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**Key Points:**
- We characterize spatial heterogeneity of 37 floodplain segments in the Southern Rockies
- Spatial heterogeneity is best explained by drainage area, channel planform, and gradient
- Heterogeneity is inversely correlated with drainage area

**Correspondence to:**
E. Wohl,
ellen.wohl@colostate.edu

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# Patterns of Floodplain Spatial Heterogeneity in the Southern Rockies, USA

**Ellen Wohl[1] and Emily Iskin[1]**

[1]Department of Geosciences, Colorado State University, Fort Collins, CO, USA

**Abstract** Floodplain spatial heterogeneity describes the three-dimensional patchiness of floodplain substrate, surface elevation, and land cover. This heterogeneity results primarily from lateral channel migration and avulsion and decreases under diverse forms of management. Heterogeneity influences floodplain storage time, resilience to disturbance, and biodiversity. We use a data set of 37 floodplain segments covering a range of drainage areas and channel geometries from sites in the Southern Rocky Mountains to examine correlations between floodplain spatial heterogeneity and lateral valley confinement, drainage area, channel planform, and river management. We hypothesized that heterogeneity correlates most strongly with channel planform but found that the best explanatory statistical model included drainage area, planform, and gradient. Pairwise comparisons of means indicate that straight channels have the least heterogeneous floodplains and meandering channels have the greatest, while braided and anastomosing channels have intermediate values. Pairwise comparison of managed and unmanaged river corridors indicates that these populations are significantly different.

## 1. Introduction

A high degree of spatial heterogeneity is one of the salient characteristics of a floodplain along an unregulated, laterally mobile channel (Appling et al., 2014; Hughes, 1997; Schwendel et al., 2015). Spatial heterogeneity here refers to three-dimensional patchiness of floodplain substrate (grain size, soil moisture, depth, porosity, and permeability), surface elevation, and land cover (vegetation type and age, standing, or flowing water). In contrast, channels with flow regulation, artificial levees, bank stabilization, floodplain land use, and channelization in the form of straightening or confinement of multichannel rivers to single channels commonly have floodplains that become progressively less spatially heterogeneous with time because of decreased overbank flows, lateral channel movement, and avulsion (Brown et al., 2018; Florsheim & Mount, 2002; Smith et al., 1989; Ward & Stanford, 1995).

Lateral channel mobility and avulsion are the primary processes that create floodplain spatial heterogeneity, although other processes including overbank flow, tributary inputs (e.g., Benda et al., 2003, 2004), and colluvial inputs from adjacent uplands can influence floodplain geomorphic heterogeneity in some river corridors. Lateral channel mobility and avulsion reflect numerous indirect controls, including flow, sediment, and large wood regimes and substrate erosional resistance. Flow, sediment, and large wood regimes might be expected to influence spatial heterogeneity by altering hydraulic driving forces within the channel, as well as floodplain erosional resistance. Investigators have documented greater lateral channel mobility and greater frequency of avulsion in relation to greater hydrologic variability (e.g., Friedman & Lee, 2002; Jones & Schumm, 1999; Nanson, 1986), greater bedload fluxes (e.g., Ashworth et al., 2004; Constantine et al., 2014), and greater wood fluxes and storage (e.g., Collins et al., 2012; Makaske et al., 2002). Floodplain erosional resistance also reflects the presence and characteristics of riparian vegetation (e.g., Güneralp & Rhoads, 2011; Vincent et al., 2009). All of these factors interact within the context of valley geometry to govern the rate and magnitude of lateral channel migration and avulsion, and the resulting floodplain spatial heterogeneity.

Floodplain spatial heterogeneity is of interest for several reasons. First, spatial heterogeneity influences residence time of diverse materials on floodplains. Floodplains store water, solutes, mineral sediment, and particulate matter for varying lengths of time. The duration of floodplain residence of these materials depends on several factors (e.g., Beechie et al., 2006; Burt, 1997; Helton et al., 2014; Wegener et al., 2017) including spatial heterogeneity. Greater spatial heterogeneity may correspond to greater floodplain residence time if diverse environments provide opportunities for enhanced storage. For example, floodplain lakes can increase surface storage of water (Lininger & Latrubesse, 2016) or woody vegetation patches can increase flow resistance and associated sediment deposition and storage (e.g., Hupp, 2000; McKenney et al., 1995).

