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Development of a geomorphic monitoring strategy for stage 0 restoration in the South Fork McKenzie River, Oregon, USA

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Abstract

The South Fork McKenzie River (SFMR) in western Oregon, USA hosts one of the largest Stage 0 stream restoration projects implemented to date. Stage 0 refers to a multichannel planform with strong hydrologic connectivity to the adjacent floodplain and surface–subsurface connectivity. Stage 0 restoration was implemented on a 900-m-long reach of the SFMR by re-grading the channel and floodplain using 65,000 m^3 of sediment to raise the channel bed. Thousands of large logs were added and the ends of some logs were buried in the sediment to provide foundations for future log jams. Our primary objective is to present a monitoring protocol based on randomly located sampling plots. We also analyze results from 2 years of data collection since project implementation. Within each plot, we measured canopy cover, wood volume, flow depth and velocity, organic cover (area covered by coarse and fine organic material), and substrate grain size. We used intracluster correlation coefficients and variance of measured variables to assess heterogeneity at three spatial scales: within plots, between adjacent plots, and across the entire site. Here, we evaluate changes in the first 2 years after restoration (i.e., not pre- vs. post-restoration). We hypothesized that heterogeneity within a plot would decrease as the plot adjusted to local-scale hydraulics and sediment and particulate material transport. We hypothesized that heterogeneity would increase between adjacent plots and across the entire site. We found that spatial heterogeneity of geomorphic variables decreased within plots. Heterogeneity of organic cover, sediment size, and flow depth increased between adjacent plots, although other variables did not change. Site-scale heterogeneity decreased for all variables except organic cover and substrate. We interpret the observed geomorphic responses to reflect decreased longitudinal connectivity and increased lateral and vertical connectivity at the restoration site.

KEYWORDS
floodplain, hydrologic connectivity, large wood, Oregon, restoration, Stage 0

1 | INTRODUCTION

1.1 | Stage 0 restoration

Process-oriented stream restoration has gained traction as an alternative to form-based restoration in recent decades (e.g., Palmer et al., 2014; Wohl et al., 2015). Process-based restoration accounts for the trajectories of channel form and function through time, beginning from pre-restoration conditions and extending decades or more beyond treatment. This type of stream restoration incorporates drivers of channel change such as water and sediment supply, anthropogenic influence, and natural trends in channel evolution (Brierley & Fryirs, 2016). Conceptual cycles of channel evolution such as the channel evolution model (Schumm et al., 1984), stream evolution

model (Cluer & Thorne, 2014), and stream evolution triangle (Castro & Thorne, 2019) have guided our understanding of how rivers evolve and respond to disturbance.

There will likely be more iterations of how geomorphologists describe the nuanced progression of fluvial landscapes, but several key components of "healthy" river corridors have already emerged. These include increased planform complexity (Martens & Connolly, 2014), more abundant large wood where applicable (Wohl, 2017a; Wohl et al., 2019), biota as an important driver of channel form (Castro & Thorne, 2019; Gurnell et al., 2016; Polvi et al., 2020), and re-establishment of three-dimensional (3D) connectivity for water, sediment, nutrients, particulate organic matter, and large wood to a degree that would be expected under natural conditions in a particular river corridor (e.g., Pringle, 2001; Stanford & Ward, 1993; Wohl, 2017b). (Here, large wood refers to pieces ≥ 10 cm diameter and 1 m long.) The emphases on planform complexity and greater abundance of large wood in the channel(s) and floodplain reflect the realization that channel and floodplain spatial heterogeneity were much greater in many rivers prior to anthropogenic modifications (e.g., Brown et al., 2018; Collins et al., 2012; Triska, 1984) and that large wood was much more common and widespread in forested river corridors (e.g., Montgomery et al., 2003; Wohl, 2014). Changes in spatial heterogeneity and large wood have in turn strongly influenced connectivity, typically by increasing longitudinal connectivity but decreasing lateral and vertical connectivity within the river corridor (Collins et al., 2012; Doughty et al., 2020; Wohl & Beckman, 2014).

