ANTHROPOGENIC HABITAT CHANGE EFFECTS ON FISH ASSEMBLAGES OF THE MIDDLE AND LOWER YELLOWSTONE RIVER

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EXECUTIVE SUMMARY

The Yellowstone River remains the longest unimpounded river in the conterminous United States. However, bank stabilization and floodplain dikes have altered its fish habitat. Therefore, I surveyed fish habitat and fish from Laurel to Sidney, Montana, to (1) quantify changes to side channels attributable to linear bank stabilization and floodplain dikes, (2) compare the habitat use of side channels to main channels by small fish during runoff and base flow, and (3) determine if bank stabilization and side channels influenced main-channel fish assemblages during base flow.

Floodplain dike frequency, but not linear bank-stabilization extent, directly correlated to a net loss of side channels from the 1950s to 2001. However, side channels provided important fish habitat. Fish catch rates were similar between side and main channels during base flow, but not during runoff when catch rates in side channels were several times higher than in main channels and assemblage structure differed between side and main channels. Shallow, slow-current velocity (SSCV) habitats were slightly slower in side channels and SSCV patches were larger in side channels than in main channels during runoff, but not during base flow. These habitat differences likely partially explained the patterns in fish catch rates between channel types.

During base flow, fish assemblages in main channels varied with bank-stabilization extent and side-channel availability in alluvial (unconfined) and bluff (confined) river bends. Bank stabilization and side channels had different and sometimes opposite influences on fish assemblage structure. Influences of bank stabilization and side channels on fish relative abundances varied depending on species and river bend geomorphology. Assemblage responses to side channels were more consistent and widespread than to bank stabilization, and more fish species were associated with side channels than bank stabilization. Physical differences probably contributed to the assemblage differences between reference and stabilized river bends; stabilized alluvial pools were deeper than reference alluvial pools. The strengths of the relationships among fish assemblages, bank stabilization, and side channels were spatial scale-dependent; optimum scales ranged from less than 200 m to 3,200 m up- and down-stream, suggesting that bank stabilization and side channels influenced fish across multiple spatial scales.

CHAPTER ONE

INTRODUCTION

The physical alteration of large rivers by anthropogenic bank-stabilization structures has uncertain consequences for fish assemblages. Banks are stabilized to prevent erosion of agricultural, residential, and urban lands, and to protect transportation structures such as roads, railroads, and bridges. However, such alterations result in concomitant changes in local main-channel bathymetry such as main-channel bed degradation, channel width reduction, and increased stream gradient (Stern and Stern 1980; Heede 1986; Shields et al. 1995). Moreover, bank stabilization may decrease floodplain connectivity and normal riverine processes such as lateral channel migration and the formation of backwaters, braids, and side channels (Leopold 1964; Stern and Stern 1980; Shields et al. 1995; Schmetterling et al. 2001; Auble et al. 2004).

Stabilization of Yellowstone River banks has been controversial (Kesselheim 2000) because it is the longest unimpounded river in the contiguous United States and its floodplain is largely intact (Koch et al. 1977; White and Bramblett 1993). The effects of anthropogenic stabilization structures on the lower Yellowstone River fish assemblage were unknown at the onset of this study. For example, it was unknown how much, if any, side channel habitat had been lost, and the importance of lower Yellowstone River side channels to the entire fishery had never been assessed. Moreover, the potential effects of bank stabilization on the Yellowstone River fish assemblage had not been examined directly in the lower Yellowstone River from Laurel to Sidney, Montana. Therefore, I quantified (1) changes in Yellowstone River side-channel areas from the

1950s to 2001 and determined if anthropogenic structures influenced these changes, (2) the habitat use of Yellowstone River fish of side and main channels during different hydroperiods, and (3) the responses of the main-stem Yellowstone River fish assemblage to bank stabilization and side channels using a spatially-explicit framework.

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CHAPTER TWO

CUMULATIVE EFFECTS OF FLOODPLAIN DIKES AND LINEAR BANK STABILIZATION ON YELLOWSTONE RIVER SIDE CHANNELS

Abstract

The lower Yellowstone River channel planform has transitioned away from multi-threaded and towards single-threaded during the second half of the 20th century, indicating a loss of side channels during this period. We hypothesized that installation of floodplain dikes and linear bank stabilization contributed to side-channel loss. We quantified the loss and gain of side channels by comparing aerial photographs from the 1950s and 2001. Side-channel loss exceeded side-channel gain in both number and areal extent. We investigated side-channel loss and side-channel gain as functions of dike frequency and bank-stabilization extent in actively migrating channels. Dike frequency was positively correlated with side-channel loss, but had no correlation with side-channel gain. Linear bank-stabilization extent correlated with neither side-channel loss nor side-channel gain. We conclude that dikes, and other anthropogenic structures that block scouring flows in side channels, contribute to reductions in Yellowstone River side-channel number and areal extent.

Introduction

The Yellowstone River is the longest unimpounded river in the contiguous United States (Figure 2.1; 1,091 km) and its floodplain has been described as largely intact (Koch et al. 1977; White and Bramblett 1993). However, Yellowstone River channel complexity has decreased; both braiding and river complexity declined markedly from the 1950s to 2001 in anabranching and braided reaches (Thatcher and Boyd 2007). At least two factors may be contributing to the loss of side channels. First, damming of the Bighorn and Tongue rivers altered the natural hydrologic regimes of these tributaries and reduced sediment inputs into the Yellowstone River (White and Bramblett 1993). Reductions in peak flows reduce scour potential during runoff and thereby enable vegetation encroachment and atrophy of side channels (Johnson 1994). Moreover, reduced sediment inputs can cause main-channel incision (Simon and Darby 1999) and consequently side-channel dewatering (Wohl 2004). Second, channel engineering structures may contribute to channel simplification. Linear bank stabilization (e.g., levees and riprap) and flow-diversion structures (e.g., dikes) are constructed to protect economically valuable lands and transportation structures from erosion, and can accelerate side-channel loss and attenuate side-channel formation (Wohl 2004). In particular, floodplain dikes directly block or reduce scouring flows in side channels causing atrophy or abandonment. Similarly, linear bank stabilization can block side channels and can also accelerate side-channel senescence or attenuate side-channel formation through a synergy of degrading the main channel bed, arresting channel migration, and decreasing rates of avulsion (Stern and Stern 1980; Wohl 2004; Florsheim et al. 2008).

Geomorphic responses to channel engineering structures can have subsequent consequences for riverine biotic communities. Side-channel loss reduces lateral connectivity, habitat heterogeneity, and habitat suitability for fish and other animals (Amoros and Bornette 2002). Reductions in lateral connectivity have detrimental effects on the biodiversity and biomass of fish (Junk 1989; Miranda 2005), amphibians (Tockner et al. 2006), turtles (Bodie et al. 2000), birds (Rumble and Gobeille 1998, 2004), and other riverine organisms (Amoros and Bornette 2002).

Here, we investigate the effects of floodplain dikes and bank stabilization on side-channel loss in the Yellowstone River to understand how channel engineering affects riverine communities. We hypothesized that floodplain dikes and bank stabilization influenced the balance of side-channel loss and gain and thus contributed to the observed reduction in side-channel habitat. To test this hypothesis, we quantified the areal changes in side channels in the lower Yellowstone River from the 1950s to 2001 and related these changes to floodplain dike frequency and bank stabilization extent.

Study Area

The Yellowstone River originates in northwestern Wyoming, flows north to Livingston, Montana, then generally northeast to its confluence with the Missouri River in North Dakota (Figure 2.1). The basin size of this 8th order stream is 182,336 km^2

(White and Bramblett 1993). Its hydrology is driven by snowmelt with peak runoff usually occurring in June. From Yellowstone County (inclusive of the confluence with the Clarks Fork Yellowstone River) to the confluence with the Missouri River, the Yellowstone River's hydrology is altered by dams on two of its major tributaries (the Bighorn and Tongue rivers) and by water withdrawals from six low-head irrigation dams (White and Bramblett 1993) and at least five industrial intakes, eight municipal intakes, 16 headgates, and 144 water pumps (estimates from the 2001 rapid aerial inventory; Yellowstone River Corridor Resource Clearinghouse 2013). Consequently, peak flows and summer base flows have been attenuated; estimated present-day mean monthly flows at Sidney, Montana, were 28% less during June and 46% less during August than if the Yellowstone's hydrology were unaltered (Chase 2013).

The study area was the main-stem Yellowstone River from its confluence with the Clarks Fork Yellowstone River near Billings, Montana, downstream to its confluence with the Missouri River. The study area is characterized by diverse channel planforms that result from valley-wall constriction or lack thereof (Koch et al. 1977; Silverman and Tomlinsen 1984; Boyd and Thatcher 2004). Reaches with valley-wall constriction are meandering or straight, whereas unconstrained reaches are braided or anabranching with islands (Koch et al. 1977; Boyd and Thatcher 2004). Constricted reaches have channels that rarely migrate and few, if any, side channels. However, unconstrained reaches have channels that actively migrate and extensive side channels. Unconstrained reaches, especially those between the Bighorn and Powder River confluences, have experienced reductions in braiding parameter (Thatcher and Boyd 2007), which may be related to the altered flow regime (Poff et al. 1997) resulting from damming the Bighorn and Tongue Rivers.

Direct anthropogenic alterations to the lower Yellowstone's geomorphology include linear bank stabilization, dikes (Silverman and Tomlinsen 1984; Boyd and Thatcher 2004), and removal of riparian vegetation (Boyd and Thatcher 2004). Linear bank stabilization includes bank armoring, levees, and transportation encroachments, such as elevated roads that act as levees. Bank armoring consists of hardening structures intended to prevent lateral bank erosion, such as concrete and rock riprap, flow deflectors, car bodies, steel retaining walls, tire revetments, and tree revetments. Levees and transportation encroachments consist of earthen ridges that constrict over-bank river flows. Dikes were of two types: wing dikes and floodplain dikes. Wing dikes, which were typically installed in main channels, consisted of rock or concrete riprap deflection structures to direct currents away from the banks on which they were located. Floodplain dikes consisted of embankments of earth and rock constructed perpendicular to channel flow in side channels to restrict flows. "Dikes" refers to floodplain dikes in this text.

Methods

Spatial Analyses

Bank-full areas were digitized from scour zones (wet or dry channels without vegetation; T. Thatcher, unpublished data) along the Yellowstone River by interpreting aerial photographs taken during the 1950s and 2001 (Yellowstone River Corridor Resource Clearinghouse 2013). River discharge varied among the 1950s photographs and between the 1950s and 2001 photographs. Therefore, precise digitizations of base-flow wetted areas were impossible, but bank-full digitizations of wetted areas from scour zones were robust to differences in discharge. Bank-full areas were classified and digitized as side channels or main channels (Figure 2.2).

Main channels were single-thread or split. A single-thread main channel clearly conveyed the bulk of the river flow. A split main channel consisted of two channels that appeared to convey equal flows that together conveyed the bulk of the river flow. Side channels were primary side channels or secondary side channels. Primary side channels originated and ended at the main channel and thus traversed the floodplain adjacent to the main channel. Secondary side channels connected the primary channel to a side channel, and thus traversed mid-channel bars or islands. Dikes and bank stabilization were rarely built on secondary side channels because mid-channel bars and islands generally were not subject to anthropogenic land use. Therefore, our analyses of anthropogenic effects on side-channel loss and gain focused exclusively on primary side channels.

We created a transition matrix by overlaying the 2001 channel configuration atop the 1950s channel configuration (Figure 2.3a). We then classified the intersecting areas of the channel configurations as follows: side-to-side (side-channel area in the 1950s that remained side-channel area in 2001), side-to-main (side channel that became main channel), side-to-floodplain (side channel that became floodplain), floodplain-to-side (floodplain that became side channel), main-to-main (main channel that remained main channel), main-to-side (main channel that became side channel), main-to-floodplain (main channel that became floodplain), and floodplain-to-main (floodplain that became main channel).

The combined categories of main-to-side and floodplain-to-side included all side-channel gain. Similarly, side-to-main and side-to-floodplain included all side-channel loss. However, these categories also contained areas of lateral side-channel migration (Figure 2.3b); when side channels move laterally, they are neither gained nor lost, so we removed areas of lateral side-channel migration from the spatial data. Side-channel transitions caused by channel migration tended to be smaller and narrower than transitions caused by true side-channel gain and loss. Therefore, we filtered side-channel transition areas according to size, perimeter, and ratios of perimeter to area. Most side channel transitions caused by migrations had areas less than 0.040 km^2, perimeters less than 2.5 km, and ratios of perimeter to area less than 20. We used these thresholds to screen out side-channel transitions caused by migration. The remaining side-channel transitions were manually examined, and we removed secondary side channels and remaining side-channel transitions caused by lateral migrations. This resulted in two GIS polygon layers: primary side channels that were lost and those that were gained from the 1950s to 2001 (Figure 2.3c).

We used digital elevation models (DEMs) and aerial photography to locate floodplain dikes. We used a pre-existing GIS layer to locate linear bank stabilization structures (Yellowstone River Corridor Resource Clearinghouse 2013). We excluded redundant linear bank stabilization structures (Figure 2.4) and bank stabilization along bluffs and terraces (because bluff banks are rock formations and are naturally stable) from our analysis. We calculated the total area of side-channel loss and gain, the total number of dikes, and bank stabilization lengths within each of 32 contiguous 16-km sections (Figure 2.6). Sections smaller than 16 km resulted in erratic variation in the response variables that masked overall longitudinal patterns (Figure 2.5); section sizes larger than 16 km yielded insufficient sample size. We completed all spatial analyses using ESRI ArcGIS 10.0.

Statistical Analyses

We examined potential spatial autocorrelation in side-channel loss and gain among the 16-km river sections by building spatial correlograms of both Moran's I and Geary's C (function sp.correlogram in R's spdep package; Borcard et al. 2011). We considered spatial autocorrelation to be present among the sections if $P < 0.05$. In subsequent analyses, we treated our sections as independent samples because spatial autocorrelation was absent ($P > 0.63$ for Moran's I and Geary's C for all variables). We conducted all statistical analyses in R 3.0.1 (R Development Core Team 2013).

The Yellowstone River channel planform ranges from stable, single-threaded to dynamic, multi-threaded along the length of our study area. Bank stabilization activities and side-channel gain and loss were largely absent where channel sections were stable and single-threaded. We included only sections where side-channel loss and gain occurred ($n = 17$ sections) in our analysis because our hypothesis was not relevant to river sections where channel migration was infrequent or absent. We refer to sections with both side-channel gain and loss as having "active channels."

Distinct geomorphic processes govern side-channel loss versus side-channel gain, and river stabilization structures may influence loss and gain differently. Therefore, we considered side-channel loss and gain separately. We regressed side-channel loss and gain against both dike frequency and bank-stabilization extent using generalized linear models (GLMs; function glm in R) to determine if the cumulative length of bank stabilization or the frequency of dikes per river section was correlated with side-channel loss or gain or both within each river section. We used a Gamma error distribution in the GLMs because side-channel gain and loss could not be less than zero; we also used an identity link because variances were similar across the ranges of dike frequencies and bank-stabilization extents.

Results

The loss in side channels summed across all river segments exceeded the gain in side channels from the 1950s to 2001 (Figure 2.7). Sixty-seven side channels were lost, 39 side channels were gained, and 91 remained stable. The total area of side-channel loss was 10.1 km^2, whereas the total area of side-channel gain was 7.1 km^2. The total area of side channels was 28.8 km^2 in the 1950s and 25.8 km^2 in 2001; thus, 10.4% of side-channel area was lost from the 1950s to 2001. In sections with active channel migration, side-channel loss was positively correlated with the frequency of dikes (Figure 2.8a) whereas side-channel gain was not (Figure 2.8b). Neither side-channel loss nor side-channel gain was correlated with bank-stabilization extent (Figure 2.8c, d).

Discussion

Side channels are gained by channel switching or channel bifurcation in actively migrating river channels (Kleinhans et al. 2013). “Channel switching” occurs at the location of an existing bifurcation when the bulk of the flow switches from the main channel to an existing side channel; the underlying channel topology remains similar. New bifurcations form side channels in three ways in braided and anabranching rivers. First, mid-channel bar deposition can bifurcate the main channel flow, thereby creating a new side channel (Leopold and Wolman 1957). Second, overbank flows can shortcut the sinuous main channel and cause chute cutoffs to form; these cutoffs become side channels by eroding headward (Ashmore 1991). Third, avulsions occur when flood flows create a new channel that captures substantial river flow (Ashmore 1982).

Side channels are lost by senescence when they do not receive scouring flows, often through a synergy of sediment accretion and vegetation encroachment (Poff et al. 1997). Lack of scouring flows in side channels can result from normal sediment transport dynamics (sediment infilling; Miall 1977), main-channel incision (Wohl 2004), and anthropogenic structures. The long-term persistence of side channels as prominent geomorphic components of a river corridor requires that the frequency and area of side-channel loss and gain are balanced through time. However, our results suggest that floodplain dikes, but not linear bank stabilization, have perturbed this balance on the Yellowstone River.

We posit that linear stabilization structures were not associated with side-channel loss on the Yellowstone River in actively migrating channels because the mechanisms by which linear stabilization results in side-channel loss are largely indirect. Linear stabilization is intended to arrest lateral channel migration caused by bank erosion. Therefore, linear stabilization is unlikely to restrict scouring flows in side channels, except when it acts as a dike by spanning the head of a side channel (Figure 2.9a, b). Moreover, linear stabilization has the potential to attenuate side-channel gain by reducing overbank flows, thereby reducing the potential for chute cutoffs to form, or by locking the channel in a particular configuration, thereby preventing channel switching. However, the lack of correlation between side-channel gains and linear bank stabilization indicates that new side channels are still being formed despite modest levels of bank stabilization along the Yellowstone River. In fact, when linear bank stabilization structures failed during flood events, they may have acted as large roughness elements (Figure 2.10), which displaced flow and further encouraged scour and channel bifurcations (*sensu* Nanson and Knighton 1996). This is not to say that linear bank stabilization does not constrain side-channel creation. Extensive and well-maintained linear bank stabilization on the Yellowstone River generally operate as intended. In developed areas along the Yellowstone River, linear bank stabilization consistently eliminated lateral channel migration and precluded the creation of new side channels during the study period (e.g., Figure 2.9c, d). Moreover, linear bank stabilization may have caused side-channel loss, but that limitations in the historical data prevented us from detecting it. A more sensitive test would have been to regress areal side-channel loss and gain against the net change in linear stabilization extent (and dike frequency) from the 1950s to 2001. However, the historical aerial photographs lacked the resolution necessary to determine which linear bank-stabilization structures were already in place in the 1950s. Additionally, the possibility remains that the existing linear stabilization in the Yellowstone River is not extensive enough to cause large-scale side-channel loss.

Dikes installed in the Yellowstone River are usually small, earthen features that reduce the frequency, duration, and magnitude of scouring flows in side channels. Dikes are not designed to withstand the erosive power of main-channel flows, which carve new channels. Therefore, the observed correlation between dike frequency and side-channel loss, but *not* gain, supports the hypothesis that dikes reduce side-channel habitat by hastening side-channel senescence rather than preventing side-channel creation. Moreover, the effects of dikes may be exacerbated by flow regulation of two major tributaries of the Yellowstone Rivers. Damming of the Bighorn and Tongue rivers caused a dampening of the magnitude and duration of the annual flood pulse (Chase 2013), probably reducing scouring flows in side channels and the forces on floodplain dikes, which probably led to more side-channel loss.

The 10% net loss of side-channel area from 1950 to 2001 changed fish habitat availability in the lower Yellowstone River, which may be detrimental to fish. However, loss in side channel area on the Yellowstone River are minor in comparison to the lower Missouri River where half of the water surface area was lost between 1879 and 1972 concomitant with extensive channel simplification and side-channel loss, resulting in detrimental effects on the fluvial communities (Funk and Robinson 1974). Seasonally inundated side channels and the shallow, slow-moving habitats that they provide are important habitats for small fish during high-discharge conditions (Brown and Hartman

1988; Pearsons et al. 1992; Aghostino and Zalewski 1995: Górski et al. 2011). Fish catch rates were up to nine times greater in side-channel margins than in main-channel margins during runoff in the lower Yellowstone River (Chapter 3). During runoff, increased water velocities may reduce the suitability of main channels for small fish (Hjort et al. 1984; Sukhodolov et al. 2009) because they are susceptible to displacement (Ottaway and Clarke 1981; Ottaway and Forest 1983; Harvey 1987). Therefore, the loss of side channels resulted in a direct loss of heavily used fish habitat (Chapter 3), probably reduced local fish abundance and richness (Chapter 3), and probably caused shifts in fish assemblage structure (Chapters 3 and 4).

Our study is the first to quantify the relationships between side-channel dynamics and both floodplain dikes and linear bank stabilization in an unimpounded and relatively unaltered large river-floodplain ecosystem. Although the Yellowstone River has a relatively intact floodplain (Koch et al. 1977; White and Bramblett 1993), side-channel senescence outpaced new side-channel formation from the 1950s to 2001, probably because of floodplain dikes and diminished flows (*sensu* Poff et al. 1997). Although we have no inference regarding how many side channels can be lost before threshold shifts in the fluvial communities occur, management practices that preserve and maintain side channels are probably important long-term conservation strategies.

Figures

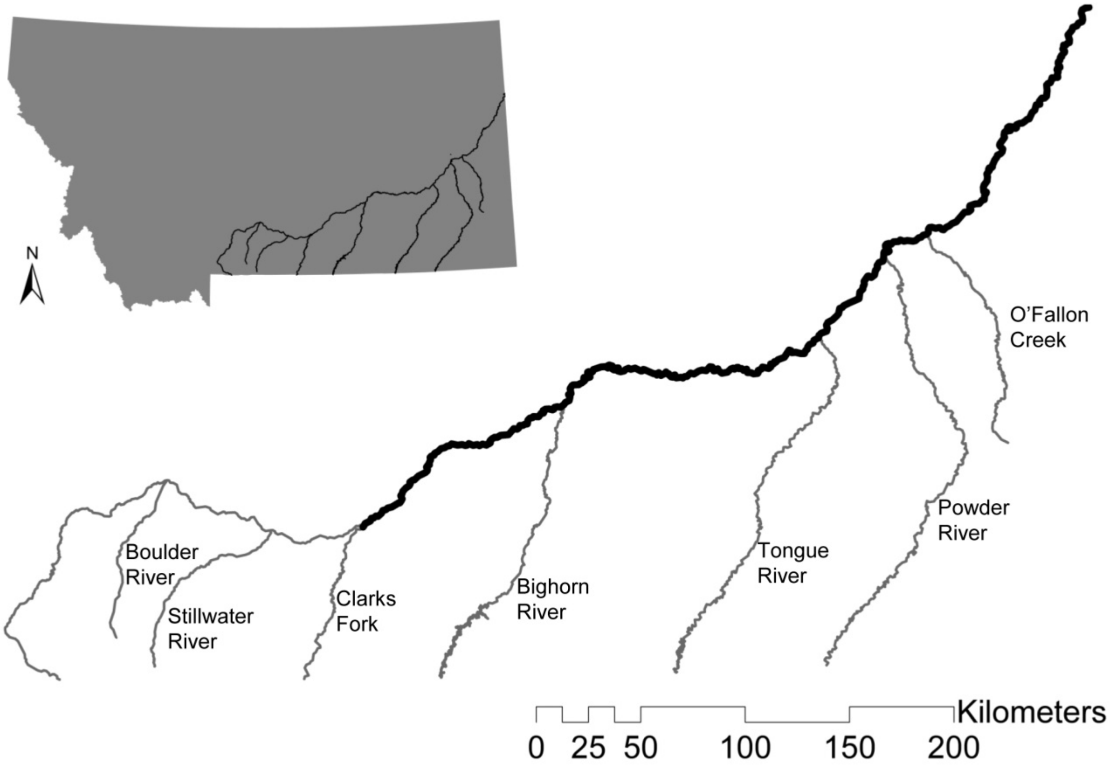

Figure 2.1. The Yellowstone River, Montana, and its major tributaries. The study area (darkened) extends from the confluence of the Clarks Fork of the Yellowstone River downstream to the confluence of the Missouri River near the Montana-North Dakota border.

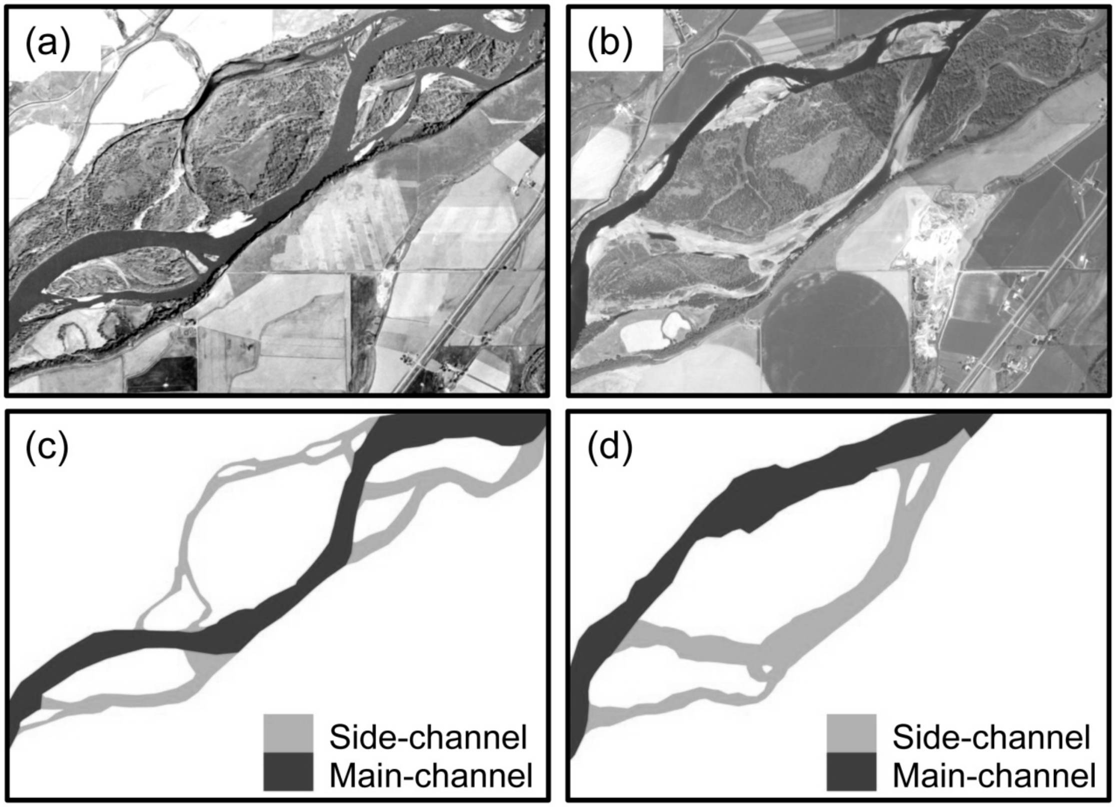

Figure 2.2. Aerial photographs and polygons depicting digitizations of bank-full side channels and main channels from the 1950s (a, c) and 2001 (b, d).

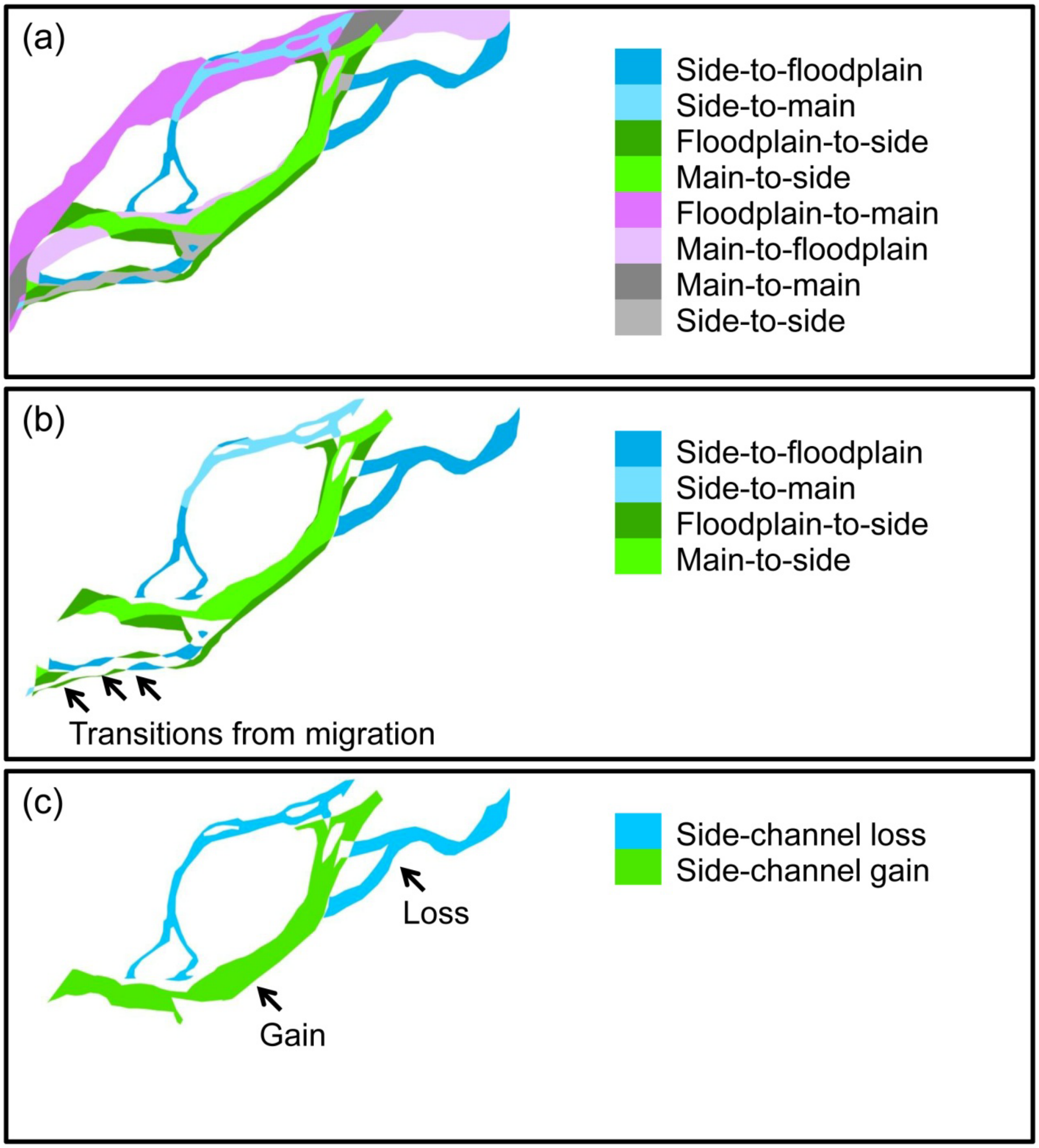

Figure 2.3. Illustration of methodology for isolating side-channel loss and gain for the river bend shown in Figure 2.2. (a) Polygons depict all channel transitions from the 1950s to 2001. (b) Polygons depict only side-channel transitions: loss, gain, and migration. (c) Polygons from side-channel migration have been filtered out; only side-channel loss and gain remain.

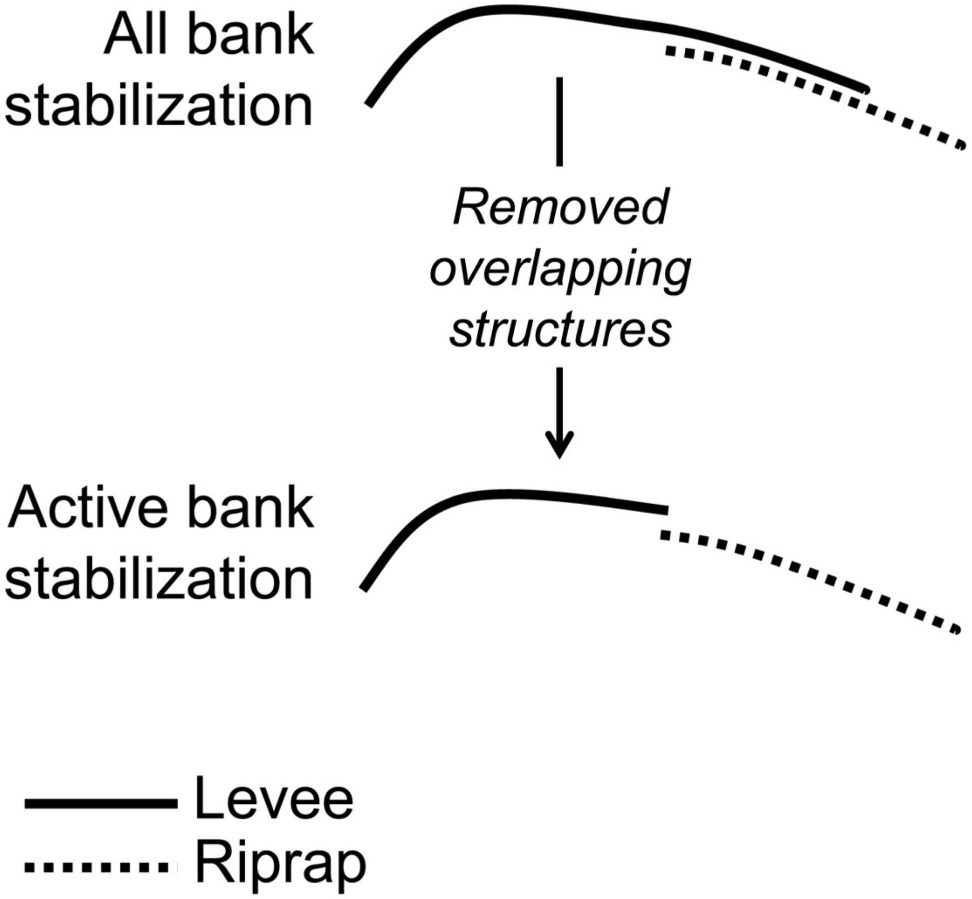

Figure 2.4. Illustration of the methodology to remove redundant linear bank stabilization. The linear stabilization structure closest to the river was retained where overlap occurred. Analyses of linear bank stabilization refer to “active bank stabilization.”

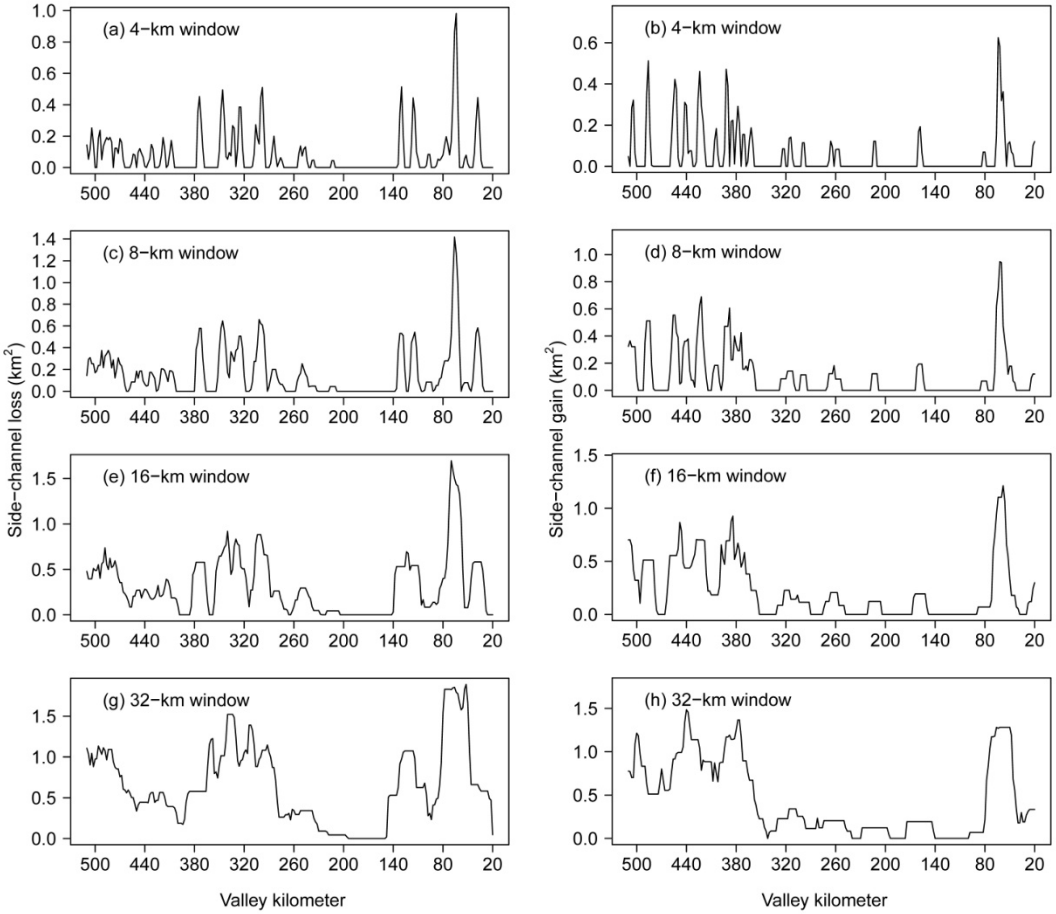

Figure 2.5. Longitudinal trends in side-channel loss (a, c, e, and g) and gain (b, d, f, and h) at four spatial scales.

