little bank retreat was observed in these locations. Instead, the thalweg mostly repeated changed locations within the existing active channel, moving toward the right and left banks. In contrast, channel meandering dominated the downstream half of the site and resulted in substantial bank retreat.

- Mean switching rates: 2.1/2.7 m yr^{-1} (right/left)
- Median switching rates: 1.1/9.3 m yr^{-1} (right/left) in where switching occurred
- Mean meandering rates: 1.4/1.1 m yr^{-1} (right/left)
- Median meandering rates: 2.3/1.7 m yr^{-1} (right/left)

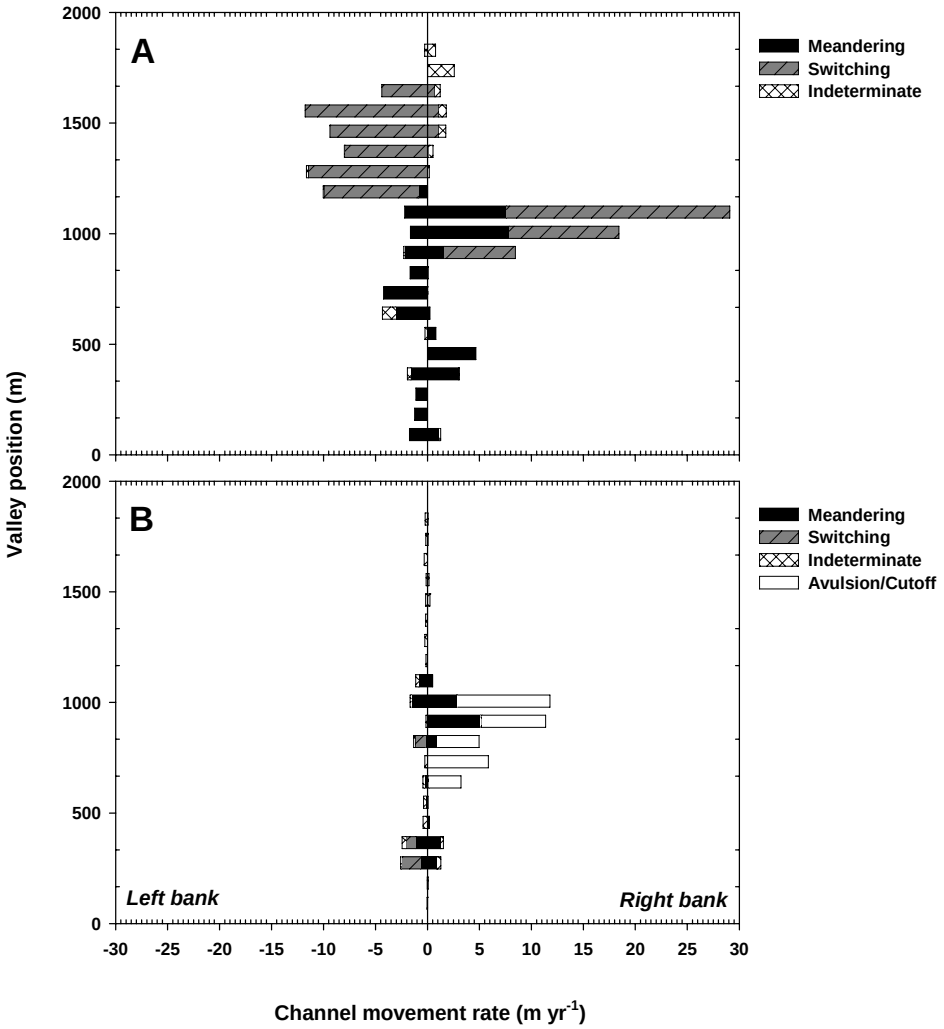
Table 6. Average channel migration rates by transect, mechanism and direction.
Mechanisms include meandering (ME), channel switching (CS), indeterminate (N), and avulsion or cutoff (AV). The position of the belt transect is indicated, relative to the downstream end of the study segment (0 m or ft). Baseline period refers to 1936-1970. Pre-restoration period refers to 1970-2006.

Belt transect		Baseline migration rate (m yr^{-1})								Pre-restoration migration rate (m yr^{-1})							
		ME		CS		N		AV		ME		CS		N		AV	
(m)	(ft)	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L
1829	6000	0.0	0.0	0.0	0.0	0.8	0.3	0.0	0.0	0	0	0	0	0.1	0.2	0	0
1737	5700	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0	0	0	0	0.1	0.2	0	0
1646	5400	0.0	0.0	0.7	4.4	0.5	0.0	0.0	0.0	0	0	0	0	0	0.3	0	0
1554	5100	0.0	0.0	1.1	11.8	0.7	0.0	0.0	0.0	0	0	0	0	0.2	0.1	0	0
1463	4800	0.0	0.0	1.1	9.4	0.7	0.0	0.0	0.0	0	0	0	0	0	0.2	0	0
1372	4500	0.0	0.0	0.2	8.0	0.3	0.0	0.0	0.0	0	0	0	0	0	0.2	0	0
1280	4200	0.0	0.0	0.0	11.5	0.2	0.2	0.0	0.0	0	0	0	0	0	0.3	0	0
1189	3900	0.0	0.8	0.0	9.1	0.0	0.1	0.0	0.0	0	0	0	0	0	0.2	0	0
1097	3600	7.6	2.2	21.5	0.0	0.0	0.0	0.0	0.0	0.5	0.8	0	0	0	0.3	0	0
1006	3300	7.9	1.6	10.6	0.0	0.0	0.0	0.0	0.0	2.8	1.6	0	0	0.1	0.1	8.9	0
914	3000	1.6	2.2	6.8	0.0	0.0	0.0	0.0	0.0	5.1	0	0	0	0.1	0.1	6.1	0
823	2700	0.0	1.7	0.0	0.0	0.1	0.0	0.0	0.0	0.9	0.2	0	1.0	0	0.2	4.0	0
732	2400	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.3	5.8	0
640	2100	0.2	3.1	0.0	0.0	0.0	1.3	0.0	0.0	0	0.3	0	0	0.2	0.1	3.1	0
549	1800	0.8	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.2	0	0	0	0.2	0	0
457	1500	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0	0	0.1	0.4	0	0
366	1200	3.0	1.6	0.0	0.0	0.1	0.3	0.0	0.0	1.3	1.1	0	1.0	0.2	0.3	0	0
274	900	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.7	0	1.8	0.4	0.1	0	0
183	600	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.1	0	0	0
91	300	1.2	1.7	0.0	0.0	0.1	0.0	0.0	0.0	0	0	0	0	0	0	0	0

During the pre-restoration period – after levees were constructed – channel switching ceased and meandering was substantially diminished (Fig. 2). The channel was fixed in place in the upper half of the segment. Limited channel meandering toward the right bank continued mid-reach, where the erodible banks remained and the valley wall did not constrain the river. Channel movements toward the left bank were halted by the levees.

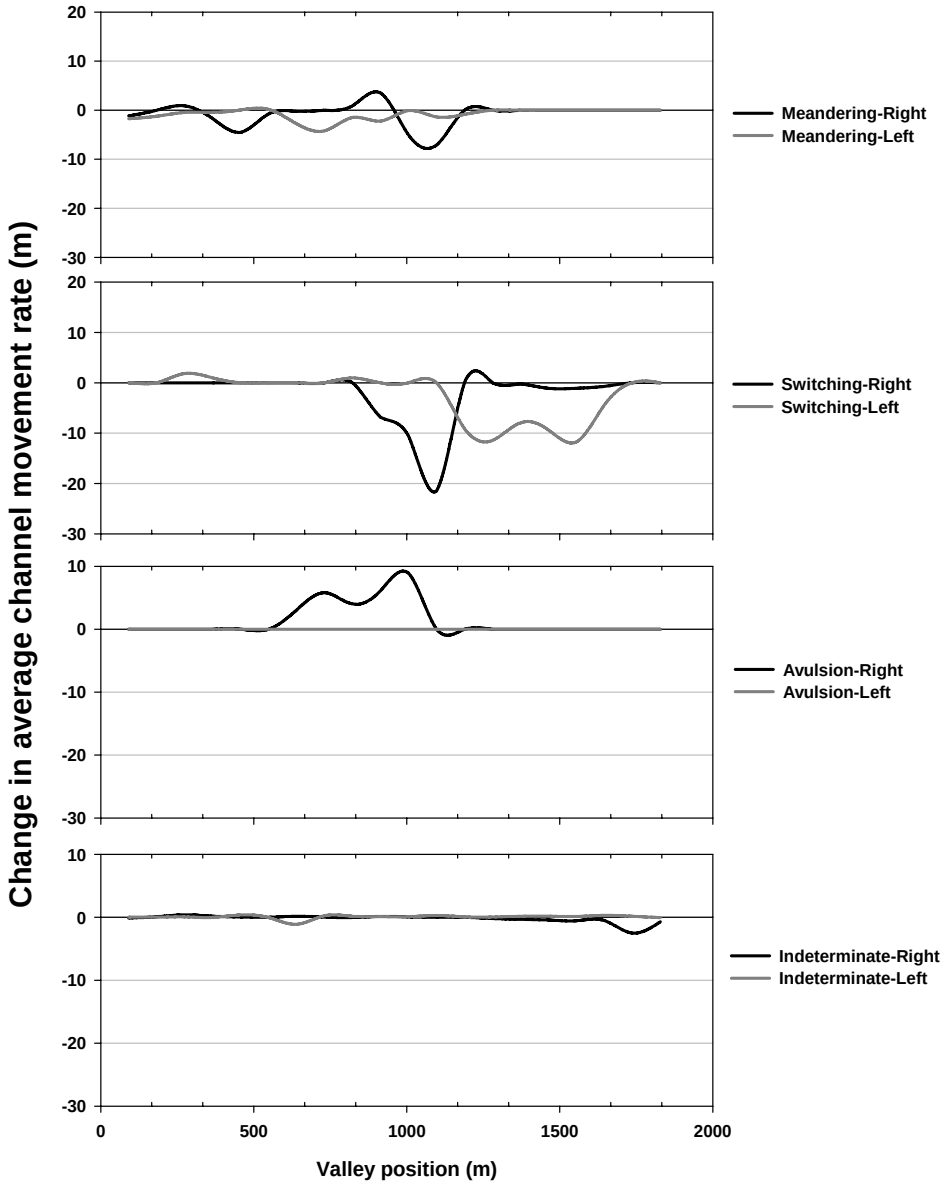
- Mean switching rates: 0.0/0.2 (right/left)
- Median switching rates: 0.0/0.1 (right/left)
- Meandering rates: 0.6/0.2 (right/left)
- Median meandering rates: 0.9/0.5 (right/left)

Figure 2. Comparison of channel migration rates and directions by mechanism during the baseline (A) and pre-restoration periods (B).



A major chute cutoff (avulsion) occurred in the middle of the segment during the late 1990's, causing the channel thalweg to jump abruptly toward the right side of the valley (Fig. 3, Appendix A). Although avulsions had not been detected in the segment in the existing photo record, this mechanism of change is natural and the backwater channels and parafluvial ponds that result are ecologically beneficial. Additionally, the event recruited substantial numbers of mature cottonwood trees to the river, forming a channel-spanning logjam, pools, and highly complex side channels. The avulsion apparently resulted from channel headcutting across a forested bar, related to the prior formation of a logjam at the channel margin.

Figure 3. Absolute changes in channel migration rates between the baseline and pre-restoration period. Each panel represents a different mechanism of channel change.



Riparian Processes

(R1) Forest Erosion

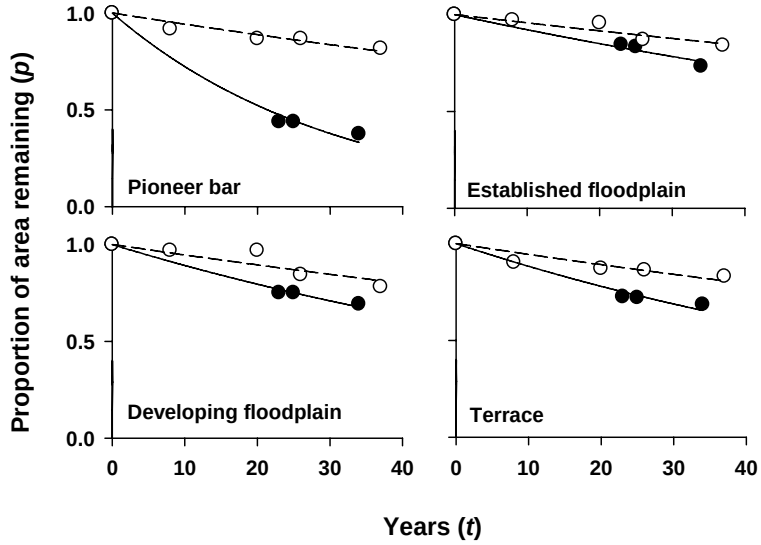
Comparisons of forest erosion rates demonstrate that all riparian patch types eroded more slowly during pre-restoration period than in the baseline period. These results are indicative of widespread terrestrialization of the river corridor: trees encroached into areas that were previously reworked by the river and maintained as unvegetated bars. Declines in erosion rates were most pronounced in pioneer bars, which were estimated to last 22 years, on average during the baseline period, compared to over 100 years during the pre-restoration period (Table 7).