In practice, stream restoration project designers may choose ideal conditions to restore to, such as Stage 0 or Stage 8 of the stream evolution model (Cluer & Thorne, 2014). Both of these stages represent anastomosing wet woodland or grassed wetland river corridors, but Stage 0 is assumed to reflect conditions prior to anthropogenic modification and Stage 8 represents a stable endpoint after multiple adjustments following anthropogenic modification. There are many interventions that can nudge a channel–floodplain complex toward Stage 0 conditions, including low-tech process-based restoration (Wheaton et al., 2019), valley-scale matching to a geomorphic grade line (Powers et al., 2019), and removal of legacy sediment (Booth et al., 2009; Hartranft et al., 2011; Walter & Merritts, 2008). Restoration toward the Stage 0 condition at the South Fork McKenzie River (SFMR) in Oregon, USA utilized the entire valley bottom to reconnect an incised channel to its floodplain, disperse surface flow into multiple complex channels via an anastomosing planform, and enhance lateral and surface–subsurface hydrologic connectivity. The primary goal of this restoration was to enhance habitat for fish by providing more in-channel complexity with large wood and side channels, which can enhance biological productivity (Bellmore et al., 2013; Ogston et al., 2014), and by retaining sediment finer than cobble- to boulder-size in order to provide salmonid spawning habitat.

1.2 | Monitoring, spatial heterogeneity, and connectivity

It is important to quantify changes and track channel evolution in response to restoration treatment. Because restoration toward Stage 0 conditions is both relatively new and becoming increasingly popular

(Hartranft et al., 2011; Powers et al., 2019), monitoring can help quantify outcomes and keep track of lessons learned from early Stage 0 projects, addressing such questions as: Are the restoration projects sustainable on decadal scales? How do channels evolve through human-made anastomosing conditions? How much added wood is appropriate to transform the full valley bottom into well-connected floodplain, and how is the wood retained and reorganized over time? These questions can be answered by long-term monitoring efforts that track restoration projects from initial construction through continuing channel adjustment over a period of years. Monitoring is critical for any restoration (e.g., Bernhardt et al., 2005; England et al., 2008), but especially in innovative styles of restoration that may become more widely adopted and repeated within a short timespan. Typically, funding for monitoring is much less available than is funding for project construction and is not allocated to support long-term monitoring efforts (Lautz et al., 2019). Thus, to utilize monitoring data to improve restoration designs, monitoring techniques must balance thorough, accurate, and frequent data collection with budget constraints.

The SFMR Floodplain Enhancement Project is a spatially extensive Stage 0 restoration project in the Western Cascade Mountains of Oregon. The large scale and strenuous nature of ground-based access at the project led to potential difficulties with traditional, transect-based geomorphic monitoring efforts on the SFMR, especially during high flows. Hence, the need for new geomorphic monitoring techniques that can apply to this project and can also be extended to other large, valley-scale restoration projects. To address this challenge, we designed a sampling strategy utilizing geomorphic field plots that can be paired with data collection by unmanned aerial vehicles (UAVs; i.e., drones). Our primary objective in this article is to present the field component of this monitoring strategy. We also explore the results of the first 2 years of field data following implementation of the new field-based monitoring strategy by examining adjustment and analyzing geomorphic spatial heterogeneity at multiple spatial scales. Addressing the questions listed earlier requires monitoring over much longer periods of years to decades. However, it is useful to provide a preliminary test of that strategy in the first years after restoration so as to determine the efficacy of the proposed strategy and identify potential modifications. In this article, we also explicitly apply the metrics measured as part of monitoring to understanding spatial heterogeneity and connectivity within the treated river corridor.

Our primary goal is to develop a field geomorphic monitoring strategy that is easily accessible, statistically viable, and pairs well with remote sensing data. We chose to measure geomorphic field plots, rather than traditional transects, because plots are more likely to capture diverse scales of spatial heterogeneity that are an emphasis of restoration at the site. Transect-based stream monitoring was developed for single-threaded systems as a means of quantifying variables used in hydraulic equations (e.g., Leopold, 1962; Osterkamp et al., 1991). Although concepts addressed by transects remain relevant, valley-scale floodplain reconnection is more complex than a single channel and needs better representation than a single variable such as the hydraulic radius. In addition, the increasing availability of monitoring with drones allows most plan-view, and sometimes vertical, hydraulic geometry variables to be estimated remotely with aerial imagery.