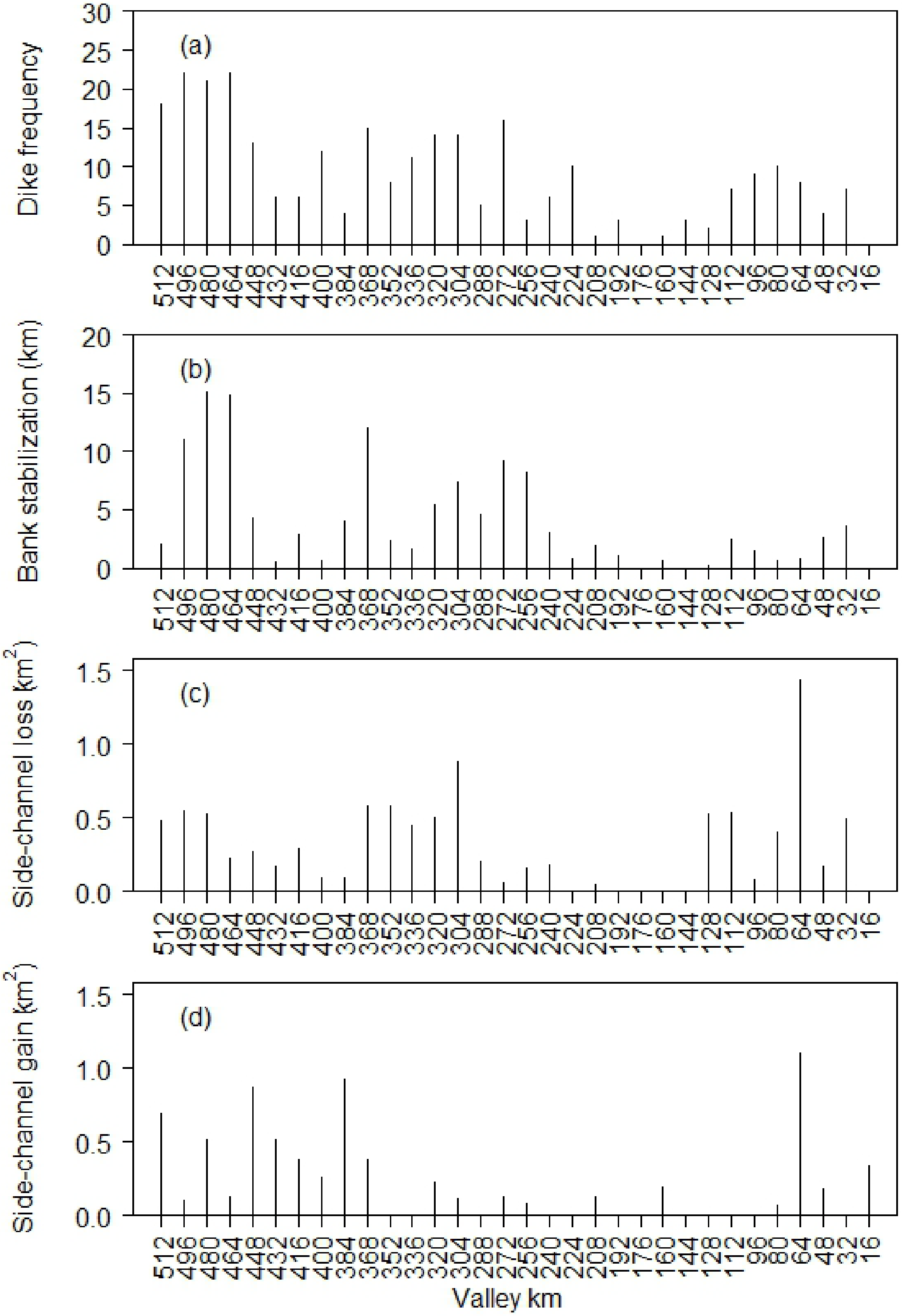

Figure 2.6. Longitudinal profiles of dike frequency (a), bank stabilization (b), and side-channel loss (c) and gain (d).

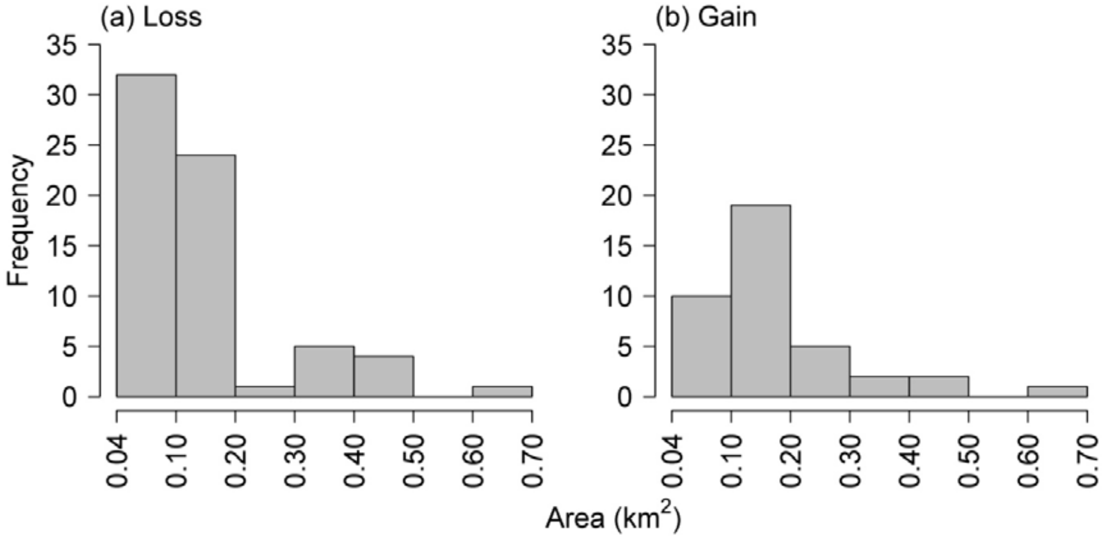

Figure 2.7. Histograms of side-channel area loss (a) and gain (b) from the 1950s to 2001.

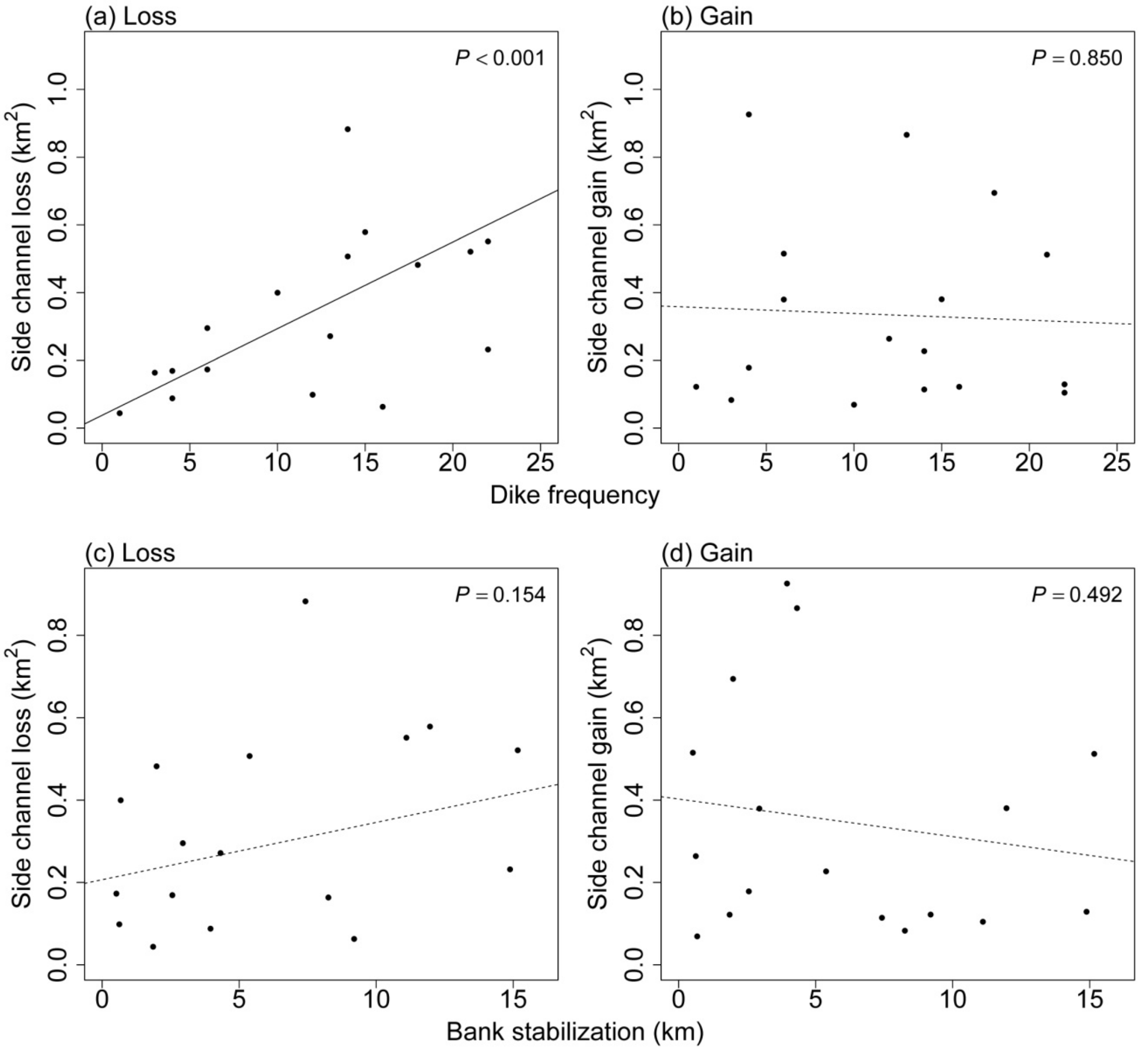

Figure 2.8. Side-channel loss and gain versus dike frequency (a and b) and bank stabilization (c and d) by river section. Lines denote slopes from regression models; a solid line denotes a significant slope whereas a dashed line denotes a non-significant slope.

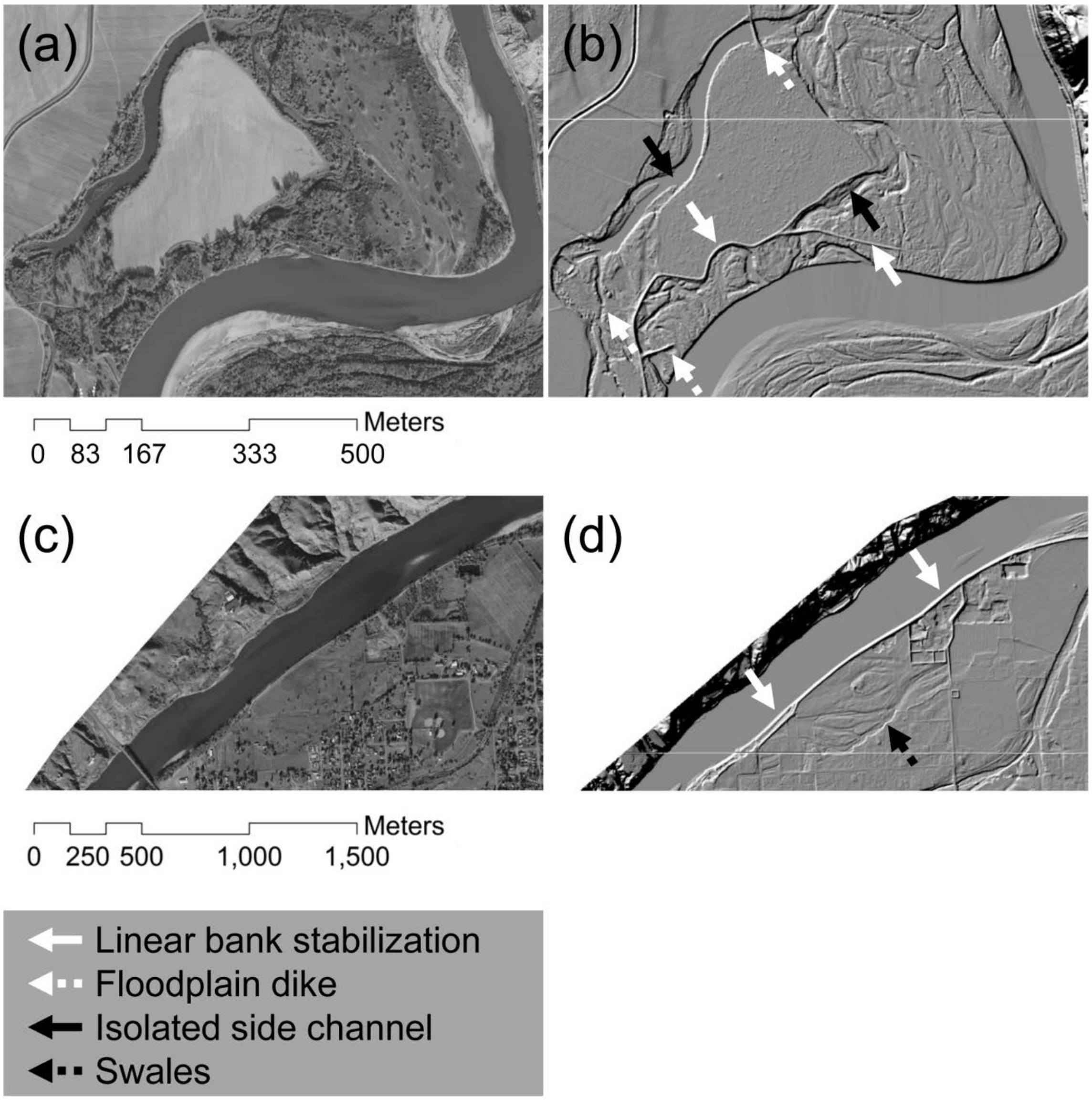

Figure 2.9. Linear bank stabilization and floodplain dikes isolated side channels and swales of the Yellowstone River, Montana. Present-day (2012) linear stabilization structures bisected side channels, effectively functioning as floodplain dikes near Hysham (a, b). The linear stabilization that arrested channel migration near Miles City (c, d) was installed prior to the 1950s. Flow direction is from bottom left to top right.

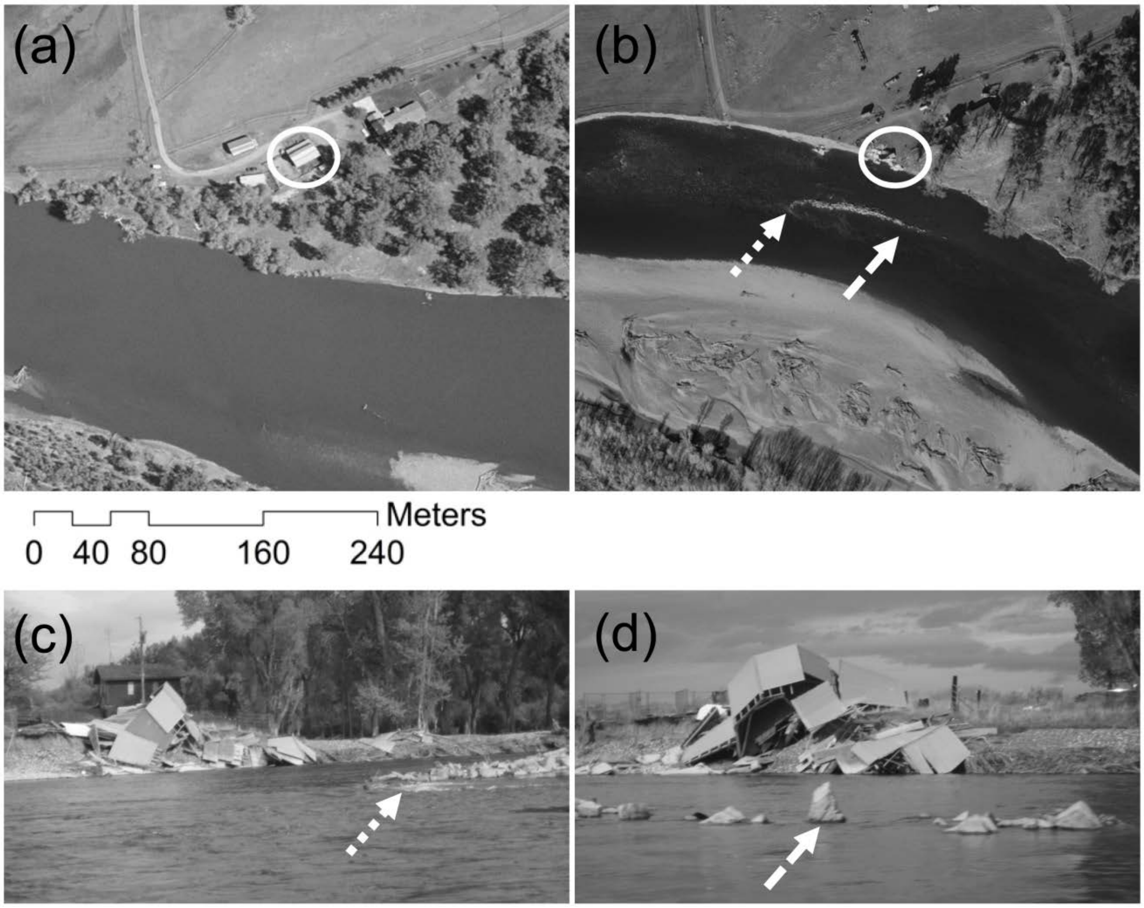

Figure 2.10. A linear bank stabilization structure failed to arrest active channel migration on the Yellowstone River near Billings, Montana, and became a large roughness element in the main channel. Aerial imagery from 2007 (a) and 2012 (b) depicts extent of channel migration; the linear stabilization structure was installed after the 2007 photograph (a). Circles denote a building that collapsed when the linear stabilization failed during snowmelt runoff in 2011. Arrow styles denote position along the large roughness element (c, d) during autumn 2011. Flow direction is from left to right.

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CHAPTER THREE

USE OF SIDE CHANNELS BY A LARGE-RIVER FISH ASSEMBLAGE

Abstract

Side channels have decreased in number and area in the lower Yellowstone River from the 1950s to 2001. Empirical evidence from the upper Yellowstone River and other rivers suggests that the shallow, slow-velocity habitats in side channels may provide important fluvial fish habitat. We compared fish assemblages in side and main channels in alluvial and bluff river bends during early and late snowmelt runoff, and base flow. Catch rates were greater in side channels than in main channels throughout runoff in alluvial river bends. Catch rates were greater in side channels than in main channels in bluff river bends during early runoff, but not during late runoff. Catch rates were not different between side channels and main channels in either alluvial or bluff river bends during base flow. Species compositions generally differed between side channels and main channels throughout hydroperiods, largely because of rare species. Proportional assemblage compositions in side and main channels were different during runoff, but not during base flow, in both alluvial and bluff river bends. Water velocities were slower and patches of shallow, slow current-velocity habitats were larger, in side channels than in main channels during runoff, but not during base flow. These physical dissimilarities may have differentially structured the side-channel and main-channel fish assemblages during runoff.

Introduction

Rivers and their floodplains form dynamic mosaics of habitat patches that vary in complexity depending on river geomorphology, floodplain topology, and flow regime (Fausch et al. 2002; Poole 2002; Wiens 2002; Allan 2004; Benda 2004). Side-channel accessibility (Ward et al. 2002) can affect fish assemblages (Fausch et al. 2002) because ecological theory (Junk 1989) and field studies (Ellis et al. 1979; Brown and Hartman 1988; Copp 1997; Gurtin et al. 2003; Zale and Rider 2003; Beechie et al. 2005; Lyons 2005; Martens and Connolly 2014) suggest that side channels provide unique habitats such as large, shallow, slow current-velocity (SSCV) patches (Bowen et al. 2003) that vary in importance seasonally as a function of river discharge (Brown and Hartman 1988; Lapointe et al. 2007; Górski et al. 2011). During runoff, seasonally inundated SSCV patches provide refugia for small fish (Brown and Hartman 1988; Pearsons et al. 1992; Aghostino and Zalewski 1995: Górski et al. 2011) and especially larvae (Ottaway and Clarke 1981; Ottaway and Forest 1983; Hjort et al. 1984; Harvey 1987; Sukhodolov et al. 2009) that can be displaced by high water velocities. Side channels provide fish habitat during base flow as well. Fish species richness is positively associated with increased habitat diversity in the upper Mississippi River during base flow conditions (Ellis et al.1979; Koel 2004) and fish species richness (Koel 2004), sizes (Copp 1997), and abundances (Lyons 2005) can be distinct between side-channel and main-channel assemblages. Moreover, the structure of the main-stem Yellowstone River fish assemblage varied as a function of side-channel availability during base flow (Chapter 4).

Anthropogenic alterations to the Yellowstone River floodplain have reduced side channel availability and, consequently, fish habitat heterogeneity (Chapter 2). The Yellowstone River is the longest unimpounded river in the contiguous Unites States (Koch et al. 1977), has a largely intact floodplain (Koch et al. 1977), and a fish assemblage dominated by native fish (White and Bramblett 1993). However, some of these fishes have declined in abundance, range, or both in the Yellowstone River and in other parts of their ranges, such as the Missouri River (Hesse et al. 1989; Dryer and Sandvol 1993; McMahon and Gardner 2001; Pegg and Pierce 2002; Jaeger et al. 2005). These declines coincide with reductions in side channel habitats (Funk and Robison 1974; Hesse et al. 1989; Chapter 2), but the importance of side channels to Yellowstone River fish is unclear. As a first step to investigating a link between side channel loss and assemblage change, we asked the question: do fish assemblages differ between main and side channels? To answer this question, we compared the fish assemblages in SSCV habitats in side channels and main channels in alluvial and bluff geomorphic river-bend types during early runoff, late runoff, and base flow.

Study Area

The Yellowstone River originates in northwestern Wyoming, flows north towards Livingston, Montana, then generally northeast to its confluence with the Missouri River in North Dakota. The study area was the main-stem Yellowstone River from its confluence with the Clarks Fork Yellowstone River near Billings, Montana, downstream to its confluence with the Missouri River (Figure 3.1). The Yellowstone River is an 8th order stream with a basin size of 182,336 km^2 and a hydrograph dominated by snowmelt runoff (White and Bramblett 1993). In the study area, discharge usually peaks during June, but the hydrology is altered by dams on two major tributaries (the Bighorn and Tongue rivers) and by water withdrawals (White and Bramblett 1993; Chase 2013; Watson 2014) leading to attenuation of flows during runoff and base flow. Average flows are estimated to be 28% less during June and 46% less during August than pre-settlement flows near Sidney, Montana (Chase 2013).

The study area is characterized by diverse geomorphologies that result from valley-wall constriction or lack thereof (Koch et al. 1977; Silverman and Tomlinsen 1984; Boyd and Thatcher 2004). Reach geomorphology governed the historic side-channel frequency and areal extent (Boyd and Thatcher 2004; Chapter 2); reaches with valley-wall constriction were meandering or straight, whereas unconstrained reaches were braided or anabranched with extensive side channels (Koch et al. 1977; Boyd and Thatcher 2004). Currently, anthropogenic perturbations interact with underlying geomorphology to govern side-channel extents (Chapter 2). From the 1950s to 2001, side-channel senescence outpaced new side-channel formation, probably because of floodplain dikes (Chapter 2) and diminished flows (*sensu* Poff et al. 1997). Such anthropogenic perturbations encourage side-channel senescence synergistically through sediment accretion and vegetation encroachment (Poff et al. 1997).

Longitudinal trends in channel slope, substrate, water temperature, and turbidity are concomitant with longitudinal shifts in fish assemblage composition. Channel slope generally decreases from 0.140% near the Clarks Fork confluence to 0.046% near the

Missouri River confluence (Koch et al. 1977; Boyd and Thatcher 2004). The study area has gravel and cobble substrates above river kilometer (RKM) 50, but transitions to a sand bed downstream of RKM 50 (Koch et al. 1977; Bramblett and White 2001). Water temperature and turbidity generally increase downstream; estimated maximum summer temperatures are 26.5 ºC at Billings to 29 ºC at Sidney (RKM 48; White and Bramblett 1993). Base flow measurements of water clarity (measured with a Fieldmaster Turbidity Tube) can exceed 120 cm near the confluence with the Clarks Fork and be as low as 0 cm near Glendive and Sidney (A. M. Reinhold, unpublished data).

Forty-nine species from 15 families compose the fish assemblage in the study area (White and Bramblett 1993). The upstream reaches of the study area encompass the transition zone of the Yellowstone River fishery, but the reaches below the Bighorn River confluence constitute the warmwater zone (White and Bramblett 1993). Cyprinids and catostomids are common throughout the study area. Abundant cyprinids shift from longnose dace in the upstream reaches to western silvery minnows, flathead chub, and emerald shiners in the downstream reaches; notably, all of these species and common carp are present throughout the entire study area. Sturgeon chub are common below the confluence of the Powder River (Duncan et al. 2012; Appendix A). Mountain and longnose suckers are common in the upstream study reaches, and white suckers and shorthead redhorses are common throughout the study area. Shovelnose sturgeon are common downstream of the Tongue River confluence and although rare, pallid sturgeon are present below the confluence with O’Fallon Creek. Native game fish include channel catfish, saugers, and burbot. With the exception of smallmouth bass, introduced game fish are generally rare in the study area; these include walleyes, black crappies, white crappies, white bass, green sunfish, pumpkinseeds, and bluegills (Appendix A).

Methods

Sampling Design

We divided the Yellowstone River into five longitudinal segments (Figure 3.1) selected to include proximate locations of stabilized and unaltered banks with similar geomorphologies, braiding, and slopes. We excluded major tributary confluences and diversion dams from segments wherever possible. However, Segment 2 included the Myers Diversion Dam to avoid both the Cartersville Diversion Dam and the Bighorn River confluence; the Cartersville Diversion is a greater fish passage barrier than the Myers Diversion, which fish are capable of passing both upstream and downstream (Helfrich et al. 1999).

We randomly selected river bends within segments after stratification by main channel geomorphology (alluvial and bluff) and anthropogenic bank hardening of the main pool (stabilized and reference) to ensure compatibility with concurrent research objectives (Chapter 4). A river bend consisted of upstream and downstream channel crossovers, a pool, and all associated side channels. Alluvial river bends were unconstrained laterally by bedrock bluffs whereas bluff river bends were constrained laterally by bedrock bluffs on one bank. Two reference alluvial river bends and two stabilized alluvial river bends were randomly selected within each segment. Analogous bluff river bends were selected only in Segments 1, 2, and 3 because bluffs were rare in

Segments 4 and 5. Reference river bends had no armoring on main pools or crossovers. Stabilized river bends had at least 35% stabilization of banks of outside bends of main pools. However, exceptions were made to the reference criteria where no other potential reference sites existed. In Segment 1, sections of bank stabilization were present on the upstream crossover (34 m of stabilization; 7% of the upstream crossover banks) of one reference bluff river bend, the downstream crossover (188 m; 34%) of one reference bluff river bend, and the upstream crossover (220 m; 37%) and pool (30 m; 1%) of one reference alluvial river bend. Bank stabilization was present on one bank of the upstream crossover (79 m; 19%) of one reference bluff river bend in Segment 3.

Fish Sampling

Runoff sampling was conducted in 2010-2012 and base flow sampling was conducted in 2009-2011; equal numbers of reference and stabilized river bends were sampled each year. All sampling was conducted with fyke nets, which efficiently target small-bodied fish in shoreline habitats in the lower Yellowstone River (Duncan et al. 2012). Each river bend was sampled three times with fyke nets: once during early runoff, once during late runoff, and once during base flow (Figure 3.2). Early runoff sampling was conducted during the ascending limb of the hydrograph whereas late runoff sampling was conducted during the descending limb of the hydrograph. Base flow sampling was conducted in autumn when water levels were consistently low.

Fyke nets had two 1.2-m wide by 0.6-m high rectangular steel frames, and two 0.6-m diameter circular steel frames covered with 3-mm nylon mesh. The fyke net lead was 4.5-m long, the cab was 3-m long, and a deployed fyke net extended 7.5 m from the shoreline. Our fyke nets were identical to the “mini-fyke nets” described in greater detail in the upper Mississippi River system Long Term Resource Monitoring Program procedures (Gutreuter et al. 1995).

Fyke nets were placed in SSCV (depth < 0.75 m; velocity < 0.50 m/s) habitats in main channels and side channels during runoff and base flow. Five nets were set in main channels and five nets were set in contiguous side channels during early and late runoff. Net location was determined by assessing all SSCV habitats in side and main channels at each river bend and dividing that into fifths. The fifths were divided into tenths and the tenth to be sampled was determined randomly by looking at the second digit in the seconds field of a digital watch when preparing to set each net. During base flow, nine nets were set in main channels and three nets were set in contiguous side channels to ensure compatibility with concurrent sampling efforts (Chapter 4). Net locations during base flow were determined by dividing each site into mesohabitats: inside bends, outside bends, channel crossovers, and side channels. Net locations were selected by dividing the mesohabitat into three equal longitudinal sections, then dividing each section into tenths and randomly selecting a location therein by looking at the second digit in the seconds field of a digital watch when preparing to set each net. Nets were set between 1600 and 1800 hours and retrieved the following morning between 0600 and 1000 hours.

We used MS-222 to anaesthetize fish prior to handling. Most fish were identified to species and counted. However, catostomids, cyprinids, and centrarchids less than 30 mm total length (TL) and ictalurids less than 20 mm TL were identified only to family and treated as separate taxa in subsequent analyses.

Physical Habitat

Depth, velocity, water chemistry, and water transparency were measured at each net deployment. Depth was measured with a wading rod. Velocity was measured with a Marsh McBirney Flo-Mate 2000 flow meter at 60% of depth. Depth and velocity were measured at the net lead, mid-net, and the cod end. Depth and velocity measurements were averaged for each net. Water temperature, dissolved oxygen concentration (DO), and specific conductance were measured at mid-net at 60% of depth with a YSI® model 556-MPS water quality meter. Water transparency was measured using a transparency tube (Fieldmaster model 78-070; Dahlgren et al. 2004). Side- and main-channel means of each physical habitat variable at each river bend in each hydroperiod were used in statistical analyses.

Statistical Analyses

We used multiple methods to assess the potential differences between side-channel and main-channel assemblages during runoff and base flow. Runoff and base flow conditions were modeled separately for all analyses. Catches were pooled within channel type at each river bend during each hydroperiod for all analyses. All statistical analyses were conducted in R 3.0.1 (R Development Core Team 2013).

The total catches of all species combined were modeled with negative binomial regression. Models included offsets for sampling effort (duration between net set and retrieval) and accounted for channel type (side or main channel), river segment, year, and river bend nested within segment. An additional term for hydroperiod (early or late runoff) was included in runoff models. All possible interactions among channel type, hydroperiod (if runoff model), and year were considered, and Akaike's Information Criterion (AIC) was used for model selection (Burnham and Anderson 2002). Catches of the five most commonly captured fishes were modeled individually using negative binomial regression with offsets for sampling effort. Runoff models included terms for channel type, year, hydroperiod, the interaction of channel type and hydroperiod, and river bend nested within segment. Base flow models included terms for channel type, year, and river bend nested within segment. All negative binomial models of catch included offsets for effort; therefore, we use the term "catch" throughout this document to refer to "catch with an offset for effort."

Potential differences in the assemblages of side channels and main channels were assessed with permutational multivariate analysis of variance (perMANOVA; function adonis in package vegan in R; Oksanen et al. 2013), which is a permutation-based analog of multivariate analysis of variance (Anderson 2001). All perMANOVAs included terms for channel type, year, and river bend while restricting permutations within river segment. Runoff models included an additional term for hydroperiod. The perMANOVAs were run on two sets of dissimilarity indices. We converted the CPUE data to binary (i.e., presence-absence) data and generated Steinhaus dissimilarity indices (Marczewski and Steinhaus 1958) from those data (function dsvdis where index = "steinhaus" in package labdsv in R; Roberts 2014); perMANOVA models of these indices assessed potential differences in species composition in side channels and main channels. We generated Bray-Curtis dissimilarity indices (Bray and Curtis 1957) from the CPUE data (function dsvdis where index = "bray/curtis" in package labdsv in R;

Roberts 2014); perMANOVA models of these indices assessed potential differences in proportional assemblage compositions in side channels and main channels. Results from Bray-Curtis perMANOVA models are herein described by "assemblage structure."

Potential differences between side- and main-channel water velocity, depth, temperature, DO, water clarity, and conductivity were modeled with ordinary least squares regression. Runoff models included terms for channel type, year, hydroperiod, the interaction of channel type and hydroperiod, and river bend nested within segment. Base flow models included terms for channel type, year, and river bend nested within segment.

Results

Habitat Use

We captured 88,880 fish during early runoff, 66,811 fish during late runoff, and 113,069 fish during base flow. Forty-five species representing 15 families of fishes were captured (Table 3.1). The assemblage was largely composed of cyprinids and catostomids. Western silvery minnow, longnose dace, and flathead chub were the three most widespread, commonly captured fishes (Figure 3.3).

We captured more fish in side channels than main channels in alluvial and bluff river bends during early runoff. This pattern persisted in alluvial river bends during late runoff, but not in bluff river bends. During base flow, catches in side and main channels were not different in either alluvial or bluff river bends (Figure 3.4). Catches of three of the five most commonly captured species (western silvery minnow, flathead chub, and sand shiner) were greater in side channels than main channels in alluvial river bends; however, longnose dace and emerald shiner catches in side and main channels were not different in alluvial river bends during late runoff (Figure 3.4b). Catches of four of the five most commonly captured species were greater in side channels than main channels in bluff river bends; however, western silvery minnow catches were greater in main channels than in side channels in bluff river bends during base flow (Figure 3.4d).

Assemblage Composition and Structure

Side channels had different assemblage compositions (binary perMANOVA), greater numbers of species (Figure 3.5), and different assemblage structures (Bray-Curtis perMANOVA, Table 3.2) compared to main channels throughout runoff in alluvial and bluff river bends. During base flow, differences existed in assemblage compositions of side and main channels only in alluvial river bends. During base flow, in both alluvial and bluff river bends, no differences existed in numbers of species (Figure 3.5) or assemblage structures (Table 3.2) of side and main channels. Assemblage composition differed between early and late runoff in both alluvial and bluff river bends; however, assemblage structure differed between early and late runoff only in alluvial river bends (Table 3.2).

Although most fish species were captured in both main channels and side channels (Figure 3.5), some fish were captured exclusively in side channels or main channels throughout all hydroperiods. All fishes captured solely in side or main channels throughout hydroperiods were captured on only one or two occurrences. Similarly, most fishes that were captured in either side channels or main channels exclusively during either runoff or base flow were rarely captured, except for black crappie and goldeye. We captured black crappies in 15% of main channels and 35% of side channels during base flow, but we only captured black crappies in side channels during runoff. We captured goldeyes in 15% of main channels and 33% of side channels during runoff, but we only captured goldeyes in main channels during base flow.

Physical Habitat

Only water velocities during runoff differed consistently between SSCV habitats of side and main channels among the six physical habitat characteristics compared (Table 3.3). Mean SSCV habitat velocities were 0.05 to 0.08 m/s slower in side than main channels in alluvial river bends and 0.07 m/s slower in side than main channels in bluff river bends during runoff. Differences in other characteristics, when present, were infrequent and sporadic.

Discussion

Prior to the onset of this study, the importance of side channels to small-bodied fish in the lower Yellowstone River throughout runoff and base flow was largely theoretical (i.e., Bowen et al. 2003). Although side channels provide important fish habitat in other rivers (e.g., Ellis et al. 1979; Eckblad et al. 1984; Sheaffer and Nickum 1986b), inferring the importance of Yellowstone River side channels from studies of other rivers was problematic because the extensive modifications of many other rivers have caused large scale reductions in side-channel habitats (Hesse 1987) that probably concentrated fish in remaining side channels. Although the Yellowstone River has fewer side channels today than during pre-settlement times (Chapter 2), the Yellowstone River has one of the least-modified temperate, large river floodplains in the world. This enabled us to establish the importance of side channels for fish without the confounding influences of a largely disconnected floodplain.

In the Yellowstone River, river bends with side channels had greater fish abundances and diversity than river bends without side channels, presumably because side channels increase channel complexity and floodplain connectivity. Yellowstone River side channels provided small-bodied fish with large, dynamic patches of complex and connected SSCV habitats, the importance of which was dynamic with hydroperiod. Therefore, we posit that the heterogeneity in fish habitats associated with complex channels provided a dynamic template with which the biota interacted.

Several mechanisms may interact to support fish abundances and diverse assemblages in complex channels of the Yellowstone River. First, Yellowstone River side channels may offer high quality spawning (*sensu* Burgess et al. 2013) and nursery (*sensu* Copp 1989) grounds, especially for fish that broadcast demersal, adhesive eggs (e.g., sand shiners; Platania and Altenbach 1998). Additionally, the ichthyoplankton of broadcast spawners with non-adhesive eggs, such as western silvery minnows (Layher 2003), flathead chub (Durham and Wilde 2005), and emerald shiners (Becker 1983), may drift into side channels during runoff, develop in the relatively slack waters of side channels, and subsequently migrate towards the main channel as seasonally-inundated side channels dewater. Such a pattern would explain the seasonal shifts in habitat use of these fish (Figure 3.4) and suggests that the ontogeny of these fish coincides with the inundation of side channels during the annual flood pulse.