Table 7. Forest unit erosion rates, including estimated patch ages.
Unit erosion is characterized by the erosion rate (k), time required for 50% ($t_{0.50}$) and 95% ($t_{0.05}$) of patch area to be eroded, and the percentage of patch area eroded after a ten year period (for illustration; 10 yr).

Unit type	Age	Baseline				Pre-restoration				Relative change	
		k	$t_{0.50}$	$t_{0.05}$	10 yr	k	$t_{0.50}$	$t_{0.05}$	10 yr	k	Area
Pioneer bar	9	-0.0316	22	95	27%	-0.0059	117	508	6%	-81%	-92%
Developing floodplain	15	-0.0114	61	263	11%	-0.0058	119	517	6%	-49%	-17%
Established floodplain	27	-0.0082	85	366	8%	-0.0045	154	667	4%	-45%	0%
Terrace	100	-0.0123	56	244	12%	-0.0057	122	526	6%	-54%	-62%
Field	>70	-0.0081	86	370	8%	0	-	-	0%	-100%	-100%

Erosion curves (Fig. 4) illustrate the differences in the proportion of each patch type remaining intact (not eroded) after a given length of time. In every case, riparian patches eroded more slowly as during the pre-restoration period, as indicated by flatter slope coefficients (k is closer to 0, Table 7). Locations that were initially wetted channel were colonized at similar rates in both periods. Fields did not erode after levees were installed. Insufficient data were available to estimate second-growth erosion rates during the baseline period.

Figure 4. Comparison of forest erosion rates during baseline (●) and pre-restoration (○) periods.
Estimates are based on the proportion of the initial unit area remaining intact (unaffected by erosion) after *t* years. Refer to Table 7 for erosion rate models and coefficients.



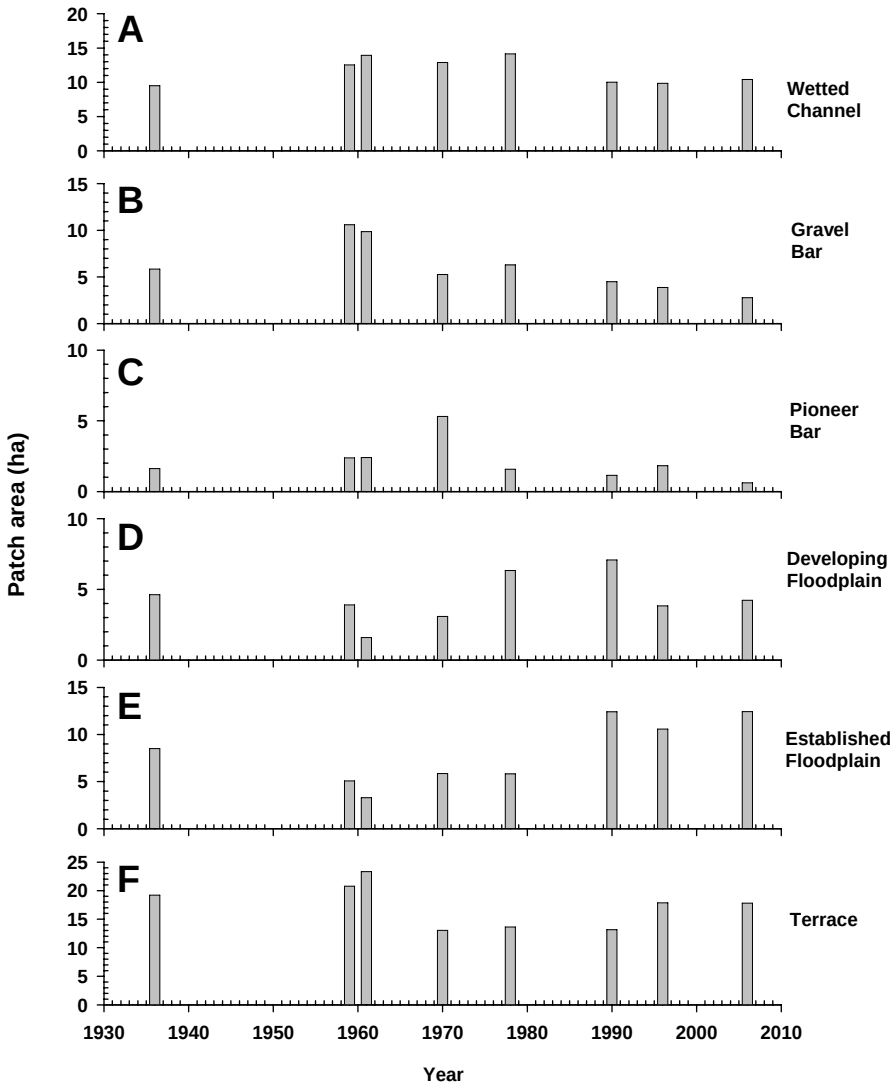
Riparian habitat area varied among years, as expected, according to the relative influence of fluvial disturbance (erosion) and the maturation of the forest (Table 7). The extent of gravel and pioneer bars decreased and the extent of floodplain forests generally increased over the period of record (Fig 5). Many areas that were previously maintained as gravel bars were colonized by pioneering hardwoods forming pioneer bars and developing floodplains. Areas that began as developing floodplains matured into established floodplains.

Table 8. Habitat area (ha) by unit type.
Unit codes are as follows: WC (wetted channel); B (unvegetated bar); PB (pioneer bar); DF (developing floodplain); EF (established floodplain); T (terrace); RV (replanted vegetation); BB (blackberry); SG (second-growth); F (field); and O (other modified areas). The false rejection (Type I error) rate is indicated by the *p*-value from *t*-tests, not assuming equal variances unless Levene's Test indicated $p>0.05$.

	Natural unit types						Modified unit types			
Year	**B**	**PB**	**DF**	**EF**	**T**	**RV**	**BB**	**SG**	**F**	**O**
1936	5.8	1.6	4.6	8.5	19.2	0.0	0.0	0.0	30.6	3.4
1959	10.6	2.4	3.9	5.1	20.8	0.0	3.6	0.0	22.2	3.1
1961	9.8	2.4	1.6	3.3	23.3	0.0	4.2	0.0	20.9	4.7
1970	5.3	5.3	3.1	5.9	13.0	0.0	3.3	8.5	21.4	5.2
1978	6.3	1.6	6.3	5.8	13.6	0.0	3.3	6.6	21.0	5.1
1990	4.5	1.1	7.1	12.4	13.1	0.0	3.3	5.8	20.8	3.7
1996	3.9	1.8	3.8	10.6	17.9	0.0	3.3	5.7	22.5	3.5
2006	2.8	0.6	4.2	12.4	17.8	7.1	5.4	4.9	9.7	3.2
Baseline	7.9	2.9	3.3	5.7	19.1		2.8	2.1	23.8	4.1
Pre-restoration	4.4	1.3	5.3	10.3	15.6		3.8	5.7	18.5	3.9
Mean difference (absolute)	-3.5	-1.6	+2.0	+4.6	3.5		+1.0	+3.6	-5.3	+0.2
Mean difference (km^{-1})	-1.9	-0.9	+1.1	+2.5	+1.9	+7.1	+0.5	+2.0	-2.9	+0.1
Percent change	-44%	-55%	61%	81%	18%		36%	171%	-22%	5%
p	0.08	0.10	0.09	0.05	0.22		0.37	0.19	0.21	0.74

Statistical analysis indicates that evidence for changes in the mean habitat area by patch type is relatively weak, due to low sampling frequency and high interannual variability (Table 8). The strongest evidence for a difference between baseline and pre-restoration conditions was observed in the area of bars, pioneer bars, developing floodplains, and established floodplains. Bars and gravels bar declined by roughly half. Concomitant increases of 61 and 81% in developing and established floodplain area was observed, as previously unvegetated bars were colonized by plants. The mean area of other patch types was largely indistinguishable among the baseline and pre-restoration periods, including the area of the wetted channel.

Figure 5. Total area of each type of riparian habitat unit by year.



Modified patch types generally transitioned from fields to blackberry stands and second growth forests became more common as native forests were cleared (Table 8). Areas that were previously cultivated fields transitioned to other patch types after cultivation ceased. Many of these areas became covered in monotypic blackberry stands.

(R2) Large Wood and Alluvium Delivery

Terraces contained the most wood volume, especially the old terrace where live stem volume exceeded 1,100 m^3 per hectare (Table 9, Fig. 6). Young terraces and established floodplains contained similar volumes of wood: roughly twice that of pioneer bars. The developing floodplain plot contained the least. Stem densities were surprisingly low in the developing floodplain plot, and it is likely a poorly representative plot in the chronosequence of stand ages and states.

Table 9. Forest stand structure of surveyed field plots.

		DBH (cm)			Height (m)			Basal area	Stem density (no. ha^{-1}) by minimum diameter class (dbh, cm)				Stem wood volume
Trees	**Patch**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**(m^2 ha^{-1})**	**>5**	**>10**	**>60**	**>100**	**(m^3 ha^{-1})**
Live	Pioneer bar	8.7	4.3	0.50	11.4	3.5	0.31	405	2967	63	0	0	503
	Developing floodplain	14.2	9.5	0.67	14.2	7.0	0.50	124	556	71	0	0	208
	Established floodplain	29.7	14.5	0.49	24.6	10.5	0.43	248	530	221	8	0	936
	Young Terrace	28.9	20.1	0.70	20.4	14.4	0.71	229	504	316	29	0	983
	Old Terrace	41.3	43.1	1.04	23.8	20.7	0.87	131	203	161	66	29	1160
Dead	Pioneer bar	6.6	1.0	0.15	6.9	2.3	0.33	34	330	0	0	0	-
	Developing floodplain							0	0	0	0	0	-
	Established floodplain	14.7	6.2	0.42	12.5	6.3	0.51	44	189	53	0	0	-
	Young Terrace	22.8	8.8	0.39	6.5	3.0	0.46	39	108	66	0	0	-
	Old Terrace	52.0	19.7	0.38	6.3	0.5	0.08	4	5	5	3	0	-

Wood recruitment potential also varies among patches depending on the minimum diameter of interest (Fig. 7). Stem diameters increase in magnitude and variability with stand age (Table 9; See stem maps in Appendix D). Pioneer bars contain numerous small diameter live trees, many of which would not qualify as large wood. Small dead stems are also common due rapid thinning attributable to competitive interactions for limited resources, as well as disturbance. Relatively few small pieces are present in stands on terraces, because tree regeneration is somewhat limited and most trees have attained larger sizes. The established floodplain and young terrace contained the greatest number of stems that qualify as large wood, with minimum diameters of 10 cm. These are important sources for the building materials of large logjams. The large logs (>60 cm) considered essential for creating fish habitat (Beechie and Sibley 1997) almost exclusively originate from terraces The young terrace contained 29 of these stems per hectare. The old terrace contained over twice as many, with 66 per hectare. The largest logs – those exceeding 1 meter in diameter – are only found in the old terrace, where they occur at densities of 29 per hectare, similar to levels in a pristine river (Latterell and Naiman 2007). This is assumed to be a conservative estimate because historic photos suggest some trees were cleared from the area during the pre-restoration period.

Figure 6. Wood recruitment potential in each unit type, in terms of stem wood volume (live).
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); T (terrace). Other types are not shown.