We align our monitoring efforts with the original goals of restoration. Geomorphic field plots can capture changes in geomorphic variables and spatial heterogeneity, which we assess using the variables of substrate (sediment size), hydraulics (surface water depth and flow velocity), wood volume, organic cover (proportion of area covered by organic material), and canopy cover. Changes in these site characteristics impact habitat conditions for spring Chinook salmon (*Oncorhynchus tshawytscha*), bull trout (*Salvelinus confluentus*), Pacific lamprey (*Entosphenus tridentatus*), and many other species.

We do not have pre-restoration plot data from the site because our plots were established after the site was treated. Consequently, we cannot directly compare pre- and post-restoration site characteristics and we focus our analyses on changes occurring in the first 2 years following restoration. We evaluate changes in each of the variables listed earlier (Table 1 lists expected changes during the 2 years). Initial conditions immediately after restoration largely reflect the placement of large wood and anthropogenic disruption of topography and sediment distribution. With time, geomorphic processes will presumably redistribute sediment, as well as large wood and particulate organic matter, creating associated changes in substrate, hydraulics (flow depth and velocity), wood volume, and organic cover.

We define three spatial scales at which we evaluate changes in heterogeneity during the first 2 years following restoration: intra-plot, intermediate-scale inter-plot, and site-scale inter-plot. Intra-plot represents heterogeneity at length scales of a few meters within sampling plots. Intermediate-scale inter-plot represents heterogeneity among adjacent plots at 10^1–10^2 m, which average 68 m apart, with a range of 29 to 204 m. Site-scale inter-plot represents heterogeneity across the entire restoration site covering 45 ha, extending along a 900-m long reach of valley floor that averages 500 m in width. We hypothesize that intra-plot heterogeneity will decrease with time since restoration as plot characteristics increasingly reflect local hydraulics and sources of sediment, wood, and particulate organic matter. We hypothesize that intermediate-scale heterogeneity will increase, such that heterogeneity between adjacent plots will be greater than heterogeneity within a single plot. We expect that abundant, newly placed large wood provides the context for diversity of depositional rates and revegetation at this intermediate scale, leading to the formation of patches. Finally, we hypothesize that site-scale inter-plot heterogeneity will increase as local controls exert progressively more influence after the initial disturbance of restoration that tended to homogenize conditions throughout the floodplain. The data collected during these first 2 years after restoration will provide a baseline for evaluating ongoing, longer-term river adjustments.

The objective of this article is to utilize and evaluate a new method for monitoring stream restoration projects where traditional monitoring is less appropriate. We compute simple statistics to assess geomorphic change over 2 years of monitoring, use field data to examine potential changes in heterogeneity at the three spatial scales, relate changes in heterogeneity to inferred connectivity, and evaluate the benefits and shortcomings of the new monitoring strategy.

2 | STUDY AREA

The SFMR (44.16°N 122.29°W; elevation 340 m) is located near Rainbow, Oregon, USA in the Western Cascade mountains. Annual precipitation exceeds 1778 mm in the Western Cascades lowlands and valleys ecoregion, supporting lush western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), western redcedar forests (*Thuja plicata*) with red alder (*Alnus rubra*) and cottonwood (*Populus trichocarpa*) adjacent to stream channels. The river drains approximately 560 km². Streams provide habitat for spring Chinook salmon and bull trout among other species (Thorson et al., 2003).