Second, Yellowstone River side channels may offer better foraging opportunities than main channels during runoff. The slightly slower velocities in side-channel SSCV may enable small fish with limited swimming capabilities to forage more efficiently than in main-channel SSCV. Similarly, food availability may be greater in side channels than in main channels (Tito de Morais et al. 1995), especially for larval and age-0 fish (Nunn et al. 2007a, 2007b). A difference in specific conductance would have suggested that nutrient availability, primary productivity, or both differed between side and main channels (Biggs and Price 1987; Biggs 1990), but no difference existed (Table 3.3). However, prey such as zooplankton (Bothar 1981) and macroinvertebrates (Eckblad et al. 1984; Sheaffer and Nickum 1986a) may have been more abundant in side channels than in main channels, but we sampled neither zooplankton nor macroinvertebrates.

Third, Yellowstone River side channels probably provide small fish refugia from swift current velocities. The temporal pattern of fish habitat use of side and main channels (Figure 3.4) was concordant with the redistribution of large SSCV patches from lateral habitats (i.e., side channels) to main channels (Bowen et al. 2003), suggesting that many small fish require access to slow velocity habitats throughout the year. Therefore, fish habitat use (Figure 3.4) and assemblage structure (Tables 3.2) were tightly coupled to patterns in current velocity (Table 3.3). Such patterns possibly arose because access to slow velocity habitats can reduce energy expenditures, increase growth rates (Putman et al. 1995), and prevent downstream displacement (Ottaway and Clarke 1981; Ottaway and Forest 1983; Hjort et al. 1984; Harvey 1987; Sukhodolov et al. 2009).

Fourth, Yellowstone River side-channel SSCV habitat patches may offer small fish greater protection from predators than main-channel SSCV habitat patches during runoff. Water transparency was equally poor in both side and main channels during runoff (Table 3.3), which probably reduced predation risk from terrestrial predators in both channel types. However, the shallow depths of side channels probably offered protection from large aquatic predators (*sensu* Harvey and Stewart 1991). Our work (A.M. Reinhold, field observations) and prior work (Bowen et al. 2003) on the Yellowstone River indicated that during runoff, SSCV patches were largely concentrated in side channels and were larger in side channels than in main channels. In contrast, main-channel SSCV patches were limited to narrow portions of channel margins (Bowen et al. 2003) that were bordered by deep water with swift currents, which may have increased the susceptibility of small fish in main-channel SSCV patches to aquatic predators, downstream displacement, or both. Thus, side-channel SSCV patches had fewer edges shared with the deep and swift portions of main channels than main-channel SSCV patches. Therefore, edge effects may have decreased the suitability of main-channel SSCV patches for small fish during runoff, suggesting that both the size and spatial context of SSCV habitat patches influenced their use by Yellowstone River fish.

Fyke net gear efficiency may have influenced side- and main-channel catches differently. Gear efficiency could have been better in side channels than in main channels because fyke nets may sample a greater portion of side-channel area than main-channel area because side channels are smaller than main channels. This would have rendered higher side-channel catches than main-channel catches and thereby inaccurately reflected fish abundances and habitat use. However, fyke nets provide cover, which can attract fish (Gritters 1994; Stone 2010), but because cover (e.g., woody debris and inundated vegetation) was sparse or absent in main channels, and more abundant in side channels, such bias would be expected to inflate main-channel catches.

Access to diverse habitats yielded diverse fish assemblages. Many fish move laterally (Hohausová et al. 2003; Csoboth and Garvey 2008; Górski et al. 2012; Burgess et al. 2013) between side and main channels, whereas other fish are side-channel or main-channel residents (Burgess et al. 2013). In our study, the differences in numbers of species and assemblage composition between side and main channels arose, in part, because of habitat use patterns of rare species. These rare species may have been present in both channel types, but not captured because their abundances were too low. In contrast, black crappies were moderately abundant and their habitat use was strongly tied to patterns in SSCV redistribution throughout hydroperiods. Side channels may have had more suitable habitat than main channels during runoff because little to no current-velocity and abundant cover make excellent black crappie habitat (Warren 2009). Moreover, black crappies have been known to shift habitats with seasonal variations in abiotic conditions (Warren 2009), and this may explain why black crappie used both side and main channels during base flow.

Habitat suitability of side and main channels varied for some fishes throughout hydroperiods. Goldeyes shifted from using both side channels and main channels during runoff to primarily using main channels during base flow. This shift in habitat use may have occurred because goldeyes are frequently found in fast currents (Pegg and Pierce 2002; Barko and Herzog 2003), which occurred primarily in the main channel during base flow (Bowen et al. 2003). However, goldeyes have been considered habitat generalists in the Missouri and lower Yellowstone Rivers (Pegg and Pierce 2002) and have been documented in side channels in the Missouri River (Moon et al. 1998) and upper Mississippi River (Barko and Herzog 2003) during base flow. However, the depths and velocities of Yellowstone River main channels (Chapter 4) are probably more similar to the depths (Moon et al. 1998; Barko and Herzog 2003) and velocities (Barko and Herzog 2003) of side channels in these other rivers than to Yellowstone River side channels. Thus, physical habitat differences between rivers could underlie this apparent inconsistency in goldeye habitat use.

Yellowstone River fish interact with side- and main-channel habitats dynamically as abiotic conditions shift throughout the year. These habitats probably provide fish with spawning and nursery grounds, foraging opportunities, and refugia from swift current velocities and aquatic predators. Therefore, our results support existing studies demonstrating that access to heterogeneous habitats throughout different hydroperiods is important for fish assemblages (Fausch et al. 2002; Lapointe et al. 2007; Górski et al. 2012; Burgess et al. 2013) and that connectivity between main channels and side channels helps maintain diverse fish assemblages (Lapointe et al. 2007; Górski et al. 2012; Burgess et al. 2013). Whereas river geomorphology governs the spatial organization of habitat patches (Poole 2002; Benda et al. 2004), some anthropogenic activities have reduced Yellowstone River side-channel availability (Chapter 2). However, the persistence of some Yellowstone River fish may depend on access to side channels, and the threshold at which side channels become limiting for Yellowstone River fish remains unknown. Therefore, management practices that allow for normal riverine dynamics and the maintenance of side channels are probably important long-term conservation strategies.

Tables

Table 3.1. Yellowstone River fishes captured in fyke nets during runoff and base flow.

Family	Abbreviation	Common name	Latin name
Catostomidae			
	BIBU	Bigmouth buffalo	*Ictiobus cyprinellus*
	LOSU	Longnose sucker	*Catostomus catostomus*
	MOSU	Mountain sucker	*Catostomus platyrhynchus*
	RICA	River carpsucker	*Carpiodes carpio*
	SHRE	Shorthead redhorse	*Moxostoma macrolepidotum*
	SMBU	Smallmouth buffalo	*Ictiobus bubalus*
	CATO	Age-0 catostomid	
	WHSU	White sucker	*Catostomus commersonii*
Centrarchidae			
	BLCR	Black crappie	*Pomoxis nigromaculatus*
	BLUE	Bluegill	*Lepomis macrochirus*
	GRSU	Green sunfish	*Lepomis cyanellus*
	LABA	Largemouth bass	*Micropterus salmoides*
	PUMP	Pumpkinseed	*Lepomis gibbosus*
	ROBA	Rock bass	*Ambloplites rupestris*
	SMBA	Smallmouth bass	*Micropterus dolomieu*
	CENT	Age-0 centrarchid	
	WHCR	White crappie	*Pomoxis annularis*
Cottidae			
	MOSC	Mottled sculpin	*Cottus bairdii*
Cyprinidae			
	COCA	Common carp	*Cyprinus carpio*
	CRCH	Creek chub	*Semotilus atromaculatus*
	EMSH	Emerald shiner	*Notropis atherinoides*
	FAMI	Fathead minnow	*Pimephales promelas*
	FLCH	Flathead chub	*Platygobio gracilis*
	LACH	Lake chub	*Couesius plumbeus*
	LODA	Longnose dace	*Rhinichthys cataractae*
	CYPR	Age-0 cyprinid	
	NORE	Northern redbelly dace	*Chrosomus eos*
	SASH	Sand shiner	*Notropis stramineus*
	STCH	Sturgeon chub	*Macrhybopsis gelida*
	WESI	Western silvery minnow	*Hybognathus argyritis*
Esocidae			
	NOPI	Northern pike	*Esox lucius*
Fundulidae			
	NOKI	Northern plains killifish	*Fundulus kansae*
Gasterosteidae			
	BRST	Brook stickleback	*Culaea inconstans*
Hiodontidae			
	GOEY	Goldeye	*Hiodon alosoides*
Ictaluridae			
	BLBU	Black bullhead	*Ameiurus melas*
	ICTA	Age-0 ictalurid	
	CHCA	Channel catfish	*Ictalurus punctatus*
	STCA	Stonecat	*Noturus flavus*

Table 3.1 Continued

Family	Abbreviation	Common name	Latin name
Ictaluridae			
	YEBU	Yellow bullhead	*Ameiurus natalis*
Lepisosteidae			
	SHGA	Shortnose gar	*Lepisosteus platostomus*
Lotidae			
	BURB	Burbot	*Lota lota*
Moronidae			
	WHBA	White bass	*Morone chrysops*
Percidae			
	SAUG	Sauger	*Sander canadensis*
	WALL	Walleye	*Sander vitreus*
	YEPE	Yellow perch	*Perca flavescens*
Salmonidae			
	BRTR	Brown trout	*Salmo trutta*
	MOWH	Mountain whitefish	*Prosopium williamsoni*
	RATR	Rainbow trout	*Oncorhynchus mykiss*
Sciaenidae			
	FRDR	Freshwater drum	*Aplodinotus grunniens*

Table 3.2. Habitat-specific differences in fish assemblages during runoff and base flow in alluvial and bluff river bends (perMANOVA). Models with Bray-Curtis dissimilarity indices assess proportional assemblage compositions. Models with binary dissimilarity indices assess species composition. The *P*-values for statistically significant terms at $\alpha = 0.05$ are bolded.

			Degrees of freedom			*P*-values	
Index	Hydroperiod	Site type	Residual	Total	R^2	Channel type	Runoff period
Bray-Curtis							
	Runoff	Alluvial	74	79	0.25	**<0.001**	**<0.001**
	Runoff	Bluff	46	51	0.31	**<0.001**	0.2427
	Base flow	Alluvial	31	35	0.16	0.669	
	Base flow	Bluff	15	19	0.38	0.154	
Binary							
	Runoff	Alluvial	74	79	0.21	**0.001**	**<0.001**
	Runoff	Bluff	46	51	0.37	**0.002**	**0.004**
	Base flow	Alluvial	31	35	0.24	**0.017**	
	Base flow	Bluff	15	19	0.38	0.087	

Table 3.3. Regression results estimating mean differences between physical habitats of side and main channels during runoff and base flow at bluff and alluvial river bends. The *P*-values for statistically significant terms at $\alpha = 0.05$ are bolded.

			Degrees of freedom					
Habitat variable	Hydroperiod	Geomorphology	Residual	Total	*P*-value	Mean	Mean difference: side versus main	95% CI
Velocity (m/s)								
	Early runoff	Alluvial	65	79	**0.0158**	0.120	-0.052	(-0.094, -0.011)
		Bluff	41	51	**0.0045**	0.111	-0.074	(-0.121, -0.026)
	Late runoff	Alluvial	65	79	**0.0004**	0.111	-0.079	(-0.121, -0.038)
		Bluff	41	51	**0.0086**	0.119	-0.067	(-0.115, -0.020)
	Base flow	Alluvial	23	35	0.4546	0.126	-0.019	(-0.066, 0.029)
		Bluff	11	19	0.2202	0.119	-0.046	(-0.115, 0.023)
Depth (m)								
	Early runoff	Alluvial	68	83	0.5442	0.338	0.026	(-0.056, 0.107)
		Bluff	42	53	0.4531	0.332	0.025	(-0.040, 0.091)
	Late runoff	Alluvial	68	83	**0.0234**	0.306	0.097	(0.015, 0.179)
		Bluff	42	53	0.1261	0.311	0.052	(-0.013, 0.118)
	Base flow	Alluvial	23	35	0.1125	0.328	0.055	(-0.010, 0.120)
		Bluff	11	19	0.9691	0.330	0.001	(-0.063, 0.065)
Temperature (°C)								
	Early runoff	Alluvial	60	75	0.0504	16.71	0.89	(0.02, 1.77)
		Bluff	42	53	0.5613	16.62	0.66	(-1.54, 2.85)
	Late runoff	Alluvial	60	75	0.1973	20.46	0.65	(-0.33, 1.64)
		Bluff	42	53	0.5751	17.45	0.63	(-1.56, 2.83)
	Base flow	Alluvial	23	35	0.2117	16.15	0.76	(-0.40, 1.92)
		Bluff	11	19	0.4100	14.85	-0.50	(-1.66, 0.65)
DO (mg/L)								
	Early runoff	Alluvial	52	67	0.2129	9.80	-0.15	(-0.39, 0.08)
		Bluff	38	49	0.4458	9.63	-0.22	(-0.78, 0.34)
	Late runoff	Alluvial	52	67	**0.0431**	9.01	-0.28	(-0.55, -0.02)
		Bluff	38	49	0.5306	9.68	-0.17	(-0.68, 0.35)
	Base flow	Alluvial	16	28	0.9486	10.78	-0.03	(-0.98, 0.92)
		Bluff	6	14	0.9725	11.18	-0.01	(-0.28, 0.27)

Table 3.3 Continued

			Degrees of freedom			:	Mean difference	
Habitat variable	Hydroperiod	Geomorphology	Residual	Total	*P*-value	Mean	side versus main	95% CI
Water transparency (mm)								
	Early runoff	Alluvial	67	82	0.5870	69.5	8.6	(-22.2, 39.4)
		Bluff	42	53	0.6454	136.8	9.7	(-31.2, 50.6)
	Late runoff	Alluvial	67	82	0.8477	122.0	3.0	(-27.8, 33.8)
		Bluff	42	53	0.6364	124.8	9.9	(-31.0, 50.8)
	Base flow	Alluvial	23	35	0.2035	422.2	-75.9	(-189.6, 37.7)
		Bluff	11	19	0.7357	547.6	-28.5	(-189.6, 132.7)
Specific conductance (μS/cm)								
	Early runoff	Alluvial	52	67	0.3282	356.6	14.4	(-14.2, 42.9)
		Bluff	38	49	0.0500	267.3	30.3	(1.0, 59.7)
	Late runoff	Alluvial	52	67	0.4506	265.3	12.5	(-19.8, 44.9)
		Bluff	38	49	0.5963	239.8	7.4	(-19.6, 34.4)
	Base flow	Alluvial	23	35	0.1269	604.5	36.6	(-8.7, 82.0)
		Bluff	11	19	0.0686	588.8	197.5	(5.7, 389.2)

Figures

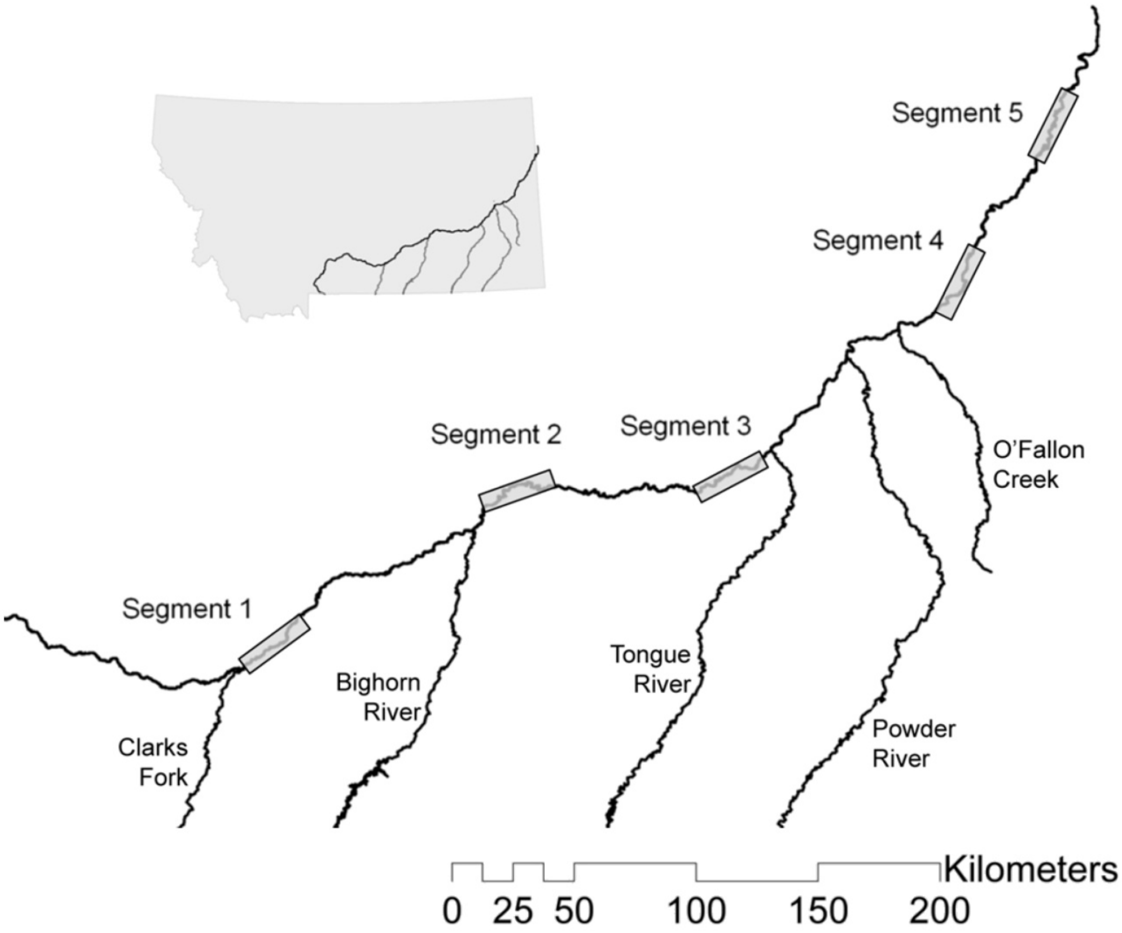

Figure 3.1. Five study segments of the Yellowstone River sampled during runoff and base flow. Four alluvial river bends were sampled in each river segment. Four bluff bends were sampled in each of the three upstream segments.

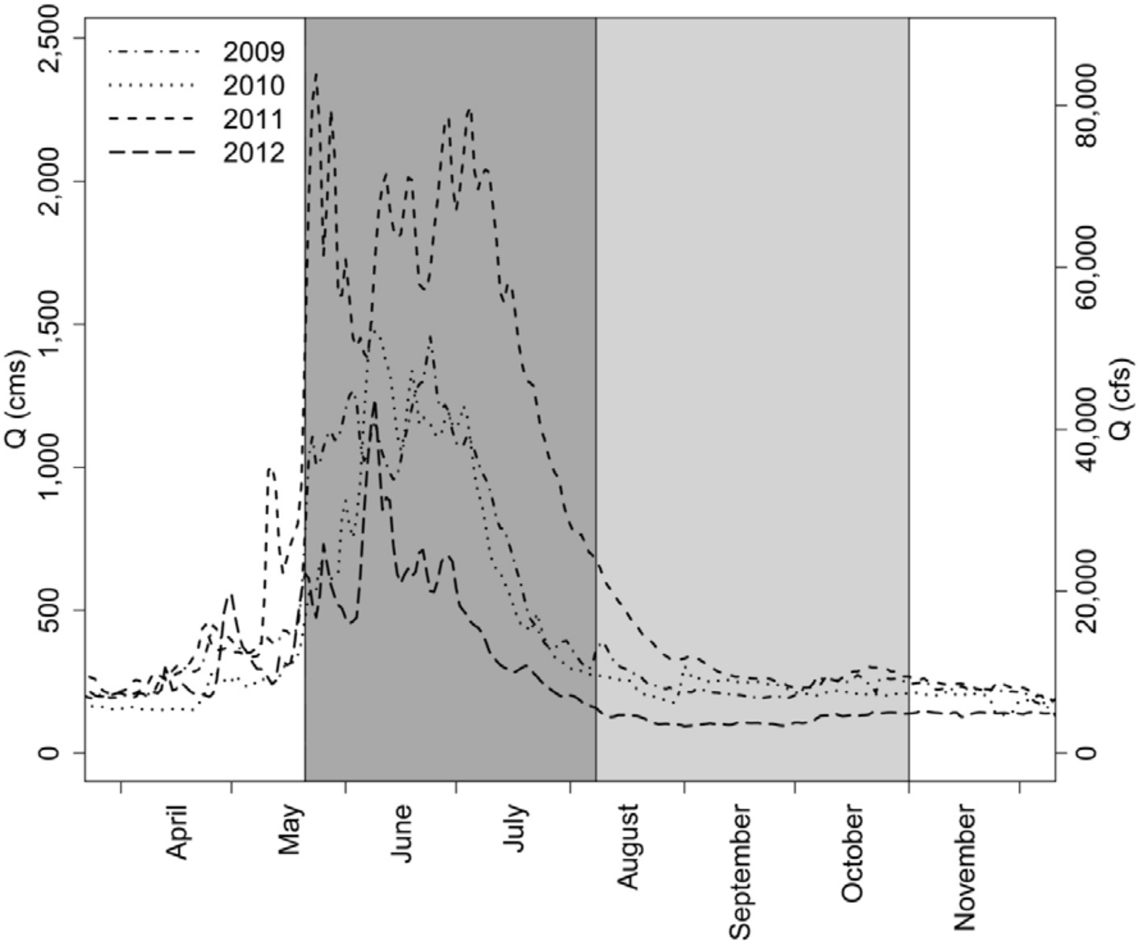

Figure 3.2. Yellowstone River hydrographs at Segment 3 for years when fish sampling occurred. Dark grey shading denotes timing of runoff sampling. Light grey shading denotes timing of base flow sampling.

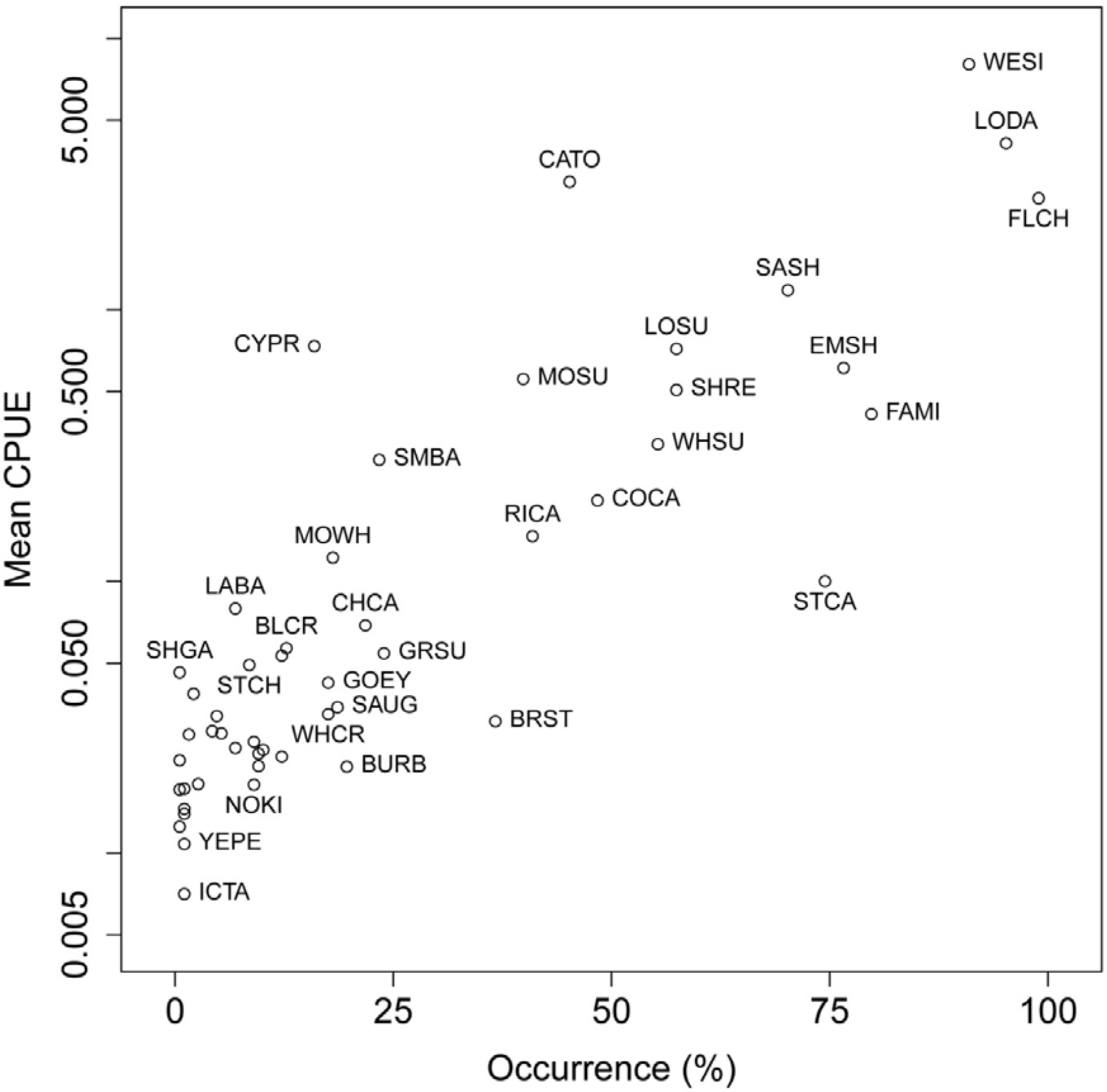

Figure 3.3. Yellowstone River fyke net catch per unit effort (CPUE) versus occurrence for fishes captured in side channels or main channels or both, during runoff or base flow or both. Catch per unit effort was calculated as fish collected per hour per net. Occurrence denotes percentage of side and main channels wherein fish were collected. Unlabeled dots represent rare species. Species abbreviations are located in Table 3.1.

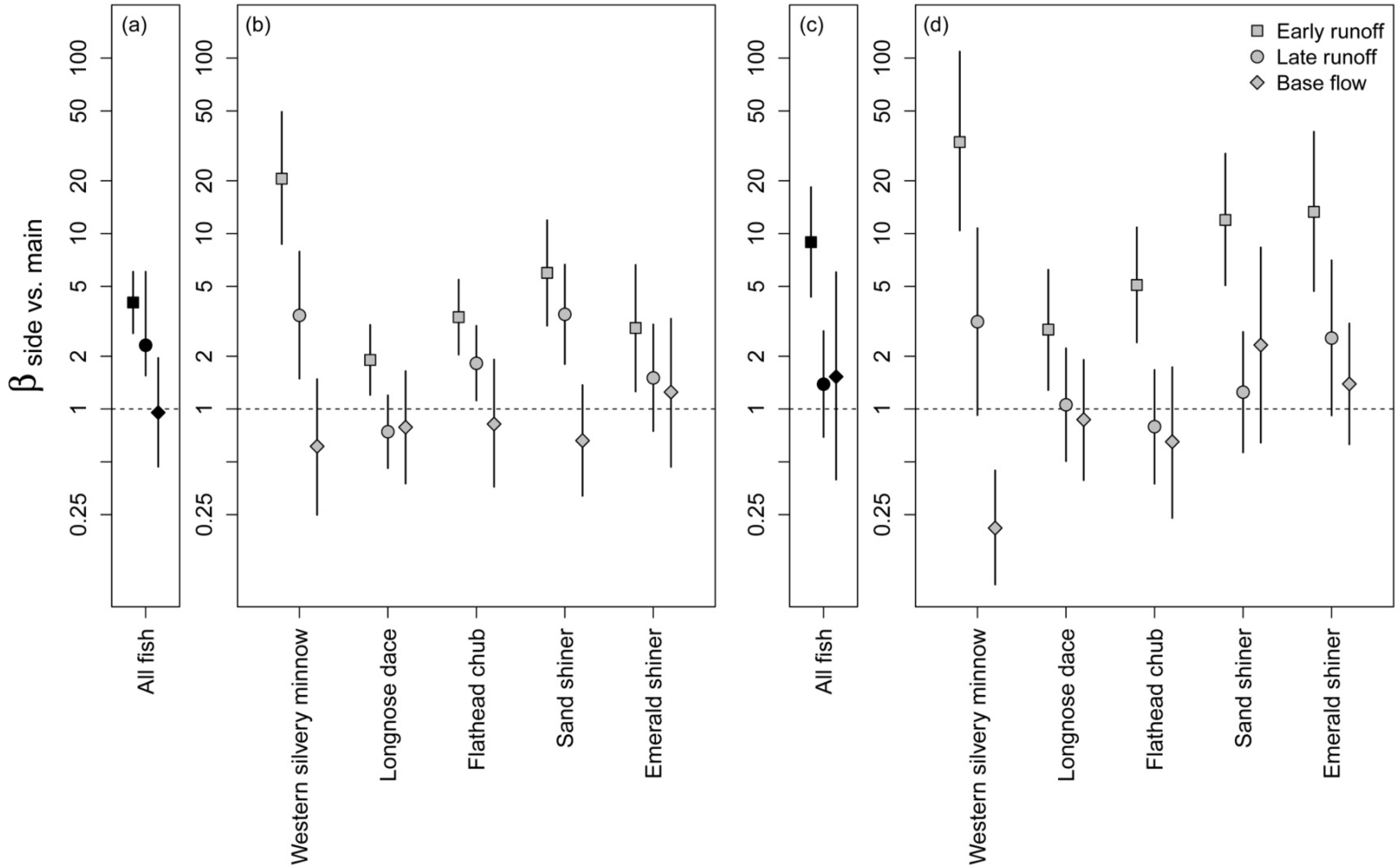

Figure 3.4. Estimated mean multiplicative differences (β) in side-channel versus main-channel catches of fish captured in fyke nets during runoff and base flow in alluvial (a and b) and bluff river bends (c and d). Estimates were generated from negative binomial regressions with offsets for sampling effort. Error bars represent 95% confidence intervals.

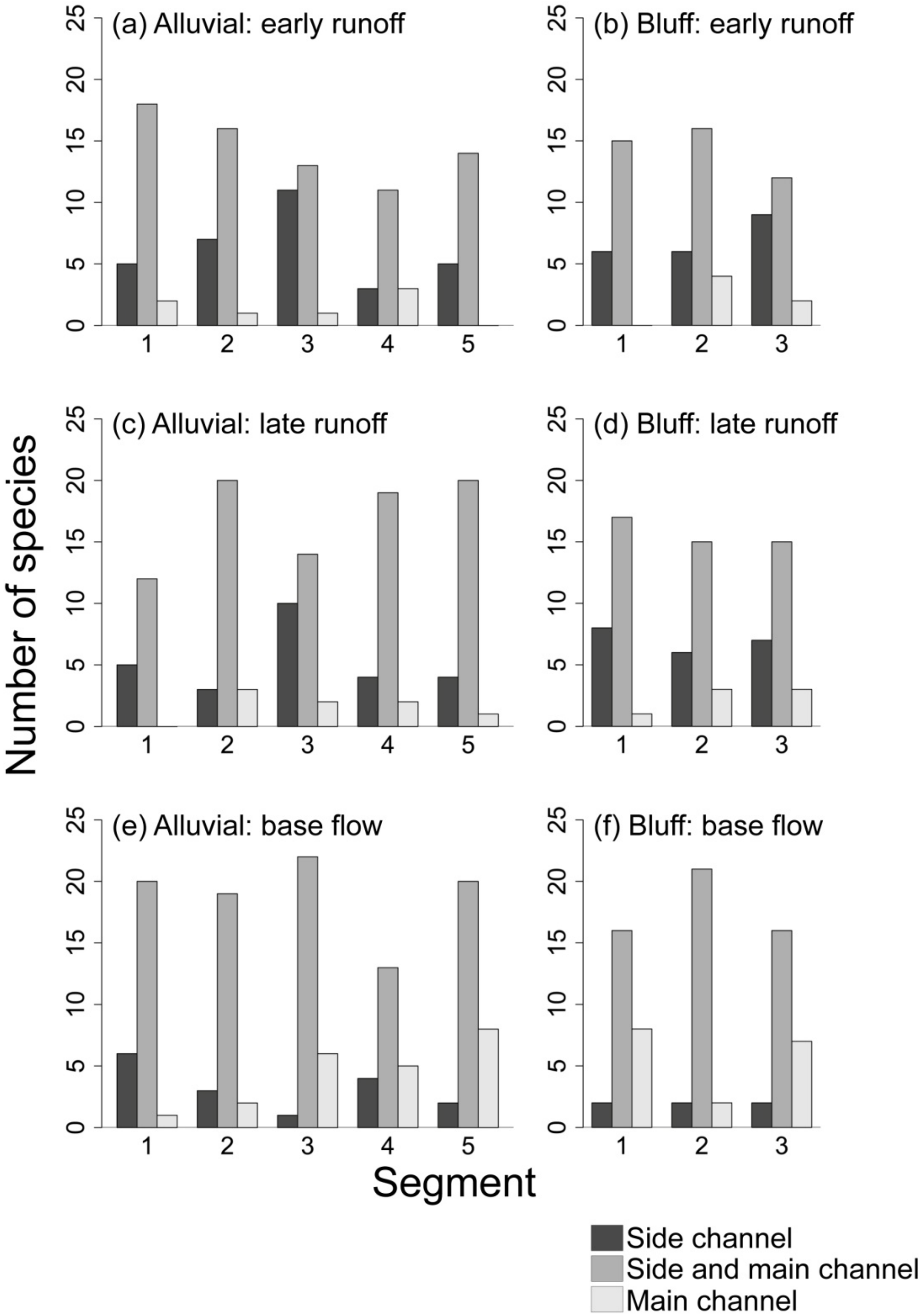

Figure 3.5. Habitat-specific comparisons of numbers of species for runoff and base flow conditions. Bar color indicates whether species were captured in side channels, main channels, or both.

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CHAPTER FOUR

SPATIALLY-DEPENDENT RESPONSES OF A LARGE-RIVER FISH ASSEMBLAGE TO BANK STABILIZATION AND SIDE CHANNELS

Abstract

The alteration of large rivers by anthropogenic bank stabilization has uncertain consequences for fish assemblages. Bank stabilization in our study area is especially controversial because the public values the Yellowstone River as the longest unimpounded river remaining in the conterminous United States. We hypothesized that bank stabilization changed main-channel fish assemblage structure by altering main-channel habitats and that side channels influenced main-channel fish assemblage structure by providing habitat heterogeneity. We hypothesized that bank stabilization and side channels would influence fish assemblage structure differently, but that both would be scale-dependent. We developed a spatially-explicit framework to test these hypotheses. Fish assemblage structure varied with bank-stabilization extent and side-channel availability; however, not all assemblage subsets were influenced. Nevertheless, bank stabilization and side channels had different and sometimes opposite influences on fish assemblages. Assemblage responses to side channels were more consistent and widespread than to bank stabilization; more fishes positively correlated with side channels than bank stabilization. Influences of bank stabilization and side channels on fish relative abundances varied depending on species and river bend geomorphology. Physical differences probably contributed to the assemblage differences between

stabilized and reference river bends; stabilized alluvial pools were deeper than reference alluvial pools, but depths of stabilized and reference bluff pools did not differ. The strengths of the relationships among fish assemblages, bank stabilization, and side channels were spatial scale-dependent; optimum spatial scales ranged from less than 200 m to 3,200 m up- and down-stream, suggesting that bank stabilization and side channels influenced fish across multiple spatial scales.

Introduction

The alteration of large rivers by anthropogenic bank stabilization structures has uncertain consequences for fish assemblages. Banks are stabilized to prevent erosion of agricultural, residential, and urban lands, and to protect transportation structures such as roads, railroads, and bridges. However, such alterations result in concomitant changes in local main-channel bathymetry such as main-channel bed degradation, channel width reduction, and increased stream gradient (Stern and Stern 1980; Heede 1986; Shields et al. 1995). Moreover, bank stabilization reduces floodplain connectivity and natural riverine processes such as lateral channel migration and the formation of backwaters, braids, and side channels (Leopold 1964; Stern and Stern 1980; Shields et al. 1995; Schmetterling et al. 2001; Auble et al. 2004; Florsheim et al. 2008; Chapter 2).

Bank stabilization alters fish habitat and probably fish habitat suitability, albeit ambiguously. Bank stabilization was associated with decreases in fish abundances in some rivers (Buer et al. 1984; Li et al. 1984; Swales et al. 1986; Knudsen and Dilley 1987; Thurow 1988; Beamer and Henderson 1998; Peters et al. 1998; Oscoz et al. 2005) increases in others (Knudsen and Dilley 1987; Binns 1994; Binns and Remmick 1994; Avery 1995; White et al. 2010), or had no effect (Madejczyk et al. 1998; McClure 1991). Similarly, fish species richness was decreased (Oscoz et al. 2005), increased (White et al. 2010), or unchanged (Madejczyk et al. 1998) in stabilized reaches. Changes in fish assemblage structure (Eros et al. 2008; Madejczyk et al. 1998) or size-class distributions (Eros et al. 2008) have occurred in bank-stabilized reaches. Thus, bank stabilization has uncertain and possibly multifaceted consequences for fish assemblages.