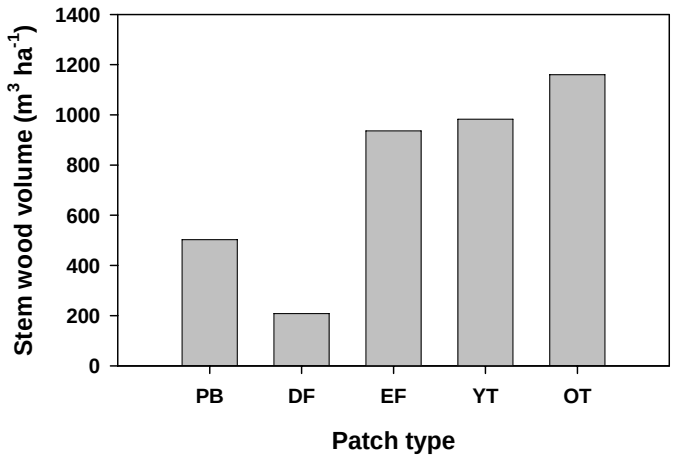
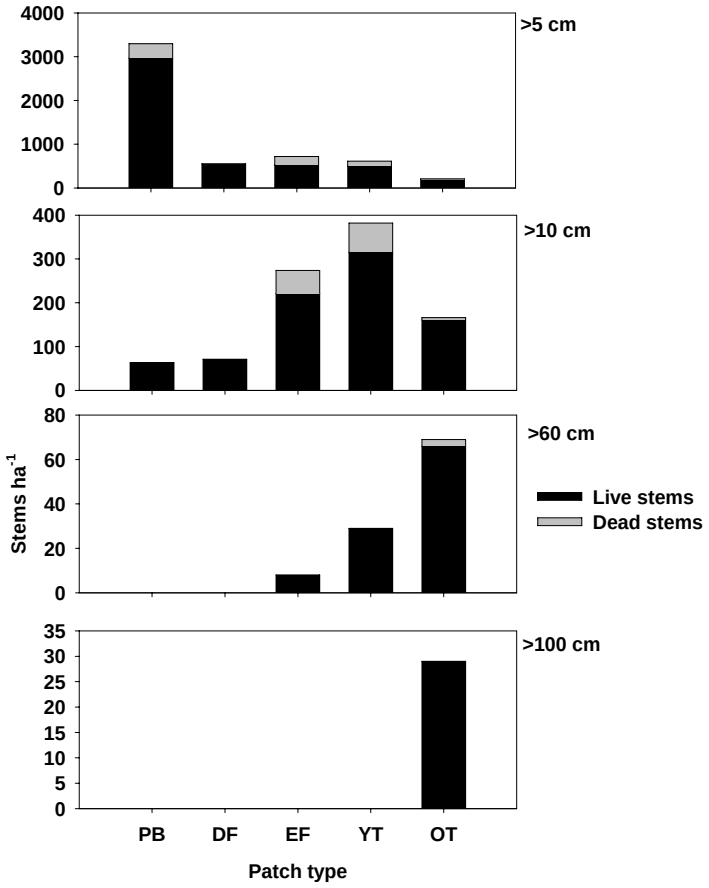
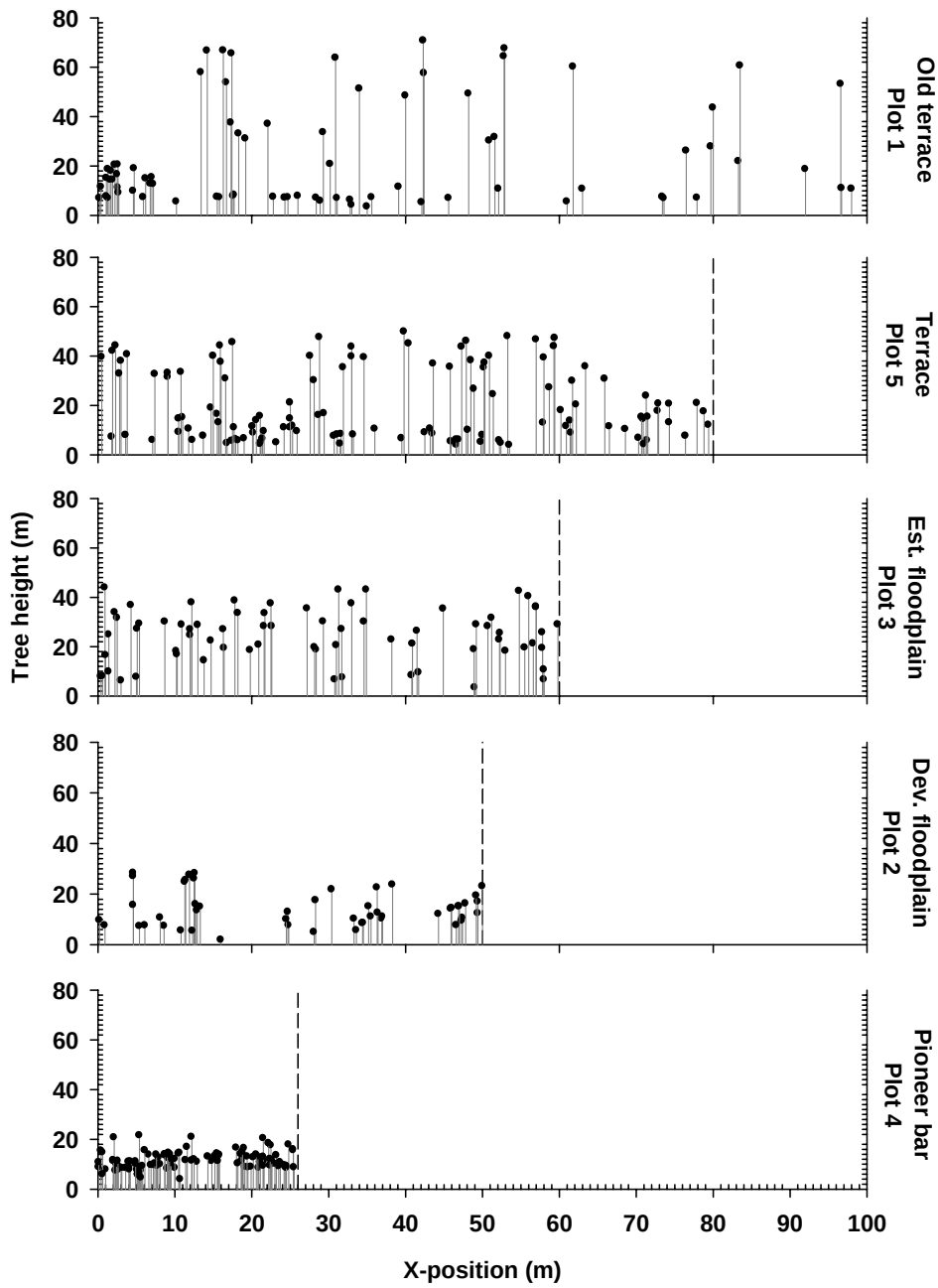


Figure 7. Wood recruitment potential by patch type and minimum stem diameter (dbh) for live and dead stems.
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); T (terrace).



Tree height profiles (Fig. 8) illustrate that only terrace plots contained substantial numbers of trees taller than the mean width of the current channel (39 m; presented later in this report). The length of the log (or height of the tree when standing) is an important factor onfluencing the stability and function of large wood once it reaches the river. Logs that exceed the width of the channel are more likely to remain stable, all else being equal.

Figure 8. Tree height profiles by riparian habitat unit type.
The development of multi-layer canopies is evident in terrace plots, where understory trees and shrubs are primarily dogwoods and cherries. The heights of the tallest trees in the old terrace were overestimated, especially in Plot 1. In this plot, measurement accuracy was reduced by estimating tree heights too close to the stem, and complicated by the morphology of stand dominant cottonwoods, which typically lack a distinguishable 'tip', as would be found on a conifer.



A summary example is provided below to illustrate the importance of understanding stand structure (e.g., Fig. 9) to patterns of wood delivery to the river – and the relative importance of older forests in maintaining river complexity. Erosion of one hectare pioneer bar will contribute approximately 3,000 living tree stems to the river, but only about 60 of them will be large enough to be considered large wood. None of trees (except remnant logs) are likely to be sufficiently large to initiate pools and jams. Erosion of one hectare of established floodplain will contribute over 500 live stems to the river; about 20 will qualify as large wood and eight of them can be expected to initiate pools and perhaps logjams. Erosion of one hectare of old terrace will deliver about 200 live stems to the river, over ¾ of these are large wood, about 70 of them can potentially form pools, and roughly 30 of them meet or exceed one meter in diameter.

Figure 9. Stem maps of field survey plots indicating the location of each stem ≥ 5 cm diameter at breast height (dbh).
Dots are scaled to dbh, but are larger than the actual measurements for illustration.

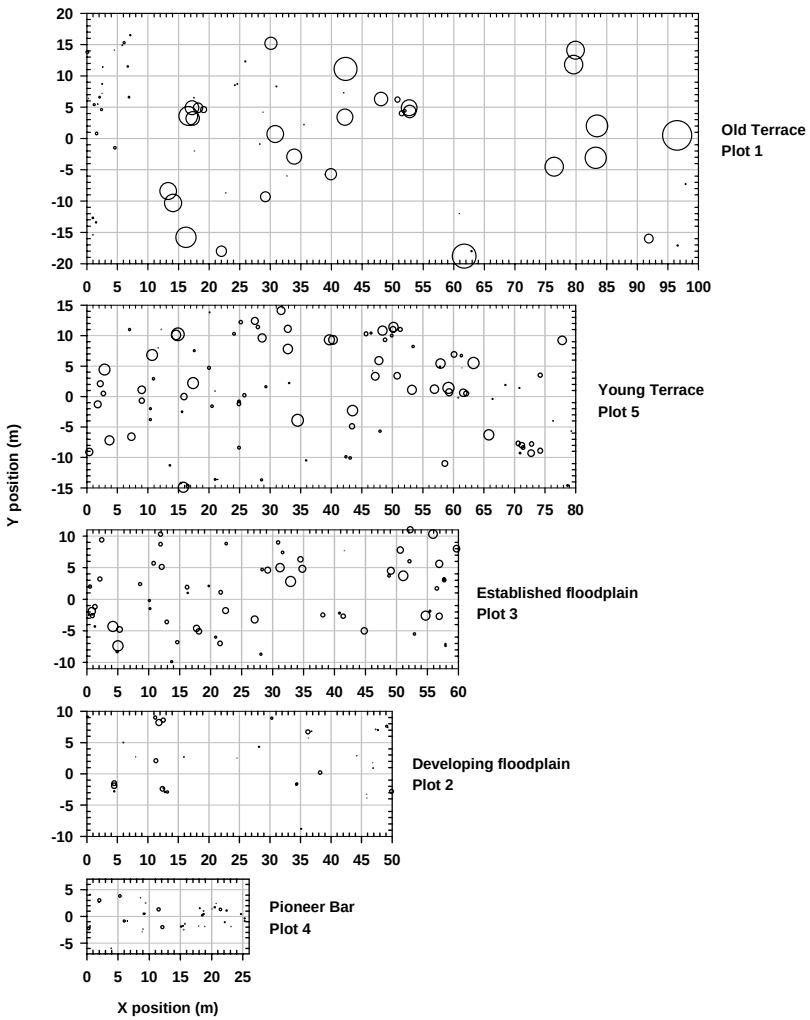


Table 10. Estimated large wood delivery rates (per km) to the river by riparian habitat unit type, large wood size class, and time period.
Delivery rates are calculated from the average area and annual erosion rate of each unit type during the baseline or pre-restoration period, and the potential wood delivery from each unit type is based on observed stand structure.

Unit type	Baseline					Pre-restoration					Difference				
	No. km^{-1} yr^{-1}				m^3 km^{-1} yr^{-1}	No. km^{-1} yr^{-1}				m^3 km^{-1} yr^{-1}	No. km^{-1} yr^{-1}				m^3 km^{-1} yr^{-1}
	≥5 cm	≥10 cm	≥60 cm	≥100 cm		≥5 cm	≥10 cm	≥60 cm	≥100 cm		≥5 cm	≥10 cm	≥60 cm	≥100 cm	
Pioneer bar	148	3	0	0	25	12	0.3	0.0	0.0	2	-135	-3	0	0	-23
Developing floodplain	11	1	0	0	4	9	1.2	0.0	0.0	4	-2	0	0	0	-1
Established floodplain	13	6	0.2	0	24	13	5.6	0.2	0.0	24	0	0	0	0	0
Old terrace	26	20	8.4	3.7	148	10	7.8	3.2	1.4	56	-16	-13	-5	-2	-92
All patches	198	31	8.6	3.7	201	45	15	3.4	1.4	86	-153	-16	-5	-2	-116
Percent change											-77%	-52%	-56%	-50%	-58%

Wood delivery (or recruitment) rates from pioneer bars and terraces declined substantially from the baseline period to the pre-restoration period (Fig. 10, 11), as inferred from on observed changes in patch erosion rates. In contrast, wood recruitment from developing and established floodplains remained largely unchanged. This is attributable to the fact that the overall increase in the extent of these patch types (through vegetation encroachment) compensated for declines in rate at which they eroded.

Table 11. Annual change in mean large wood (LW) recruitment rate by number of stems across riparian habitat unit types, by minimum stem diameter.