Floodplain spatial heterogeneity is also important because it can correlate with the resilience of river corridors to natural and human-induced disturbances. Resilience here refers to the persistence of an ecosystem and its ability to return to predisturbance conditions following disturbance (Holling, 1973; Webster et al., 1975). A resilient system recovers quickly from disturbance and is persistent. Floodplains influenced by beaver ecosystem engineering, for example, are spatially heterogeneous and highly resilient to floods, drought, and wildfire (e.g., Hood & Bayley, 2008).

Greater floodplain heterogeneity can also correlate with greater biodiversity and bioproductivity (e.g., Bellmore & Baxter, 2014; Greene & Knox, 2014; Scott et al., 2003; Ward & Stanford, 1995), although other factors such as introduced species or limited connectivity can constrain the biodiversity of spatially heterogeneous river environments (e.g., Lepori et al., 2005; Palmer et al., 2010).

Floodplain spatial heterogeneity also both reflects and influences river processes, and as such is increasingly a focus of river management. Substantial bedload, for example, can enhance lateral channel migration (Constantine et al., 2014), and enhanced lateral migration can result in abandoned cutoff meanders that increase floodplain heterogeneity, habitat diversity, and sediment and water retention (Choné & Biron, 2016). Analogously, Makaske et al. (2002) describe an avulsion sequence in which a crevasse splay channel enlarges and then subsequently infills and is abandoned, creating a laterally and vertically heterogeneous pattern of grain size distribution, soil moisture, and floodplain vegetation. Spatial heterogeneity influences continuing erosion and deposition by creating patches of greater erosional resistance that influence channel migration (e.g., Collins et al., 2012; Schwendel et al., 2015).

Here we address the question of whether there are characteristic levels of floodplain spatial heterogeneity in relation to lateral valley confinement, drainage area, channel planform, or river corridor management. Documentation of consistent levels of floodplain spatial heterogeneity in relation to potential control variables could enhance understanding of the processes that create and maintain spatial heterogeneity and inform management designed to restore floodplain spatial heterogeneity in order to enhance floodplain residence time, habitat diversity, and biodiversity (e.g., Buijse et al., 2002).

Lateral valley confinement might influence spatial heterogeneity by limiting the lateral mobility of the active channel and decreasing the turnover time of the floodplain (Wohl, 2015). Drainage area might influence heterogeneity via a correlation with valley confinement (valley bottoms tend to become progressively wider as drainage area increases, although this trend can be weak in some river basins) and via changes in hydraulic force relative to floodplain erosional resistance as drainage area and discharge increase. Channel pattern might influence spatial heterogeneity in that channels that are highly laterally mobile (e.g., braided) or minimally laterally mobile (e.g., straight) might be expected to have less spatially heterogeneous floodplains than channels with an intermediate level of lateral mobility (e.g., meandering and anastomosing). River corridor management could reduce floodplain spatial heterogeneity via channelization, bank stabilization, or flow regulation that reduce lateral channel movement, or land drainage and land cover change that alter floodplain vegetation.

This study focuses on floodplain spatial heterogeneity along channels in the Southern Rockies of Colorado, USA. Although study sites include diverse values of valley confinement, drainage area, channel planform, and river corridor management, all of the study sites fall within the medium-energy, noncohesive floodplain category in the Nanson and Croke (1992) floodplain classification. In addition, the limited geographic scope of the study sites makes this a pilot study and a preliminary test of the hypothesis that floodplain spatial heterogeneity correlates most strongly with channel pattern.

## 2. Study Area

Sites were chosen within the Southern Rockies of Colorado in order to avoid the channelization and artificial levees that are present on some channels in the Great Plains of Colorado. Consequently, all of the sites have a snowmelt-dominated flow regime, with annual peak flow in late spring to early summer.