The discrepancies in the findings of previous studies may result from differences in rivers. In highly altered or naturally homogenous rivers, bank stabilization may provide habitat diversity that is otherwise lacking (Schmetterling et al. 2001; Zale and Rider 2003), and cause localized increases in fish density and species richness. Conversely, in unaltered or relatively heterogeneous rivers, moderate amounts of bank stabilization may have little or no effect on fish assemblages. Moreover, with the exception of studies by Zale and Rider (2003) and White et al. (2010), all studies of the effects of bank stabilization in large rivers have been conducted in regulated rivers (Michny 1988; Garland et al. 2002; Eros et al. 2008; Schloesser et al. 2012) where the effects of bank stabilization may be confounded by or interact with the effects of dams.

Differences in study approaches may also underlie differences in the results of previous research. For example, previous studies differed with regard to the fish taxa studied and the spatial scales at which effects were examined. Many previous studies were limited to a single family of fish (e.g., salmonids) or particular age classes (e.g., juveniles). The emphasis on a subset of the assemblage may underlie the apparent inconsistencies in the conclusions because effects could remain undetected if some species and age classes were not sampled (Zale and Rider 2003). Moreover, failing to account for spatial scale-dependence or side-channel availability may lead to differing conclusions.

Ecological theory (Junk 1989) and empirical field studies (Ellis et al. 1979; Brown and Hartman 1988; Copp 1997; Gurtin et al. 2003; Zale and Rider 2003; Beechie et al. 2005; Chapter 3) suggest that side channels are crucial fish habitats because of the habitat heterogeneity they provide. Fish species richness was positively associated with increased habitat heterogeneity in the upper Mississippi River (Ellis et al.1979; Koel 2004). Lateral connectivity is also important; twice as many fishes were found in connected aquatic floodplain habitats than in disconnected habitats in the impounded lower Missouri River (Galat et al. 1998). However, extensive bank stabilization and altered hydrographs in the upper Mississippi River and the lower Missouri River confound the inference of these studies because both bank stabilization and altered hydrographs reduce side-channel inundation both spatially and temporally. Therefore, the limited amount of remaining side-channel habitats may have concentrated fish.

The Yellowstone River (Figure 4.1) has side channels and reaches with and without bank stabilization (Figure 4.2) and lacks the confounding influence of mainstem dams (Koch et al. 1977), making it ideal for study of the effects of bank stabilization and side channels. We examined the influence of bank stabilization and side channels on the structure of the mainstem Yellowstone River fish assemblage from Laurel to Sidney, Montana, during late summer and early autumn base flow conditions in 2009-2011. Our primary objective was to determine if main-channel fish assemblages differed as a function of bank stabilization. Our secondary objective was to determine if main-channel fish assemblages differed as a function of side channels. We hypothesized that bank stabilization and side channels would influence fish assemblage structure differently, but that both would be scale-dependent. We targeted our sampling and analyses to include the entire Yellowstone River fish assemblage to address this hypothesis. Moreover, we explicitly examined potential scale-dependence in the relationships between fish assemblages and bank stabilization, and fish assemblages and side channels. In addition, we compared depths and velocities of stabilized and reference pools to determine if bank stabilization altered local fish habitat.

Study Area

The Yellowstone River originates in northwestern Wyoming, and flows north to Livingston, Montana, and then generally northeast to its confluence with the Missouri River in North Dakota (Figure 2.1). The basin size of this 8th order stream is 182,336 km^2 (White and Bramblett 1993). Its hydrology is driven by snowmelt with peak runoff usually occurring in June. The Yellowstone River's hydrology is altered by dams on two of its major tributaries (the Bighorn and Tongue rivers) and by water withdrawals (White and Bramblett 1993; Chase 2013; Watson 2014). As a result, peak flows and summer base flows have been attenuated; estimated present-day mean monthly flows at Sidney, Montana, were 28% less during June and 46% less during August than if the Yellowstone's hydrology were unaltered (Chase 2013).

The study area is characterized by diverse geomorphologies that result from valley-wall constriction or lack thereof (Koch et al. 1977; Silverman and Tomlinsen 1984; Boyd and Thatcher 2004). Reach geomorphology governed the historic side channel frequency and areal extent (Boyd and Thatcher 2004; Chapter 2); reaches with valley-wall constriction were meandering or straight, whereas unconstrained reaches were braided or anabranched with extensive side channels (Koch et al. 1977; Boyd and Thatcher 2004). Presently, anthropogenic perturbations interact with underlying geomorphology to govern side-channel extents (Chapter 2). From the 1950s to 2001, side-channel senescence outpaced new side-channel formation, probably because of floodplain dikes (Chapter 2) and diminished flows (*sensu* Poff et al. 1997). Such anthropogenic perturbations encourage side channel senescence synergistically through sediment accretion and vegetation encroachment (Poff et al. 1997).

Anthropogenic alterations to the Yellowstone's fluvial geomorphology include six low-head irrigation dams, in-stream linear bank armoring, floodplain levees, dikes (Silverman and Tomlinsen 1984; Boyd and Thatcher 2004), and removal of riparian vegetation (Boyd and Thatcher 2004). The low-head irrigation dams consist of rock or concrete structures constructed perpendicular to the current to divert water from the channel into ditches. Linear bank stabilization consists of rock and concrete riprap constructed longitudinally along river banks to prevent bank erosion. Floodplain levees consist of earthen ridges constructed around developed lands to prevent inundation during high flows. Dikes are of two types: wing dikes and floodplain dikes. Wing dikes consist of rock or concrete riprap deflection structures to direct currents away from the banks on which they are located. Floodplain dikes consist of embankments of earth and rock constructed perpendicular to channel flow in side channels to restrict flows.

Longitudinal trends in channel slope, substrate, water temperature, and turbidity are concomitant with longitudinal shifts in fish assemblage composition. Channel slope generally decreases from 0.140% near the Clarks Fork confluence to 0.046% near the Missouri River confluence (Koch et al. 1977; Boyd and Thatcher 2004). The study area has gravel and cobble substrates above river kilometer (RKM) 50, but transitions to a sand bed downstream of RKM 50 (Koch et al. 1977; Bramblett and White 2001). Water temperature and turbidity generally increase downstream; estimated maximum summer temperatures are 26.5 ºC at Billings to 29 ºC at Sidney (RKM 48; White and Bramblett 1993). Base flow measurements of water clarity (measured with a Fieldmaster Turbidity Tube) can exceed 120 cm near the confluence with the Clarks Fork and be as low as 0 cm near Glendive and Sidney (A. M. Reinhold, unpublished data).

Forty-nine species from 15 families compose the fish assemblage in the study area (White and Bramblett 1993). The upstream reaches of the study area encompass the transition zone of the Yellowstone River fishery, but the reaches below the Bighorn River confluence constitute the warmwater zone (White and Bramblett 1993). Cyprinids and catostomids are common throughout the study area. Abundant cyprinids shift from longnose dace in the upstream reaches to western silvery minnows, flathead chub, and emerald shiners in the downstream reaches; notably, all of these species and common carp are present throughout the entire study area. Sturgeon chub are common below the confluence of the Powder River (Duncan et al. 2012; Appendix A). Mountain and longnose suckers are common in the upstream study reaches, and white suckers and shorthead redhorses are common throughout the study area. Shovelnose sturgeon are common downstream of the Tongue River confluence and although rare, pallid sturgeon are present below the confluence with O'Fallon Creek. Native game fish include channel catfish, saugers, and burbot. With the exception of smallmouth bass, introduced game fish are generally rare in the study area; these include walleyes, black crappies, white crappies, white bass, green sunfish, pumpkinseeds, and bluegills (Appendix A).

Methods

Sampling Design

The sampling design was a nested hierarchy. We divided the study area into five longitudinal segments (Figure 4.1). The five longitudinal segments were selected to include proximate locations of bank stabilization and unaltered banks, and similar local geomorphology, braiding parameter, and slope. Major tributary confluences and diversion dams were excluded from segments wherever possible. However, Segment 2 included the Myers Diversion Dam to avoid splitting this segment by both the Cartersville Diversion Dam and the Bighorn River confluence; the Cartersville Diversion was a greater fish passage barrier than the Myers Diversion, where fish were capable of passing both upstream and downstream (Helfrich et al. 1999).

We selected stabilized and reference alluvial and bluff sites (i.e., river bends) from braided and anabranching reaches (Boyd and Thatcher 2004) within segments using stratified random sampling. Sites consisted of upstream and downstream channel crossovers, and main pools. Alluvial sites were unconstrained laterally by bedrock bluffs whereas bluff sites were constrained laterally by bedrock bluffs. Sites within 1.5 km of either a major tributary confluence or diversion dam were excluded from consideration. Other exclusion criteria were related to having a unique feature; for example, one potential site was excluded because it was about twice as long as all other potential sites.

Reference sites had no armoring on main pools or crossovers. Stabilized sites had at least 35% stabilization of banks of outside bends of main pools. However, some exceptions were made to these reference-site criteria where no other potential reference sites existed. In Segment 1, sections of bank stabilization were present on the upstream crossover (34 m of stabilization; 7% of the upstream crossover banks) of one reference bluff site, the downstream crossover (188 m; 34%) of one reference bluff site, and the upstream crossover (220 m; 37%) and pool (30 m; 1%) of one reference alluvial site. Bank stabilization was present on one bank of the upstream crossover (79 m; 19%) of one reference bluff site in Segment 3. We accounted for these exceptions to our reference site criteria by quantitatively assessing the lengths of bank stabilization and treating bank stabilization as a continuous rather than categorical variable in our analyses of the potential effects of bank stabilization on the fish assemblage.

Fish Sampling

Fish sampling was conducted during late summer and autumn base flow conditions: September through early November 2009 and mid-August through mid-October in 2010 and 2011. Fish sampling occurred in mesohabitats: inside bends of pools, outside bends of pools, and channel crossovers.

We sampled fish with five gears. Fyke nets, bag seines, and otter trawls were deployed to target small-bodied fish whereas electrofishing and trammel nets were employed to target large-bodied fish. Nevertheless, large-bodied fishes were occasionally captured with fyke nets, bag seines, or otter trawls, and small-bodied fishes were occasionally captured with electrofishing or trammel nets. Otter trawls were only deployed in Segments 4 and 5 because otter trawls target sicklefin and sturgeon chub, and the ranges of these species did not include Segments 1-3 (Duncan et al. 2012). Fyke nets, bag seines, and boat electrofishing were used to sample fish along shorelines. Trammel nets and otter trawls were used to sample the fish in the deep portions of the channel in each mesohabitat. Each gear deployment was a subsample.

Fyke nets had two 1.2-m wide and 0.6-m high rectangular steel frames and two 0.6-m diameter circular steel frames covered with 3-mm nylon mesh. The fyke net lead was 4.5-m long, the cab was 3-m long, and a deployed fyke net extended 7.5 m from the shoreline. Our fyke nets were identical to the “mini-fyke nets” described in detail in the upper Mississippi River system Long Term Resource Monitoring Program procedures (Gutreuter et al. 1995). Three fyke nets were set at the shoreline in channel crossovers, inside bends, and outside bends. However, we were unable to sample two outside bends in Segment 1 because the banks were too steep at one site and the banks were too steep and the currents were too swift at the other site. The locations of fyke net deployments were randomly selected by dividing the mesohabitat into three equal longitudinal sections, then dividing each section into tenths and randomly selecting a starting location therein using the second digit in the seconds field of a digital watch. When sampling crossovers, we flipped a coin to decide which bank to sample. The GPS coordinates of each net location were recorded.

Seines were constructed of 6.4-mm mesh and were 9.1-m long and 1.8-m high with a centrally located cubic bag measuring 0.9 m on each side. Two 100-m downstream seine hauls were made in wadeable (less than 1.5 m deep) portions of channel crossovers and inside bends. The locations of seine hauls were randomly selected by dividing the mesohabitat into two longitudinal sections, then dividing each section into tenths and randomly selecting a starting location therein using the second digit in the seconds field of a digital watch. The GPS coordinates of the start and endpoints of each seine haul were recorded.

Boat electrofishing was conducted with a Smith-Root model 5.0 Generator Powered Pulsator using pulsed direct current at 60 pulses per second. One-pass upstream-to-downstream electrofishing was conducted along the entire shoreline of each mesohabitat where depths were 0.8 m or greater. The GPS coordinates of the start and endpoints of each electrofishing pass were recorded.

Trammel nets were 38.1-m long with 9.5-mm float line at the top and 13.6-kg lead line at the bottom. Trammel nets had two panels; the inner panel was 2.4 m in height with 2.5-cm bar mesh, and the outer panel was 1.8 m in height with 20.3-cm bar mesh. Otter trawls were 4.9-m wide, 0.91-m tall, and 7.6-m long. The inner mesh size was 6.4 mm and outer mesh size was 38.1 mm. Trawl doors were 76.2 cm by 38.1 cm and weighed 13.6 kg each. The trawl was towed downstream with two 30-m ropes. Otter trawls were identical to those used for the Missouri River Pallid Sturgeon

Population Assessment Program (model OT16; Hamel et al. 2009). Trammel nets and otter trawls were randomly deployed; we divided each mesohabitat into two equal longitudinal sections, divided the two sections into longitudinal tenths, and selected the starting location that corresponded to the second digit in the seconds field of a digital watch. The GPS coordinates at the start and end of each deployment were recorded.

We used MS-222 to anaesthetize fish prior to handling. All fish greater than 30 mm total length (TL) were identified to species and counted. However, catostomids, cyprinids, and centrarchids less than 30 mm TL and ictalurids less than 20 mm TL were identified to family and treated as separate "species" in subsequent analyses.

Spatial Analyses

We used ESRI ArcGIS 10.0 and existing digitizations of bank stabilization, flow lines (Yellowstone River Corridor Resource Clearinghouse 2013), and channel margins (T. Thatcher, DTM Consulting, unpublished data) for all spatial analyses. We examined the longitudinal variation in bank stabilization and side channels on the Yellowstone River to ensure that selected sites reflected a diverse sample (Figure 4.2).

We calculated the spatial center of each subsample from its GPS coordinates and established its longitudinal position. We used ArcGIS Network Analyst to identify all bank stabilization and side channels around the center of each subsample and at upstream and downstream distances of 50, 100, 200, 400, 800, 1,200, 1,600, 2,000, 2,400, 2,800, and 3,200 m from the center (Figure 4.3). We used a 200-m lateral buffer to extract main-channel bank stabilization lengths, and main-channel and side-channel bank lengths for each of the twelve buffered distances for each subsample. The buffered distances are referred to as spatial scales in the remainder of this document.

We standardized the lengths of bank stabilization and side-channel banks for each subsample for each spatial scale by calculating bank-stabilization and side-channel proportions. Each bank-stabilization proportion was calculated by dividing the length of bank stabilization by main-channel bank length. Each side-channel proportion was calculated by dividing the length of side-channel banks by the length of all banks. The bank-stabilization and side-channel proportions for all subsamples of each gear type within each mesohabitat were averaged and resulted in one bank-stabilization proportion and one side-channel proportion for each combination of mesohabitat, gear type, and spatial scale.

Statistical Analyses

We examined the relationships of individual fish species and fish assemblage structure to bank-stabilization and side-channel proportions. Catch per unit effort (CPUE) was calculated for each species captured by each gear type. Trammel-net and seine-haul CPUE was calculated by dividing catch by the distance sampled. Electrofishing CPUE was calculated by dividing catch by the time electrofished. Fyke CPUE was calculated by dividing catch by the set duration. The CPUE for each mesohabitat × gear combination was averaged for each site because our sampling design was balanced at the mesohabitat level. Few species showed clear differences in CPUE between reference and stabilized sites (Appendix C). All statistical analyses were conducted in R 3.0.1 (R Development Core Team 2013).

Assemblage Structure Analyses. The fish-assemblage subset captured by each gear at each geomorphic site type was analyzed separately. A Bray-Curtis dissimilarity matrix (Bray and Curtis 1957) was generated from the CPUEs of species from each assemblage subset (function vegdist in R’s vegan package; Oksanen et al. 2013) and analyzed with permutational multivariate analysis of variance (perMANOVA; function adonis in R’s vegan package), an analog to multivariate analysis of variance (Anderson 2001). Each perMANOVA was stratified by river segment to restrict permutations therein, and included bank-stabilization proportion, side-channel proportion, mesohabitat, year, and site. Each assemblage subset was modeled at the twelve bank-stabilization and side-channel spatial scales, and all combinations thereof. The model that maximized the coefficient of determination, R^2, for each assemblage subset was selected as the best-fitting model. Bank-stabilization and side-channel terms were only interpreted from the best fitting model for each assemblage subset.

Kruskal's non-metric multidimensional scaling (NMDS, function isoMDS in R’s MASS package; Venables and Ripley 2002) of each Bray-Curtis dissimilarity matrix was used to visualize similarities among the fish assemblage subsets. Correlation coefficients were calculated for bank-stabilization and side-channel proportions (function envfit; package vegan; Oksanen et al. 2013) and corresponding eigenvectors were plotted from the centroids of each river segment (function ordispider; package vegan; Oksanen et al. 2013) to visualize how assemblage structure varied with bank-stabilization and side-channel proportions. Eigenvectors represent one-dimensional relationships to the assemblage subsets in ordination space, and do not account for all potential interrelationships in the assemblage data. Rather, eigenvectors pointed to probabilistic assemblage responses to bank stabilization or side channels wherein eigenvector arrow lengths were proportional to strength of correlation, and directionality indicated general shifts in assemblage structure related to bank-stabilization and side-channel proportions. We examined longitudinal consistency in eigenvector directionality across segments for each NMDS. Where eigenvectors were not longitudinally consistent, inferring fish responses to bank stabilization and side channel proportions was problematic because responses varied according to longitudinal river position. However, where eigenvectors were longitudinally consistent, we then qualitatively inferred which fish species had longitudinally consistent responses to bank stabilization and side channel proportions. We highlighted these species in the NMDS figures and reported them in the NMDS table. However, we could not discern between positive correlation with bank stabilization and negative correlation with side channels (or vice versa), because either could result in the same species position in ordination space.

Single Species Analyses. We calculated subsample relative abundance by dividing the catch of each species by the total catch of each subsample. Subsample relative abundance was averaged within gear types and mesohabitats to generate gear by mesohabitat relative abundance (GMRA) for each species (Figure 4.4). We generated three gear-group relative abundances (GGRAs) from the GMRAs. First, we averaged the electrofishing GMRAs and the trammel net GMRAs within each mesohabitat type because these gears targeted large-bodied fish (Figure 4.4a and 4.4d) and were deployed in all mesohabitat types. Second, we averaged the seine GMRAs and the fyke GMRAs within channel crossover and inside bend mesohabitat types because these gears targeted small-bodied fish (Figure 4.4b and 4.4c); we omitted outside bends from this analysis because we were unable to seine outside bends. Third, we considered otter trawls separately because we deployed them solely in Segments 4 and 5; thus, otter trawl GMRAs and GGRAs were equivalent.

We used ordinary least squares regression to determine the estimated changes in GGRAs as a function of bank-stabilization and side-channel proportions at both bluff and alluvial sites; all GGRAs from alluvial and bluff sites were analyzed separately because we expected that the effects of bank stabilization on fish were different at bluff and alluvial sites. We restricted the regressions to the primary longitudinal range for each species (i.e., segments where a species had 25% or fewer absences) to avoid zero inflation. We restricted our regression analyses to species GGRAs for which we had a minimum of 1.5 degrees of freedom to estimate each regression term; this constraint was applied to limit overparameterization. This constraint limited our regression analysis to 12 species by GGRA combinations. We nested site within segment to account for longitudinal differences in relative abundances and modeled changes to relative abundances with terms for bank-stabilization proportion, side-channel proportion, mesohabitat, year, and site. The GGRA of each species was modeled at all combinations of the twelve bank-stabilization and side-channel spatial scales. The combination of bank-stabilization and side-channel spatial scales that maximized the adjusted R^2 for each species GGRA was selected as the best-fitting model, and was the only model for that species GGRA from which coefficients were interpreted. We resampled our data 5,000 times with replacement to generate 95% nonparametric, bootstrapped confidence intervals for regression coefficients because the data were not normally distributed. Although we applied the same statistical test to 12 GGRAs, we did not narrow the range of our confidence intervals to account for potential multiple testing error. We decided that an increased Type I error rate was preferable to failing to identify true, weakly statistically significant results because of a multiple test correction (*sensu* Brosi and Biber 2009). However, true departures from the null hypotheses (no effect of bank stabilization or side channels) cannot be discerned with certainty from departures caused by random chance alone. We estimated changes in GGRA for a 10% increase in bank-stabilization or side-channel proportion because a 10% change was within the range of bank-stabilization and side-channel proportions in our data. Interpretation of these estimated changes indicated general trends in relative abundances. However, this analysis was simplified and exploratory because an assumption of our statistical model structure was that relative abundance changed linearly with changes in bank-stabilization and side-channel proportions. Consequently, this analysis was unable to detect possible threshold, interaction, or density-dependent effects; nevertheless, this analysis improves our understanding of which species were influenced by bank stabilization.

Our primary objective was to determine if main-channel fish assemblages differed as a function of bank-stabilization proportion. Our secondary objective was to determine if main-channel fish assemblages differed as a function of side-channel proportion. Therefore, we fitted all regression and perMANOVA models using sequential sums of squares, such that the effects of bank stabilization were accounted for prior to estimating the effects of side channels on the fish assemblage. Accordingly, the lack of a statistically significant effect of side channels cannot be interpreted as a lack of a side-channel effect, but as a lack of a side-channel effect after accounting for a bank-stabilization effect.

Each fish species was classified into a feeding guild based on Brown (1971), Scott and Crossman (1973), Simon (1998), and Bramblett et al. (2005). Carnivores consumed at least 90% vertebrates, herbivores consumed at least 90% plants or detritus, invertivores-carnivores consumed at least 25% both invertebrates and vertebrates, invertivores consumed at least 75% invertebrates, and omnivores consumed 25 to 90% plants or detritus.

Depth and Velocity Profiling

Each site was surveyed with an Acoustic Doppler Current Profiler (ADCP) during base flow in 2011 to determine if depths and velocities differed significantly between stabilized and reference pools. Profiles were conducted along evenly spaced transects that varied in number as a function of pool length (< 550 m, two transects; 550 to 850 m, three transects; 850 to 1,150 m, four transects; 1,150 to 1,450 m, five transects; > 1,450 m, six transects).

We determined whether main-channel bank stabilization was present within 50 m upstream or downstream of each ADCP transect to locate partially stabilized pools because some “reference” pools had small amounts of bank stabilization. Partially stabilized pools were classified as “stabilized” because even short lengths of bank stabilization could cause local changes in pool depth or current velocity. We calculated the means, 95th percentiles, and maximum variances of depth and velocity of each pool and regressed these against bank stabilization and river segment using ordinary least squares regression. We used the 95th percentiles of depth and velocity instead of the true maxima to avoid reporting overestimations resulting from potentially spurious ADCP readings. Nevertheless, we refer to the 95th percentile as the “maximum” in this text.

Results

Fish Assemblage

We captured 45 species of fish and 94,490 fish in total. We captured 72,905 fish with fyke nets, 11,666 with seines, 7,211 by electrofishing, 2,121 with trammel nets, and 587 with otter trawls. The majorities of both our fyke and seine catches were composed of cyprinids and juvenile catostomids, with introduced fishes (e.g., centrarchids) and large-bodied fish captured occasionally (Appendix A, B). By contrast, the majority of our electrofishing catch was adult fish, especially catostomids, goldeyes, and common carp; rare species included burbot, bigmouth buffalo, stonecat, and sauger. Although we targeted large-bodied fishes with electrofishing, we also captured some small-bodied fish with this method. The majority of our trammel net catch was shorthead redhorses, channel catfish, shovelnose sturgeon, and goldeyes; rare species included smallmouth buffalo, pallid sturgeon, and common carp. The majority of the otter trawl catches was sturgeon chub, but saugers, flathead chub, and shovelnose sturgeon were also fairly common; rare species included burbot, stonecat, and walleye. Only flathead chub and shorthead redhorses were captured by all sampling methods (Figure 4.4; Appendix A).

The assemblage compositions for the fyke and seine assemblage subsets varied taxonomically (Appendix A) and functionally by river segment. These subsets were dominated by benthic invertivores in the uppermost segment, composed of a combination of herbivores (western silvery minnows), benthic invertivores (flathead chub), and omnivores (sand shiners) in the middle two segments, and dominated by a combination of benthic (flathead chub) and water column (emerald shiners) invertivores and herbivores (western silvery minnows) in the lower two segments.

The electrofishing and trammel net subsets varied taxonomically by river segment (Appendix A), but were from similar feeding guilds across river segments. Invertivores were the most commonly captured feeding guild in the electrofishing subset in all segments. The most commonly captured species was shorthead redhorse in Segments 1-3, flathead chub in Segment 4, and emerald shiner in Segment 5. Similarly, benthic invertivores were the most commonly captured feeding guild in the trammel net subsets across river segments. The most commonly captured species was longnose sucker in Segment 1, shorthead redhorse in Segments 2-4, and shovelnose sturgeon in Segment 5. In contrast, the otter trawl subset was taxonomically, and therefore functionally, similar in Segments 4 and 5.

The taxonomic differences across river segments were the source of the strong longitudinal trends in the fish assemblage structure (herein described by proportional assemblage compositions calculated from Bray-Curtis dissimilarities of CPUE). The assemblage subsets (Figures 4.5 and 4.6, left panels) and segment centroids (right panels) were generally arranged sequentially along the first dimensions (horizontal axis) of the

NMDSs, indicating that longitudinal influences were of primary importance in structuring the assemblage subsets. The patterns of species in ordination space were concordant with this. For example, in the trammel net subset at alluvial sites, mountain whitefish, brown trout, rainbow trout, longnose suckers, and mountain suckers were more common in upstream segments and pallid sturgeon, shovelnose sturgeon, saugers, and freshwater drums were more common in downstream segments; these species were arranged in ordination space along the horizontal axis, generally concordant with their longitudinal abundances (Figure 4.5d; Appendix A). However, the variation in the assemblage subsets along the second dimensions of the NMDSs (vertical axis) was often well explained by bank stabilization and side channels, indicating that bank stabilization and side channels were of secondary importance in structuring the assemblage subsets.

Bank stabilization and side channels influenced the fish assemblage structure of many assemblage subsets (Table 4.2). Fish assemblage structure also varied with site, year, and mesohabitat as we expected; in fact, terms for site and year generally explained a greater portion of the assemblage structure than either bank stabilization or side channels. Moreover, the perMANOVA results for bank-stabilization and side-channel terms generally confirmed the eigenanalysis of the NMDSs, but there were some exceptions that probably arose from differences in the assumptions of these two statistical techniques; for example, the large site and year effects that we identified in the perMANOVA results (Table 4.2) cannot be directly accounted for in the NMDS results.

The influences of bank stabilization and side channels on the fish assemblage subsets differed as indicated by the differing and often opposing eigenvector directions for bank-stabilization and side-channel proportions (Figures 4.5 and 4.6, right panels). The influences of bank stabilization and side channels on the fyke and seine fish assemblage subsets varied longitudinally across river segments. For example, in the seine subset at alluvial sites (Figure 4.5c), the close proximity of the centroids for Segments 3-5 indicated similar overall species pools for species seined in these segments, but varying eigenvector directions indicated that bank stabilization and side channels were correlated with different species in different segments. However, the bank-stabilization and side-channel eigenvector directions were generally similar across segments for the electrofishing and trammel net subsets (Figures 4.5a, 4.5d and 4.6a). Thus, the assemblage subsets captured with electrofishing and trammel nets generally exhibited more consistent responses to bank stabilization and side channels across river segments than the fyke and seine subsets.

Where eigenvector directionality was longitudinally consistent, species correlations with side channels were more frequent than with bank stabilization (29 correlations with side channels versus 15 correlations with bank stabilization; Table 4.3) and species correlations with side channels were more consistent than with bank stabilization. For example, some species correlated to side channels consistently across sampling methods (e.g., freshwater drum) or across sampling methods and site geomorphologies (e.g., white sucker; Figures 4.5 and 4.6). However, no species correlated to bank stabilization consistently across sampling methods or site geomorphologies (Figures 4.5 and 4.6). Moreover, some species correlations to bank stabilization and side channels varied by gear type (e.g., channel catfish; Figures 4.5a, d), site geomorphology (e.g., emerald shiner; Figures 4.5a and 4.6a), or both (e.g., shovelnose sturgeon; Figures 4.5a, d and 4.6a).

Individual species responses to bank stabilization and side channels generally varied according to site geomorphology and sampling method (Figures 4.7 and 4.8). Flathead chub responses to bank stabilization varied according to sampling method in alluvial sites; the relative abundances of flathead chub captured with fykes and seines increased with bank-stabilization proportion, but the relative abundances of flathead chub caught by electrofishing and trammel nets did not differ with bank-stabilization proportion. Only white suckers captured with electrofishing and trammel nets responded to bank stabilization consistently across site geomorphologies; white sucker relative abundances decreased with bank stabilization at both alluvial and bluff sites. Goldeye responses to side channels and goldeye, shorthead redhorse, and longnose sucker responses to bank stabilization varied according to site geomorphology when captured with electrofishing and trammel nets. Moreover, goldeye responses to bank stabilization and side channels were opposite at alluvial sites; goldeye relative abundances increased with bank-stabilization proportion and decreased with side-channel proportion.

Spatial Scale-dependence

The spatial scales of measurement for bank-stabilization and side-channel proportions influenced the explanatory power of the models of main-channel assemblage structure for the assemblage subsets (Figure 4.9; Table 4.2). Although the range in overall R^2 values for each assemblage subset is modest, the magnitude of variation in overall R^2 values is attributable solely to the scale-dependence of bank-stabilization and side-channel proportions; all other model terms (i.e., site, year, and mesohabitat) are independent of, and therefore do not change with, spatial scale. Further, because the R^2 values for bank-stabilization and side-channel terms are also modest (0.02 to 0.10), a 0.01 increase in overall R^2 equates to a 10-50% improvement in the R^2 for bank-stabilization and side-channel proportions.

The scale-dependent distributions in explanatory power attributable to bank-stabilization proportions were often bimodal (Figure 4.9). Bank-stabilization influences were best modeled at the coarsest spatial scale we considered (3,200 m up and down stream) for the seine subset at alluvial sites and the electrofishing subset at bluff sites, but both of these subsets had a second, smaller peak in R^2 values at a moderate scale (1,600 m for seines and 1,200 m for electrofishing). The influence of bank stabilization peaked at a fairly coarse scale (1,600 m) for the fyke subset and a fine scale (100 m) for the trammel subset at alluvial sites, but both of these subsets had a second, smaller peak in R^2 values at a coarser scale (3,200 m for fykes and 2,400 m for trammel nets). Bank-stabilization terms were not significant for the other subsets (Table 4.2).

The scale-dependent distributions in explanatory power attributable to side-channel proportions were generally unimodal and varied by assemblage subset. At alluvial sites, fyke and trammel subsets were best modeled at coarse scales (2,800 to 3,200 m), whereas the seine and electrofishing subsets were best modeled at finer scales (800 m or less). At bluff sites, the seine and electrofishing subsets were best modeled at intermediate scales (1,200 to 1,600 m), but the fyke subset was best modeled at the finest scale (0 m). Only the electrofishing and trammel net subsets at alluvial sites had bimodal patterns in R^2 values on the side-channel axis (Figure 4.9)

The scale-dependent distributions in explanatory power attributable to bank stabilization and side channels were generally unimodal for the single-species models. Among the species with significant bank-stabilization or side-channel terms, the optimum spatial scales ranged from 0 to 1,200 m for bank stabilization and from 800 to 2,800 m for side channels (Figure 4.10). Measuring bank stabilization at finer spatial scales (200 m or less) improved model fits for flathead chub, goldeye, and shorthead redhorse at alluvial sites, but moderate scales (800 to 1,200 m) improved fits for white sucker at both alluvial and bluff sites and longnose sucker at bluff sites. Only goldeye had a bimodal distribution in adjusted R^2 values along the bank stabilization axis; peaks were present at both 0 m and 3,200 m scales. Measuring side channels at a moderate scale (800 m) improved model fits for sturgeon chub at alluvial sites, but larger scales (2,400 to 2,800 m) improved fits for goldeye at alluvial sites and common carp at bluff sites. Only one peak was present in the adjusted R^2 values along the side-channel axis for these species.

Depths and Velocities in Stabilized and Reference Pools

Depths differed between reference and stabilized alluvial sites (Figure 4.11a), but velocities did not (Figure 4.12a). Stabilized alluvial pools were deeper (linear regression of mean depths: $t_{5,\,14} = 2.18$, $P = 0.047$; linear regression of maximum depths: $t_{5,\,14} = 3.12$, $P = 0.008$) and had a greater variance in depths (linear regression of maximum variances in depths: $t_{5,\,14} = 2.36$, $P = 0.033$) than reference alluvial pools. The mean depths of stabilized alluvial pools were 0.41 m deeper than reference pools (95% confidence interval [CI] from 0.01 to 0.81 m deeper) and the maximum depths of stabilized alluvial pools were 1.26 m deeper than reference pools (95% CI from 0.39 to 2.13 m deeper). The maximum variances in depths were 0.92 m greater in stabilized alluvial pools than reference alluvial pools (95% CI from 0.09 m greater to 1.76 m greater). The mean velocities (linear regression: $t_{5,\,14} = -0.12$, $P = 0.907$), maximum velocities (linear regression: $t_{5,\,14} = -0.46$, $P = 0.654$), and variances in velocities (linear regression: $t_{5,\,14} = -1.30$, $P = 0.214$) were not different between stabilized and reference alluvial pools.

Neither depths (Figure 4.11b) nor velocities (Figure 4.12b) differed between reference and stabilized bluff sites. The mean depths (linear regression: $t_{3,\,8} = 1.93$, $P = 0.089$), maximum depths (linear regression: $t_{3,\,8} = 1.58$, $P = 0.153$), and variances in depths (linear regression: $t_{3,\,8} = 1.70$, $P = 0.128$) were not different between stabilized and reference bluff pools. The mean velocities (linear regression: $t_{3,8} = 0.58$, $P = 0.577$), maximum velocities (linear regression: $t_{3,8} = 0.20$, $P = 0.851$), and variances in velocities (linear regression: $t_{3,\,8} = 0.63$, $P = 0.544$) were not different between reference and stabilized bluff pools.

Discussion

The lower Yellowstone River fish assemblage varied with bank-stabilization extent and side-channel availability. However, the responses of fish to bank stabilization and side channels often varied with fish assemblage function, longitudinal location, and site geomorphology. Moreover, these responses were dependent on species and life history stage, and the spatial scale at which these responses were measured.

The longitudinal variation in fish assemblage responses to bank stabilization may have been a result of longitudinal differences in the ecological function of fish species. For example, the influences of bank stabilization on trammel net subsets (large-bodied fishes) sampled in deep portions of alluvial channels were largely consistent across river segments. Although the species identities of fishes captured in trammel nets varied longitudinally, all trammel net catches were dominated by large-bodied benthic invertivores (longnose suckers, shorthead redhorses, and shovelnose sturgeon; Appendix A). Therefore, perhaps these fish responded similarly to bank stabilization across river segments because they were ecological analogs. In contrast, fyke and seine assemblage subsets (small-bodied fishes) lacked ecological analogs among longitudinal river segments. Fyke and seine catches were dominated by benthic invertivores (longnose dace, flathead chub, and age-0 catostomids) in Segment 1. However in Segments 2 and 3, the most commonly captured species were more diverse, composed of a combination of herbivores (western silvery minnows), benthic invertivores (flathead chub), and omnivores (sand shiners). In Segments 4 and 5, catches were dominated by a combination of benthic (flathead chub) and water column (emerald shiners) invertivores and herbivores (western silvery minnows; Appendix A). Therefore, fyke and seine catches varied both taxonomically and functionally with river segment whereas the variation in trammel net catches was largely taxonomic.

Longitudinal variation in fish assemblage responses to bank stabilization may relate to the extent to which bank stabilization materials differed from naturally-occurring substrates. The large rock or concrete substrates used for riprap (Boyd and Thatcher 2004) more closely match the naturally-occurring larger substrates in upstream segments than they do in lower segments where smaller substrates are more prevalent. Thus, the trammel net subsets probably had more consistent longitudinal responses to bank stabilization than the shoreline subsets because fish captured in trammel nets were in deep portions of the channel, and therefore, not interacting directly with the bank-stabilization substrates, unlike the shoreline assemblage subsets. Therefore, bank-stabilization substrates in downstream segments could have increased suitable habitat areas for fish that interacted directly with stabilization structures, particularly those that use large substrates for spawning, cover, or feeding (e.g., channel catfish; McMahon and Terrell 1982).