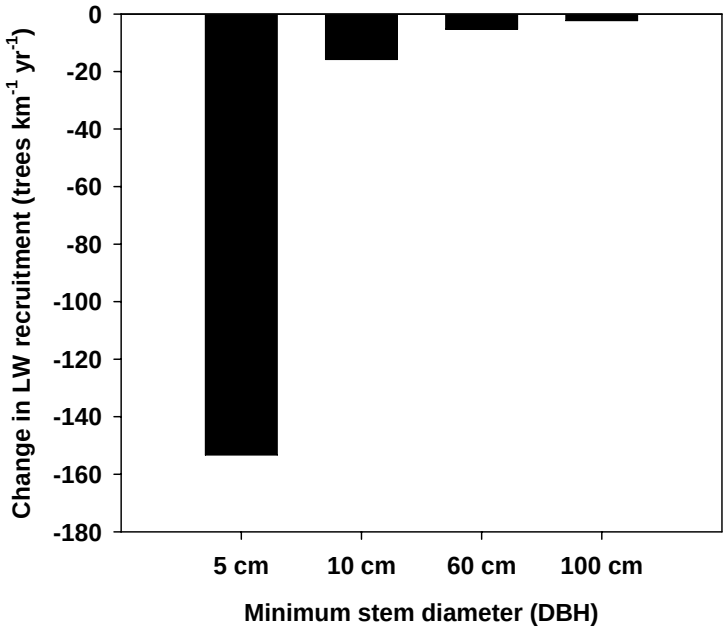
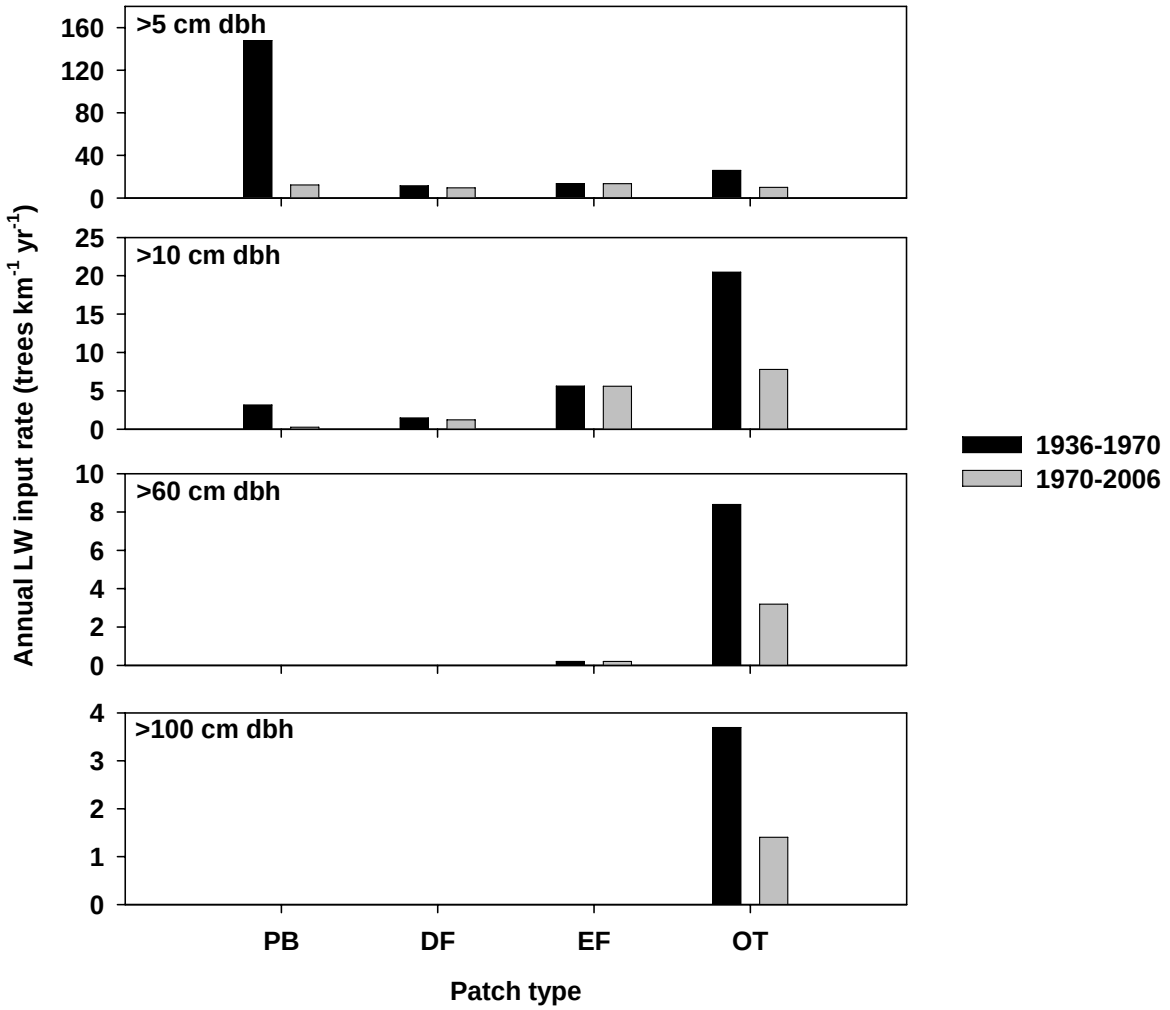
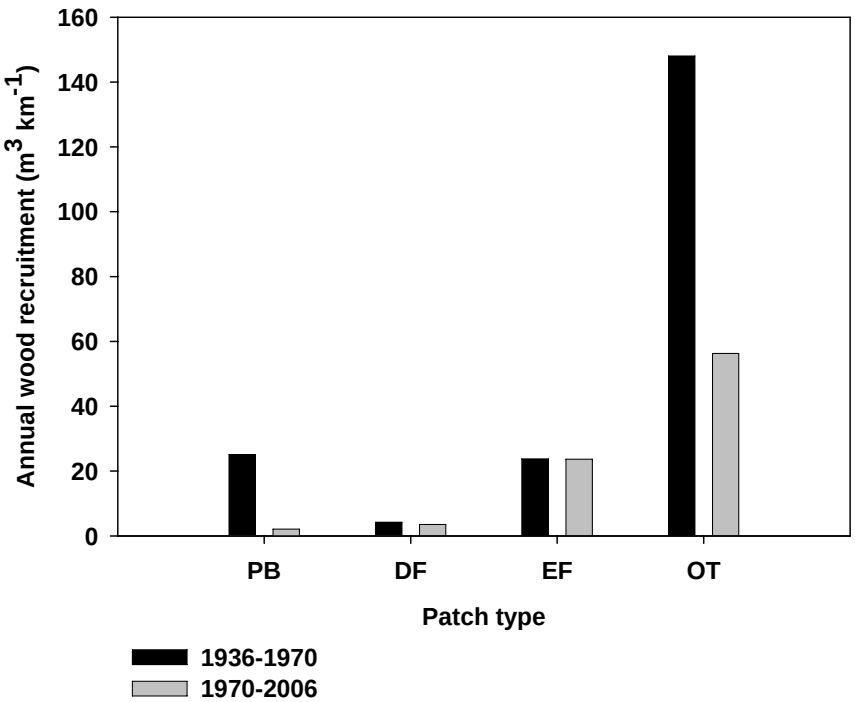


Figure 10. Comparison of annual large wood (LW) inputs rates, by number of stems, in the baseline (1936-1970) period and the pre-restoration (1970-2006) period.
Each panel indicates the minimum diameter at breast height (dbh) of the wood. Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); T (terrace).



Changes in volumetric wood delivery rates were pronounced in pioneer bars and terraces (Fig. 11). The volume of wood contributed by pioneer bars declined from 25 m^3 km^{-1} yr^{-1} in the baseline period to 2 m^3 km^{-1} yr^{-1} in the pre-restoration period; a 92% decline. The volume of wood contributed by developing and established floodplain patches was nearly identical between periods. An estimated 148 m^3 km^{-1} yr^{-1} of wood originated from terraces during the baseline period, compared to only 56 m^3 km^{-1} yr^{-1} in the pre-restoration period; a 62% decline.

Figure 11. Comparison of annual large wood (LW) inputs rates, by volume, in the baseline (1936-1970) period and the pre-restoration (1970-2006) period.
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); T (terrace).



Soil depth generally increased and became more uniform across the chronosequence of unit types, though patterns were not consistent. Terrace and established floodplain soils were deeper than those of pioneer bars and developing floodplains (Fig. 12). Soil depth varied substantially within younger unit types. For example, the coefficient of variation in soil depth was greatest (63%) in the pioneer bar (Table 12). Variation in soil depth is primarily attributable to the heterogeneous microtopography of the buried streambed in each unit. The uniformity of the soil depth in the terrace plot is misleading, however. In this unit, soil depth frequently exceeded the length of the soil probe and the cobble surfaces could not be detected. In this case, soil depth is represented as a minimum estimate.

Table 12. Soil characteristics in riparian habitat units.
Sample size (N) refers to the number of sampling points along the survey transect in a single plot. Soil texture refers to the percentage of points with texture indicated.

Unit type	Plot	N	Soil depth			Surficial soil texture		
			Mean	SD	CV	Silt	Fine sand	Coarse sand
Pioneer bar	4	26	0.71	0.45	0.63	0%	100%	0%
Developing floodplain	2	50	0.34	0.18	0.54	63%	35%	2%
Established floodplain	3	60	1.26	0.28	0.22	93%	0%	7%
Young terrace	5	80	1.10	0.39	0.35	99%	1%	0%
Old terrace	1	100	1.48	0.06	0.04	100%	0%	0%

Figure 12. Plot profiles showing soil depth (shaded)and water level elevation (horizontal gray lines) at time of survey.
The river stage was 16.63 m and the mean daily flow was 1,040 cfs at USGS station 12113000. The X-position indicates the distance along transects from the river margin (0 m) landward. Water levels were not measured at the young terrace plot. Note: The uniformity of the soil depth in the terrace plot is misleading, because soil depth frequently exceeded the length of the soil probe and the cobble surfaces could not be detected. In this case, soil depth is represented as a minimum estimate.

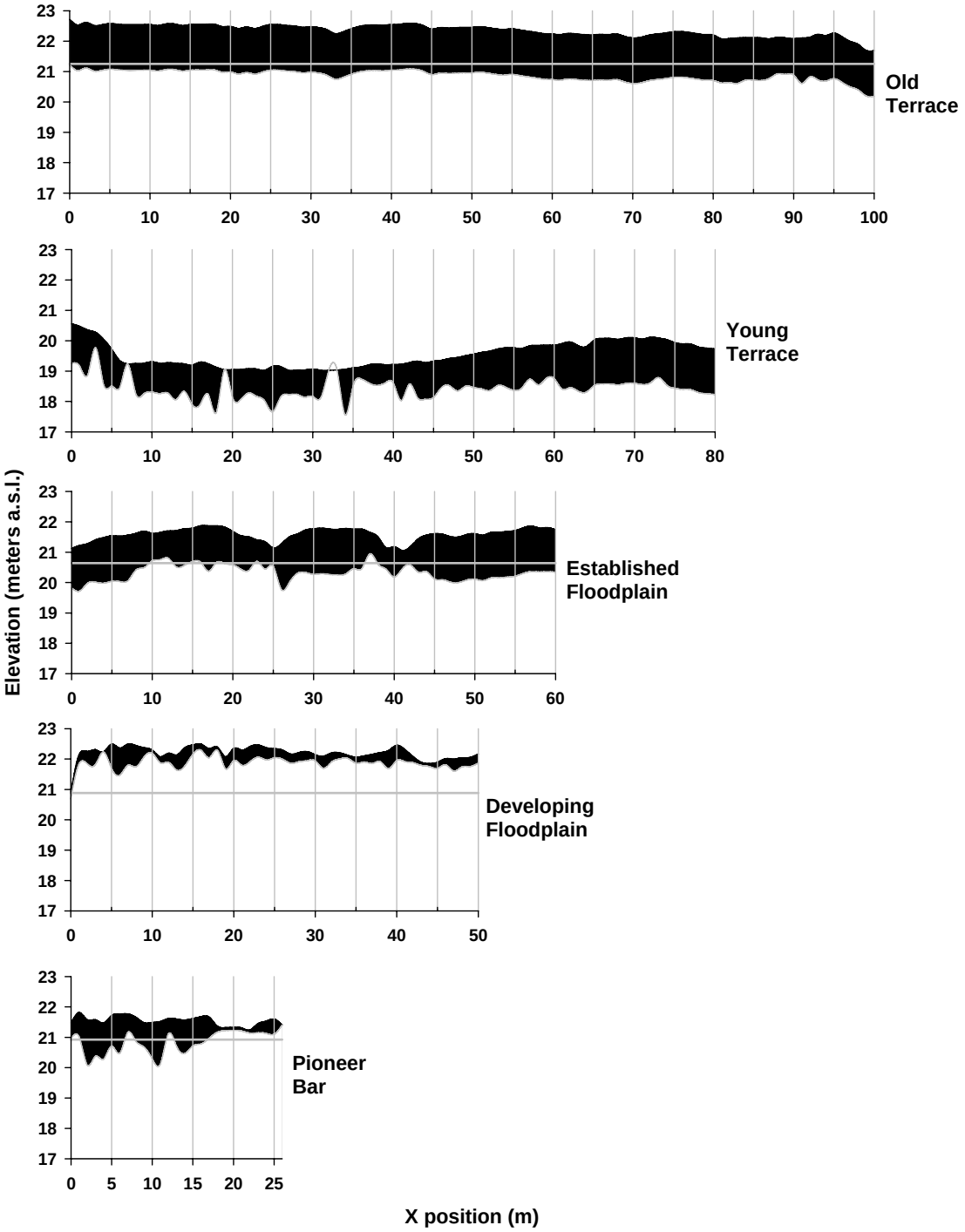
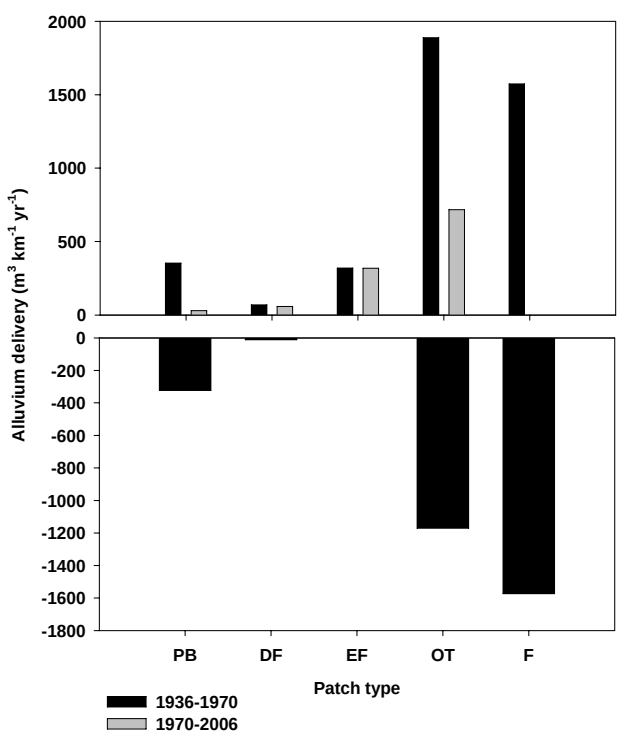


Table 13. Estimated fine alluvium delivery from erosion of forested landforms within the study area.
Delivery rates are calculated from the average area and erosion rate of each patch type during the baseline or pre-restoration period, and the potential fine alluvium delivery from each patch type based on observed average soil depth to cobble. Values for the old terrace and cross-patch summaries are underestimated because soil depth typically exceeded the length of the soil probe in that patch type. Soil depths in the field were assumed to be same as old terraces.