**Table 1**
*Summary Characteristics of the Study Sites, Which Are Listed in Ascending Order for Drainage Area*

| Site | A ($km^2$)[a] | S (m/m)[b] | $Q_2$ (cms)[c] | Planform | Mgmt[d] | Veg[e] | $P_{main}$[f] | $P_{total}$[g] | Confine[h] | SH[i] |
|---|---|---|---|---|---|---|---|---|---|---|
| Cascade 1 | 0.3 | 0.060 | 0.1 | meander | no | grass | 1.79 | 1.79 | 26.0 | 0.347 |
| Timber 1 | 3.9 | 0.037 | 1.4 | straight | no | grass | 1.36 | 1.36 | 28.3 | 0.134 |
| Timber 2 | 3.9 | 0.030 | 1.4 | meander | no | grass | 1.56 | 1.56 | 17.9 | 0.241 |
| U Poudre | 4.4 | 0.024 | 1.4 | straight | no | grass | 1.18 | 1.18 | 42.0 | 0.138 |
| Cascade 2 | 5.0 | 0.030 | 1.2 | meander | no | grass | 1.59 | 1.59 | 57.5 | 0.045 |
| Bulldog 1 | 12.2 | 0.074 | 3.5 | braided | no | w shrub | 1.14 | 1.67 | 5.1 | 0.098 |
| Bulldog 2 | 12.5 | 0.074 | 3.5 | braided | no | w shrub | 1.03 | 2.85 | 2.0 | 0.156 |
| Corral 1 | 13.1 | 0.015 | 3.7 | meander | no | w shrub | 1.55 | 1.55 | 21.8 | 0.081 |
| Corral 2 | 13.6 | 0.016 | 3.7 | meander | no | w shrub | 1.68 | 1.68 | 6.4 | 0.165 |
| Corral 3 | 13.7 | 0.018 | 3.7 | straight | no | w shrub | 1.33 | 1.33 | 15.7 | 0.128 |
| Hollowell | 14.4 | 0.020 | 2.6 | anastom | no | w shrub | 1.27 | 2.70 | 41.7 | 0.047 |
| NSV upper | 15.9 | 0.066 | 5.4 | anastom | no | forest | 1.07 | 4.96 | 83.4 | 0.017 |
| NSV lower | 20.0 | 0.031 | 5.9 | anastom | no | forest | 1.19 | 2.59 | 96.7 | 0.011 |
| LPP 1 | 24.3 | 0.011 | 5.7 | meander | yes | w shrub | 1.81 | 1.81 | 6.1 | 0.078 |
| LPP 2 | 24.4 | 0.049 | 5.7 | straight | yes | w shrub | 1.00 | 1.00 | 1.6 | 0.199 |
| Hague | 37.5 | 0.012 | 6.0 | straight | no | w shrub | 1.41 | 1.41 | 7.6 | 0.088 |
| NSV u str | 60.0 | 0.043 | 12.0 | straight | no | forest | 1.07 | 1.07 | 4.3 | 0.061 |
| E Inlet | 76.7 | 0.012 | 13.4 | meander | no | grass | 1.72 | 2.48 | 9.3 | 0.076 |
| N Inlet | 78.3 | 0.006 | 14.2 | meander | no | grass | 2.36 | 2.90 | 18.6 | 0.055 |
| NSV 1 str | 82.5 | 0.023 | 14.8 | straight | no | forest | 1.12 | 1.12 | 8.3 | 0.050 |
| Fall | 86.7 | 0.004 | 12.3 | meander | no | w shrub | 2.17 | 2.17 | 38.2 | 0.035 |
| Poudre | 94.2 | 0.020 | 13.5 | straight | no | w shrub | 1.00 | 1.00 | 1.9 | 0.121 |
| Upper CO | 101.7 | 0.006 | 15.1 | meander | yes | grass | 1.75 | 1.76 | 36.2 | 0.019 |
| MP | 110.0 | 0.005 | 17.3 | anastom | yes | grass | 1.53 | 3.87 | 58.2 | 0.038 |
| Avalanche | 115.3 | 0.066 | 21.5 | braided | no | w shrub | 1.07 | 2.32 | 7.1 | 0.061 |
| Upper CO 2 | 182.5 | 0.006 | 20.6 | meander | yes | grass | 3.50 | 3.72 | 29.2 | 0.027 |
| SFP 1 | 195.8 | 0.03 | 8.2 | straight | yes | forest | 1.06 | 1.06 | 5.8 | 0.055 |
| SFP 2 | 196.7 | 0.014 | 8.2 | straight | yes | w shrub | 1.22 | 1.22 | 9.7 | 0.033 |
| Crystal 5 | 212.0 | 0.01 | 39.7 | braided | yes | w shrub | 1.06 | 2.76 | 5.2 | 0.038 |
| Crystal 4 | 353.0 | 0.008 | 51.7 | braided | yes | w shrub | 1.17 | 5.17 | 2.4 | 0.045 |
| Crystal 3 | 467.0 | 0.012 | 59.8 | braided | yes | w shrub | 1.10 | 2.35 | 1.4 | 0.083 |
| Crystal 2 | 480.0 | 0.012 | 59.6 | braided | yes | w shrub | 1.04 | 1.92 | 3.3 | 0.058 |
| Illinois | 502.8 | 0.002 | 17.1 | anastom | yes | w shrub | 1.70 | 7.72 | 105.3 | 0.022 |
| Crystal 1 | 597.2 | 0.013 | 71.6 | braided | yes | grass | 1.06 | 1.65 | 5.5 | 0.036 |
| Michigan | 1297.2 | 0.005 | 29.8 | anastom | yes | grass | 1.99 | 4.73 | 107.5 | 0.014 |
| N Platte | 1802.8 | 0.002 | 58.4 | anastom | yes | w shrub | 1.81 | 3.37 | 27.1 | 0.016 |
| Upper CO 3 | 3805.6 | 0.001 | 100.0 | anastom | yes | grass | 1.39 | 3.81 | 23.6 | 0.018 |