Fish may have used stabilized habitats because foraging success was greater in proximity to these structures. The introduction of large rock substrates was associated with shifts in invertebrate assemblage structure (Beckett et al. 1983) and increased invertebrate abundances (Hjort et al. 1984) in other large rivers. If such changes occurred in the Yellowstone River, food webs would have been altered. Altered invertebrate prey availability or abundances may have influenced how fish used stabilized habitats. For example, relative abundances of the invertivorous longnose sucker were greater in stabilized than in reference bluff pools and may have responded to altered prey availability or suitability in stabilized bluff pools. Similarly, goldeyes (drift feeders;

Simon 1998) were more abundant in stabilized alluvial pools than reference alluvial pools. Goldeyes may have positioned themselves in velocity refugia proximate to stabilization structures—but adjacent to higher current velocities—to increase foraging efficiency and net energy gain (*sensu* Fausch 1984). However, longnose sucker and goldeye responses to stabilization were not consistent across site geomorphology. Therefore, fish responses to bank stabilization were probably interactive among abiotic factors, such as geomorphology and novel substrates, and biotic factors, such as altered food sources and concomitant changes to food webs.

Bank stabilization influenced fish habitat and fish-habitat use differently at alluvial and bluff sites. Bank stabilization probably caused the deepening of alluvial pools by attenuating lateral erosion and accelerating bed degradation, whereas bedrock bluffs constrained lateral erosion regardless of bank stabilization. The trammel net subset may have responded directly to such changes in depths, because the assemblage structure of this subset differed according to bank-stabilization proportion at alluvial but not bluff sites (Table 4.2). At alluvial sites, channel catfish and shovelnose sturgeon positively correlated with bank stabilization in the electrofishing subset, but negatively correlated with bank stabilization in the trammel net subset (Figure 4.5 and Table 4.3). This apparent contradiction in responses to stabilization was possibly caused by fish shifting their habitat use from deep portions of the channel (sampled with trammel nets) to shorelines (sampled with electrofishing). For example, channel catfish inhabit pools with abundant cover, and require hard substrates for spawning (McMahon and Terrell 1982) and therefore may have exploited riprap for cover or spawning. Similarly, shovelnose sturgeon are invertivores (e.g., Siebert et al. 2011) that inhabit both riprap and shoreline habitats (Berry 2002), and therefore may have exploited increased prey availability along riprapped shorelines.

Bank stabilization effects can be indirect and vary according to fish species and life history stage. The increased depths of stabilized alluvial pools probably resulted in narrower SSCV (shallow, slow-current velocity) patches along inside bend margins. Smaller SSCV patch sizes in stabilized alluvial pools, but not bluff pools, could have contributed to fish assemblage differences attributed to bank stabilization in the fyke and seine subsets. Smaller SSCV patches in channel margins probably resulted in a reduction in suitable habitat area for small fish, especially fish that depend on shallow habitats for refugia from aquatic predators and slow current velocities to avoid downstream displacement. However, flathead chub, which can occupy deeper water with swifter current velocities, were therefore probably more resilient to smaller SSCV patch sizes in channel margins than other small fish. The relative abundances of small flathead chub (captured with fykes and seines; Appendix A, B) were greater in inside bend and channel crossover shorelines of stabilized alluvial pools than reference alluvial pools. Unlike small flathead chub, large flathead chub (captured using electrofishing and trammel nets; Appendix A, B) did not differ according to stabilization extent (Figure 4.7a).

Bank stabilization may be detrimental to the long-term persistence of fish, including fishes that positively associated with bank stabilization during base flow. For example, the relative abundances of juvenile flathead chub positively correlated with bank stabilization at alluvial sites during base flow, but this does not indicate that bank stabilization ultimately benefits flathead chub populations. Flathead chub abundances may be limited by critical habitats or life history constraints that that occur during periods other than base flow. Flathead chub used floodplain habitats extensively during runoff (Chapter 3), and bank stabilization decreases floodplain connectivity (Florsheim et al. 2008). Moreover, flathead chub extirpation from the unimpounded upper Mississippi River was concomitant with the anthropogenic disconnection of its floodplain (Barko et al. 2004b). Therefore, if bank-stabilization extent exceeds threshold levels, fishes that depend on floodplain habitats will probably experience population declines, regardless of whether those fishes positively associated with bank stabilization during base flow.

Although the Yellowstone River fish assemblage varied with bank stabilization extent, much overlap existed between the species compositions of stabilized and reference sites, which was concordant with similar investigations from other large rivers (Barko et al. 2004a; White et al. 2010; Schloesser et al. 2012). Likewise, the relative abundances of some species were lower at stabilized sites than at reference sites whereas other species exhibited the opposite trend. This variability in individual species responses to bank stabilization was consistent with similar investigations in the Kansas River (White et al. 2010) and the upper Mississippi River (Madejczyk et al. 1998). However, unlike investigations in other large rivers, our study was not confounded by the influences of impoundment, dredging, channelization, locks and dams, or a largely disconnected floodplain. Such differences complicate specific, direct comparison of our study to many other studies. For example, the responses of *Moxostoma* species to bank stabilization differed between the upper Mississippi and lower Yellowstone rivers.

Shorthead redhorse use of stabilized alluvial sites was less than that of reference sites in the Yellowstone River, but *Moxostoma* species preferentially occupied wing dikes in the Mississippi River (Madejczyk et al. 1998). However, *Moxostoma* species may have been concentrated at wing dikes because wing dikes offered some of the only slow current-velocity habitat in the upper Mississippi River (Barko et al. 2004a, 2004b). In contrast, fish could access slow velocity habitats in both the mainstem and side channels of the Yellowstone River (Bowen et al. 2003). Moreover, we did not study wing dikes, but rather linear bank stabilization.

Side channels influenced fish assemblages in main channels of both alluvial and bluff sites (Table 4.2). Mechanistically, small fish were more abundant in side channels than main channels during runoff (Copp 1989; Chapter 3) and moved into the main channel during flow recession (Chapter 3). River bends with side channels had more small-bodied fish than river bends without side channels (Chapter 3). Side channels increase habitat heterogeneity (Lapointe et al. 2007). Water velocity, substrate, shading, food availability, and piscivore density may differ between side and main channels (A. M. Reinhold, field observations) and could have influenced fish growth rates (Putman et al. 1995), making access to side channels potentially advantageous to fish. Therefore, lateral movements of fish between side and main channels may have led to differences in the mainstem assemblage subsets sampled with fyke nets and seines, although the extent to which fish move laterally between side channels and main channels is unknown for Yellowstone River fish and merits future study.

Side-channel availability may influence fish foraging efficiencies. Main-channel habitats with connected side channels in other large rivers had higher densities of zooplankton (Bothar 1981) and larval fish (Eckblad et al. 1984; Sheaffer and Nickum 1986b) than main-channel habitats without connected side channels. Thus, proximity to side channels may increase prey availability for some fish (e.g., common carp and sturgeon chub in our study; Figure 4.8) in the main channel. However, zooplankton (Bothar 1981), macroinvertebrates (Eckblad et al. 1984; Sheaffer and Nickum 1986a), and larval (Eckblad et al. 1984) and juvenile fish (Eckblad et al. 1984; Sheaffer and Nickum 1986b) densities were greatest in side channels of other large rivers. Therefore in our study, perhaps some fish were less common in main channels with side channels because fish were concentrated in side channels where foraging efficiency was maximized.

Although the overall fish assemblage exhibited clear differences in structure associated with the proportions of bank stabilization and side channels, and some species correlated with bank stabilization or side channels, the response of any particular species to bank stabilization or side channels can be difficult to ascertain based on NMDS. The eigenvectors in Figures 4.5 and 4.6 show, generally, which species most likely drive the shifts in assemblage composition associated with different levels of bank-stabilization and side-channel proportions along the river. Yet, taken alone, the correlation of any individual species with an eigenvector is difficult to interpret because a species correlation with a bank-stabilization or side-channel eigenvector could actually be the result of compressing a multidimensional assemblage into two dimensions. Therefore, conclusions regarding individual species correlations to bank stabilization or side channels interpreted from NMDS should be considered provisional and warrant further study.

The influences of bank stabilization and side channels were scale-dependent (Figures 4.9 and 4.10), probably because Yellowstone River fish have access to heterogeneous habitats. If bank stabilization had reached an extent wherein it caused ubiquitous, large-scale habitat simplification, then we would not expect the effects of bank stabilization to be scale-dependent because habitats would be homogenized and bank-stabilization proportions would be similar at all scales. However, Yellowstone River fish habitats were heterogeneous in terms of braids, meanders, sinuosities, slopes, depths, velocities, substrates, and bank-stabilization extent. Nevertheless, the ecology underlying the patterns in the spatial-scale dependence in the responses of fish to bank stabilization and side channels remains speculative and merits future study.

White et al. (2010) proposed that bank stabilization may increase fish species richness and diversity at finer spatial scales by creating novel bank habitat, but may influence fish at coarser spatial scales by altering normal riverine function. This suggests that bank stabilization influences at least two processes that structure fish assemblages—one at finer spatial scales and another at coarser spatial scales. Implicit in this hypothesis is the assumption that the extent of bank stabilization has reached a threshold by which riverine function is altered and that the altered function is important for fish. We tested a related hypothesis, and bank stabilization was positively correlated with some fish and negatively correlated with others. However, the bimodal distribution in the scale-dependence of several of the assemblage subsets indicated that two processes structured those subsets—one at finer scales and another at coarser scales. We speculate that introducing novel substrates and increasing pool depth may directly structure the assemblage at finer scales and that channel simplification or land use practices associated with bank stabilization may indirectly structure the assemblage at coarser scales. Coarse-scale influences of bank stabilization on fish may be confounded with land-use practices on the lands that bank stabilization protects. Urbanization, agriculture, and transportation can increase concentrations of nutrients, pesticides, or petrochemicals by non-point source runoff (Federal Interagency Stream Restoration Working Group 1998).

The effects of many anthropogenic modifications on large rivers are poorly understood (Barko et al. 2004a). However, our study advances the understanding of how bank stabilization influences large river fish assemblages. To a large extent, the influence of bank stabilization on the Yellowstone River fish assemblage depended on the natural riverine template and how bank stabilization altered the physical habitat therein. Fish assemblage subsets responded differently based on local geomorphology and access to side channels. Additionally, the influences of bank stabilization generally differed from, and often opposed, the influences of side channels on the fish assemblage subsets. Therefore, conservation or restoration of side channels may provide an appropriate mitigation strategy for bank stabilization in the lower Yellowstone River. Although the shifts in the fish assemblage associated with bank stabilization did not result in completely different assemblage structures at stabilized and reference sites, such shifts in the fish assemblage are widespread; bank stabilization was present in many lower Yellowstone River reaches (Boyd and Thatcher 2004). Moreover, we suspect that the present-day fish assemblage reflects the incremental changes in fish habitat that resulted from installation of bank stabilization and loss of side channels, concomitant with increased land use and development of the Yellowstone River basin (Chapter 2).

Tables

Table 4.1. Lower Yellowstone River fishes and their feeding guilds. Abbreviations are used in Table 4.3 and Figures 4.4-4.6. Fish guilds were adopted from Brown (1971), Scott and Crossman (1973), Simon (1998), and Bramblett et al. (2005).

Family	Abbreviation	Common name	Latin name	Feeding guild
Acipenseridae				
	past	Pallid sturgeon	*Scaphirhynchus albus*	Invertivore-carnivore
	shst	Shovelnose sturgeon	*Scaphirhynchus platorynchus*	Invertivore
Catostomidae				
	bibu	Bigmouth buffalo	*Ictiobus cyprinellus*	Invertivore
	blsu	Blue sucker	*Cycleptus elongatus*	Invertivore-herbivore
	cato	Juvenile sucker		
	losu	Longnose sucker	*Catostomus catostomus*	Invertivore
	mosu	Mountain sucker	*Catostomus platyrhynchus*	Herbivore
	rica	River carpsucker	*Carpiodes carpio*	Omnivore
	shre	Shorthead redhorse	*Moxostoma macrolepidotum*	Invertivore
	smbu	Smallmouth buffalo	*Ictiobus bubalus*	Omnivore
	whsu	White sucker	*Catostomus commersonii*	Omnivore
Centrarchidae				
	blcr	Black crappie	*Pomoxis nigromaculatus*	Invertivore-carnivore
	blue	Bluegill	*Lepomis macrochirus*	Invertivore-carnivore
	centr	Juvenile sunfish		
	grsu	Green sunfish	*Lepomis cyanellus*	Invertivore-carnivore
	laba	Largemouth bass	*Micropterus salmoides*	Invertivore-carnivore
	pump	Pumpkinseed	*Lepomis gibbosus*	Invertivore-carnivore
	smba	Smallmouth bass	*Micropterus dolomieu*	Invertivore-carnivore
	whcr	White crappie	*Pomoxis annularis*	Invertivore-carnivore

Table 4.1 Continued

Family	Abbreviation	Common name	Latin name	Feeding guild
Cyprinidae				
	coca	Common carp	*Cyprinus carpio*	Omnivore
	crch	Creek chub	*Semotilus atromaculatus*	Invertivore-carnivore
	cypr	Juvenile minnow		
	emsh	Emerald shiner	*Notropis atherinoides*	Invertivore
	fami	Fathead minnow	*Pimephales promelas*	Omnivore
	flch	Flathead chub	*Platygobio gracilis*	Invertivore
	lach	Lake chub	*Couesius plumbeus*	Invertivore
	loda	Longnose dace	*Rhinichthys cataractae*	Invertivore
	sash	Sand shiner	*Notropis stramineus*	Omnivore
	sich	Sicklefin chub	*Macrhybopsis meeki*	Invertivore
	stch	Sturgeon chub	*Macrhybopsis gelida*	Invertivore
	wesi	Western silvery minnow	*Hybognathus argyritis*	Herbivore
Esocidae				
	nopi	Northern pike	*Esox lucius*	Carnivore
Fundulidae				
	noki	Northern plains killifish	*Fundulus kansae*	Omnivore
Gasterosteidae				
	brst	Brook stickleback	*Culaea inconstans*	Invertivore
Hiodontidae				
	goey	Goldeye	*Hiodon alosoides*	Invertivore-carnivore
Ictaluridae				
	blbu	Black bullhead	*Ameiurus melas*	Invertivore-carnivore
	chca	Channel catfish	*Ictalurus punctatus*	Invertivore-carnivore
	icta	Juvenile catfish		
	stca	Stonecat	*Noturus flavus*	Invertivore-carnivore

Table 4.1 Continued

Family	Abbreviation	Common name	Latin name	Feeding guild
Lepisosteidae				
	shga	Shortnose gar	*Lepisosteus platostomus*	Carnivore
Lotidae				
	burb	Burbot	*Lota lota*	Invertivore-carnivore
Moronidae				
	whba	White bass	*Morone chrysops*	Invertivore-carnivore
Percidae				
	saug	Sauger	*Sander canadensis*	Invertivore-carnivore
	wall	Walleye	*Sander vitreus*	Invertivore-carnivore
	yepe	Yellow perch	*Perca flavescens*	Invertivore-carnivore
Salmonidae				
	brtr	Brown trout	*Salmo trutta*	Invertivore-carnivore
	frdr	Freshwater drum	*Aplodinotus grunniens*	Invertivore-carnivore
	mowh	Mountain whitefish	*Prosopium williamsoni*	Invertivore-carnivore
	ratr	Rainbow trout	*Oncorhynchus mykiss*	Invertivore-carnivore

Table 4.2. Bray-Curtis perMANOVA results for alluvial and bluff sites. Bolded spatial scales, *P*-values, and R^2 values indicate that fish assemblage structure varied significantly with the factor indicated in the column heading.

		Optimum spatial scale (m)		Degrees of freedom			Bank stabilization		Side channels		Mesohabitat		Year		Site	
Site type	Gear	Bank stab.	Side chan.	Residual	Total	Model R^2	*P*-value	R^2	*P*-value	R^2	*P*-value	R^2	*P*-value	R^2	*P*-value	R^2
Alluvial																
	Electrofishing	0	**200**	36	59	0.61	0.081	0.02	**0.013**	**0.03**	**0.041**	**0.04**	**<0.001**	**0.08**	**<0.001**	**0.44**
	Fyke	**1,600**	**3,200**	35	58	0.60	**<0.001**	**0.06**	**0.019**	**0.03**	**0.001**	**0.07**	**0.008**	**0.05**	**<0.001**	**0.39**
	Seine	**3,200**	**800**	14	36	0.81	**0.001**	**0.05**	**0.049**	**0.03**	0.475	0.01	**<0.001**	**0.13**	**0.002**	**0.60**
	Trammel net	**100**	**2,800**	35	58	0.68	**0.021**	**0.02**	**0.010**	**0.02**	**0.007**	**0.04**	**<0.001**	**0.12**	**<0.001**	**0.46**
	Otter trawl	1,600	0	12	23	0.52	0.612	0.03	0.542	0.03	0.747	0.05	0.050	0.09	0.167	0.32
Bluff																
	Electrofishing	**3,200**	**1,600**	20	35	0.65	**<0.001**	**0.10**	**0.026**	**0.04**	**0.011**	**0.07**	**<0.001**	**0.14**	**<0.001**	**0.31**
	Fyke	1,200	**0**	19	34	0.69	0.082	0.03	**0.001**	**0.08**	**0.039**	**0.06**	**<0.001**	**0.25**	**0.002**	**0.28**
	Seine	1,200	**1,200**	8	22	0.72	0.353	0.04	**0.024**	**0.09**	0.429	0.03	**0.004**	**0.18**	0.225	0.38
	Trammel net	200	1,200	19	34	0.62	0.117	0.03	0.145	0.03	0.613	0.03	**<0.001**	**0.16**	**<0.001**	**0.37**

Table 4.3. Species collections with longitudinally consistent correlations to bank stabilization and side channels interpreted from NMDSs. Species collections that positively correlated with bank stabilization, negatively correlated with side channels, or both (BS) are highlighted orange in Figures 4.5 and 4.6. Species collections that positively correlated with side channels, negatively correlated with bank stabilization, or both (SC) are highlighted yellow in Figures 4.5 and 4.6. Species codes are defined in Table 4.1.

	Alluvial		Bluff	
Species	Electrofishing	Trammel net	Electrofishing	Fyke
blbu	-	-	-	BS
blcr	-	-	-	BS
blsu	BS	-	-	-
brst	-	-	-	SC
brtr	-	-	SC	-
burb	-	-	SC	SC
chca	BS	SC	BS	BS
coca	SC	SC	-	-
emsh	SC	-	BS	-
fami	SC	-	SC	-
flch	-	-	BS	-
frdr	SC	SC	-	-
loda	SC	-	-	SC
losu	SC	-	-	-
mosu	-	SC	-	-
mowh	-	-	SC	-
nopi	BS	-	-	-
pump	-	-	-	SC
ratr	-	SC	-	-
rica	-	-	-	BS
sash	-	-	SC	-
saug	-	-	BS	-
shre	SC	-	-	-
shst	BS	SC	SC	-
stca	-	SC	-	-
wall	SC	-	BS	-
wesi	SC	-	-	BS
whcr	-	-	-	BS
whsu	SC	SC	-	SC

Figures

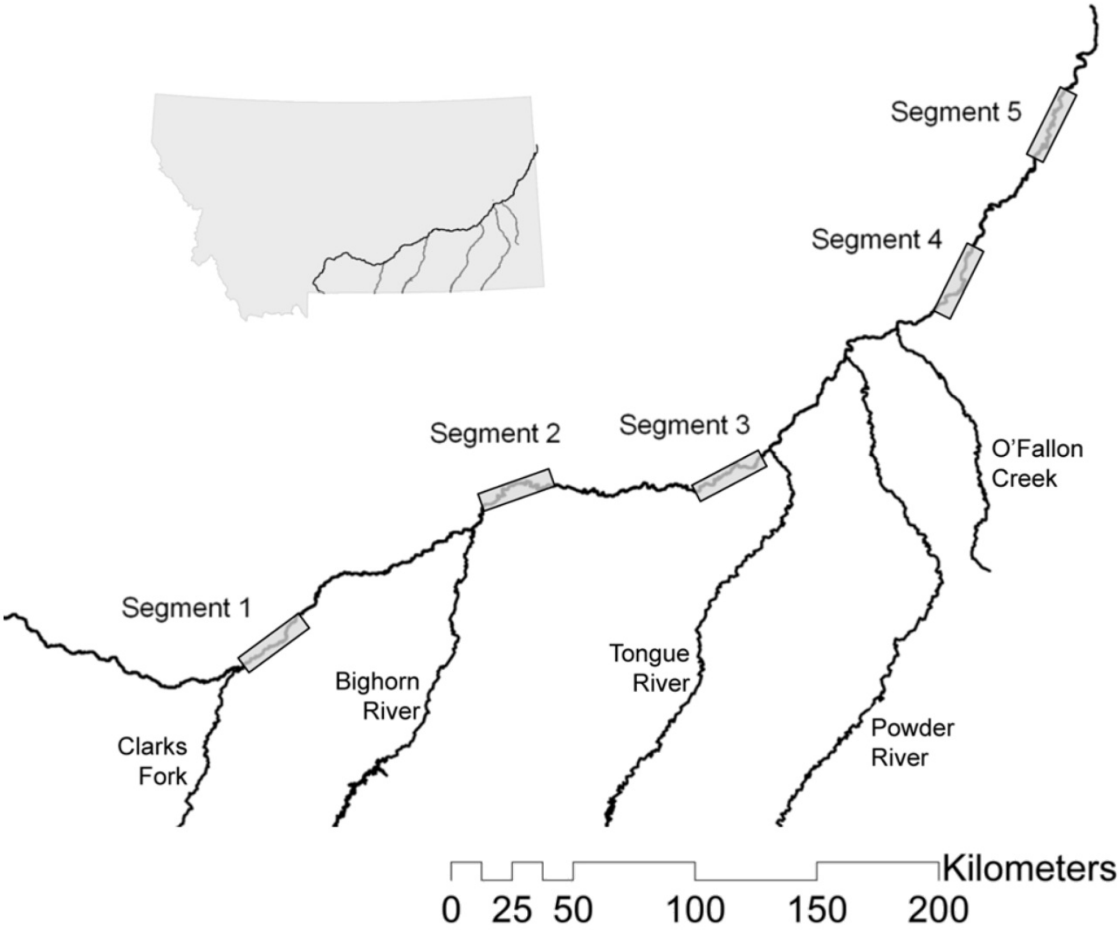
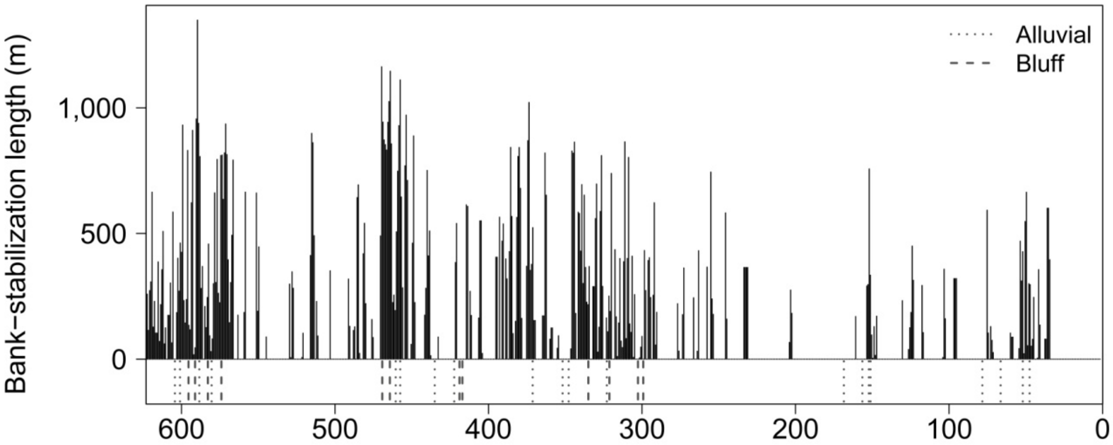


Figure 4.1. Locations of the five study segments in the Yellowstone River.


(a) Longitudinal profile of main−channel bank stabilization

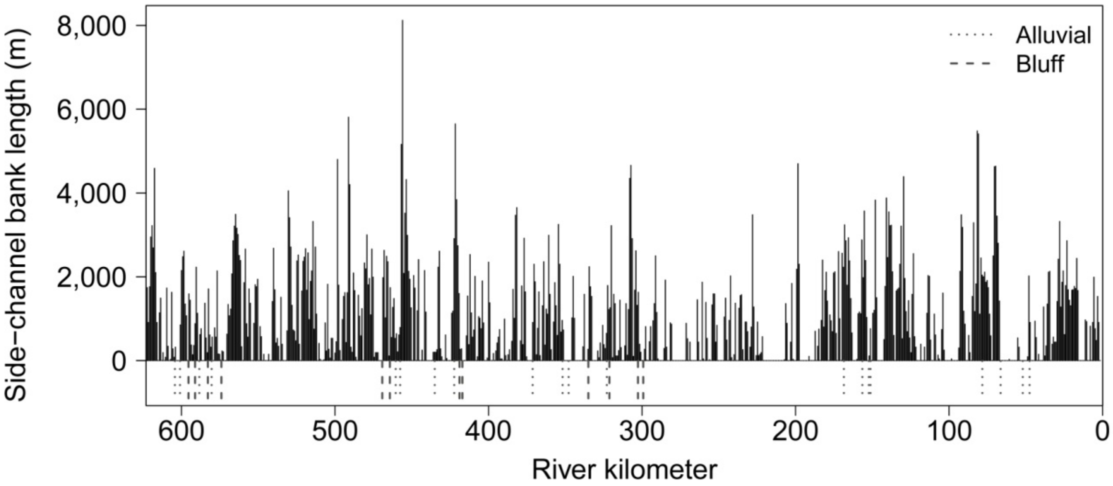

(b) Longitudinal profile of side channels

Figure 4.2. Longitudinal profiles of main-channel bank-stabilization lengths (a) and side-channel bank lengths (b) in the Yellowstone River study area. Sampling sites are marked by dashed lines along the x-axes. Segment 1 (Billings) included the sites near RKM 600; Segment 2 (Hysham) included the sites near RKM 440; Segment 3 (Miles City) included the sites near RKM 340; Segment 4 (Glendive) included the sites near RKM 160; and Segment 5 (Sidney) included the sites near RKM 75.

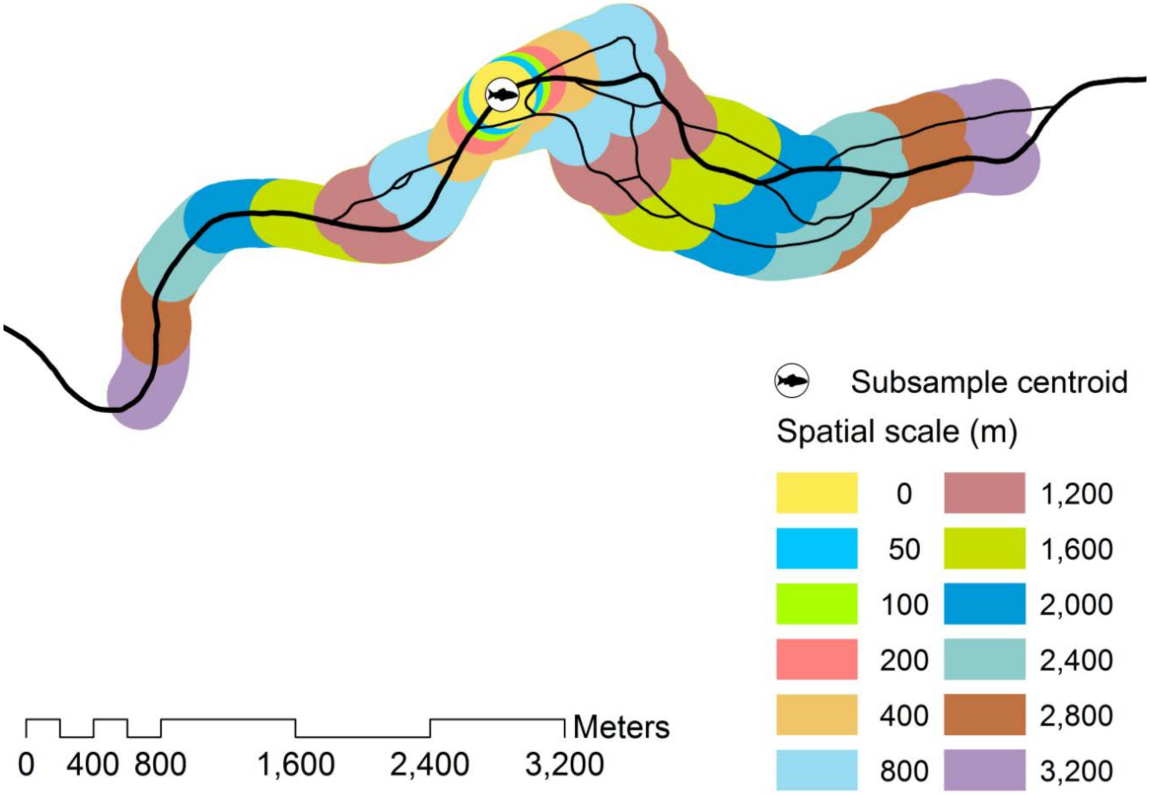


Figure 4.3. Depiction of the twelve buffered spatial scales around one subsample. Buffers were used to extract bank-stabilization lengths, lengths of side-channel banks, and main-channel border lengths at each spatial scale.

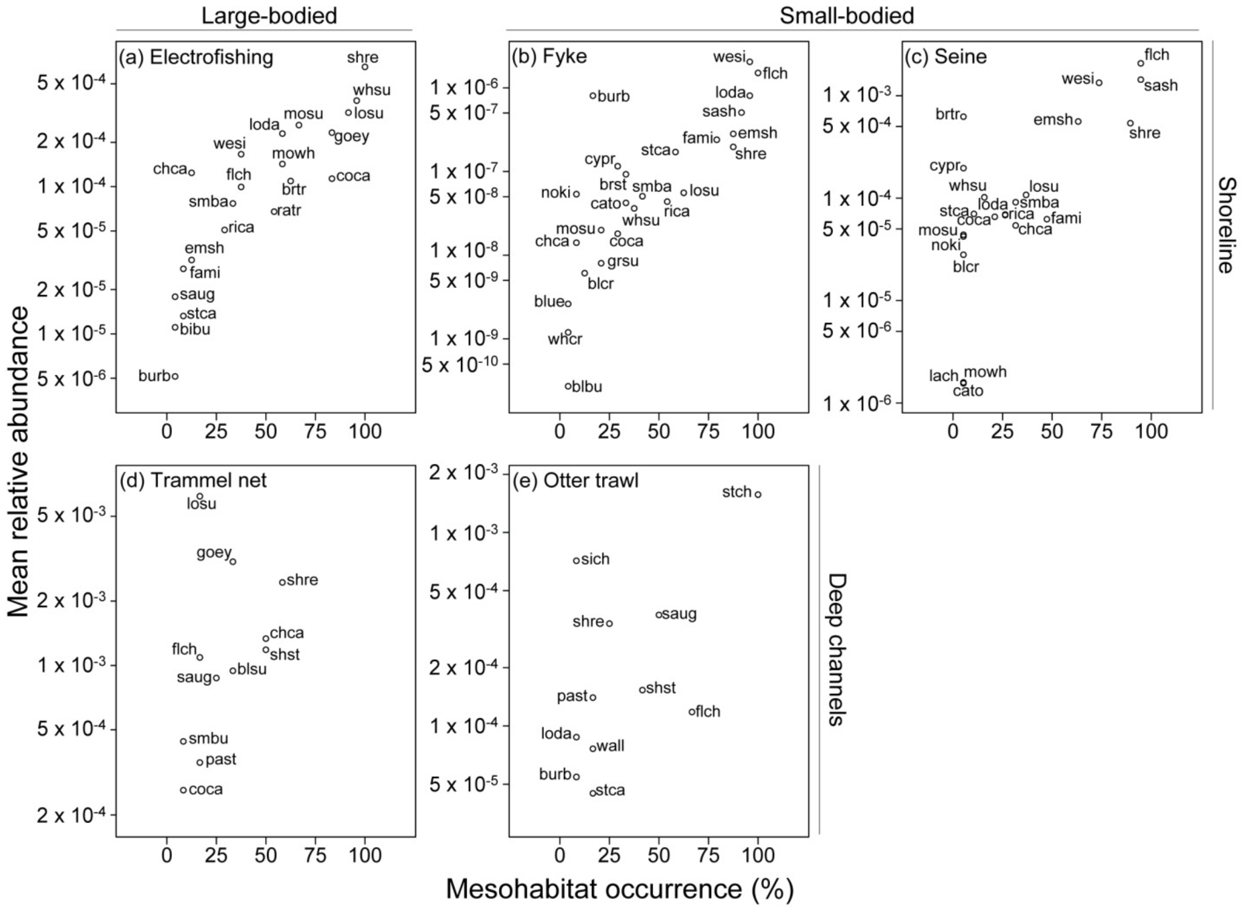


Figure 4.4. Relative abundances and occurrences of Yellowstone River fishes. The mean relative abundance of each species was calculated by averaging the GMRA of each species from all mesohabitats wherein each species occurred. We targeted the large-bodied fish assemblage subset with electrofishing (a) and trammel nets (d) and the small-bodied fish assemblage subset with fyke nets (b), seines (c), and otter trawls (e). Electrofishing, fyke nets, and seines were deployed near shorelines (top row) whereas trammel nets and otter trawls were deployed in deep channels (bottom row). Otter trawls were only deployed in Segments 4 and 5. Species abbreviations are defined in Table 4.1.

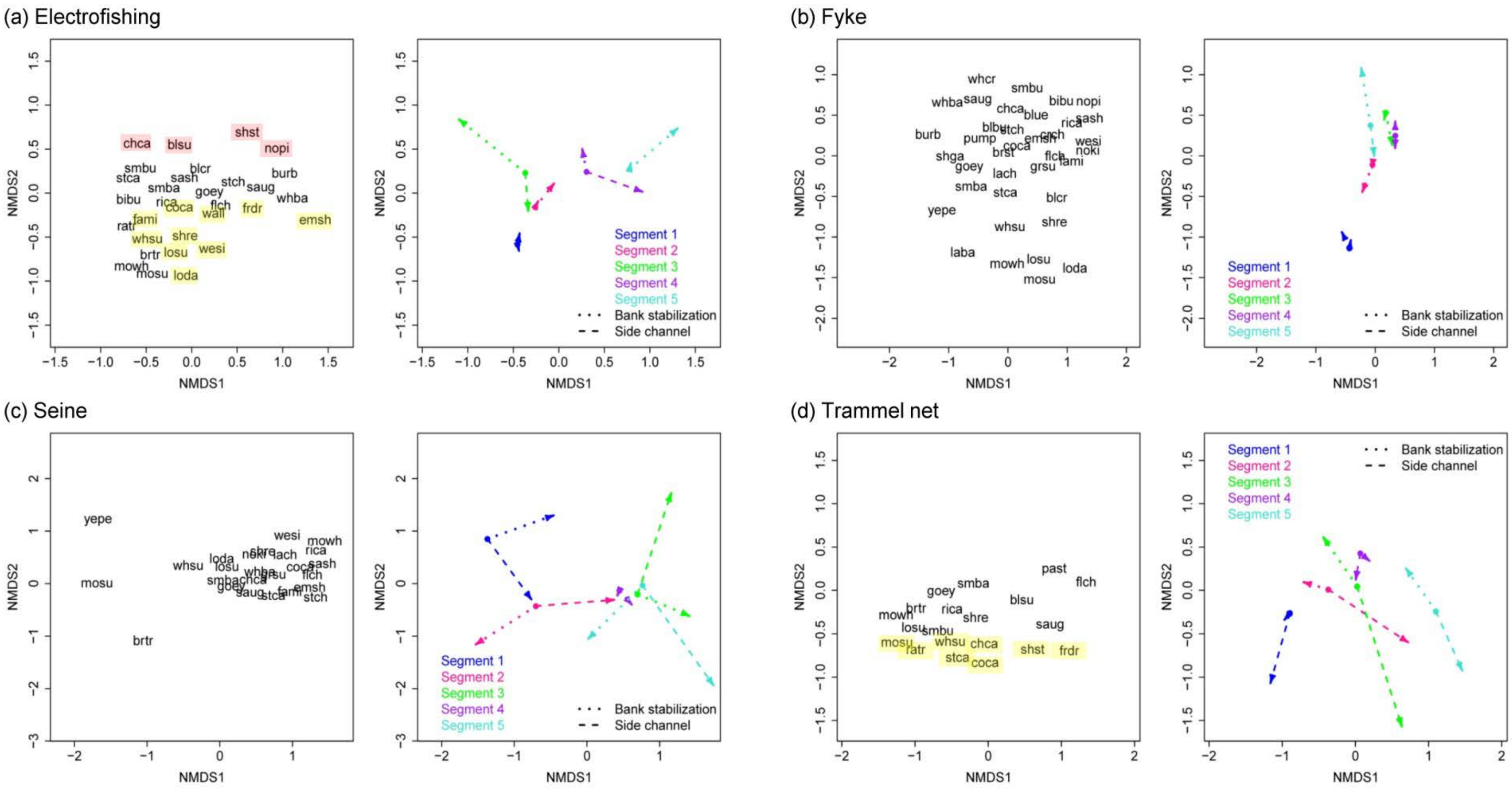
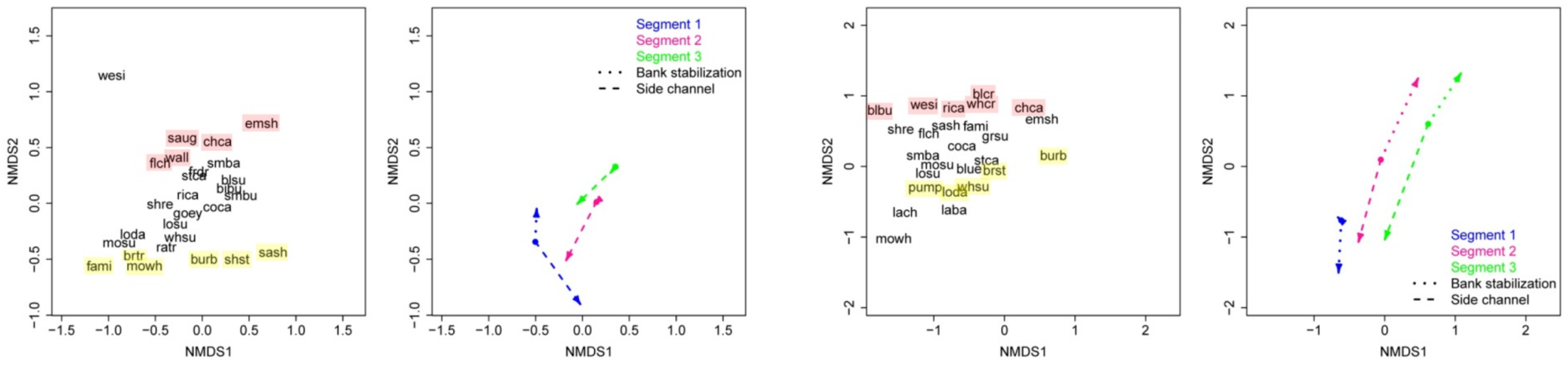


Figure 4.5. Two-dimensional NMDS ordinations of fish assemblage structure at alluvial sites for assemblage subsets with significant perMANOVA terms for bank stabilization, side channels, or both. The fyke, seine, and trammel net subsets had significant bank-stabilization terms; all shown subsets had significant side-channel terms. Species (Table 4.1) were arrayed in mesohabitat ordination space (left panels). Bank-stabilization and side-channel eigenvector lengths (right panels) correspond to the magnitude of the correlation coefficients; eigenvector directions correspond to directions of shifts in assemblage structure related to bank stabilization and side channels. In assemblage subsets with longitudinally consistent bank-stabilization and side-channel eigenvector directions (a and d), orange highlights denote positive correlation with bank stabilization, negative correlation with side channels, or both; yellow highlights denote positive correlation with side channels, negative correlation with bank stabilization, or both (Table 4.3).