Patch	Baseline $m^3\ km^{-1}\ yr^{-1}$	Pre-restoration $m^3\ km^{-1}\ yr^{-1}$	Difference $m^3\ km^{-1}\ yr^{-1}$
Pioneer bar	353	30	-324
Developing floodplain	69	58	-12
Established floodplain	320	319	-1
Old terrace*	1888	718	-1170
Field	1573	0	-1573
All patches	4,204	1,124	-3,080
Percent change			-73%

Estimated changes in the delivery of alluvial soils to the channel from the erosion within the study segment were most pronounced in pioneer bars, old terraces, as well as historic agricultural fields (Fig. 13). Field soils were assumed to be 1.5 m deep, similar to the old terrace. Alluvium delivery rates declined by roughly 3,100 $m^3\ km^{-1}\ yr^{-1}$. During the baseline period, roughly 4,200 $m^3\ km^{-1}\ yr^{-1}$ of alluvium entered the channel, compared to only 1,100 $m^3\ km^{-1}\ yr^{-1}$ during the pre-restoration period. Approximately half (51%) of this decline is attributed to the protection of fields by bank hardening. Most of the remainder (38%) is attributed to reduced erosion of terraces.

Figure 13. Estimated fine alluvium delivery from erosion of forested landforms within the study area (top panel), and the estimate change between the baseline and pre-restoration period.
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); OT (old terrace); and F (field).



(R3) Tree Regeneration

Cottonwood seedling density was highest in the pioneer bar and developing floodplain patch, ranging from 192 to 375 stems ha^{-1}, respectively (Table 14). This observation is consistent with the expectation that cottonwood seedlings are regenerating naturally in young, frequently inundated patches with reasonably good access to water. Cottonwoods were the most abundant seedlings in the developing floodplain, outnumbering willow by 1.5:1. By contrast, pioneer bars were heavily dominated by willow, which outnumbered cottonwood seedlings by 62:1.

Table 14. Seedling densities by habitat unit type, tree species, and overall.

Plot	Patch	Sampled area	Seedlings	Seedling density (per ha)				
				All	Conifer	Cottonwood	Salix	Dogwood
4	pioneer bar	0.0104	126	12115	0	192	11827	0
2	developing floodplain	0.04	27	675	25	375	250	0
3	established floodplain	0.054	25	463	0	0	0	463
5	young terrace	0.096	209	2177	0	0	0	2156
1	old terrace	0.15	40	267	87	47	27	0

The great majority of tree regeneration has occurred in younger patch types. Cottonwood regeneration was not observed in the established floodplain or young terrace (Fig. 14). Several cottonwood seedlings were observed in the old terrace, though these were located at relatively low elevations near the river. Dogwoods, by comparison, emerged as a major component of the forest understory community in the established floodplain patches, and were even more common in the young terrace, where dogwood seedling densities exceeded 2,100 ha^{-1}. Natural conifer regeneration was only detected in the developing floodplain, where Douglas-firs had colonized relatively thin soils in areas with open canopy. The only other conifers that were detected, either as seedlings or larger stems, occurred in the old terrace (Fig. 15). These were planted prior to the main restoration project implementation (M. Bowles, *pers. comm.*). Assessments of cottonwood structural characteristics illustrate changes in the diameter, height, crown width, and canopy height across unit types (Fig. 15). The broad distribution of diameters in the old terrace is attributed to the inclusion of some young trees near the channel margin.

Airphoto-based measurements of vegetation colonization on bars indicate that bars were colonized by vegetation nearly twice as frequently during the pre-restoration period (Table 15).

Table 15. Vegetation colonization rates.
Vegetation colonization rate is presented as the percentage of unvegetated patches remaining vegetated after time *t*. The time required for 50% ($t_{0.50}$) and 95% ($t_{0.05}$) of patch area to be colonized is also indicated; as is the, percentage of patch area vegetated after a ten year period (10 yr). Relative change in the colonization rate *k* is shown.

Unit type	Baseline				Pre-restoration				Relative change
	k	$t_{0.50}$	$t_{0.05}$	10 yr	k	$t_{0.50}$	$t_{0.05}$	10 yr	k
Bar	-0.0302	23	99	26%	-0.0594	12	51	45%	97%
Wetted channel	-0.0187	37	160	17%	-0.0214	32	140	19%	14%

Figure 14. Seedling density in study plots.
Seedlings are trees < 5 cm diameter at breast height (DBH).

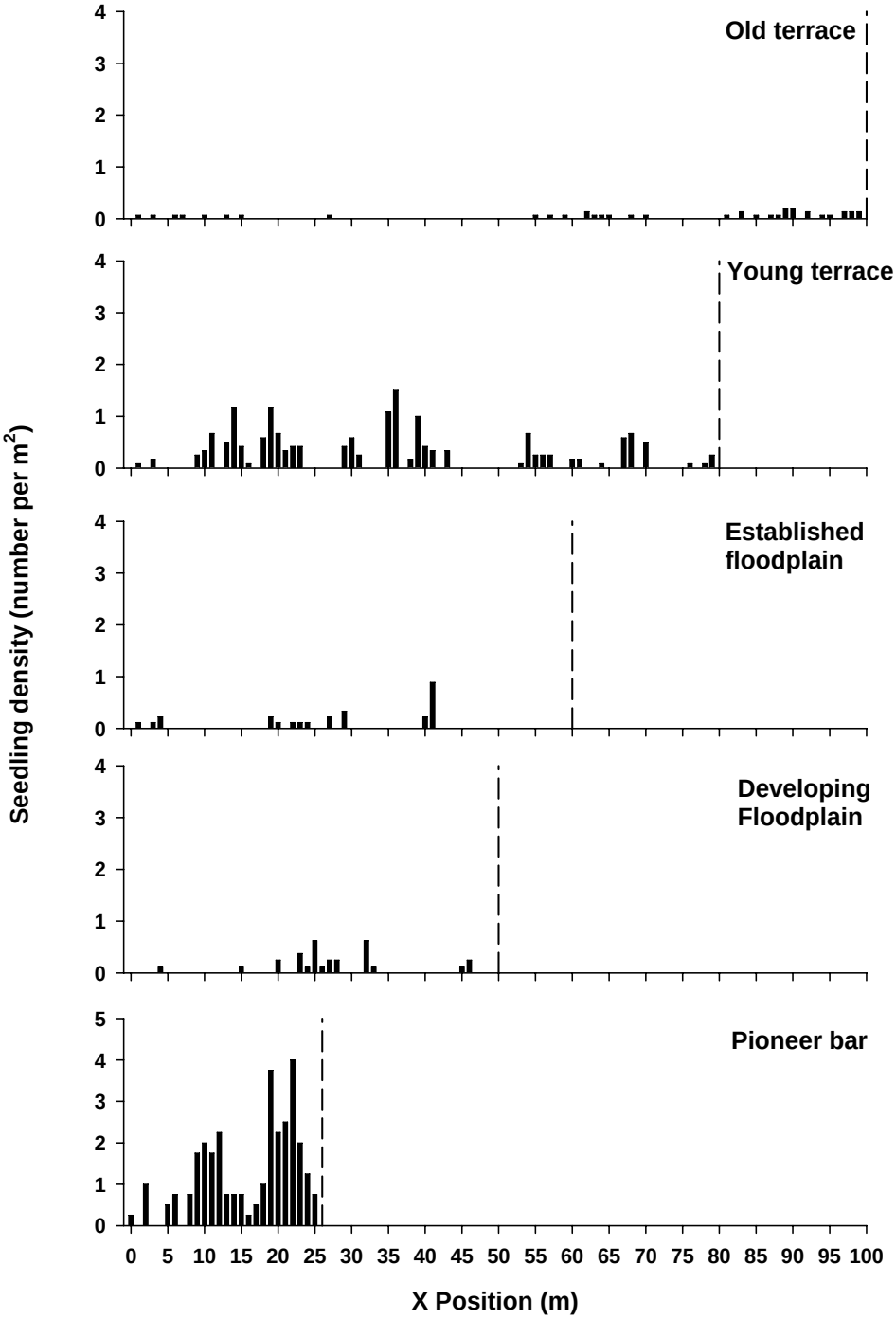


Figure 15. Comparison of seedling density by species with overall stem density and basal area (live and dead) across patch types.
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); YT (young terrace); OT (old terrace).

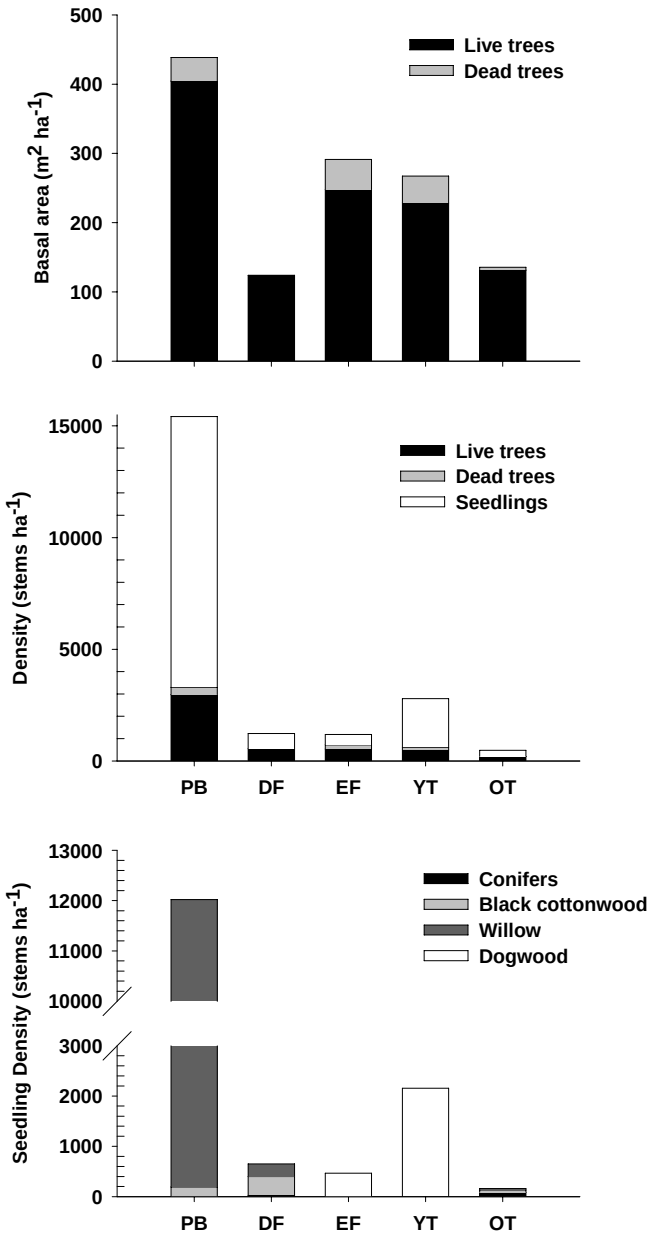
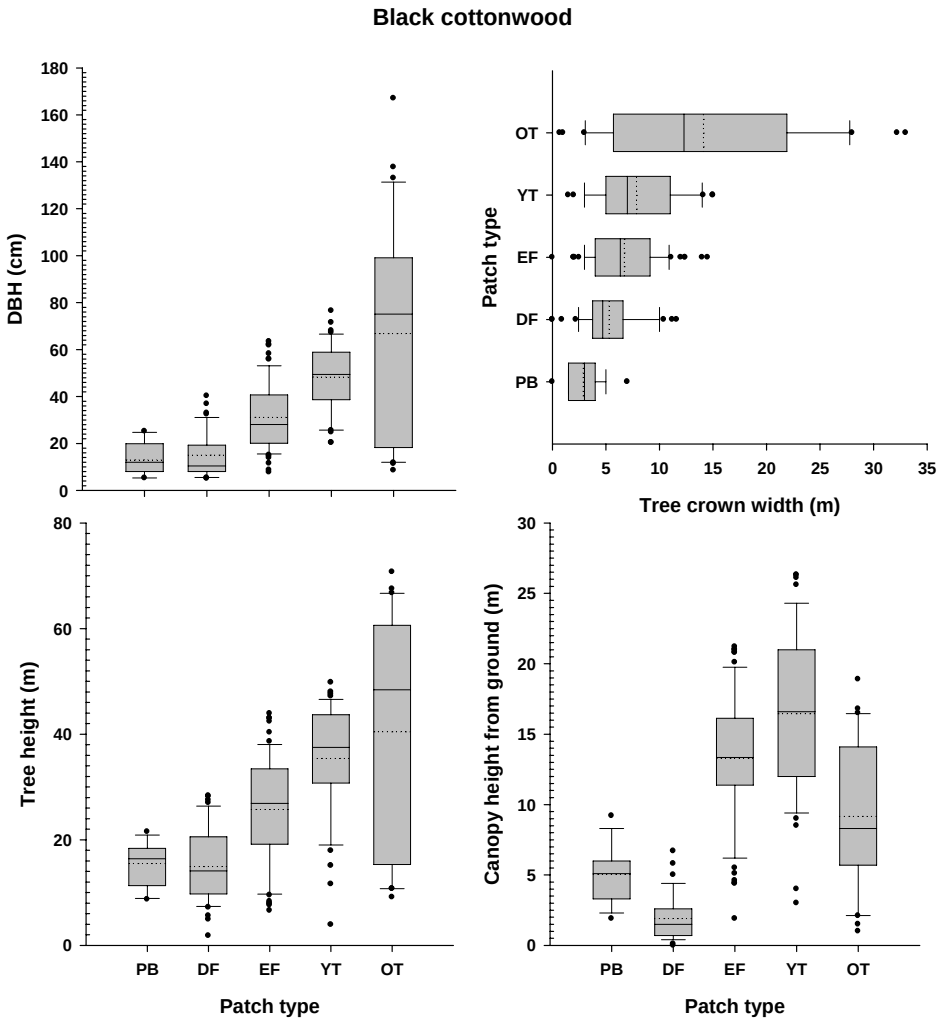