[a]Drainage area. [b]Average main channel gradient in the study reach. [c]$Q_2$ is the peak flood with an average recurrence interval of 2 years. [d]Mgmt indicates whether some type of human-induced change in the channel and/or floodplain is present. [e]Veg indicates predominant category of floodplain vegetation in the study reach (grass, woody shrub, conifer forest, and mixed). [f]$P_{main}$ is sinuosity of the main channel. [g]$P_{total}$ is ratio of total channel length to straight-line length. [h]Confinement is ratio of average valley bottom width to average bankfull channel width. [i]SH is the floodplain spatial heterogeneity metric.

Among the 36 study sites, drainage areas range over 4 orders of magnitude (0.3 to 3,800 $km^2$) and elevations range from 2,040 to 3,320 m. Floodplain vegetation varies from nonwoody (grasses, sedges, and rushes) to woody shrubs (predominantly willows; *Salix* spp.) to forest (predominantly conifers). Channel substrate and morphology vary widely among sites, from boulder-bed, step-pool mountain streams to sand-bed, pool-riffle streams in lower-gradient valleys. Channel substrate and bedforms correspond to reach-scale channel gradient. Table 1 summarizes site characteristics, and Figure 1 shows the location of study sites. Within the inset map in Figure 1, the cluster at lower left is the braided-channel sites on Bulldog and Avalanche Creeks and the Crystal River. The three sites at top center are the Illinois, Michigan, and North Platte Rivers anastomosing sites. The site at the center of the map is Upper Colorado River site 3, an anastomosing channel site. The remainder of the study sites are clustered in Rocky Mountain National Park and adjacent portions of the Arapaho-Roosevelt National Forest, where management such as flow regulation and direct human alteration of channel and floodplain form is minimal.

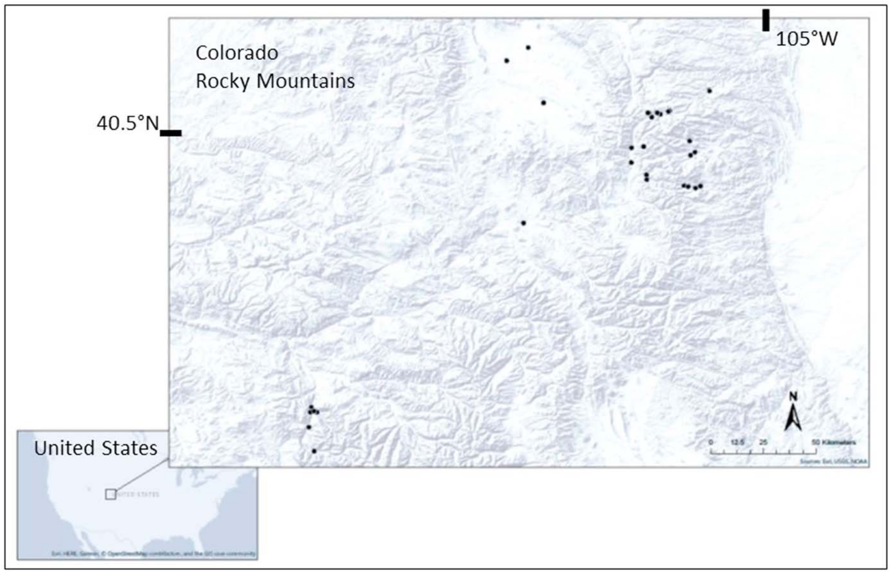


**Figure 1.** Location map of the study sites (black dots) within the Rocky Mountains of Colorado, USA. Inset map of the conterminous United States indicates regional location of the study area.