(a) Electrofishing

(b) Fyke

(c) Seine

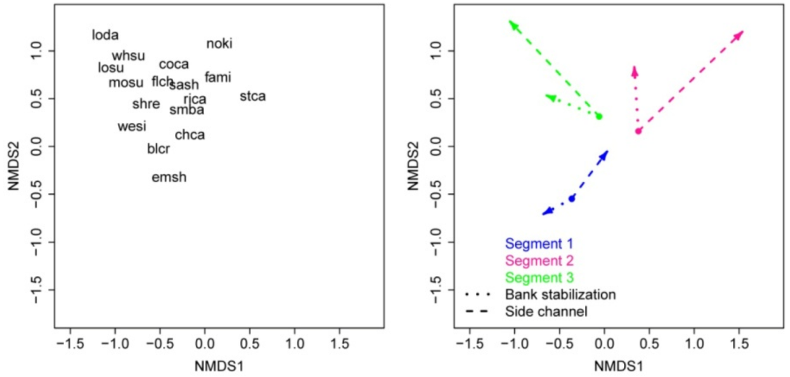


Figure 4.6. Two-dimensional NMDS ordinations of fish assemblage structure at bluff sites for assemblage subsets with significant perMANOVA terms for bank stabilization, side channels, or both. The electrofishing subset had a significant bank-stabilization term; all shown subsets had significant side-channel terms. Species (Table 4.1) were arrayed in mesohabitat ordination space (left panels). Bank-stabilization and side-channel eigenvector lengths (right panels) correspond to the magnitude of the correlation coefficients; eigenvector directions correspond to directions of shifts in assemblage structure related to bank stabilization and side channels. In assemblage subsets with longitudinally consistent bank-stabilization and side-channel eigenvector directions (a and b), orange highlights denote positive correlation with bank stabilization, negative correlation with side channels, or both; yellow highlights denote positive correlation with side channels, negative correlation with bank stabilization, or both (Table 4.3).

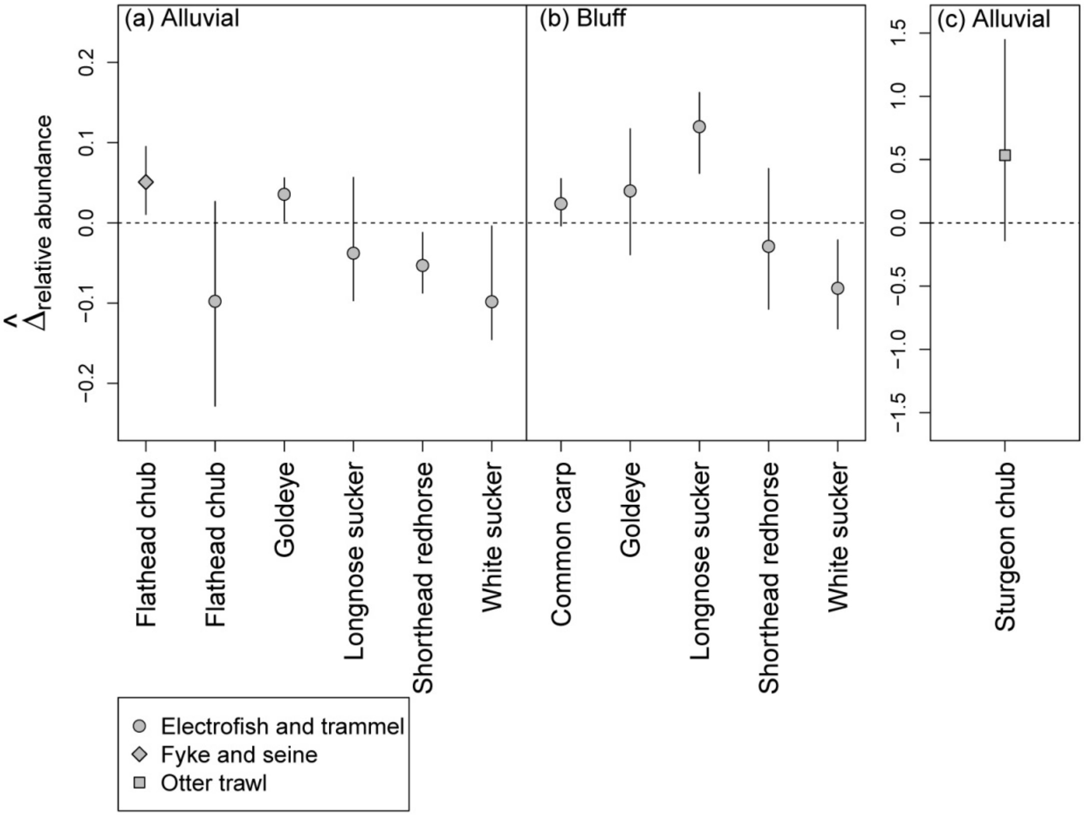


Figure 4.7. Species-specific estimated changes in GGRA as a function of a 10% increase in bank-stabilization proportion at alluvial (a and c) and bluff (b) sites. Error bars represent 95% bootstrap confidence intervals. Bank-stabilization proportion was the linear length of bank stabilization per main-channel bank length at the optimal spatial scale for each species and gear combination.

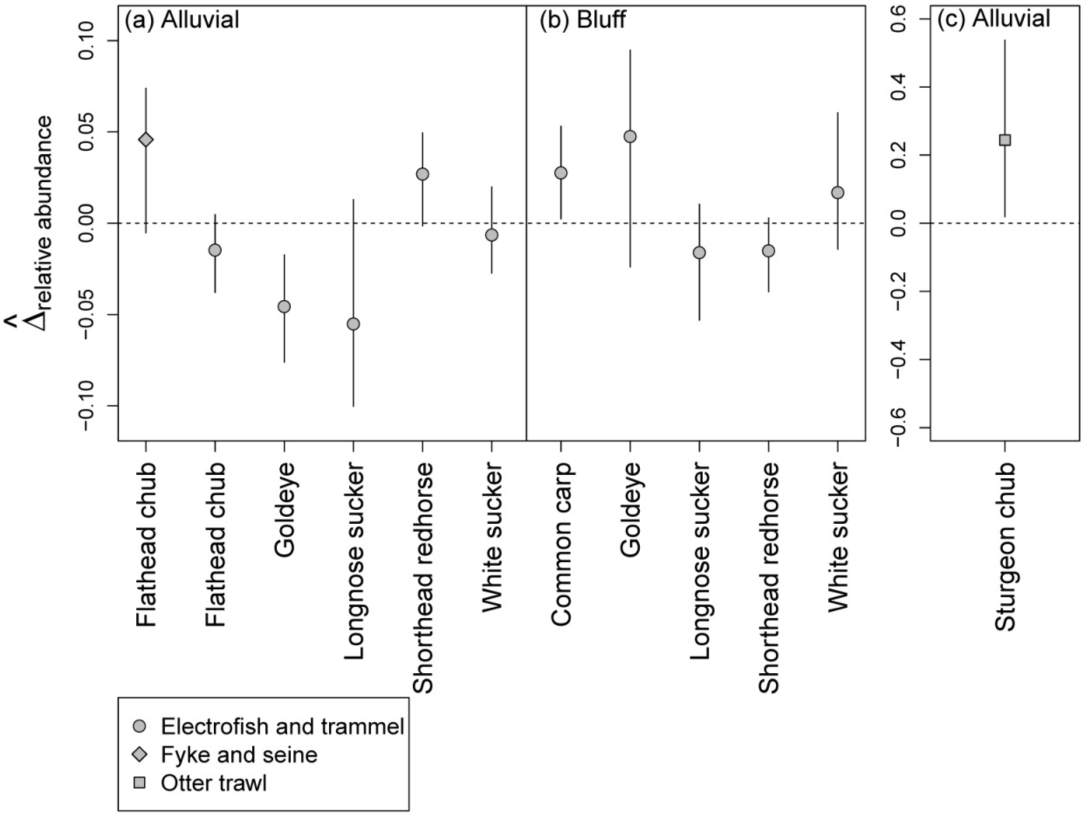


Figure 4.8. Species-specific estimated changes in GGRA as a function of a 10% increase in side-channel proportion at alluvial (a and c) and bluff (b) sites. Error bars represent 95% bootstrap confidence intervals. Side-channel proportion was the linear length of side-channel banks divided by the total length of side- and main-channel banks at the optimal spatial scale for each species and gear combination.

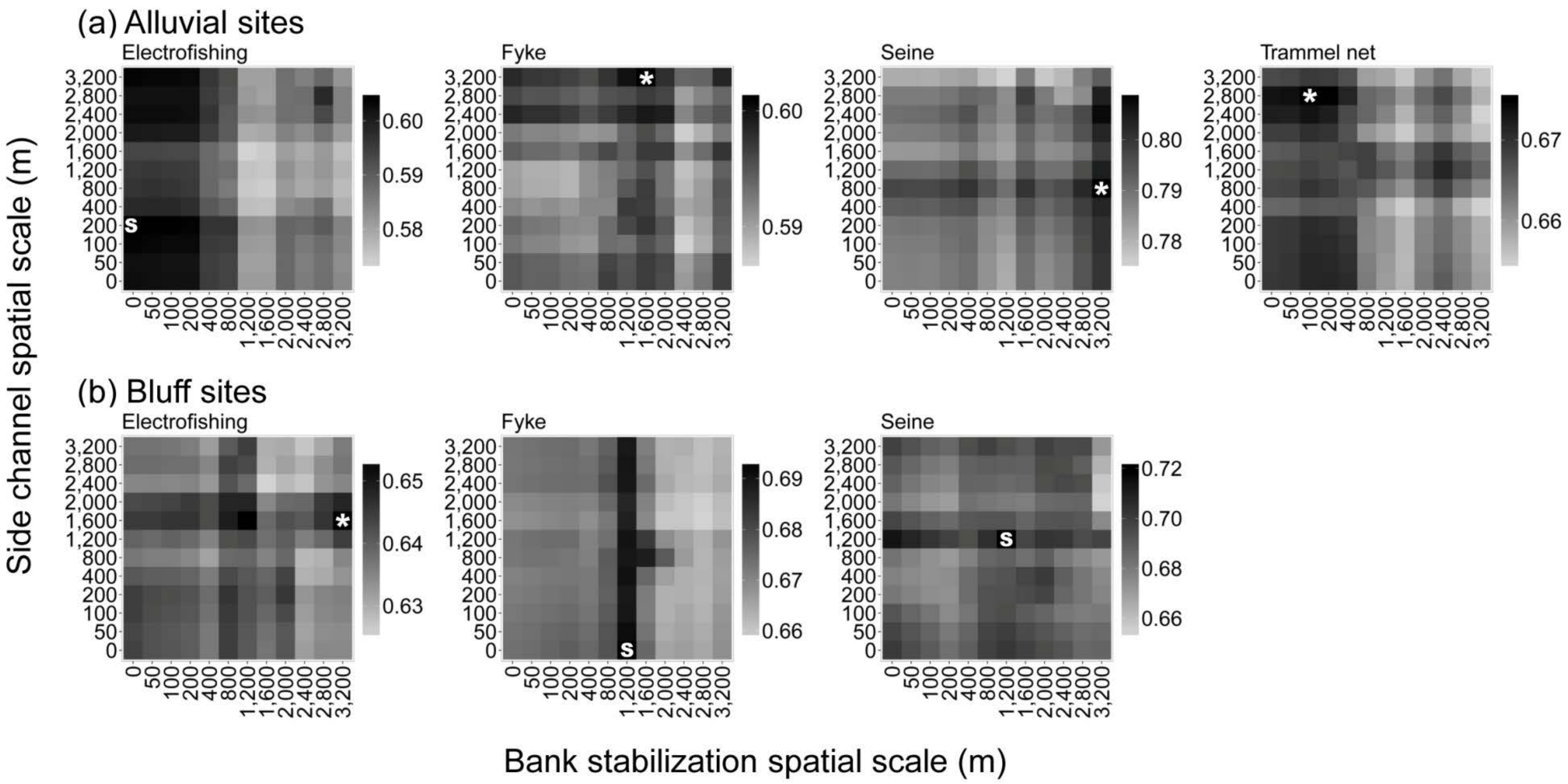


Figure 4.9. Spatial scale-dependence patterns in R^2 values for Bray-Curtis perMANOVA results for alluvial (a) and bluff (b) sites. Better fitting models are black and poorer fitting models are light grey. The maximum R^2 values (Table 4.2) are shown for assemblage subsets with significant terms for bank stabilization, side channels (S), or both (*).

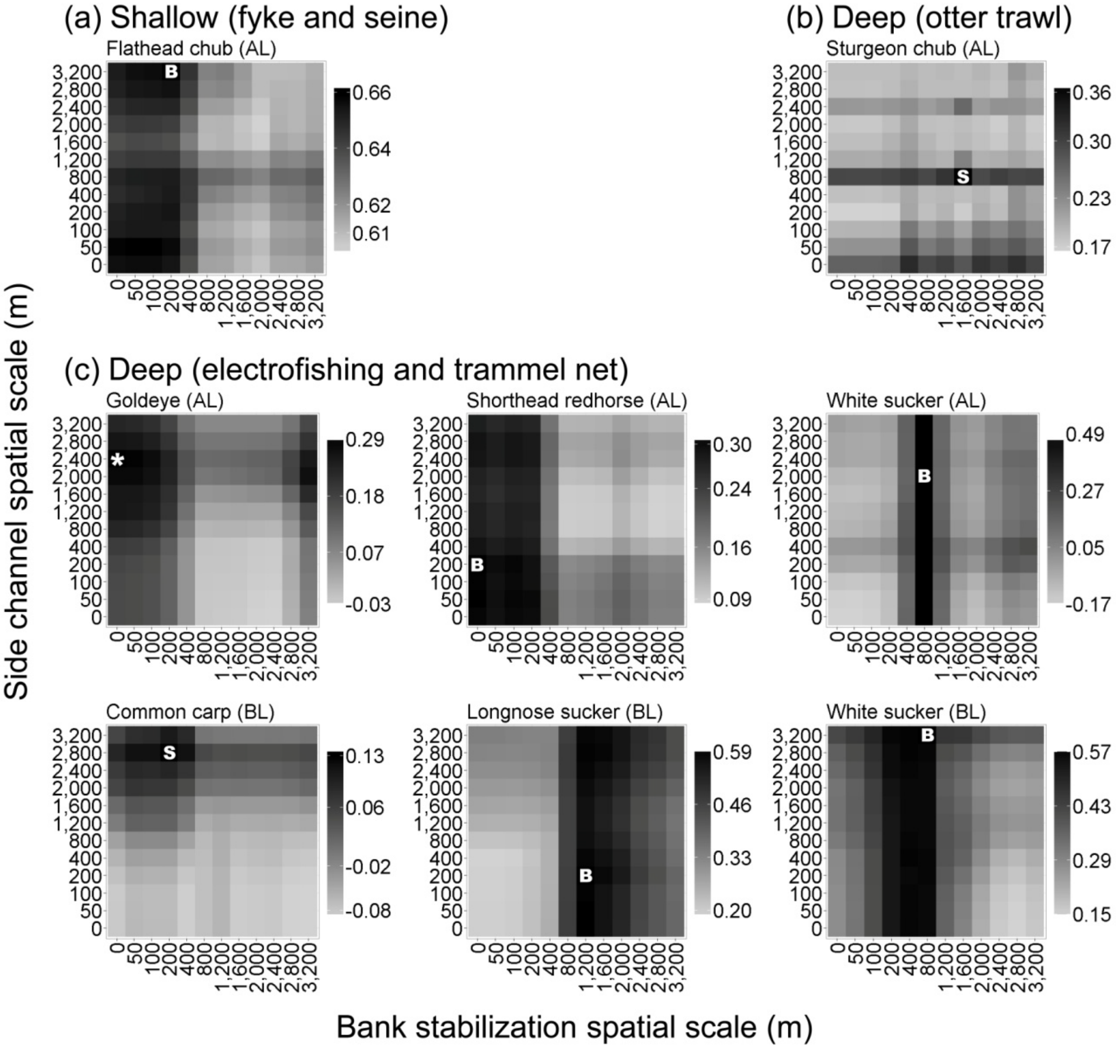
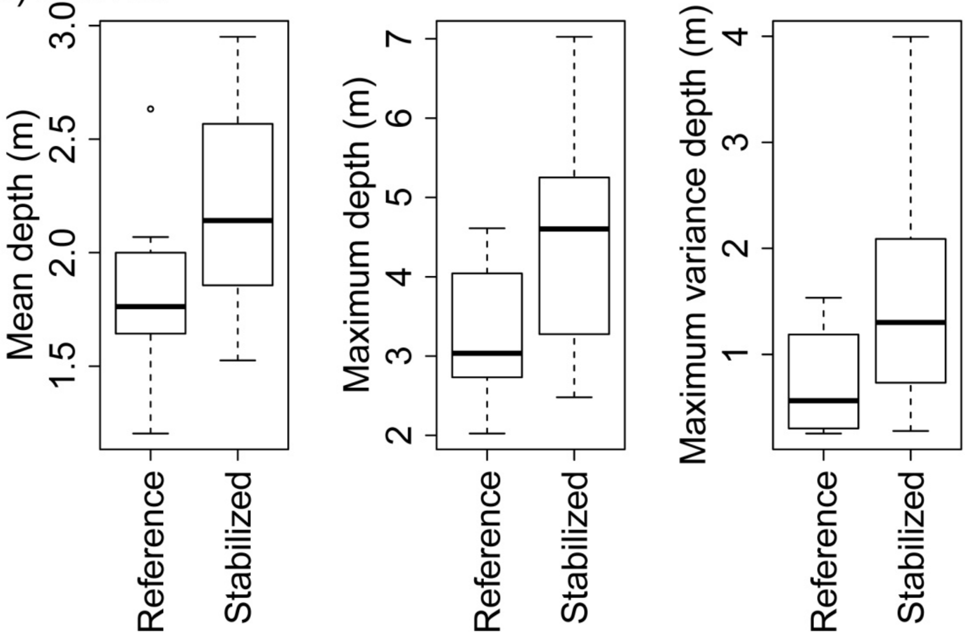


Figure 4.10. Spatial scale-dependence patterns in adjusted R^2 values for regression results for species captured in shallow (a) and deep (b and c) habitats at alluvial (AL) and bluff (BL) sites. Better fitting models are black and poorer fitting models are light grey. The maximum adjusted R^2 values are shown for species-habitat combinations with significant terms for bank stabilization (B), side channels (S), or both (*; Figures 4.7 and 4.8).

(a) Alluvial



(b) Bluff

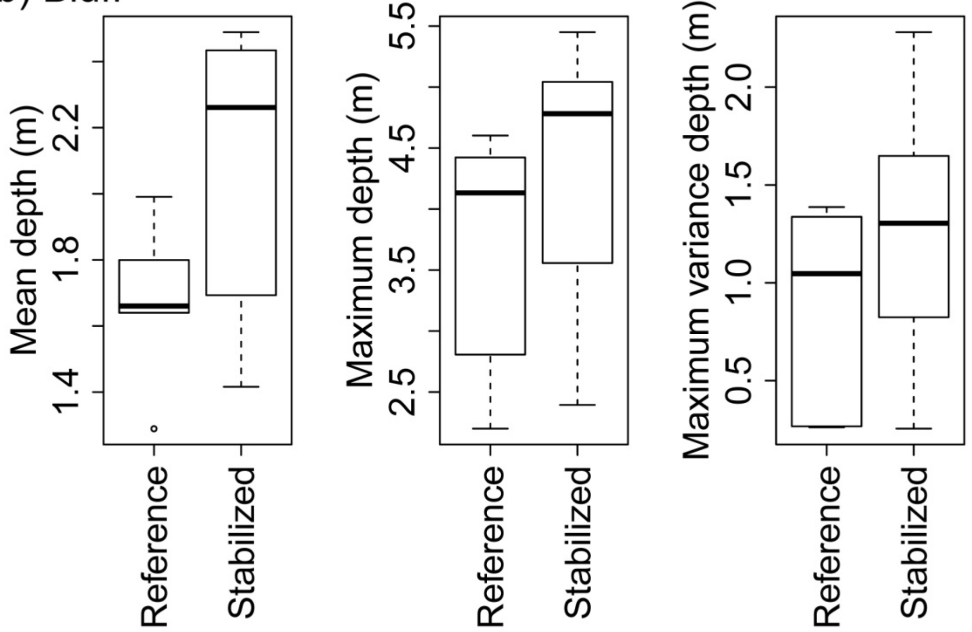
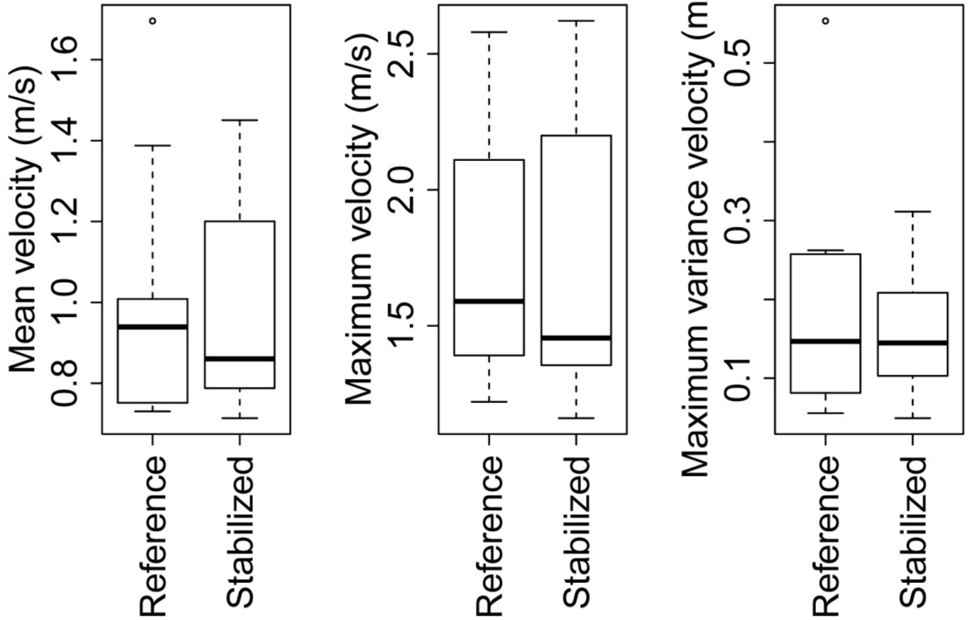


Figure 4.11. Mean, maximum, and maximum variances of depth profiles of reference (a) and stabilized (b) alluvial and bluff pools. Depths were collected with an ADCP. Bold horizontal lines denote medians. Boxes represent interquartile ranges. Vertical bars indicate values within 1.5 interquartile ranges. Points denote values outside 1.5 interquartile ranges.


(a) Alluvial

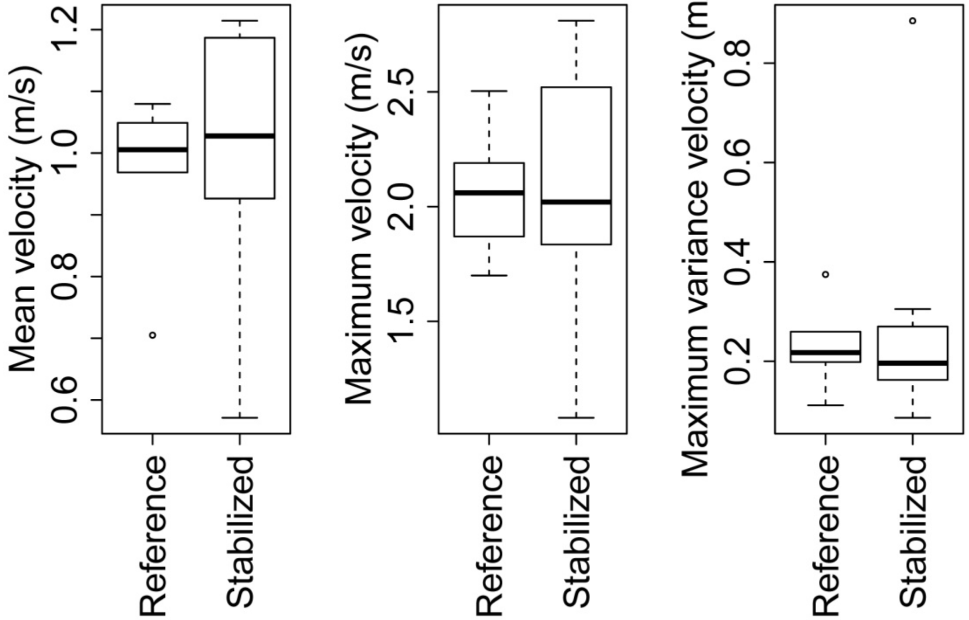

(b) Bluff

Figure 4.12. Mean, maximum, and maximum variances of velocity profiles of reference (a) and stabilized (b) alluvial and bluff pools. Velocities were collected with an ADCP. Bold horizontal lines denote medians. Boxes represent interquartile ranges. Vertical bars indicate values within 1.5 interquartile ranges. Points denote values outside 1.5 interquartile ranges.

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CHAPTER FIVE

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The lower Yellowstone River remains perhaps the least-modified temperate river of its size in the conterminous United States but nonetheless is perturbed by anthropogenic factors. We determined that both bank stabilization and side channels influenced its fish assemblages.

Bank stabilization influenced both physical habitat and fish assemblage structure (i.e., species richness and abundance). Bank stabilization was associated with deeper alluvial pools and linear riprap provided novel bank habitat (Chapter 4). Floodplain diking, but not linear bank stabilization, was associated with reductions in side-channel areas (Chapter 2). However, linear bank stabilization was associated with structural shifts in the fish assemblage and these shifts were scale-dependent (Chapter 4). This suggests that linear bank stabilization (e.g., riprap) influences fish at multiple scales.

Side channels influenced fish assemblages and provided important physical habitat. Total catch rates, commonly-captured individual-species catch rates, and numbers of species were generally greater in side channels than in main channels during runoff, but not during base flow (Chapter 3). Fish assemblage structure also differed between side and main channels during runoff, but not during base flow (Chapter 3). During runoff, the velocities in the shallow, slow current velocity (SSCV) habitat patches were slightly slower, and SSCV patch sizes were generally larger in side channels than in main channels (Chapter 3). These differences in velocity or SSCV patch size possibly contributed to the differences in the fish assemblages between side and main channels.

Side-channel availability also influenced main-channel fish assemblage structure. During base flow, fish assemblages in main channels varied with side-channel availability in alluvial (unconfined) and bluff (confined) river bends. Structural shifts in the main-channel base-flow fish assemblage were scale-dependent (Chapter 4). This again suggests that the spatial context of side channels is important when considering the effects of side channel availability on fish assemblages. Shifts in fish assemblage structure attributable to side channels were consistently different from, and often opposed, the shifts in assemblage structure associated with bank stabilization (Chapter 4). Moreover, more gear-specific fish assemblage subsets were significantly associated with side channels than bank stabilization.

Because both bank stabilization and side channels influence the Yellowstone River fish assemblage, management activities that focus on these two aspects of the ecosystem will probably influence the fishery. Specific management implications from our study include considering the spatial context of bank stabilization projects and side channel availability. The amount of existing bank stabilization on scales of up to a few kilometers influenced the strength of the relationship between fish assemblages and bank stabilization. Therefore, small bank stabilization projects in reaches with mostly natural banks may have limited effects on the fishery. However, in reaches with a moderate extent of existing bank stabilization, additional bank stabilization may elicit substantial shifts in the fish assemblage. In areas with extensive existing bank stabilization, fish assemblages have probably shifted away from the pre-stabilization condition, and any management actions that allow for unaltered riverine function—specifically increases in side-channel availability, may shift the assemblage towards the pre-stabilization condition. Although we have no inference regarding how many side channels can be lost before threshold shifts in the fish assemblage occur, our study illustrates the importance of side channels for fish. Therefore, the protection of existing side channels and the processes that create and maintain them will provide maximal benefit to the preservation of the Yellowstone River fish assemblage.