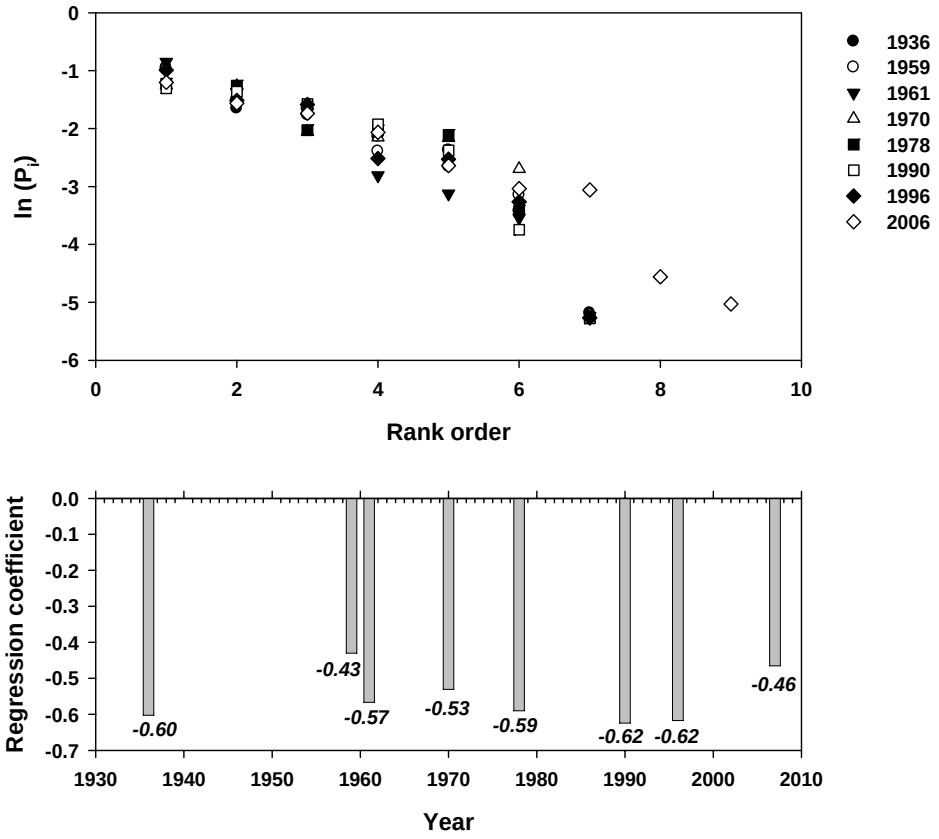
Figure 16. Characteristics of black cottonwood trees by unit type.
Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); YT (young terrace); OT (old terrace). Boxes indicate interquartile range of values. Horizontal lines in boxes represent the mean (bold) and median (thin). Whiskers show the 10th and 90th percentile values. Dots are outliers.



(R4) Forest Complexity

Riparian forest complexity, as indicated by planform metrics, has fluctuated substantially over the period of record but is currently higher than that observed in 1936. Current levels are comparable with the observed complexity in the late 1950's.

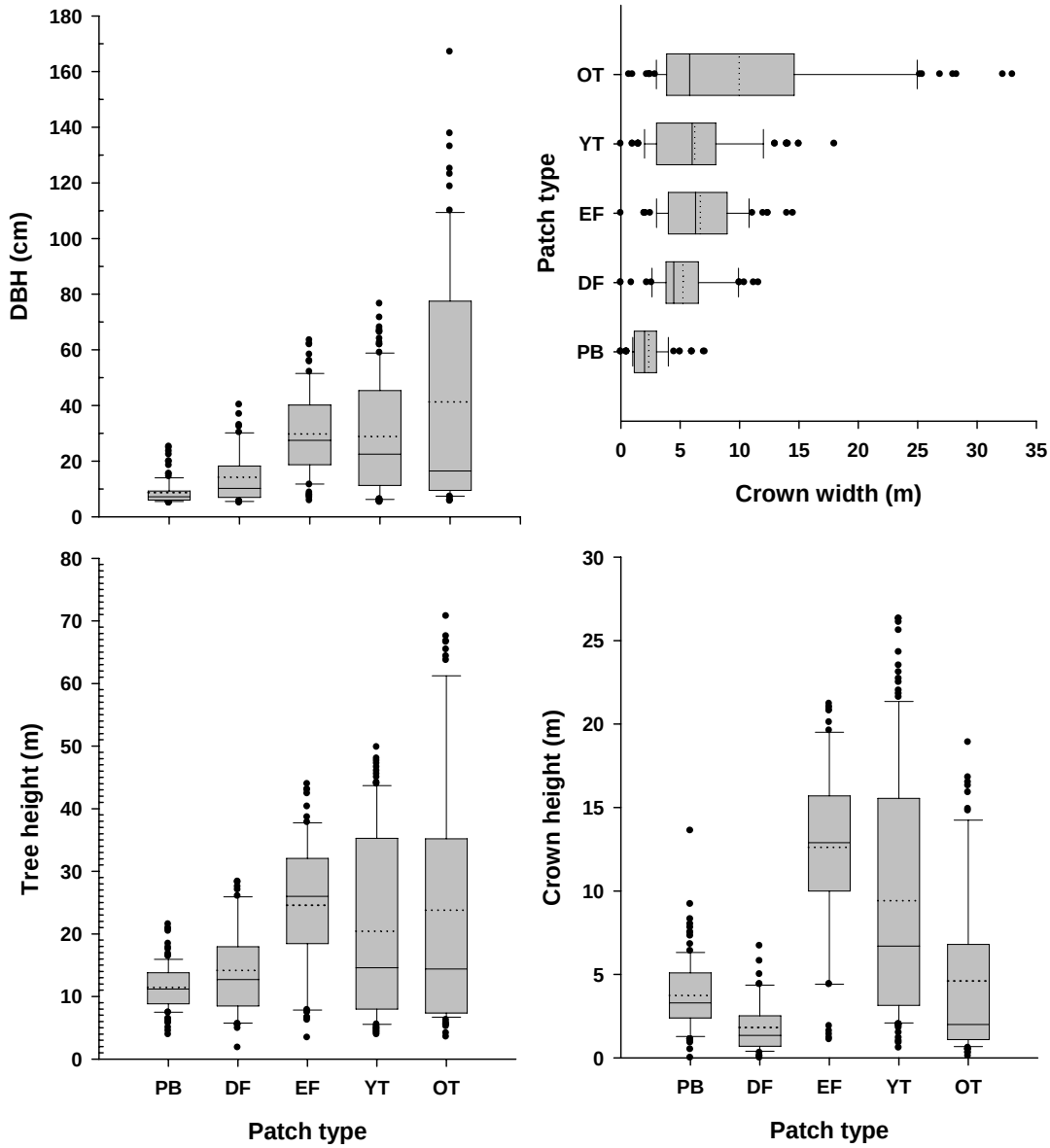
Figure 17. Riparian forest (planform) complexity.



Assessments of stand structure illustrate how structural complexity of riparian forests increases with stand age (across the chronosequence of patch types; Fig. 18). Box and whisker diagrams indicate that the distribution of stem diameter and tree heights expand greatly over time. Median diameters and crown widths increase consistently from young to old stands. Median tree heights remain relatively constant, however, beginning with established floodplains. Crown heights vary substantially and inconsistently among patches.

Figure 18. Stand structure, including diameter, stem height, crown height and width for all surveyed trees by patch type.

Height was overestimated for several trees in the old terrace plot. Unit type codes are: PB (pioneer bar); DF (developing floodplain); EF (established floodplain); YT (young terrace); OT (old terrace). Boxes indicate interquartile range of values. Horizontal lines in boxes represent the mean (bold) and median (thin). Whiskers show the 10th and 90th percentile values. Dots are outliers.



Aquatic habitat characteristics

(A1) Channel Dimensions, Branching, and Edge Habitat

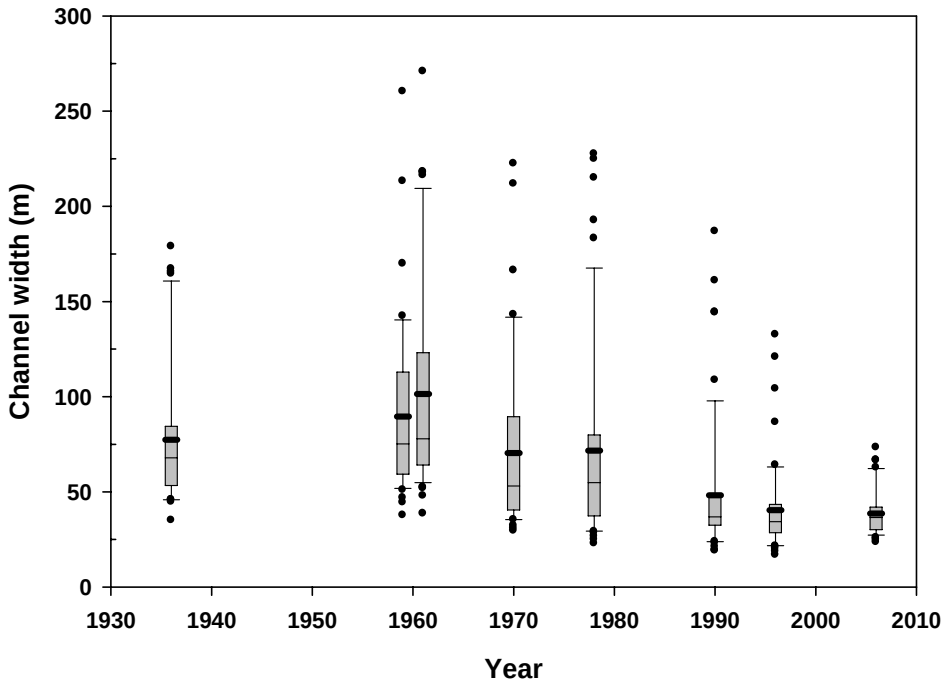
The channel has become substantially narrower within the study segment over the period of record (Table 16). Channel width fluctuated but remained relatively constant overall during the baseline period, averaging 84.5 m from 1936-1970. Government Land Office notes from 1867 report that the channel width was approximately 73 m near the study site. The similarity of this value to measurements from 1936 suggest that channel widths at the beginning of the baseline period were at least somewhat similar to those during true 'reference' conditions. Between the late 1970's and 2000's, channel width exhibited a steep year-to-year decline, which slowed from the mid-1990's to 2006 (Fig. 19). Spatial variability in the width of the channel exhibited a decline, as well. The current channel is substantially more uniform in width (CV = 32%) than it was during the baseline period (average CV = 53%), though the average coefficients of variation between the two periods were indistinguishable.