## 3. Methods

Sites were chosen to represent a range of drainage areas, channel planforms, lateral valley confinement, and management history. Sites were also chosen to be accessible for ground measurements. At each site, five floodplain transects were designated perpendicular to the main valley trend. The distance between the upstream- and downstream-most transects spanned a length of channel at least ten times the average bankfull channel width. Each transect began at the outer edge of the floodplain. Boundaries between floodplain units were surveyed using a handheld Garmin eTrex GPS unit (±3-m horizontal accuracy) and the transect continued to the opposite edge of the floodplain. Floodplain units were differentiated based on relative elevation, vegetation, and soil texture and moisture.

Channel planform was categorized as straight, meandering (single channel with sinuosity ≥1.5), braided (multiple channels separated by mobile bars), or anastomosing (multiple channels separated by vegetated interfluves wider than average bankfull channel width and composed of the same material that is present in the floodplain; Carling et al., 2014; Nanson & Croke, 1992). Lateral valley confinement was calculated as the ratio of average floodplain width to average bankfull channel width. Floodplain and bankfull channel width were measured in the field using a laser rangefinder (±0.1-m horizontal accuracy). Floodplain boundaries were designated based on topography, vegetation, and indicators of fluvial processes. Management history was categorized as either unmanaged (no history of human alteration within the river corridor) or managed. Management history in these sites includes a road, buildings, or timber harvest within the river corridor, flow regulation, and manipulation of wildlife populations that result in loss of beaver populations. In the latter scenario, multichannel planforms can metamorphose to single-channel planforms, as described in the alternative states of beaver meadows versus elk grasslands (Polvi & Wohl, 2013; Wolf et al., 2007). Floodplain vegetation was categorized as grass (grasses, rushes, and sedges), woody shrub (predominantly willows), or forest (mostly conifers).

Additional variables calculated for each site include drainage area (as determined using the U.S. Geological Survey program StreamStats: https://streamstats.usgs.gov/ss/), sinuosity of the main channel (ratio of main channel length to straight line length), total sinuosity (ratio of total channel length to straight line length), channel gradient, and 2-year peak flow. Sinuosity and total sinuosity were measured from Google Earth imagery taken at base flow conditions. Channel gradient for each site was calculated from the upstream- to downstream-most floodplain transects using topographic maps. The 2-year peak flood is estimated at a delineated point along a stream using regional regression statistics in StreamStats (Capesius & Stephens, 2009).

**Table 2**
*Summary of Final Model Fit to sqrt (Floodplain Heterogeneity)*

| Parameter | Estimate | Standard error | *P* value | Akaike weights |
|---|---|---|---|---|
| Intercept | 0.308093 | 0.045879 | $1.632 \times 10^{-7}$ | |
| ln (drainage area) | -0.029884 | 0.007399 | 0.0003280 | 0.96 |
| Planform | | | 0.0007759 | 0.91 |
| Gradient | -1.402679 | 0.667641 | 0.0438733 | 0.60 |

We used a simple, linear metric of spatial heterogeneity adapted from Graf (2006), who proposed the ratio of number of channel units along a transect to transect length as a measure of channel geomorphic diversity. The modified Graf metric is the ratio of total number of floodplain units along a transect to transect length.

Statistical analyses were performed using the R statistical package (R Core Team, 2018). To determine the dominant controls on floodplain spatial heterogeneity, we performed a multivariate analysis between hypothesized predictors and floodplain heterogeneity. Predictors included the three categorical variables of channel planform, management, and vegetation, and the six continuous variables of drainage area, channel gradient, main channel sinuosity, total sinuosity, valley confinement ratio, and 2-year peak flow. We performed all subset model selection on a multiple linear regression model based on Akaike Information Criterion correction, a statistical technique that prevents selection of models with too many parameters relative to the sample size (Wagenmakers & Farrell, 2004). In our model selection, drainage area was log-transformed and floodplain heterogeneity was square-rooted in order to better fit the assumptions required for this type of analysis.