APPENDICES

APPENDIX A

CATCH PER UNIT EFFORT OF YELLOWSTONE RIVER FISH

Table A.1. Base flow electrofishing catch per unit effort (CPUE) of lower Yellowstone River fish. Fish CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of the CPUE of each species were calculated from all electrofishing passes within each river segment. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	0.00007	0.00035	0.00001	0.00010	0.00005	0.00027	0.00000	0.00000	0.00000	0.00000
Black bullhead	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Black crappie	0.00000	0.00000	0.00000	0.00000	0.00002	0.00011	0.00000	0.00000	0.00000	0.00000
Blue sucker	0.00000	0.00000	0.00000	0.00000	0.00006	0.00029	0.00026	0.00087	0.00000	0.00000
Bluegill	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brook stickleback	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brown trout	0.00298	0.00463	0.00006	0.00044	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Burbot	0.00002	0.00014	0.00005	0.00038	0.00000	0.00000	0.00000	0.00000	0.00061	0.00187
Channel catfish	0.00113	0.00534	0.00702	0.01399	0.00796	0.01280	0.00150	0.00270	0.00079	0.00162
Common carp	0.00503	0.00510	0.00582	0.00578	0.00482	0.00616	0.00279	0.00492	0.00245	0.00398
Creek chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Emerald shiner	0.00022	0.00101	0.00455	0.01681	0.01335	0.03268	0.01838	0.06281	0.10735	0.20646
Fathead minnow	0.00015	0.00078	0.00001	0.00010	0.00002	0.00016	0.00000	0.00000	0.00000	0.00000
Flathead chub	0.00250	0.00552	0.00371	0.00621	0.00267	0.00582	0.01693	0.01486	0.00432	0.00468
Freshwater drum	0.00000	0.00000	0.00057	0.00167	0.00082	0.00194	0.00051	0.00163	0.00230	0.00332
Goldeye	0.00957	0.01503	0.00618	0.01287	0.00895	0.01089	0.00481	0.00928	0.00722	0.00703
Green sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile catfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile minnow	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile sucker	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Lake chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Largemouth bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.1 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Longnose dace	0.00743	0.02057	0.00090	0.00284	0.00006	0.00042	0.00000	0.00000	0.00000	0.00000
Longnose sucker	0.01618	0.01963	0.00653	0.01883	0.00116	0.00340	0.00000	0.00000	0.00000	0.00000
Mountain sucker	0.00964	0.01832	0.00005	0.00038	0.00016	0.00116	0.00000	0.00000	0.00000	0.00000
Mountain whitefish	0.00361	0.00864	0.00003	0.00025	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Northern pike	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00025	0.00069
Northern plains killifish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Pallid sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Pumpkinseed	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Rainbow trout	0.00159	0.00261	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
River carpsucker	0.00099	0.00234	0.00792	0.01027	0.00462	0.00657	0.00088	0.00264	0.00089	0.00181
Sand shiner	0.00000	0.00000	0.00044	0.00168	0.00011	0.00048	0.00000	0.00000	0.00000	0.00000
Sauger	0.00007	0.00051	0.00095	0.00230	0.00194	0.00334	0.00575	0.00711	0.00585	0.00707
Shorthead redhorse	0.04060	0.03344	0.01921	0.01971	0.01957	0.02084	0.00760	0.00904	0.00112	0.00174
Shortnose gar	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Shovelnose sturgeon	0.00000	0.00000	0.00000	0.00000	0.00032	0.00232	0.00000	0.00000	0.00280	0.00739
Sicklefin chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Smallmouth bass	0.00098	0.00270	0.00304	0.00443	0.00213	0.00316	0.00014	0.00071	0.00000	0.00000
Smallmouth buffalo	0.00000	0.00000	0.00039	0.00141	0.00052	0.00126	0.00009	0.00044	0.00000	0.00000
Stonecat	0.00010	0.00050	0.00017	0.00081	0.00004	0.00021	0.00000	0.00000	0.00000	0.00000
Sturgeon chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00510	0.00955	0.00053	0.00146
Walleye	0.00000	0.00000	0.00022	0.00070	0.00026	0.00184	0.00051	0.00175	0.00000	0.00000
Western silvery minnow	0.01061	0.05602	0.01791	0.06458	0.02052	0.12902	0.00196	0.00556	0.00569	0.01521
White bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00024	0.00090
White crappie	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
White sucker	0.02308	0.02457	0.00544	0.00697	0.00177	0.00331	0.00040	0.00121	0.00023	0.00112
Yellow perch	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.2. Base flow fyke catch per unit effort (CPUE) of lower Yellowstone River fish. Fish CPUE is the count of fish captured divided by the duration (in hours) that each net was fishing. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of the CPUE of each species were calculated from all fyke nets deployed within each river segment. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	0.00000	0.00000	0.00000	0.00000	0.00085	0.00768	0.00000	0.00000	0.00189	0.01088
Black bullhead	0.00000	0.00000	0.00088	0.00778	0.00437	0.02346	0.00000	0.00000	0.00209	0.01199
Black crappie	0.00000	0.00000	0.00259	0.01304	0.00145	0.00926	0.00000	0.00000	0.00000	0.00000
Blue sucker	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Bluegill	0.00388	0.01876	0.00177	0.01565	0.01183	0.04065	0.00000	0.00000	0.00000	0.00000
Brook stickleback	0.00490	0.01699	0.02167	0.07058	0.00487	0.01749	0.00189	0.01148	0.00648	0.02082
Brown trout	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Burbot	0.00000	0.00000	0.00332	0.01440	0.00200	0.01040	0.00158	0.00962	0.00000	0.00000
Channel catfish	0.00000	0.00000	0.00172	0.01072	0.02797	0.14892	0.00355	0.01505	0.02520	0.05480
Common carp	0.00951	0.02690	0.01214	0.03940	0.01161	0.03775	0.00000	0.00000	0.00000	0.00000
Creek chub	0.00000	0.00000	0.00000	0.00000	0.00091	0.00821	0.00000	0.00000	0.01207	0.03070
Emerald shiner	0.00781	0.03048	0.29111	0.71039	1.00525	2.89967	1.40202	3.60945	0.81084	2.79451
Fathead minnow	0.06099	0.11418	0.99784	5.80986	0.54321	1.68394	0.00874	0.02660	0.13421	0.43764
Flathead chub	1.08860	2.02886	5.32153	15.28368	2.01542	6.71467	3.09524	4.92693	4.00584	9.50647
Freshwater drum	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Goldeye	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00186	0.01066
Green sunfish	0.00767	0.02319	0.00556	0.02027	0.01281	0.04100	0.00728	0.02121	0.01332	0.05823
Juvenile catfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00172	0.01044	0.00000	0.00000
Juvenile minnow	0.00000	0.00000	0.10153	0.45682	1.40855	6.38159	0.32076	0.79888	0.40449	1.01135
Juvenile sucker	1.90350	4.21273	0.08310	0.26192	0.03048	0.11868	0.00178	0.01080	0.02247	0.04958
Juvenile sunfish	0.00198	0.01113	0.00000	0.00000	0.00090	0.00811	0.00000	0.00000	0.01397	0.04359
Lake chub	0.00572	0.02603	0.00000	0.00000	0.00351	0.02490	0.00000	0.00000	0.00186	0.01066
Largemouth bass	0.00476	0.01649	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.2 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Longnose dace	11.37410	21.59657	3.23313	8.82077	0.06234	0.21704	0.09518	0.12633	0.05483	0.09233
Longnose sucker	0.48778	1.07946	0.11503	0.44819	0.00436	0.02054	0.00000	0.00000	0.00000	0.00000
Mountain sucker	0.23981	0.81663	0.01719	0.06957	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Mountain whitefish	0.00485	0.01682	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Northern pike	0.00000	0.00000	0.00000	0.00000	0.00084	0.00763	0.00000	0.00000	0.00190	0.01090
Northern plains killifish	0.00000	0.00000	0.00389	0.02087	0.00000	0.00000	0.00000	0.00000	0.00571	0.03281
Pallid sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Pumpkinseed	0.00190	0.01067	0.00000	0.00000	0.00000	0.00000	0.00182	0.01108	0.00000	0.00000
Rainbow trout	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
River carpsucker	0.00000	0.00000	0.07884	0.27386	0.14857	0.44556	0.01214	0.03265	0.03062	0.09153
Sand shiner	0.00093	0.00744	1.03154	2.37747	1.84439	7.12325	0.22297	0.41253	0.11622	0.33275
Sauger	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.01329	0.02866
Shorthead redhorse	0.14642	0.63993	0.79234	3.60109	0.02422	0.04599	0.01073	0.02475	0.00381	0.02187
Shortnose gar	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00786	0.03146
Shovelnose sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sicklefin chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Smallmouth bass	0.02431	0.06207	0.03100	0.14484	0.00595	0.01830	0.00000	0.00000	0.00000	0.00000
Smallmouth buffalo	0.00000	0.00000	0.00000	0.00000	0.00264	0.01788	0.00000	0.00000	0.00190	0.01094
Stonecat	0.09345	0.14438	0.04880	0.15733	0.01351	0.03672	0.07056	0.12654	0.01163	0.04512
Sturgeon chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04919	0.06525	0.02302	0.08013
Walleye	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Western silvery minnow	0.52742	2.55201	12.26152	41.21673	4.96889	12.60056	4.26225	6.91263	5.62684	24.03546
White bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00213	0.01224
White crappie	0.00000	0.00000	0.00075	0.00667	0.00414	0.01637	0.00000	0.00000	0.00230	0.01320
White sucker	0.08222	0.19393	0.02103	0.06178	0.01285	0.03185	0.00000	0.00000	0.00000	0.00000
Yellow perch	0.00102	0.00817	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.3. Base flow seine catch per unit effort (CPUE) of lower Yellowstone River fish. Fish CPUE is the count of fish captured divided by the length (in meters) of each seine haul. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of the CPUE of each species were calculated from all seine hauls within each river segment. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Black bullhead	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Black crappie	0.00000	0.00000	0.00000	0.00000	0.00026	0.00162	0.00000	0.00000	0.00000	0.00000
Blue sucker	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Bluegill	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brook stickleback	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brown trout	0.00000	0.00000	0.00000	0.00000	0.00025	0.00152	0.00000	0.00000	0.00000	0.00000
Burbot	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Channel catfish	0.00000	0.00000	0.00000	0.00000	0.00156	0.00434	0.00222	0.00548	0.00194	0.00419
Common carp	0.00067	0.00254	0.00028	0.00160	0.00510	0.01903	0.00000	0.00000	0.00125	0.00342
Creek chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Emerald shiner	0.01958	0.04415	0.01207	0.02523	0.07403	0.14692	0.25632	0.50893	0.30793	0.44401
Fathead minnow	0.00100	0.00305	0.00178	0.00450	0.01989	0.04874	0.00000	0.00000	0.02875	0.04646
Flathead chub	0.04164	0.16564	0.05556	0.11034	0.42473	0.95700	0.43879	0.45650	0.86401	0.70289
Freshwater drum	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Goldeye	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00062	0.00250
Green sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00062	0.00250
Juvenile catfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile minnow	0.00000	0.00000	0.00000	0.00000	0.00184	0.01136	0.00056	0.00236	0.00062	0.00250
Juvenile sucker	0.05067	0.22487	0.00125	0.00551	0.00026	0.00162	0.00000	0.00000	0.00000	0.00000
Juvenile sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Lake chub	0.00000	0.00000	0.00000	0.00000	0.00026	0.00162	0.00000	0.00000	0.00062	0.00250
Largemouth bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.3 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Longnose dace	0.20568	1.01624	0.01868	0.05243	0.00761	0.02454	0.00218	0.00420	0.00438	0.00727
Longnose sucker	0.02289	0.08886	0.00313	0.00614	0.00552	0.01135	0.00000	0.00000	0.00000	0.00000
Mountain sucker	0.00417	0.00933	0.00060	0.00241	0.00026	0.00162	0.00000	0.00000	0.00000	0.00000
Mountain whitefish	0.00000	0.00000	0.00000	0.00000	0.00026	0.00162	0.00000	0.00000	0.00000	0.00000
Northern pike	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Northern plains killifish	0.00000	0.00000	0.00059	0.00341	0.00025	0.00156	0.00000	0.00000	0.00125	0.00342
Pallid sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Pumpkinseed	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Rainbow trout	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
River carpsucker	0.00000	0.00000	0.00463	0.01905	0.00872	0.03044	0.00316	0.00566	0.01250	0.04480
Sand shiner	0.00000	0.00000	0.06838	0.19056	0.27583	0.87183	0.01339	0.02344	0.00511	0.00902
Sauger	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00111	0.00323	0.00188	0.00403
Shorthead redhorse	0.01233	0.05488	0.02180	0.04636	0.05007	0.11269	0.00106	0.00309	0.00000	0.00000
Shortnose gar	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Shovelnose sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sicklefin chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Smallmouth bass	0.00067	0.00365	0.00060	0.00239	0.00186	0.00396	0.00000	0.00000	0.00000	0.00000
Smallmouth buffalo	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Stonecat	0.00000	0.00000	0.00000	0.00000	0.00052	0.00225	0.00118	0.00343	0.00062	0.00250
Sturgeon chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00643	0.01132	0.07313	0.12705
Walleye	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Western silvery minnow	0.03282	0.11021	0.06170	0.15556	0.66601	1.62143	0.10904	0.17475	0.11487	0.17640
White bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00132	0.00361
White crappie	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
White sucker	0.00768	0.03830	0.00633	0.02471	0.00107	0.00316	0.00000	0.00000	0.00000	0.00000
Yellow perch	0.00043	0.00234	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.4. Base flow trammel net catch per unit effort (CPUE) of lower Yellowstone River fish. Fish CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of the CPUE of each species were calculated from all trammel net drifts within each river segment. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Black bullhead	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Black crappie	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Blue sucker	0.00000	0.00000	0.00000	0.00000	0.00027	0.00114	0.00151	0.00397	0.00033	0.00115
Bluegill	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brook stickleback	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Brown trout	0.00350	0.00565	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Burbot	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Channel catfish	0.00103	0.00544	0.01239	0.04667	0.00763	0.01506	0.00170	0.00348	0.00223	0.00512
Common carp	0.00023	0.00162	0.00086	0.00363	0.00027	0.00107	0.00021	0.00112	0.00000	0.00000
Creek chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Emerald shiner	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Fathead minnow	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Flathead chub	0.00000	0.00000	0.00000	0.00000	0.00007	0.00058	0.00042	0.00170	0.00038	0.00135
Freshwater drum	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00022	0.00107
Goldeye	0.00708	0.01446	0.00576	0.01040	0.00563	0.01521	0.00225	0.00563	0.00058	0.00203
Green sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile catfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile minnow	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile sucker	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Juvenile sunfish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Lake chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Largemouth bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.4 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Longnose dace	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Longnose sucker	0.02827	0.03227	0.00506	0.00974	0.00034	0.00113	0.00113	0.00470	0.00000	0.00000
Mountain sucker	0.00046	0.00193	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Mountain whitefish	0.00054	0.00227	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Northern pike	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Northern plains killifish	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Pallid sturgeon	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00029	0.00119	0.00084	0.00195
Pumpkinseed	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Rainbow trout	0.00043	0.00142	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
River carpsucker	0.00039	0.00320	0.00047	0.00201	0.00007	0.00045	0.00000	0.00000	0.00000	0.00000
Sand shiner	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sauger	0.00015	0.00124	0.00072	0.00400	0.00061	0.00283	0.00102	0.00352	0.00293	0.00497
Shorthead redhorse	0.01793	0.03555	0.01719	0.02619	0.01251	0.01716	0.00586	0.00989	0.00132	0.00645
Shortnose gar	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Shovelnose sturgeon	0.00000	0.00000	0.00000	0.00000	0.00461	0.00964	0.00457	0.00841	0.04079	0.06463
Sicklefin chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Smallmouth bass	0.00000	0.00000	0.00018	0.00069	0.00076	0.00245	0.00000	0.00000	0.00000	0.00000
Smallmouth buffalo	0.00000	0.00000	0.00058	0.00183	0.00013	0.00083	0.00008	0.00042	0.00000	0.00000
Stonecat	0.00000	0.00000	0.00095	0.00316	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sturgeon chub	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Walleye	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Western silvery minnow	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
White bass	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
White crappie	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
White sucker	0.00571	0.01073	0.00111	0.00279	0.00018	0.00097	0.00000	0.00000	0.00000	0.00000
Yellow perch	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table A.5. Base flow otter trawl catch per unit effort (CPUE) of lower Yellowstone River fish. Fish CPUE is the count of fish captured divided by the length (in meters) of each otter trawl deployment. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of the CPUE of each species were calculated from all otter trawl deployments within river segments 4 and 5. Scientific names of fish are in Table 4.1.

	River segment			
	4		5	
	μ	σ	μ	σ
Bigmouth buffalo	0.00000	0.00000	0.00000	0.00000
Black bullhead	0.00000	0.00000	0.00000	0.00000
Black crappie	0.00000	0.00000	0.00000	0.00000
Blue sucker	0.00000	0.00000	0.00000	0.00000
Bluegill	0.00000	0.00000	0.00000	0.00000
Brook stickleback	0.00000	0.00000	0.00000	0.00000
Brown trout	0.00000	0.00000	0.00000	0.00000
Burbot	0.00000	0.00000	0.00018	0.00090
Channel catfish	0.00066	0.00281	0.00000	0.00000
Common carp	0.00019	0.00093	0.00000	0.00000
Creek chub	0.00000	0.00000	0.00000	0.00000
Emerald shiner	0.00000	0.00000	0.00000	0.00000
Fathead minnow	0.00000	0.00000	0.00000	0.00000
Flathead chub	0.00360	0.00782	0.00278	0.00442
Freshwater drum	0.00000	0.00000	0.00000	0.00000
Goldeye	0.00000	0.00000	0.00000	0.00000
Green sunfish	0.00000	0.00000	0.00000	0.00000
Juvenile catfish	0.00000	0.00000	0.00000	0.00000
Juvenile minnow	0.00000	0.00000	0.00000	0.00000
Juvenile sucker	0.00000	0.00000	0.00000	0.00000
Juvenile sunfish	0.00000	0.00000	0.00000	0.00000
Lake chub	0.00000	0.00000	0.00000	0.00000
Largemouth bass	0.00000	0.00000	0.00000	0.00000

Table A.5 Continued

	River segment			
	4		5	
	μ	σ	μ	σ
Longnose dace	0.00073	0.00150	0.00015	0.00072
Longnose sucker	0.00050	0.00139	0.00000	0.00000
Mountain sucker	0.00000	0.00000	0.00000	0.00000
Mountain whitefish	0.00000	0.00000	0.00000	0.00000
Northern pike	0.00000	0.00000	0.00000	0.00000
Northern plains killifish	0.00000	0.00000	0.00000	0.00000
Pallid sturgeon	0.00000	0.00000	0.00045	0.00157
Pumpkinseed	0.00000	0.00000	0.00000	0.00000
Rainbow trout	0.00000	0.00000	0.00000	0.00000
River carpsucker	0.00000	0.00000	0.00000	0.00000
Sand shiner	0.00000	0.00000	0.00000	0.00000
Sauger	0.00129	0.00268	0.00442	0.00595
Shorthead redhorse	0.00142	0.00356	0.00246	0.00526
Shortnose gar	0.00000	0.00000	0.00000	0.00000
Shovelnose sturgeon	0.00035	0.00122	0.00122	0.00243
Sicklefin chub	0.00000	0.00000	0.00047	0.00177
Smallmouth bass	0.00000	0.00000	0.00000	0.00000
Smallmouth buffalo	0.00000	0.00000	0.00000	0.00000
Stonecat	0.00000	0.00000	0.00027	0.00092
Sturgeon chub	0.02967	0.03474	0.04069	0.04654
Walleye	0.00000	0.00000	0.00026	0.00089
Western silvery minnow	0.00000	0.00000	0.00000	0.00000
White bass	0.00000	0.00000	0.00000	0.00000
White crappie	0.00000	0.00000	0.00000	0.00000
White sucker	0.00000	0.00000	0.00000	0.00000
Yellow perch	0.00000	0.00000	0.00000	0.00000

APPENDIX B

LENGTHS OF YELLOWSTONE RIVER FISH

Table B.1. Lengths of lower Yellowstone River fish captured during base flow with electrofishing. Lengths (in mm) were measured for up to 25 arbitrarily selected individuals of each species captured with each electrofishing pass; all individuals of a species were measured if 25 or fewer individuals of a species were captured. Length refers to total length for all species except sturgeons for which fork length was measured. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of fish lengths were calculated from all electrofishing passes within each river segment; however, a standard deviation was not calculated (*) if only one individual was captured. Dashes (-) denote species that were not captured. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	750	1	548	*	640	165	-	-	-	-
Black bullhead	-	-	-	-	-	-	-	-	-	-
Black crappie	-	-	-	-	163	*	-	-	-	-
Blue sucker	-	-	-	-	664	30	726	28	-	-
Bluegill	-	-	-	-	-	-	-	-	-	-
Brook stickleback	-	-	-	-	-	-	-	-	-	-
Brown trout	268	82	212	*	-	-	-	-	-	-
Burbot	788	*	400	*	-	-	-	-	201	28
Channel catfish	476	67	460	78	426	108	380	52	368	202
Common carp	590	66	554	97	537	101	537	89	553	70
Creek chub	-	-	-	-	-	-	-	-	-	-
Emerald shiner	82	9	84	11	81	6	82	6	81	5
Fathead minnow	46	12	57	*	52	*	-	-	-	-
Flathead chub	139	36	109	38	119	42	131	28	122	23
Freshwater drum	-	-	361	14	357	32	386	67	329	74
Goldeye	351	16	347	10	334	14	296	40	189	87
Green sunfish	-	-	-	-	-	-	-	-	-	-
Juvenile catfish	-	-	-	-	-	-	-	-	-	-
Juvenile minnow	-	-	-	-	-	-	-	-	-	-
Juvenile sucker	-	-	-	-	-	-	-	-	-	-
Juvenile sunfish	-	-	-	-	-	-	-	-	-	-

Table B.1 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Lake chub	-	-	-	-	-	-	-	-	-	-
Largemouth bass	-	-	-	-	-	-	-	-	-	-
Longnose dace	59	14	57	16	79	*	-	-	-	-
Longnose sucker	253	100	246	108	270	146	-	-	-	-
Mountain sucker	131	34	91	*	119	*	-	-	-	-
Mountain whitefish	199	90	105	*	-	-	-	-	-	-
Northern pike	-	-	-	-	-	-	-	-	612	132
Northern plains killifish	-	-	-	-	-	-	-	-	-	-
Pallid sturgeon	-	-	-	-	-	-	-	-	-	-
Pumpkinseed	-	-	-	-	-	-	-	-	-	-
Rainbow trout	321	86	-	-	-	-	-	-	-	-
River carpsucker	428	49	389	67	376	33	363	72	393	138
Sand shiner	-	-	58	2	52	7	-	-	-	-
Sauger	365	*	361	45	391	69	271	100	265	84
Shorthead redhorse	401	26	293	92	308	74	254	58	264	94
Shortnose gar	-	-	-	-	-	-	-	-	-	-
Shovelnose sturgeon	-	-	-	-	829	*	-	-	574	77
Sicklefin chub	-	-	-	-	-	-	-	-	-	-
Smallmouth bass	259	60	180	77	258	56	504	*	-	-
Smallmouth buffalo	-	-	554	49	541	56	693	*	-	-
Stonecat	179	21	167	28	79	30	-	-	-	-
Sturgeon chub	-	-	-	-	-	-	67	13	61	25
Walleye	-	-	567	54	672	*	253	55	-	-
Western silvery minnow	111	11	100	14	86	24	88	15	79	6
White bass	-	-	-	-	-	-	-	-	90	3
White crappie	-	-	-	-	-	-	-	-	-	-
White sucker	303	82	335	70	338	50	313	118	350	*
Yellow perch	-	-	-	-	-	-	-	-	-	-

Table B.2. Lengths of lower Yellowstone River fish captured during base flow with fyke nets. Lengths (in mm) were measured for up to 25 arbitrarily selected individuals of each species captured with each fyke net deployment; all individuals of a species were measured if 25 or fewer individuals of a species were captured. Length refers to total length for all species except sturgeons for which fork length was measured. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of fish lengths were calculated from all fyke net deployments within each river segment; however, a standard deviation was not calculated (*) if only one individual was captured. Dashes (-) denote species that were not captured. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	-	-	-	-	58	*	-	-	43	*
Black bullhead	-	-	37	*	35	2	-	-	51	*
Black crappie	-	-	50	17	130	93	-	-	-	-
Blue sucker	-	-	-	-	-	-	-	-	-	-
Bluegill	40	16	94	*	34	9	-	-	-	-
Brook stickleback	44	5	33	9	46	9	29	*	32	7
Brown trout	-	-	-	-	-	-	-	-	-	-
Burbot	-	-	493	62	447	24	126	*	-	-
Channel catfish	-	-	46	5	122	201	55	6	44	7
Common carp	64	25	137	168	110	162	-	-	-	-
Creek chub	-	-	-	-	60	*	-	-	51	8
Emerald shiner	79	8	69	14	67	18	56	21	73	21
Fathead minnow	41	10	38	8	39	8	40	11	37	3
Flathead chub	50	19	48	14	51	19	48	17	42	15
Freshwater drum	-	-	-	-	-	-	-	-	-	-
Goldeye	-	-	-	-	-	-	-	-	119	*
Green sunfish	58	8	40	6	38	4	47	1	42	2
Juvenile catfish	-	-	-	-	-	-	15	*	-	-
Juvenile minnow	-	-	19	1	21	1	19	2	19	1
Juvenile sucker	26	2	25	3	22	3	21	*	21	2
Juvenile sunfish	24	3	-	-	26	*	-	-	25	9

Table B.2 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Lake chub	49	4	-	-	38	1	-	-	53	*
Largemouth bass	39	10	-	-	-	-	-	-	-	-
Longnose dace	34	7	33	3	34	8	30	5	31	4
Longnose sucker	44	19	60	38	48	19	-	-	-	-
Mountain sucker	71	45	44	8	-	-	-	-	-	-
Mountain whitefish	75	12	-	-	-	-	-	-	-	-
Northern pike	-	-	-	-	60	*	-	-	41	*
Northern plains killifish	-	-	54	6	-	-	-	-	46	*
Pallid sturgeon	-	-	-	-	-	-	-	-	-	-
Pumpkinseed	106	8	-	-	-	-	39	*	-	-
Rainbow trout	-	-	-	-	-	-	-	-	-	-
River carpsucker	-	-	38	6	72	101	28	6	38	19
Sand shiner	53	*	38	8	41	7	35	8	38	7
Sauger	-	-	-	-	-	-	-	-	133	15
Shorthead redhorse	41	29	51	36	66	45	29	7	30	*
Shortnose gar	-	-	-	-	-	-	-	-	525	6
Shovelnose sturgeon	-	-	-	-	-	-	-	-	-	-
Sicklefin chub	-	-	-	-	-	-	-	-	-	-
Smallmouth bass	47	17	58	18	112	84	-	-	-	-
Smallmouth buffalo	-	-	-	-	70	4	-	-	30	*
Stonecat	118	69	111	80	67	64	36	26	44	15
Sturgeon chub	-	-	-	-	-	-	33	6	41	2
Walleye	-	-	-	-	-	-	-	-	-	-
Western silvery minnow	81	12	36	7	44	17	37	11	34	9
White bass	-	-	-	-	-	-	-	-	412	*
White crappie	-	-	74	*	78	57	-	-	231	*
White sucker	78	84	93	56	94	33	-	-	-	-
Yellow perch	65	*	-	-	-	-	-	-	-	-

Table B.3. Lengths of lower Yellowstone River fish captured during base flow with seines. Lengths (in mm) were measured for up to 25 arbitrarily selected individuals of each species captured with each seine haul; all individuals of a species were measured if 25 or fewer individuals of a species were captured. Length refers to total length for all species except sturgeons for which fork length was measured. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of fish lengths were calculated from all seine hauls within each river segment; however, a standard deviation was not calculated (*) if only one individual was captured. Dashes (-) denote species that were not captured. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	-	-	-	-	-	-	-	-	-	-
Black bullhead	-	-	-	-	-	-	-	-	-	-
Black crappie	-	-	-	-	54	*	-	-	-	-
Blue sucker	-	-	-	-	-	-	-	-	-	-
Bluegill	-	-	-	-	-	-	-	-	-	-
Brook stickleback	-	-	-	-	-	-	-	-	-	-
Brown trout	-	-	-	-	109	*	-	-	-	-
Burbot	-	-	-	-	-	-	-	-	-	-
Channel catfish	-	-	-	-	363	298	62	7	49	6
Common carp	40	4	67	*	104	94	-	-	53	4
Creek chub	-	-	-	-	-	-	-	-	-	-
Emerald shiner	73	8	58	15	80	9	73	15	84	4
Fathead minnow	40	4	45	6	45	5	-	-	46	4
Flathead chub	68	28	43	12	58	21	71	22	63	18
Freshwater drum	-	-	-	-	-	-	-	-	-	-
Goldeye	-	-	-	-	-	-	-	-	117	*
Green sunfish	-	-	-	-	-	-	-	-	51	*
Juvenile catfish	-	-	-	-	-	-	-	-	-	-
Juvenile minnow	-	-	-	-	20	*	37	*	19	*
Juvenile sucker	26	1	25	1	29	*	-	-	-	-
Juvenile sunfish	-	-	-	-	-	-	-	-	-	-

Table B.3 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Lake chub	-	-	-	-	46	*	-	-	49	*
Largemouth bass	-	-	-	-	-	-	-	-	-	-
Longnose dace	33	8	32	6	52	16	52	23	47	14
Longnose sucker	52	22	47	8	114	72	-	-	-	-
Mountain sucker	56	19	42	6	53	*	-	-	-	-
Mountain whitefish	-	-	-	-	87	*	-	-	-	-
Northern pike	-	-	-	-	-	-	-	-	-	-
Northern plains killifish	-	-	62	*	59	*	-	-	46	2
Pallid sturgeon	-	-	-	-	-	-	-	-	-	-
Pumpkinseed	-	-	-	-	-	-	-	-	-	-
Rainbow trout	-	-	-	-	-	-	-	-	-	-
River carpsucker	-	-	52	17	96	142	56	13	153	161
Sand shiner	-	-	44	11	50	9	44	12	44	11
Sauger	-	-	-	-	-	-	144	16	126	6
Shorthead redhorse	32	3	44	8	85	45	37	1	-	-
Shortnose gar	-	-	-	-	-	-	-	-	-	-
Shovelnose sturgeon	-	-	-	-	-	-	-	-	-	-
Sicklefin chub	-	-	-	-	-	-	-	-	-	-
Smallmouth bass	46	*	60	13	87	16	-	-	-	-
Smallmouth buffalo	-	-	-	-	-	-	-	-	-	-
Stonecat	-	-	-	-	52	28	68	47	146	*
Sturgeon chub	-	-	-	-	-	-	50	14	52	7
Walleye	-	-	-	-	-	-	-	-	-	-
Western silvery minnow	76	3	47	25	66	20	84	31	64	23
White bass	-	-	-	-	-	-	-	-	106	3
White crappie	-	-	-	-	-	-	-	-	-	-
White sucker	38	3	52	11	78	28	-	-	-	-
Yellow perch	61	*	-	-	-	-	-	-	-	-

Table B.4. Lengths of lower Yellowstone River fish captured during base flow with trammel nets. Lengths (in mm) were measured for up to 25 arbitrarily selected individuals of each species captured with each trammel net drift; all individuals of a species were measured if 25 or fewer individuals of a species were captured. Length refers to total length for all species except sturgeons for which fork length was measured. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of fish lengths were calculated from all trammel net drifts within each river segment; however, a standard deviation was not calculated (*) if only one individual was captured. Dashes (-) denote species that were not captured. Scientific names of fish are in Table 4.1.

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bigmouth buffalo	-	-	-	-	-	-	-	-	-	-
Black bullhead	-	-	-	-	-	-	-	-	-	-
Black crappie	-	-	-	-	-	-	-	-	-	-
Blue sucker	-	-	-	-	755	71	719	16	681	13
Bluegill	-	-	-	-	-	-	-	-	-	-
Brook stickleback	-	-	-	-	-	-	-	-	-	-
Brown trout	319	60	-	-	-	-	-	-	-	-
Burbot	-	-	-	-	-	-	-	-	-	-
Channel catfish	418	25	319	55	332	67	312	38	242	12
Common carp	710	70	562	42	534	75	438	*	-	-
Creek chub	-	-	-	-	-	-	-	-	-	-
Emerald shiner	-	-	-	-	-	-	-	-	-	-
Fathead minnow	-	-	-	-	-	-	-	-	-	-
Flathead chub	-	-	-	-	186	*	218	19	214	8
Freshwater drum	-	-	-	-	-	-	-	-	354	*
Goldeye	347	10	339	11	333	16	291	55	355	33
Green sunfish	-	-	-	-	-	-	-	-	-	-
Juvenile catfish	-	-	-	-	-	-	-	-	-	-
Juvenile minnow	-	-	-	-	-	-	-	-	-	-
Juvenile sucker	-	-	-	-	-	-	-	-	-	-
Juvenile sunfish	-	-	-	-	-	-	-	-	-	-

Table B.4 Continued

	River segment									
	1		2		3		4		5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Lake chub	-	-	-	-	-	-	-	-	-	-
Largemouth bass	-	-	-	-	-	-	-	-	-	-
Longnose dace	-	-	-	-	-	-	-	-	-	-
Longnose sucker	314	52	339	105	407	39	333	3	-	-
Mountain sucker	202	7	-	-	-	-	-	-	-	-
Mountain whitefish	249	14	-	-	-	-	-	-	-	-
Northern pike	-	-	-	-	-	-	-	-	-	-
Northern plains killifish	-	-	-	-	-	-	-	-	-	-
Pallid sturgeon	-	-	-	-	-	-	224	110	668	246
Pumpkinseed	-	-	-	-	-	-	-	-	-	-
Rainbow trout	265	79	-	-	-	-	-	-	-	-
River carpsucker	557	*	391	46	408	48	-	-	-	-
Sand shiner	-	-	-	-	-	-	-	-	-	-
Sauger	384	*	394	83	336	34	318	25	328	41
Shorthead redhorse	413	46	365	54	343	49	277	35	258	*
Shortnose gar	-	-	-	-	-	-	-	-	-	-
Shovelnose sturgeon	-	-	-	-	776	103	755	68	590	73
Sicklefin chub	-	-	-	-	-	-	-	-	-	-
Smallmouth bass	-	-	222	30	272	49	-	-	-	-
Smallmouth buffalo	-	-	704	61	628	31	730	*	-	-
Stonecat	-	-	177	15	-	-	-	-	-	-
Sturgeon chub	-	-	-	-	-	-	-	-	-	-
Walleye	-	-	-	-	-	-	-	-	-	-
Western silvery minnow	-	-	-	-	-	-	-	-	-	-
White bass	-	-	-	-	-	-	-	-	-	-
White crappie	-	-	-	-	-	-	-	-	-	-
White sucker	349	64	360	60	399	57	-	-	-	-
Yellow perch	-	-	-	-	-	-	-	-	-	-

Table B.5. Lengths of lower Yellowstone River fish captured during base flow with otter trawls. Lengths (in mm) were measured for up to 25 arbitrarily selected individuals of each species captured with each trawl deployment; all individuals of a species were measured if 25 or fewer individuals of a species were captured. Length refers to total length for all species except sturgeons for which fork length was measured. Detailed fish capture methods are presented in Chapter 4. The mean (μ) and standard deviation (σ) of fish lengths were calculated from all trawl deployments within river segments 4 and 5; however, a standard deviation was not calculated (*) if only one individual was captured. Dashes (-) denote species that were not captured. Scientific names of fish are in Table 4.1.

	River segment			
	4		5	
	μ	σ	μ	σ
Bigmouth buffalo	-	-	-	-
Black bullhead	-	-	-	-
Black crappie	-	-	-	-
Blue sucker	-	-	-	-
Bluegill	-	-	-	-
Brook stickleback	-	-	-	-
Brown trout	-	-	-	-
Burbot	-	-	360	*
Channel catfish	469	24	-	-
Common carp	430	*	-	-
Creek chub	-	-	-	-
Emerald shiner	-	-	-	-
Fathead minnow	-	-	-	-
Flathead chub	162	35	152	45
Freshwater drum	-	-	-	-
Goldeye	-	-	-	-
Green sunfish	-	-	-	-
Juvenile catfish	-	-	-	-
Juvenile minnow	-	-	-	-
Juvenile sucker	-	-	-	-
Juvenile sunfish	-	-	-	-

Table B.5 Continued

	River segment			
	4		5	
	μ	σ	μ	σ
Lake chub	-	-	-	-
Largemouth bass	-	-	-	-
Longnose dace	66	24	65	*
Longnose sucker	201	6	-	-
Mountain sucker	-	-	-	-
Mountain whitefish	-	-	-	-
Northern pike	-	-	-	-
Northern plains killifish	-	-	-	-
Pallid sturgeon	-	-	320	33
Pumpkinseed	-	-	-	-
Rainbow trout	-	-	-	-
River carpsucker	-	-	-	-
Sand shiner	-	-	-	-
Sauger	231	85	232	73
Shorthead redhorse	215	44	239	68
Shortnose gar	-	-	-	-
Shovelnose sturgeon	600	156	532	181
Sicklefin chub	-	-	94	9
Smallmouth bass	-	-	-	-
Smallmouth buffalo	-	-	-	-
Stonecat	-	-	108	23
Sturgeon chub	61	12	54	12
Walleye	-	-	373	64
Western silvery minnow	-	-	-	-
White bass	-	-	-	-
White crappie	-	-	-	-
White sucker	-	-	-	-
Yellow perch	-	-	-	-

APPENDIX C

CATCH PER UNIT EFFORTS OF SELECT COMMONLY CAPTURED SPECIES AT REFERENCE AND STABILIZED SITES

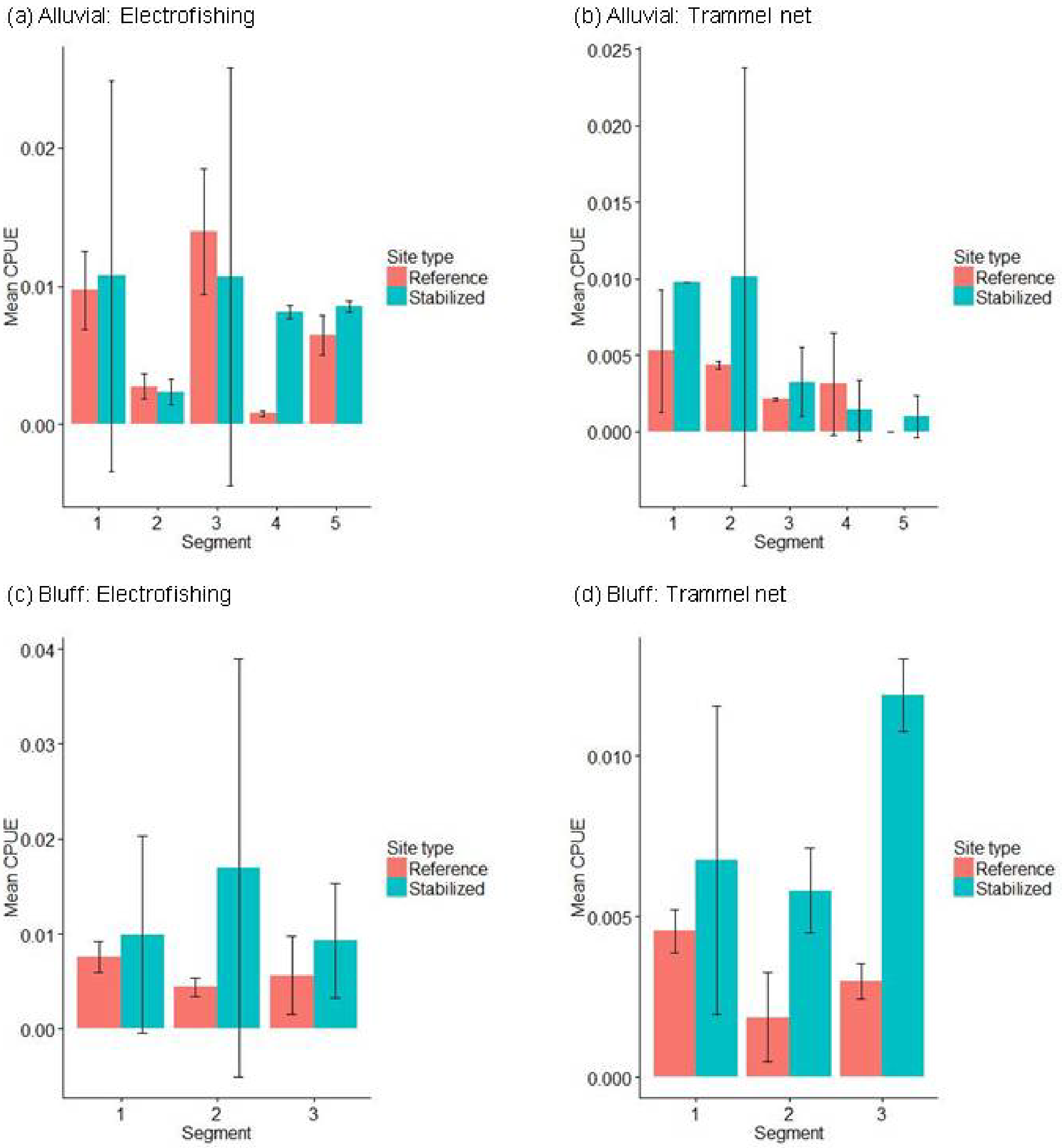


Figure C.1. Mean catch per unit effort (CPUE) of goldeyes at alluvial and bluff sites captured with electrofishing and trammel nets. Error bars represent standard deviations. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

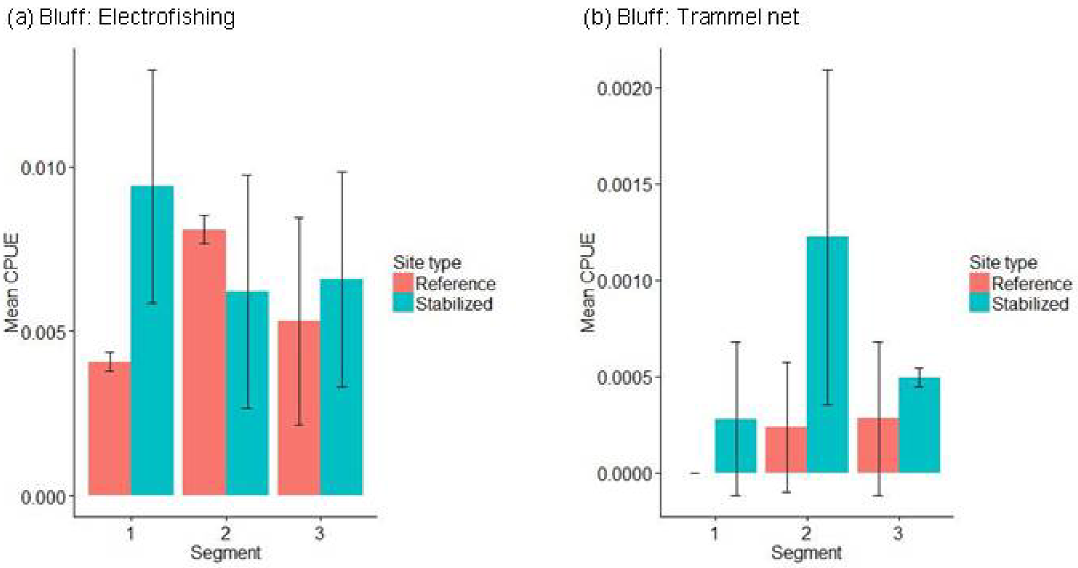


Figure C.2. Mean catch per unit effort (CPUE) of common carp at bluff sites captured with electrofishing and trammel nets. Error bars represent standard deviations. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