Table 16. Historical channel dimensions and characteristics.
Symbols for channel types are T (mainstem thalweg), M2 (secondary mainstem), S (side channel), BW (backwater), and E (engineered). In comparisons among baseline and pre-restoration periods, the false rejection (Type I error) rate is indicated by the *p*-value from *t*-tests, not assuming equal variances.

Year	Length (m)						Width (m)			Area (ha)	Sinuosity	Junctions	RC Index
	T	M2	S	BW	E.	Total	Mean	SD	CV	Wetted		(per RK)	
1867							73						
1936	2447	490	0	0	0	2937	77	36	47%	9.5	1.6	6	11
1959	2776	771	558	566	0	4672	90	44	50%	12.5	2.6	13	36
1961	2817	1785	0	355	0	4957	101	54	53%	13.9	2.7	10	30
1970	2904	653	1237	207	0	5001	70	44	63%	12.9	2.7	14	41
1978	3148	0	992	167	0	4307	72	52	73%	14.1	2.4	6	16
1990	3317	738	691	0	0	4746	48	35	73%	10.0	2.6	10	29
1996	3245	706	1164	66	0	5181	40	23	57%	9.8	2.8	16	48
2006	2412	768	1789	0	444	5413	39	12	32%	10.4	3.0	11	36
Baseline	2736	925	449	282	-	4391	82		53%	12.2	2.4	11	29
Pre-rest.	3030	553	1159	58	-	4911	48		58%	11.1	2.7	11	32
Mean diff.	+294	-372	+710	-224	444	+520	-32		+5%	-1.1	+0.3	0	+3
Mean diff. per km	+161	-204	+388	-123						-0.6	0.2	0.0	+1.6
Percent change	11%	-40%	158%	-79%		12%	-39%		9%	-9%	13%	11%	-40%
p	0.27	0.33	0.11	0.16		0.39	0.01		0.62	0.45	0.35	1.0	0.78

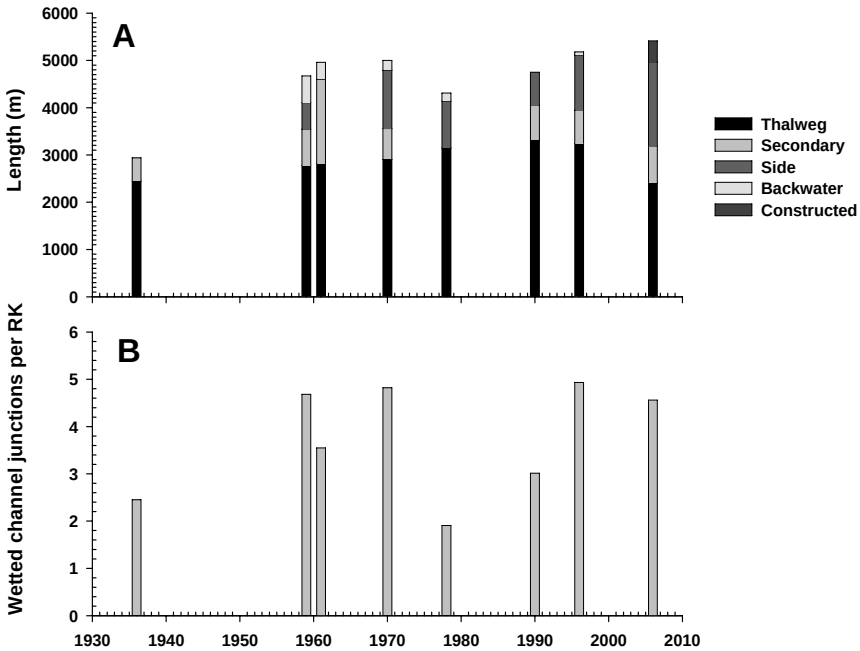
Changes in other metrics were less pronounced and inconsistent across time. Changes in the River Complexity (RC) Index strongly reflect differences in the number of channel junctions between years. Neither has changed consistently over time and both are quite variable. Channel sinuosity has fluctuated, but is slightly higher in the current condition than in 1936. Besides channel width, the strongest evidence for a difference between periods was observed in comparisons of the average side channel length, in which a 158% increase was noted in the pre-restoration period. The average length of backwater channels declined by 79%.

Figure 19. Channel width boxplots.
Boxes indicate interquartile range of values. Horizontal lines in boxes represent the mean (bold) and median (thin). Whiskers show the 10th and 90th percentile values. Dots are outliers.



The area of the pre-restoration wetted channel is comparable to that of the baseline period because declining channel width was offset by increases in the length of the mainstem and in side channels (Table 16, Fig. 20). Changes in the length of the mainstem and the total amount of side channel can be largely attributed to: (1) the occurrence of a chute cutoff in approximately 1996, which greatly shortened the thalweg and formed a large backwater and side channel in the abandoned channel; and (2) transitions between a multi-thread and single thread meandering channel pattern over time.

Figure 20. Channel length by channel type and year (A), and the frequency of channel junctions in the wetted channel (B).

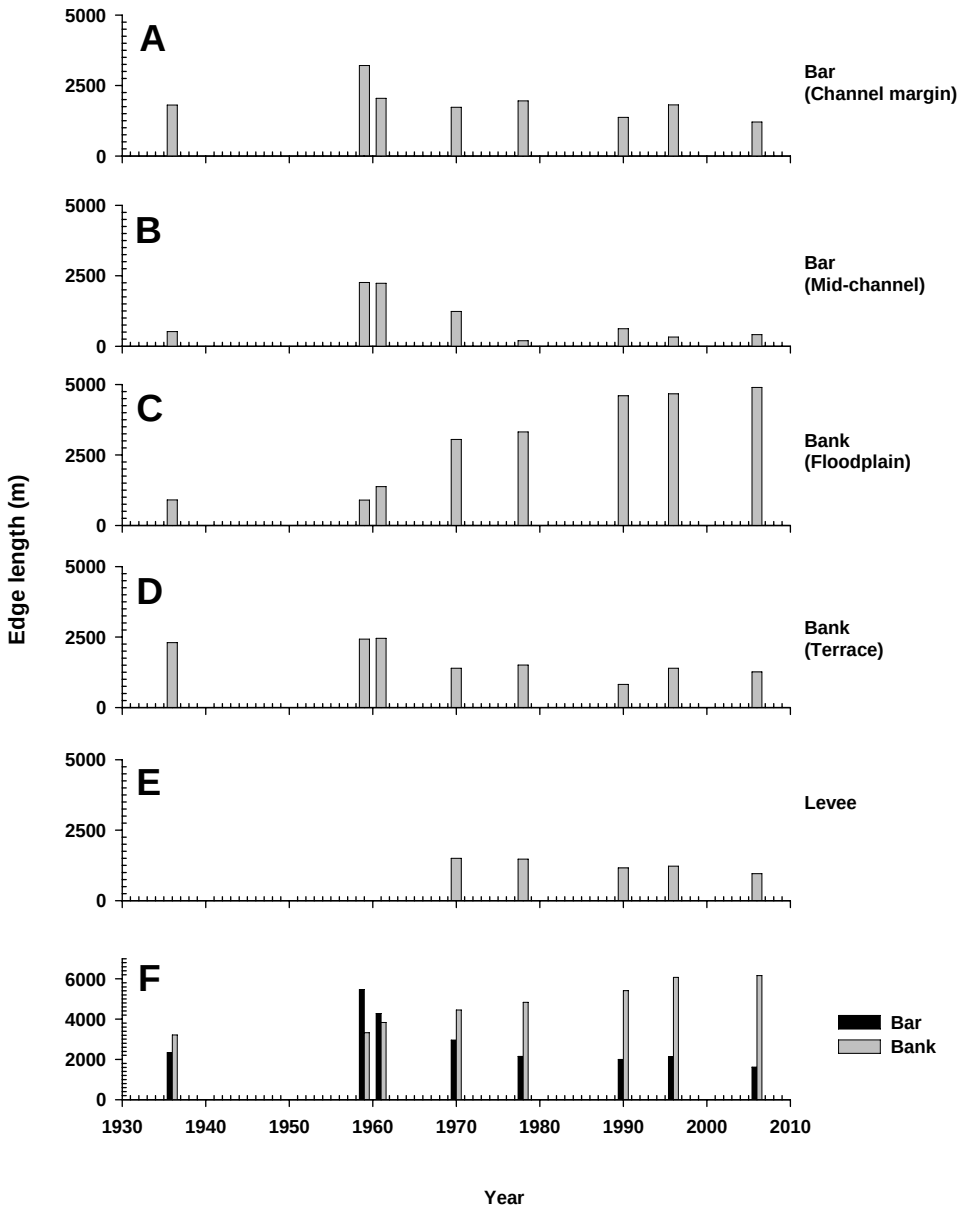


Bar edge habitat declined from the baseline to the pre-restoration period, and bank edge habitat increased (Table 17; See edge habitat maps in Appendix E). Both point bar and mid-channel bar edge habitat declined. In contrast, increases in bank edge habitat were driven by a near-doubling of floodplain bank, which overcame a 42% decline in terrace bank habitat. Total bank edge habitat increased by approximately half. The length of hardened bank length more than doubled during the pre-restoration period, the direct result of levee construction. Total edge length did not change substantially, however; a slight increase of 12% was observed. A key difference between the baseline and pre-restoration periods was that the amount of bank edge habitat had been similar to the amount of bar edge habitat during the baseline period, but bank edge habitat became far more prevalent by 2006 (Fig. 21).

Table 17. Edge habitat along the wetted channel by type and year.
The false rejection (Type I error) rate is indicated by the *p*-value from *t*-tests, not assuming equal variances.

		Bar (m km^{-1})		Bank (m km^{-1})			Hardened	Total Edge
Year	**Point**	**Mid-channel**	**Total**	**Floodplain**	**Terrace**	**Total**	**(m km^{-1})**	**(m km^{-1})**
1936	990	285	1274	497	1259	1755	0	3029
1959	1752	1237	2989	492	1328	1819	0	4809
1961	1117	1222	2339	752	1344	2095	0	4434
1970	945	676	1621	1669	763	2433	825	4878
1978	1067	108	1175	1814	827	2641	808	4624
1990	749	341	1090	2514	449	2963	638	4691
1996	991	179	1171	2552	764	3316	670	5157
2006	657	225	883	2679	693	3371	523	4777
Baseline	1201	855	2056	853	1174	2025	206	4288
Pre-restoration	866	213	1080	2390	683	3073	659	4812
Mean difference	-335	-642	-976	+1537	-490	+1047	+453	+524
Percent change	-28%	-75%	-47%	+180%	-42%	+52%	+220%	+12%
p	0.16	0.07	0.08	0.004	0.02	0.004	0.07	0.29

Figure 21. Total edge habitat length in the study segment by type (Panels A through E), and year. Total bar and bank length is shown in Panel F.



(A2) Logjams

Several sources of error contribute to uncertainty in estimates of historical wood loading in the study reach, including temporal variation in the ground resolution of airphotos, and temporal variation in the size of individual logs and their distribution within the river. Photo-based estimates have not been calibrated with on-the-ground measurements. Airphoto quality was insufficient to reliably identify large wood in several years, so quantities are only reported for five sampling events.

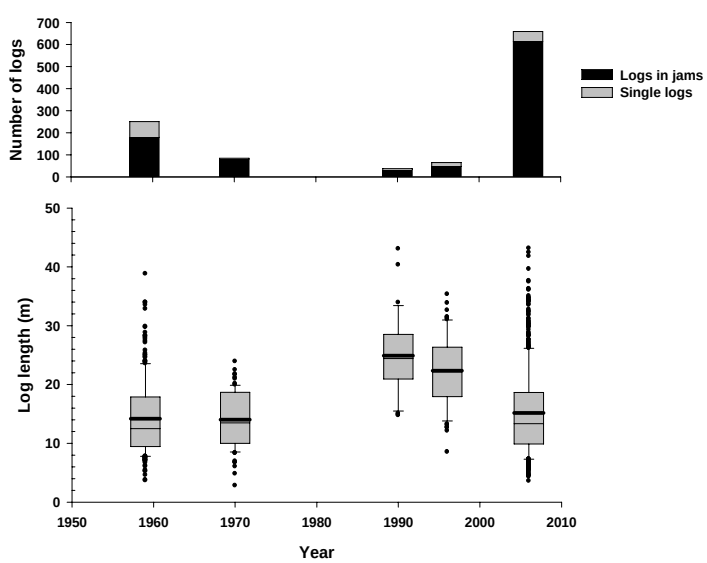
Large wood abundance, as determined from airphoto mapping ranged from 20 to 361 logs km^{-1} (Table 18; See maps of logs in Appendix F). Wood abundance declined by roughly 66% from 1959 to 1970. From 1970-1996 wood abundance was low, ranging from 20-46 logs km^{-1}. However, the estimated number of logs in the study reach in 2006 exceeds that observed in 1959 by a factor of 2.6. Most of the logs present in 2006 are large cottonwoods that originated from local stands that were eroded during a major chute cutoff occurring after 1996.