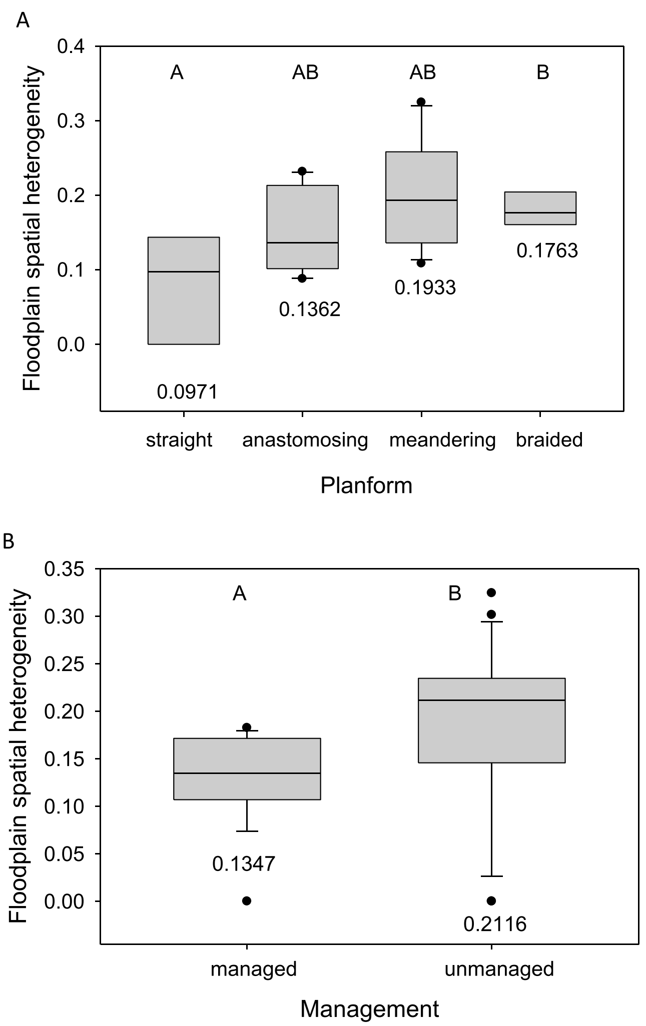


**Figure 2.** Comparison of median values of floodplain spatial heterogeneity with respect to (a) planform and (b) management category. Letters above boxes indicate statistical similarity or difference. Number below each box is the median value.

## 4. Results

The statistical model with the lowest Akaike Information Criterion correction value includes drainage area, planform, and gradient as the strongest predictors of floodplain spatial heterogeneity (multiple $R^2 = 0.58$). A summary of the final model is given in Table 2. Of these variables, drainage area has the greatest importance as a predictor variable. Tukey-adjusted pairwise comparison of means ($\alpha = 0.05$) was performed on planform, the categorical predictor in the final model (Figure 2). This analysis indicates that straight channels have the lowest median value of floodplain heterogeneity and meandering channels have the greatest, while anastomosing and braided channels have intermediate values. The analysis also indicates that straight and braided planforms have significantly different floodplain heterogeneity from one another. Pairwise comparison of managed and unmanaged channels indicates that these populations are significantly different.

## 5. Discussion and Conclusions

The results only partially supported our original hypothesis. Although floodplain spatial heterogeneity does correlate with channel planform category, the strongest predictor variable is drainage area. The correlation with drainage area does not simply reflect an increasing ratio of floodplain width to channel width and associated greater space for channel migration, because the ratio of floodplain width to channel width was not a significant predictor variable. Instead, the correlation may reflect a greater ratio of hydraulic driving forces relative to substrate erosional resistance, and associated greater lateral channel mobility and avulsion, as also reflected in the absence of straight channels at the study sites with larger drainage areas. The relatively low predictive power of the statistical model ($R^2 = 0.58$), however, indicates that a more rigorous test of these ideas will require a larger data set with more diverse rivers.

The significant difference in managed and unmanaged floodplains is surprising because none of the managed floodplains are urbanized. Consequently, even though native land cover has been removed for crops at some sites, and beavers that were present as recently as the past two to three decades have abandoned some of the other sites categorized as managed, the heterogeneity created by past channel migration is commonly still visible and was included in our analyses. These results suggest that even relatively modest and recent human-induced changes in channels and floodplains can significantly reduce floodplain spatial heterogeneity. It is important in this context to note that our measure of floodplain spatial heterogeneity does not necessarily reflect floodplain functionality. A secondary channel that might remain intermittently connected to surface flow under unmanaged conditions, for example, likely functions differently in a managed floodplain in which the secondary channel no longer experiences surface flow but remains a visually distinct unit that we differentiated in our field surveys. The finding that floodplains lose basic spatial heterogeneity—even without considering functionality—under management supports the assertions of previous studies (e.g., Florsheim & Mount, 2002; Ward & Stanford, 1995) that floodplain management designed to maintain or restore floodplain ecosystems should focus on the processes driving floodplain spatial heterogeneity.

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Data collected for this study and used in statistical analyses are presented in Table 1. This paper was improved by insightful review comments from Joan Florsheim and an anonymous reviewer.

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