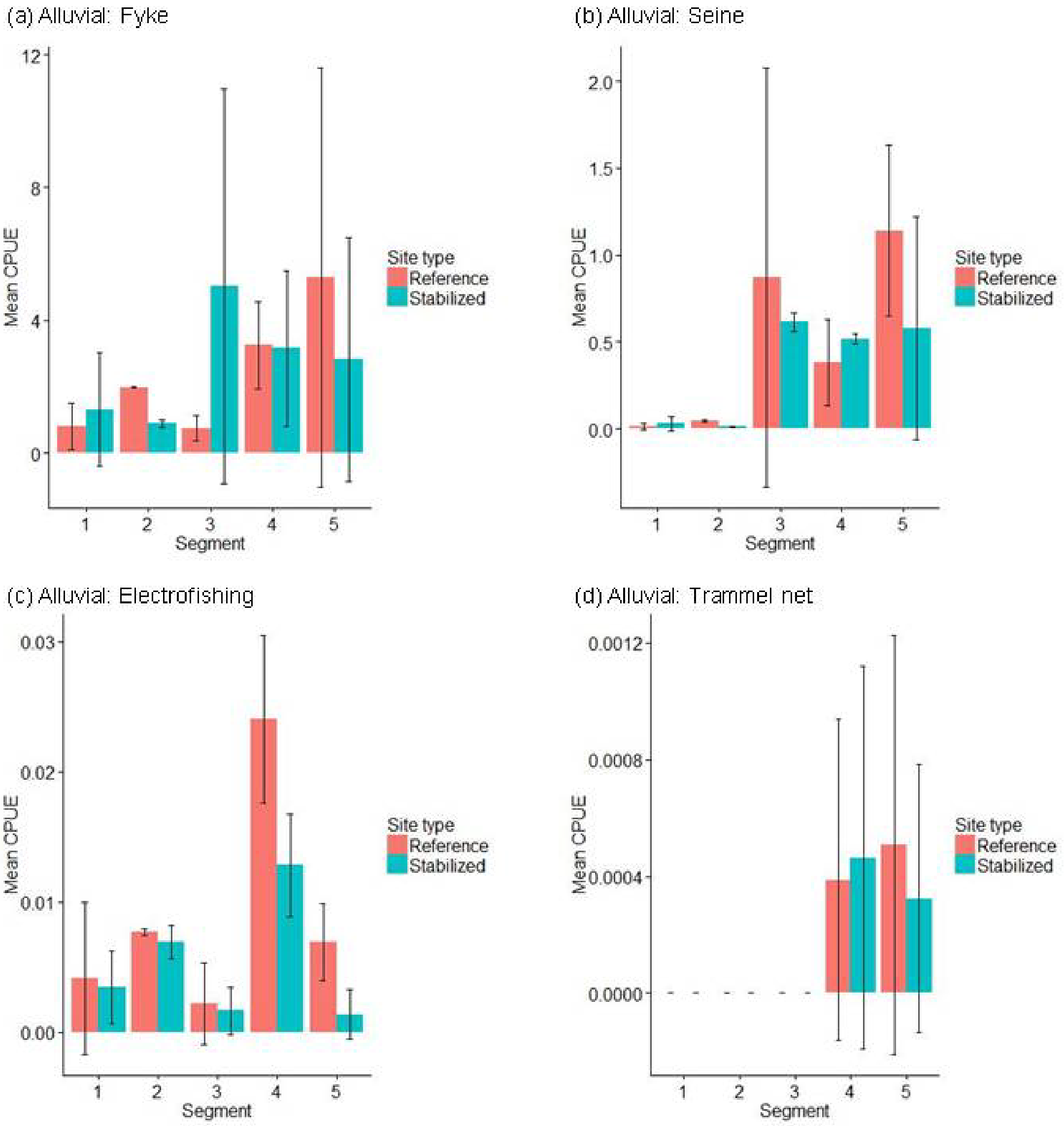


Figure C.3. Mean catch per unit effort (CPUE) of flathead chub at alluvial sites captured with electrofishing and fyke, seine, and trammel nets. Error bars represent standard deviations. Fyke CPUE is the count of fish captured divided by the duration (in hours) that each net was fishing. Seine CPUE is the count of fish captured divided by the length (in meters) of each seine haul. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

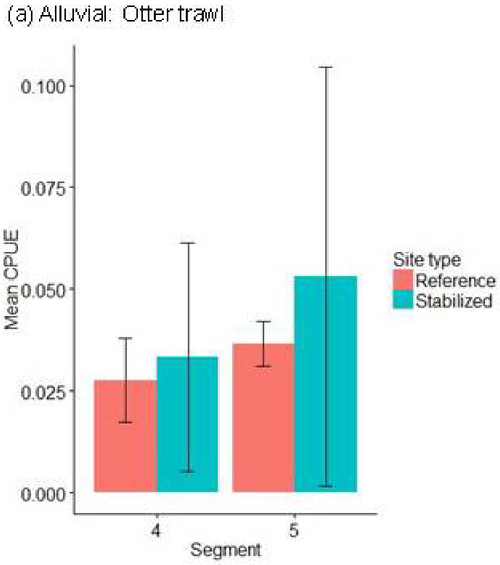
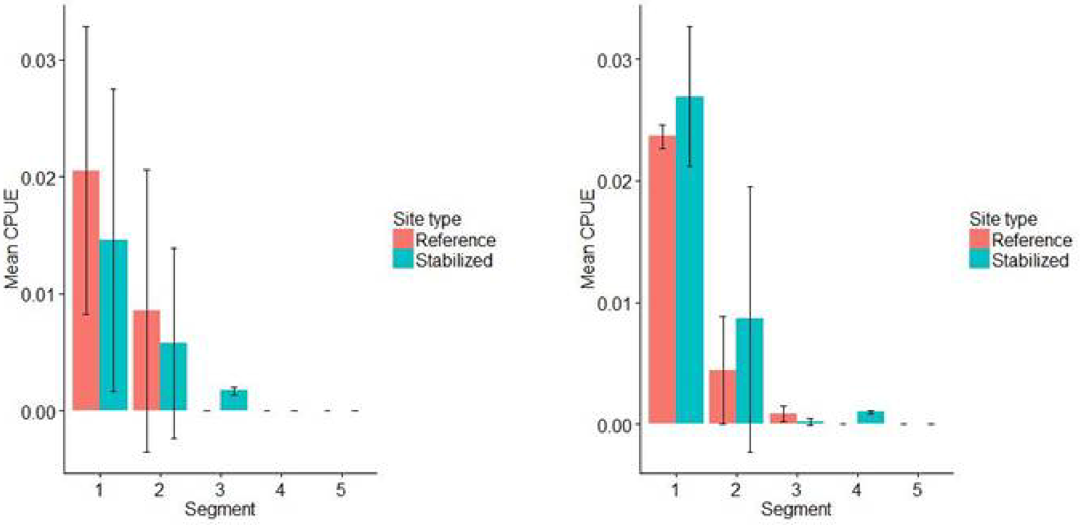


Figure C.4. Mean catch per unit effort (CPUE) of sturgeon chub at alluvial sites captured with otter trawls. Error bars represent standard deviations. Otter trawl CPUE is the count of fish captured divided by the length (in meters) of each otter trawl deployment. Detailed fish capture methods are presented in Chapter 4.

(a) Alluvial: Electrofishing (b) Alluvial: Trammel net



(c) Bluff: Electrofishing (d) Bluff: Trammel net

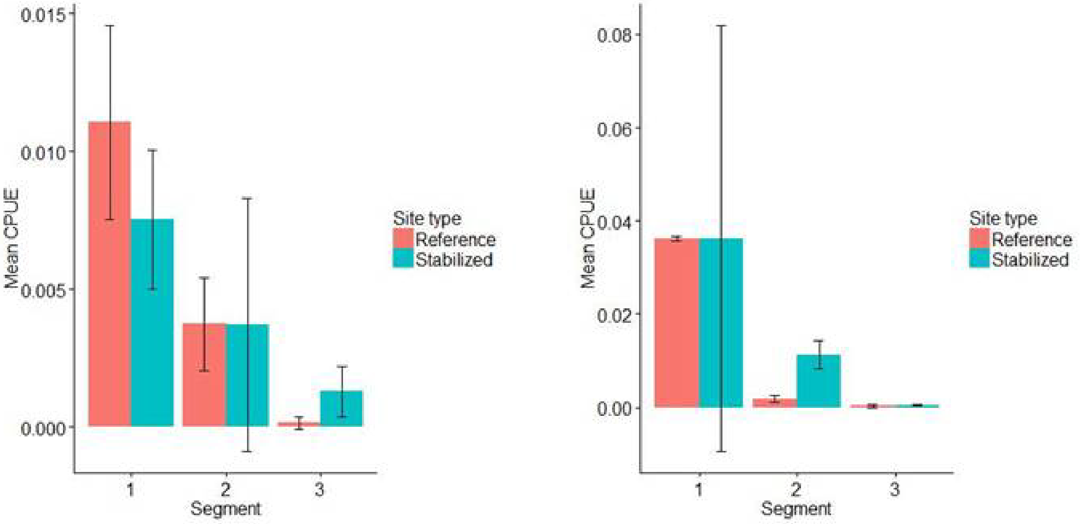


Figure C.5. Mean catch per unit effort (CPUE) of longnose suckers at alluvial and bluff sites captured with electrofishing and trammel nets. Error bars represent standard deviations. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

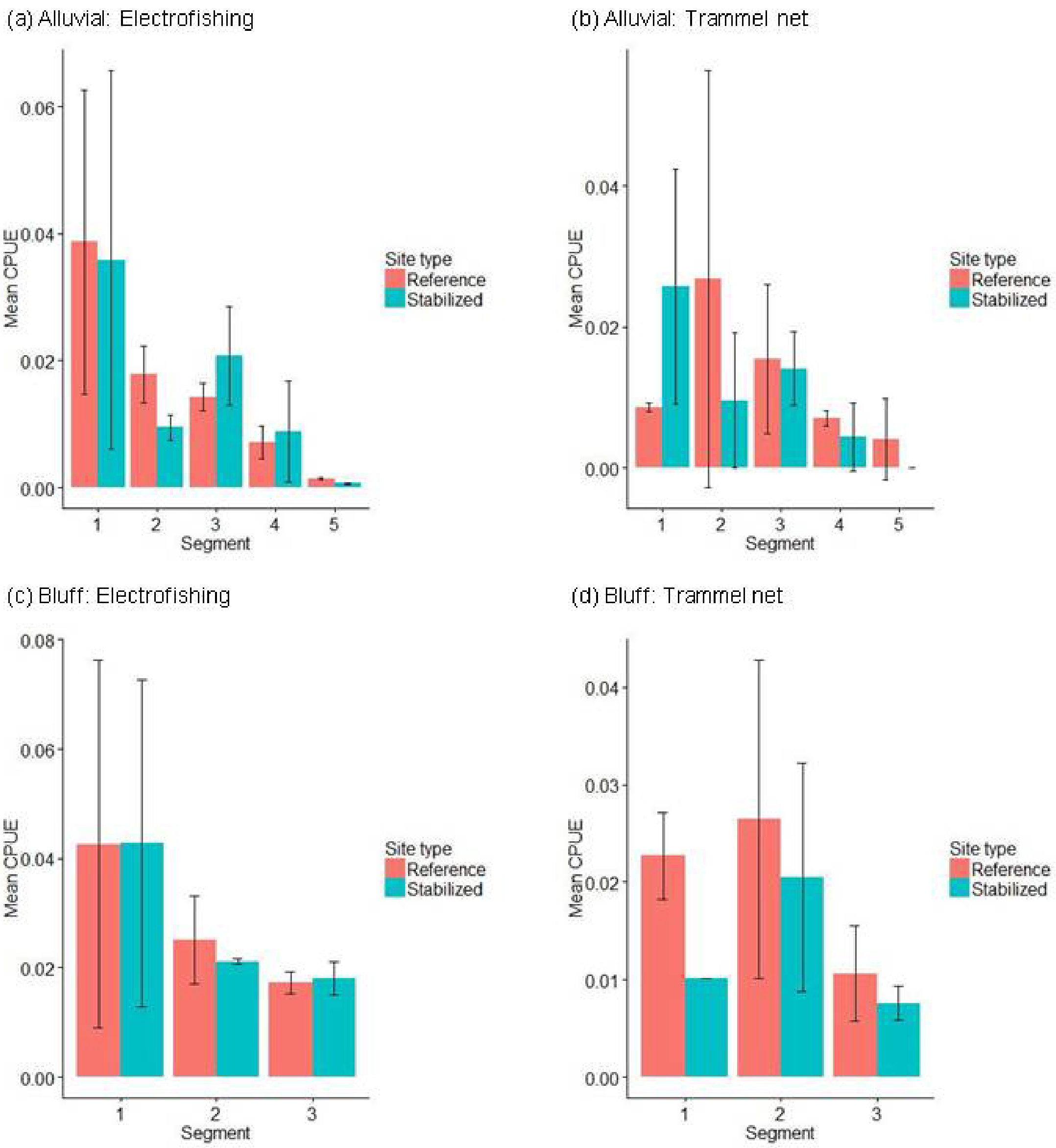


Figure C.6. Mean catch per unit effort (CPUE) of shorthead redhorses at alluvial and bluff sites captured with electrofishing and trammel nets. Error bars represent standard deviations. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

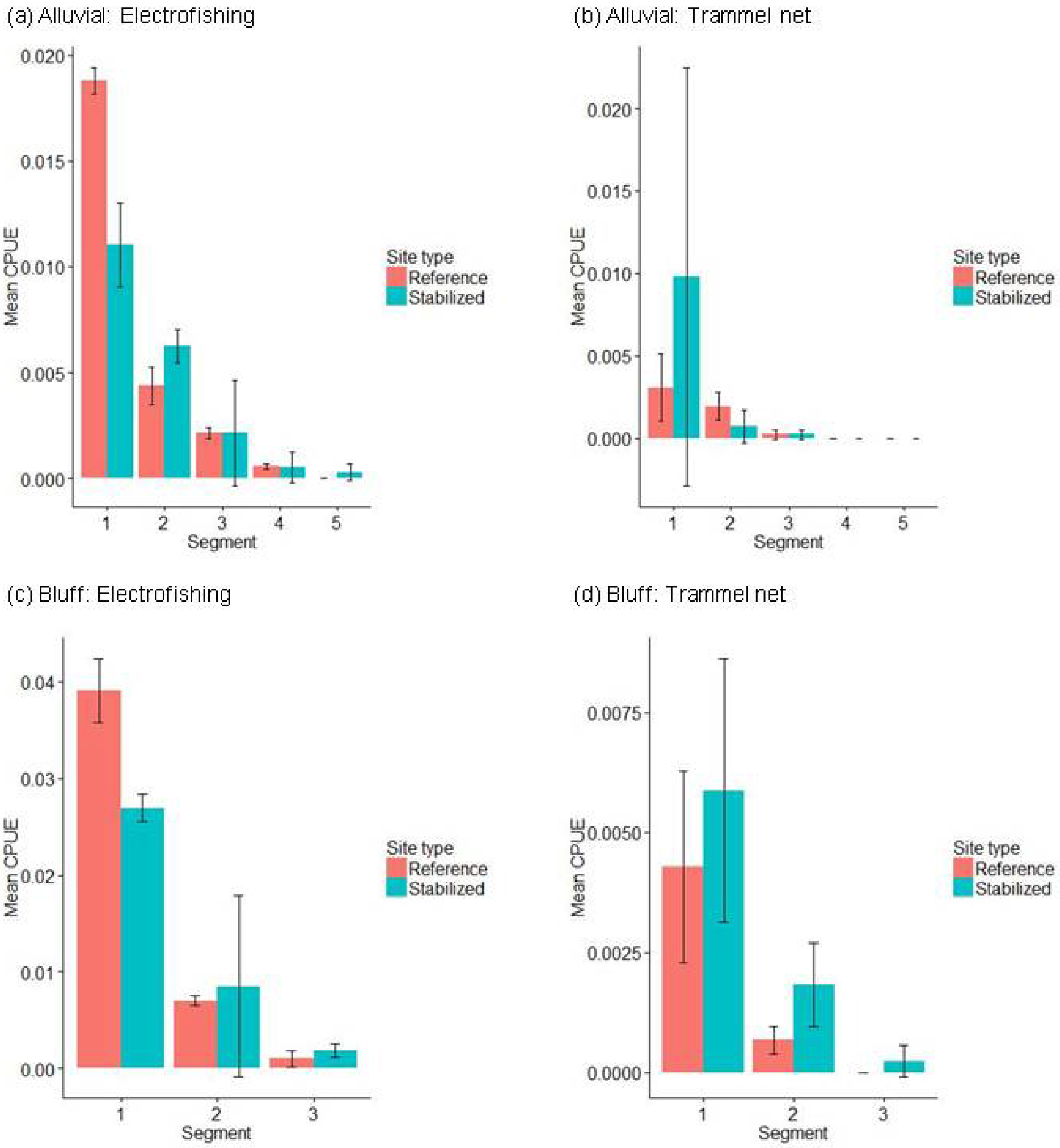


Figure C.7. Mean catch per unit effort (CPUE) of white suckers at alluvial and bluff sites captured with electrofishing and trammel nets. Error bars represent standard deviations. Electrofishing CPUE is the count of fish captured divided by the duration (in seconds) of each electrofishing pass. Trammel net CPUE is the count of fish captured divided by the length (in meters) of each trammel net drift. Detailed fish capture methods are presented in Chapter 4.

APPENDIX D

AREAL CHANGES IN FISHERIES HABITAT UNITS FROM THE 1950s TO 2001

Bank stabilization has changed the types and distributions of Yellowstone River fish habitats. However, the extent of these changes was unknown at the onset of this study. Therefore, we quantified changes in fish habitat types from the 1950s to 2001 from digitized habitat categories.

Thatcher (2009 memorandum to YRCDC Fisheries Group on Fisheries habitat mapping attributes) classified bank full fish habitats into eight primary categories (Table D.1) and manually digitized each instance of each of these categories from historical (1950s) and present day (2001) aerial photographs of the lower Yellowstone River (T. Thatcher, unpublished data). We calculated the areal changes in these categories within the ten geomorphic reach types outlined by Boyd and Thatcher (2004; Table D.2) to account for differences in how bank stabilization interacted with the underlying riverine geomorphology. Our spatial analysis was a two-step process and was performed on the 1950s and 2001 digitizations. First, we intersected the habitat category polygons with the reach breaks polylines. Second, we performed a multipart dissolve of the intersect layer on the habitat, reach identification, and reach type fields. The result was the area of each habitat category within each reach for the 1950s (Table D.3) and 2001 (Table D.4).

From the 1950s to 2001, areas of side channels decreased in unconfined braided (UB) and unconfined straight (US/I) reach types (Figure D.1). However, these decreases in side channels were concomitant with increases in seasonal side channels in UB and US/I reach types. Therefore, perhaps side channels were converted to seasonal side channels in these reaches. A potential mechanism for this conversion is that bank stabilization may have reduced scouring flows in side channels, encouraging deposition and vegetation encroachment.

Pool habitat areas changed from the 1950s to 2001. Scour pool areas generally decreased in most reach types, but these decreases were coincident with increases in riprap bottom pool areas. Such changes may represent direct conversion of scour pools to riprap bottom pools resulting from bank stabilization. Little change was observed in bluff and riprap margin pool areas, and this may be because valley wall constriction limits channel migration in these habitats and much of the bank stabilization that is present on riprap margin pools was installed prior to the 1950s. Terrace pools decreased in area in confined meandering (CM) and confined straight (CM/S) reaches coincident with increases in channel crossover areas. Plausible mechanisms for these losses in terrace pool area and increases in channel crossover areas were unclear, but may be due to limitations in the underlying datasets.

Importantly, all analyses of habitat category areas are limited by the quality and consistency in the aerial images on which they are based. In this study, the resolutions and photograph types differed between the 1950s and 2001 datasets. Moreover, there is variability in river discharge and the seasons when images were collected. Such limitations of the underlying datasets added to the challenges of aerial photographic interpretation and should be considered as potential sources of unquantified error in these results.

Tables

Table D.1. Fisheries habitat unit categories. Categories adapted from Thatcher (memorandum).

Habitat classification	Description
Scour pool	Scour pool occurring in otherwise unconstrained river channel. Generally occurs on the outsides of bend ways.
Bluff pool	Scour pool located at the base of a bedrock bluff. Indicates a relatively permanent pool location bounded by a geologic constraint.
Terrace pool	Scour pool located at the base of a terrace (Quarternary Alluvium). Terrace units generally were identified from LiDAR mapping as part of the Channel Migration Zone work. Indicates a relatively permanent pool location bounded by a geologic constraint.
Riprap bottom pool	Scour pool occurring in riprap constrained channel where riprap is located in the middle of the active channel area.
Riprap margin pool	Scour pool occurring in riprap constrained channel where riprap is located at the edge of the active channel area.
Channel crossover	A transitional unit where the river is translating from one bendway or pool to the next.
Side channel	Undifferentiated low flow channel. No additional habitat typing is defined, though the channel likely contains areas of pool and riffle with multiple bar habitats.
Seasonal side channel	These units represent areas where there may not be connected flow at the time of photography, but regularly are inundated by seasonal flow.

Table D.2. Geomorphic reach type classifications. Adapted from Boyd and Thatcher (2004).

Type abbrev.	Classification	Number of reaches	Slope (ft/ft)	Planform/ Sinuosity	Natural confinement	Gravel bar frequency	Side channel frequency
UA	Unconfined anabranching	11	<0.0022	Multiple channels	Low	Moderate	High
PCA	Partially confined anabranching	11	<0.0023	Multiple channels	Moderate	Moderate	High
UB	Unconfined braided	6	<0.0024	Multiple channels	Low	High	High
PCB	Partially confined braided	11	<0.0022	Multiple channels	Moderate	High	High
PCM	Partially confined meandering	2	<0.0014	>1.2	Moderate	Low/ moderate	Moderate
PCS	Partially confined straight	9	<0.0020	<1.3	Moderate	Low/ moderate	Low
PCM/I	Partially confined meandering/ islands	11	<0.0007	Multiple channels	Moderate	Low/ moderate	Moderate
CM/S	Confined straight	1	<0.0001	<1.2	High	Low	Low
CM	Confined meandering	3	<0.0008	<1.5	High	Low	Low
US/I	Unconfined straight/ islands	1	<0.0003	<1.2	Low	Low/ moderate	Moderate

Table D.3. Bank full habitat unit areas by reach in the 1950s. Reaches were delineated by Boyd and Thatcher (2004). Habitat unit areas are reported in km^2.

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
A15	PCB	0.573	0.196	0.268	0.280	0.125	0.000	0.380	0.000
A16	PCA	0.295	0.479	0.452	0.540	0.087	0.000	1.168	0.000
A17	UA	0.444	0.296	0.214	0.289	0.019	0.000	1.004	0.000
A18	UA	0.139	0.055	0.020	0.175	0.086	0.000	0.325	0.000
B01	UB	1.347	1.023	0.095	1.306	0.260	0.405	2.697	0.182
B02	PCB	0.475	0.152	0.481	0.435	0.170	0.000	0.383	0.000
B03	UB	0.668	0.301	0.000	0.368	0.000	0.026	0.971	0.000
B04	PCS	0.248	0.128	0.000	0.095	0.174	0.245	0.166	0.000
B05	UA	0.332	0.883	0.095	0.657	0.000	0.098	1.541	0.000
B06	PCB	0.489	0.448	0.411	0.252	0.000	0.000	0.760	0.000
B07	UB	0.875	0.711	0.268	0.632	0.000	0.000	1.383	0.000
B08	PCA	0.375	0.833	0.885	0.592	0.000	0.000	1.569	0.000
B09	UA	0.343	0.093	0.155	0.394	0.000	0.099	0.882	0.000
B10	PCM	0.409	0.190	0.831	0.438	0.012	0.000	0.966	0.000
B11	PCA	0.668	0.207	0.563	0.559	0.000	0.000	1.711	0.000
B12	UA	0.561	0.086	0.024	0.381	0.391	0.000	0.666	0.000
C01	UA	0.343	0.220	0.373	0.566	0.000	0.036	1.150	0.000
C02	PCB	0.341	0.472	0.000	0.288	0.000	0.755	0.559	0.000
C03	UA	0.125	0.944	0.000	0.319	0.000	0.000	1.354	0.074
C04	PCB	0.000	0.123	0.071	0.314	0.000	0.000	0.849	0.000
C05	PCS	0.275	0.046	0.557	0.200	0.000	0.000	0.206	0.000
C06	UA	0.000	0.929	0.000	0.504	0.000	0.000	1.216	0.000
C07	UA	0.742	0.929	0.431	0.872	0.000	0.000	2.090	0.054
C08	PCS	0.104	0.629	1.058	0.179	0.000	0.000	0.781	0.000

Table D.3 Continued

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
C09	UA	0.856	1.413	0.000	1.040	0.000	0.000	3.014	0.000
C10	PCM	0.000	0.137	0.000	0.353	0.000	0.544	1.234	0.000
C11	PCM/I	0.524	0.900	0.000	0.798	0.604	0.520	1.972	0.000
C12	PCM/I	0.176	0.883	0.082	0.646	0.000	0.075	2.542	0.000
C13	PCM/I	0.149	0.527	0.000	0.479	0.489	0.412	1.114	0.000
C14	PCM/I	0.263	0.341	0.000	1.154	0.276	0.322	3.131	0.000
C15	PCS	0.000	0.125	0.000	0.191	0.178	0.193	0.805	0.000
C16	PCM/I	0.183	0.652	0.529	0.713	0.344	0.126	0.890	0.000
C17	PCS	0.000	0.266	0.552	0.125	0.766	0.000	0.256	0.000
C18	PCS	0.000	0.057	0.870	0.153	0.000	0.000	0.229	0.000
C19	CM/S	0.000	0.375	0.697	0.884	0.000	1.074	2.067	0.000
C20	CM/S	0.151	0.123	0.208	0.632	0.000	0.456	0.834	0.828
C21	CM	0.000	0.364	0.000	0.637	0.000	0.454	0.642	1.756
D01	CM	0.179	0.273	1.167	1.232	0.000	0.000	0.368	1.901
D02	CM	0.000	0.008	0.845	0.845	0.033	0.000	0.000	2.348
D03	PCS	0.150	0.157	0.327	0.724	0.024	0.000	1.560	0.534
D04	PCM/I	0.098	0.764	0.696	1.324	0.000	0.000	1.500	1.081
D05	PCA	0.670	2.624	0.000	1.634	0.000	0.000	2.611	0.904
D06	PCM/I	0.113	0.772	0.000	0.615	0.000	0.284	1.226	0.270
D07	PCA	0.520	0.742	0.772	1.298	0.000	0.000	1.518	0.103
D08	PCA	0.203	1.492	0.242	1.123	0.000	0.117	2.295	0.237
D09	PCM/I	0.000	0.340	0.251	0.486	0.000	0.000	0.683	0.000
D10	PCA	0.736	2.259	0.706	1.947	0.000	0.000	1.706	0.105
D11	PCA	0.305	2.160	0.098	0.975	0.000	0.000	1.659	0.000
D12	PCA	1.791	1.725	0.000	2.299	0.000	0.000	3.083	0.164
D13	PCM/I	0.401	1.044	0.000	0.782	0.252	0.132	2.096	0.000

Table D.3 Continued

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
D14	PCM/I	1.072	0.074	0.654	2.443	0.000	0.000	4.146	0.539
D15	PCM/I	0.000	0.634	1.034	0.219	0.000	0.000	1.065	1.047
D16	US/I	0.958	0.188	0.000	1.309	0.000	0.000	3.675	0.000

Table D.4. Bank full habitat unit areas by reach in 2001. Reaches were delineated by Boyd and Thatcher (2004). Habitat unit areas are reported in km^2.

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
A15	PCB	0.317	0.272	0.401	0.525	0.101	0.000	0.436	0.000
A16	PCA	0.251	0.725	0.256	0.812	0.141	0.000	0.903	0.075
A17	UA	0.078	0.582	0.000	0.596	0.070	0.000	1.196	0.066
A18	UA	0.340	0.272	0.000	0.098	0.190	0.000	0.235	0.000
B01	UB	0.603	1.766	0.062	1.051	1.292	0.775	1.039	0.140
B02	PCB	0.042	0.536	0.422	0.454	0.375	0.078	0.239	0.000
B03	UB	0.165	0.855	0.000	0.470	0.387	0.114	0.196	0.000
B04	PCS	0.003	0.318	0.000	0.237	0.195	0.390	0.000	0.000
B05	UA	1.210	1.021	0.343	0.608	0.353	0.000	0.569	0.000
B06	PCB	0.282	0.557	0.335	0.435	0.023	0.000	0.868	0.000
B07	UB	0.000	0.906	0.098	0.999	0.221	0.000	1.465	0.000
B08	PCA	0.446	1.584	0.599	0.629	0.335	0.000	1.002	0.000
B09	UA	0.427	0.351	0.054	0.515	0.000	0.083	0.664	0.000
B10	PCM	0.000	0.663	1.333	0.407	0.203	0.000	0.509	0.000
B11	PCA	0.202	1.555	0.360	0.607	0.069	0.000	1.159	0.000
B12	UA	0.129	0.923	0.000	0.200	0.259	0.000	0.726	0.000
C01	UA	0.260	0.671	0.188	0.585	0.000	0.013	1.233	0.000
C02	PCB	0.319	0.449	0.000	0.539	0.000	0.674	0.406	0.000
C03	UA	0.085	0.874	0.000	0.594	0.280	0.000	0.500	0.000
C04	PCB	0.164	0.188	0.326	0.492	0.313	0.000	0.100	0.000
C05	PCS	0.000	0.254	0.670	0.262	0.000	0.000	0.104	0.000
C06	UA	0.000	0.456	0.000	0.385	0.400	0.000	0.980	0.000
C07	UA	0.598	1.460	0.216	0.935	0.187	0.000	1.528	0.000
C08	PCS	0.212	0.228	0.737	0.577	0.319	0.000	0.480	0.000

Table D.4 Continued

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
C09	UA	0.050	1.895	0.142	1.149	0.198	0.000	1.964	0.000
C10	PCM	0.116	0.289	0.000	0.445	0.127	0.494	0.732	0.000
C11	PCM/I	0.448	0.423	0.000	1.183	0.816	0.574	1.327	0.046
C12	PCM/I	0.439	0.589	0.000	0.937	0.258	0.123	1.885	0.000
C13	PCM/I	0.000	0.581	0.000	0.607	0.813	0.504	0.358	0.000
C14	PCM/I	0.273	0.739	0.000	1.555	1.129	0.339	1.141	0.000
C15	PCS	0.114	0.062	0.000	0.498	0.000	0.381	0.425	0.000
C16	PCM/I	0.357	0.444	0.396	0.760	0.238	0.212	0.948	0.028
C17	PCS	0.053	0.242	0.794	0.414	0.182	0.000	0.150	0.000
C18	PCS	0.000	0.056	1.062	0.100	0.000	0.000	0.168	0.000
C19	CM/S	0.102	0.203	0.858	1.524	0.000	0.441	1.545	0.000
C20	CM/S	0.000	0.168	0.000	0.590	0.000	0.578	1.365	0.254
C21	CM	0.111	0.193	0.000	0.959	0.317	0.254	0.297	1.556
D01	CM	0.256	0.119	0.951	1.511	0.316	0.000	0.365	1.419
D02	CM	0.000	0.077	0.935	0.728	0.000	0.000	0.000	2.222
D03	PCS	0.227	0.165	0.325	0.743	0.000	0.000	1.177	0.905
D04	PCM/I	0.333	0.515	0.641	1.625	0.000	0.000	1.038	0.843
D05	PCA	1.137	1.957	0.000	1.177	0.112	0.000	1.743	1.283
D06	PCM/I	0.210	0.209	0.000	0.510	0.000	0.076	0.966	0.619
D07	PCA	0.754	1.070	0.559	0.665	0.000	0.000	1.415	0.000
D08	PCA	0.430	0.789	0.000	1.168	0.085	0.261	2.031	0.208
D09	PCM/I	0.000	0.360	0.455	0.232	0.000	0.000	0.648	0.000
D10	PCA	0.417	1.821	0.761	1.114	0.468	0.000	1.243	0.000
D11	PCA	0.857	1.230	0.000	0.619	0.000	0.000	1.226	0.000
D12	PCA	0.497	1.941	0.066	1.780	0.094	0.099	2.462	0.162
D13	PCM/I	0.000	0.901	0.000	0.713	1.061	0.104	1.036	0.000

Table D.4 Continued

Reach	Reach Type	Side channel	Seasonal side channel	Bluff pool	Channel crossover	Riprap bottom pool	Riprap margin pool	Scour pool	Terrace pool
D14	PCM/I	0.203	0.943	0.291	1.968	0.606	0.247	3.258	0.162
D15	PCM/I	0.013	0.287	0.260	0.769	0.538	0.155	0.798	0.413
D16	US/I	0.000	0.876	0.000	0.658	0.000	0.000	2.329	0.000

Figures

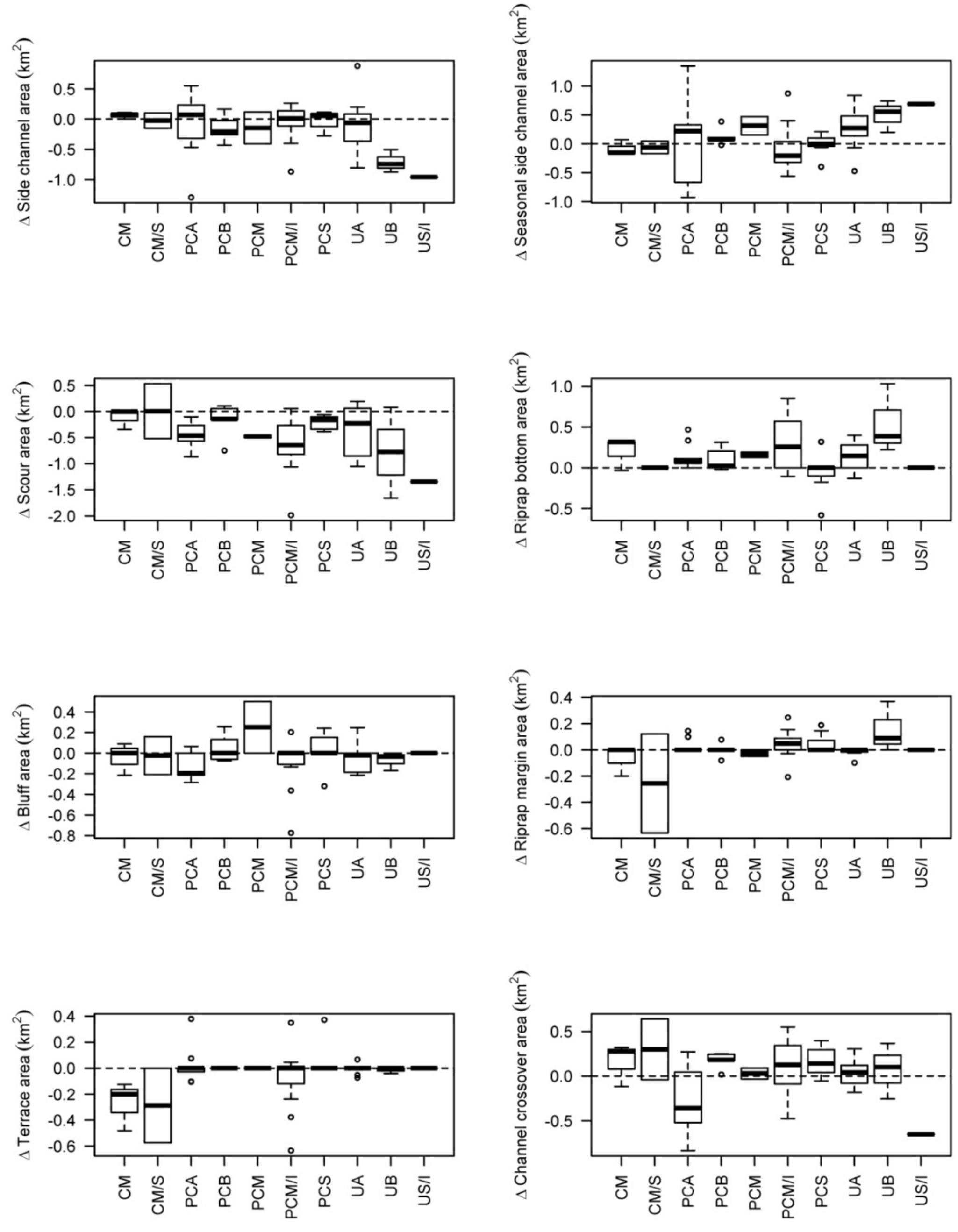


Figure D.1. Changes in fisheries habitat unit areas from the 1950s to 2001 by reach type. Delta is the difference in unit area from 1950s to 2001. Values above dotted line indicate that the habitat category was larger in 2001 than in the 1950s. Values below dotted line indicate that the habitat category was smaller in 2001 than in the 1950s. Reach type abbreviations are located in table D.2.

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