Table 18. Large wood abundance, log length, and log jam characteristics.

Year	Logs km^{-1}		Log length (m)				Jams			
	Total	Percent in jams	Mean	SD	Max	Median	Count km^{-1}	Mean no. logs	SD	Max
1959	137	72%	14	21	39	12	5	25	22	58
1970	46	95%	14	16	24	13	3	46	8	29
1990	20	89%	25	22	43	24	1	33		33
1996	36	74%	22	20	35	22	1	24	18	37
2006	361	93%	15	24	43	13	2	154	271	560

On average, 85% of the large wood pieces in the study reach was accumulated in jams, ranging from 72 to 95% across years. Jam density was low in each year of the study. Jam size, in terms of the number of pieces in each jam varied widely among years. The largest jam was observed in 2006, in which a jam containing at least 560 logs spanned the channel, resulting from the previous chute cutoff that began to form in 1996.

Figure 22. Total large wood abundance and log dimensions derived from airphotos over study segment.



Synthesis

Changes from baseline to pre-restoration conditions

This study confirms that important channel and riparian processes and aquatic habitats have changed between baseline and pre-restoration time periods (Table 19).

Table 19. Comparison of notable changes from baseline to pre-restoration conditions and potential driving factors.

Category	Hypothesis	Most Notable Changes	Potential Driving Factors
Channel processes	C1	▪ Conversion from dynamic multi-thread channel to stable single thread meandering channel. ▪ Reduced lateral migration ▪ Loss of channel switching ▪ Occurrence of avulsion	▪ Increased bank resistance ▪ Siltation of secondary channels ▪ Reduced shear stress on bed ▪ Aggradation upstream from logjams and meander bends and headcutting across point bar
Riparian processes	R1	▪ Loss of unvegetated gravel bars ▪ Increased longevity (reduced turnover rate) of all forest patches, especially pioneer bars	▪ Reduced channel migration ▪ Increased survival of pioneering vegetation
	R2	▪ Reduced delivery of all size classes of wood ▪ Reduced delivery especially from pioneer bars (small pieces) and from old terraces (large pieces) ▪ Large decline in volumetric delivery rate from old terraces ▪ Reduced local sediment delivery	▪ Reduced channel migration ▪ Expansion of developing and established floodplain vegetation compensated for reduced erosion rate
	R3	▪ Enhanced tree regeneration success for deciduous species, particularly willow but also including cottonwood. ▪ Regeneration gap appears likely due to declines of new, unvegetated bars ▪ Very little conifer regeneration, except in dry, rocky locations.	▪ Increased survival rate of pioneering vegetation due to altered disturbance frequency and magnitude ▪ Lack of either dry, coarse substrates for Douglas-fir regeneration or floodplain large wood for Sitka spruce and hemlock.
	R4	▪ Little change in planform forest complexity, though reduced complexity is anticipated in coming decades unless new unvegetated bars are replaced.	▪ Colonization of gravel bars compensated forestalled losses in planform complexity that lag behind impacts of channel confinement.
Aquatic habitat	A1	▪ Decline in channel width and increasing uniformity in width ▪ Increase in side channel length ▪ Declines in bar edge and terrace bank edge habitat ▪ Increases in floodplain bank edge habitat ▪ Increase in hardened bank	▪ Reduced channel migration ▪ Shift in channel pattern ▪ Avulsion ▪ Afforestation of gravel bars ▪ Levee construction ▪ Forest clearing
	A2	▪ Recent increase in wood loading and jam size	▪ Punctuated wood delivery from channel avulsion through gallery forest

Interpretation of baseline conditions

The use of baseline conditions from the early 20th century is intended to provide benchmarks to determine how successful restoration projects will be in returning the system to a condition during which Green River salmon populations were stronger and habitat was acknowledged to be relatively more productive than it is now. However, returning the river to a pre-levee condition is not the same as returning it to a pristine state. It is assumed that pristine conditions are unattainable under the modified flow regime and existing land use and infrastructure. Baseline conditions characterized in this study reflect up to 60 years of prior human impacts, including historic snagging, land use conversion, forest clearing, and construction of transportation infrastructure, and therefore do not represent pristine conditions. Whether attaining these benchmarks results in sufficient improvement in salmon habitat productivity remains to be determined. It is important to correctly interpret the outputs of this study in accordance with these assumptions to avoid the pitfalls of 'creeping baselines'.

Expectations for post-restoration period

In the post-restoration period, the restoration efforts may be considered successful if most of the hypotheses are validated. If so, the river segment should exhibit a shifting mosaic steady state (Latterell et al. 2006; Stanford 2006), where conditions (e.g., the composition of the landscape and biological communities) and processes (e.g., rates of bank erosion, cutoffs, vegetation establishment) fluctuate over time but are relatively predictable and increasingly stable over the long term. The specific distribution, sequencing, and extent of the changes are somewhat uncertain. This uncertainty is in part, the result of the underlying dynamics of the river ecosystem.

For example, a common assumption is that by replacing missing structures and alleviating constraints on impaired processes, the river will 'return' to baseline conditions. This may be true if the riverine ecosystem has a single equilibrium point, and is strongly regulated by local (internal) processes and stabilizing (negative) feedbacks (Suding and Gross 2006). If so, conditions should move steadily toward equilibrium conditions over time. Restoration goals and trajectories can therefore be stated precisely because system dynamics are relatively predictable, at least at large scales.

However, if the ecosystem exhibits non-equilibrium dynamics (and multiple stable states), or persistent non-equilibrium dynamics, then future conditions will be relatively unpredictable; the system cannot be expected to trend toward a single condition (Suding and Gross 2006). In this case, the future state of the system may be strongly influenced by external factors such as climatic variation (droughts and floods), chance dispersal events, or the biological legacies of past events (landslides, cutoffs, and logjams). The quantitative benchmarks outlined in Table 20 should be interpreted in a fashion consistent with the issues described here.

Table 20. Quantitative benchmarks for post-restoration conditions relative to baseline.

Category	Hypothesis	Evaluation Metric (Indicator)	Units	Baseline conditions	Pre-restoration conditions	Benchmarks for post-restoration (percent of baseline)		
						50%	75%	90%
Channel processes	C1	Median meandering rate (R)	m yr^{-1}	2.3	0.9	1.2	1.7	2.1
		Median meandering rate (L)	m yr^{-1}	1.7	0.5	0.9	1.3	1.5
		Median channel switching rate (R)	m yr^{-1}	1.1	0.0	0.6	0.8	1.0
		Median channel switching rate (L)	m yr^{-1}	9.3	0.1	4.7	7.0	8.4
Riparian processes	R1	Pioneer bar erosion rate	*k*	-0.0316	-0.0059	-0.0158	-0.0237	-0.0284
		Developing floodplain erosion rate	*k*	-0.0114	-0.0058	-0.0057	-0.0086	-0.0103
		Established floodplain erosion rate	*k*	-0.0082	-0.0045	-0.0041	-0.0062	-0.0074
		Terrace erosion rate	*k*	-0.0123	-0.0057	-0.0062	-0.0092	-0.0111
		Field erosion rate	*k*	-0.0081	-0.0	-0.0041	-0.0061	-0.0073
		Bar area	ha km^{-1}	7.9	4.4	4.0	5.9	7.1
		Pioneer bar area	ha km^{-1}	2.9	1.3	1.5	2.2	2.6
	R2	Wood pieces > 5 cm	no. km^{-1} yr^{-1}	198	45	99	149	178
		Wood pieces > 10 cm	no. km^{-1} yr^{-1}	31	15	16	23	28
		Wood pieces > 60 cm	no. km^{-1} yr^{-1}	8.6	3.4	4	6	8
		Wood pieces > 100 cm	no. km^{-1} yr^{-1}	3.7	1.4	2	3	3
		Wood volume	m^3 km^{-1} yr^{-1}	201	86	101	151	181
		Alluvium delivery	m^3 km^{-1} yr^{-1}	4204	1124	2102	3153	3784
	R3	Wetted channel colonization	*k*	-0.0302	-0.0594	-0.0151	-0.0227	-0.0272
		Bar colonization	*k*	-0.0187	-0.0214	-0.0094	-0.0140	-0.0168
		Tree regeneration in pioneer bars	Seedlings ha^{-1}	-	~200 *Populus* @ 9 yrs	-	-	-
		Tree regeneration in developing floodplains	Seedlings ha^{-1}	-	~25 conifer @ 15 yrs	-	-	-
	R4	Planform complexity of riparian forest	Average slope coefficient from rank-abundance plots	-0.53	0.57	-0.27	-0.40	-0.48
Aquatic habitat	A1	Channel width	m	82	48	41	62	74
		Secondary mainstem length	m	925	553	463	694	833
		Side channel length	m	449	1159	225	337	404
		Backwater channel length	m	282	58	141	212	254
		Bar edge	m	2056	1080	1028	1542	1850
		Bank edge	m	2025	3073	1013	1519	1823
	A2	Logjam frequency	no. km^{-1}	5* (in 1959)		-	-	-
		Large wood number	no. km^{-1}		361* (in 2006)	-	-	-

*Some metrics are not listed here because they did not change substantially from baseline to post-restoration.

Post-Restoration Workplan

This report constitutes the baseline monitoring, and additional studies will be necessary to evaluate restoration effectiveness (Table 21). In order to ensure data compatibility with results presented herein, future surveys should use the same sampling and analysis protocols. The long duration of the post-restoration surveys reflects the fact that many of the key floodplain processes occur over years to decades and a similar amount of time may be required to detect and interpret meaningful responses. Sampling frequency should be increased as resources and logistics allow.

Table 21. Suggested workplan for post-restoration surveys.

Category	Hypothesis	Metric	Sampling frequency and interval	Primary Sampling Method
Channel processes	C1	Channel migration	At least one airphoto series every five years for 20 years	Airphoto analysis
Riparian processes	R1	Forest erosion rate	At least one airphoto series every five years for 20 years	Airphoto analysis
	R2	Wood and sediment delivery	At least one airphoto series every five years for 20 years	Airphoto analysis
	R3	Tree regeneration	Repeat field surveys in existing and new study plots in 2012 and 2017	Field survey
	R4	Forest complexity	At least one airphoto series every five years for 20 years, repeat field surveys in existing and new study plots in 2012 and 2017	Airphoto analysis and field survey
Aquatic habitat	A1	Channel dimensions and edge habitat	At least one airphoto series every five years for 20 years, coupled with simultaneous field surveys to map aquatic habitat units	Airphoto analysis
	A2	Logjam frequency, size, and longevity	At least one airphoto series every five years for 20 years, coupled with simultaneous field surveys. **Use expanded methodology from Appendix G.	Airphoto analysis and field survey

Limitations

In addition to the limitations related to basic assumptions about how rivers respond to restoration, this study is affected by sampling error and measurement error, which in combination determine the total study error. The total study error limits the estimation accuracy of indicator metrics and the decisions that are based on their interpretation.

The primary sources of potential sampling error in this study are related to the inherent variability in the landscape, and to sampling design. This study imposed a patch type classification scheme on a continuum of riparian conditions. Stratification necessarily oversimplifies the true variation in nature. Additionally, the patches were assumed to be internally homogenous – representative of that patch type – though estimates are certainly influenced by the inclusion of transitional areas between patches and other kinds of edge effects. Logistical constraints limited the sample size to one study plot in each patch type, forcing the assumption that each sample adequately describes the average condition of that patch type. The variability within patch types could not be quantified. To maximize the chance that samples were indeed representative, patches were selected purposefully in the field and other patches of a given type did not have an equal chance of selection. Forest structure and soil characteristics in existing stands were assumed to be representative of the same patch type during baseline conditions. The veracity of this assumption cannot be verified.

The primary sources of measurement error are related to the accuracy and precision of tree size and position measurements, soil depth measurements, aerial photo mosiacs, photo-interpretation, and maps based on heads-up digitizing. Tree diameter measurements are precise. Tree heights are accurate for pioneer bars, developing and established floodplains, but relatively inaccurate in young and old terraces. The laser rangefinder routine used to measure tree height was designed for conifers, which often have a single, straight stem that extends to the highest point, permitting simple trigonometric calcuations. Cottonwoods, however have a more indeterminate canopy lacking a single central stem at the highest point. This apparently added substantial error and bias into height estimates, causing relatively tall trees to be overestimated. Soil depth measurements in the terrace plot could only be used as minimum estimates because the soil probe was not long enough to penetrate to cobble. Some spatial error is also likely present in the aerial photo mosaics used as base maps for planform maps of channel and forest features. Additional error is introduced by potential misinterpretation of visual cues when mapping features through heads up digitizing. Sources of measurement error related to data handling – for example, transcription error – were avoided by entering field data in a Pocket PC computer which allow measurements to be downloaded without transcription.

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