TABLE 1 Expected changes for the South Fork McKenzie River

Variable	Expected change	Influences: Short term	Long term
Canopy cover	Decrease	Trees falling due to raised water table	Decrease until stable vegetated islands form, then increase with growth of riparian trees
Organic cover	Increase	Accumulation of organic matter due to lower slope and trapping potential by large wood, depositional setting	Increase to stable level
Wood volume	Dependent on flows	(1) Insufficient peak flows to move large wood or (2) with sufficient flow, large wood pieces will condense into jams, reducing the average encountered large wood volume per plot	Decrease as wood forms jams, jams initiate island formation, and islands become vegetated
Grain size	Decrease	Construction upstream (Phase 2) loosened fine materials that are deposited in Phase 1	Depending on peak flows, fines from construction may be flushed. Main channels: gravel and cobble expected, Side channels: Sand and silt expected until incision to a former channel surface, then gravel
Water velocity	Stay the same	Water is spread out across the floodplain; 2 years not adequate to form channels	Eventual formation of more established multithreaded channels with many pockets of slow areas
Water depth	Stay the same	2 years not enough time for more defined channels to form below a dam.	Increase until a threshold is reached as stable multithreaded channels form
Heterogeneity	Increase	Stay the same over 2 years, but has increased compared to pre-restoration	Islands form, vegetation establishes, flow is diverted to secondary channels and forms patches of different substrate size; wetlands form in forested floodplain

Potential flood hazards to the city of Eugene and surrounding areas led to the construction of dams and reservoirs throughout the Western Cascade mountains in the mid-20th century, including Cougar Dam on the SFMR. These reservoirs generate hydroelectricity, store snow melt for irrigation, and augment summer low flows and thus improve water quality in the downstream Willamette Valley. The construction of Cougar Dam in 1963 reduced sediment supply to the lower river and led to channel degradation in the lower SFMR. Peak flows were drastically reduced from 280 to 120 m^3/s, with base flows around 9 m^3/s (Figure 1, Supporting Information Figure S1). Based on valley-floor morphology and nearby reference sites that have not been affected by flow regulation, the portion of the SFMR below the dam likely transformed after dam construction from a multithreaded system into a single thread, high energy, transport-dominated system. Despite the reduction in peak flows, simplification to a single channel and lack of sediment connectivity with upstream reaches caused streambed incision of up to 4.3 m (Meyer, 2019). The channel bed became armored with boulders, with little to no gravel-sized sediment to provide spawning habitat for Chinook salmon. Streambed substrate suitable for spawning is critical for sustaining salmonids. Fish of a given species or length can spawn in a range of substrate sizes. In general, however, individual fish can spawn in sediment with a median diameter up to about 10% of their body length (Kondolf & Wolman, 1993). For Chinook salmon, this equates to a range of about 25 to 150 mm median diameter (Merz & Setka, 2003).

In an effort to improve habitat and reconnect the SFMR to its floodplain, the US Forest Service and McKenzie Watershed Council partnered to reset the valley bottom in the 6 km stretch between Cougar Dam and the confluence with the McKenzie River.

The project is divided into phases that progress from downstream to upstream. Phases I and II were completed in 2018 and 2019, respectively. Project construction followed the Geomorphic Grade Line approach of Powers et al. (2019), where the channel and floodplain are graded to match the average slope of the valley. Nearly 4000 large wood pieces were placed throughout the valley bottom

and 65,000 m^3 of sediment were redistributed from leveed banks and other high portions of the floodplain in Phase I (Figure 2; Meyer et al., 2018). Monitoring efforts in 2019 and 2020 included teams of geomorphic, ecologic, remote sensing, aquatic invertebrate, and fisheries scientists. The monitoring strategy described in this article was piloted in Phase I for the geomorphic characteristics of the restoration area. Phase I lies downstream from Phase II and was implemented before restoration activities immediately upstream in Phase II. Due to construction during 2019 in Phase II upstream, the portion of floodplain restored during Phase I may have been affected by mobilization of sediment during restoration-related disturbances in Phase II. However, flow is diverted during in-channel work and because the wetted channel is widened and large wood pieces increase hydraulic roughness, it is not clear how much the upstream restoration work would influence our results from the second year of monitoring.

3 | METHODS

Our geomorphic sampling design includes 40 hexagonal plots selected at random from a 4000-plot tessellation overlaid on the 0.45 km^2 Phase I treatment area. Each plot has an area of 42 m^2 and contains four 1-m-radius circular subplots. Plots are distinguished as either interfluve forested land (not flooded at typical high flows) or surface inundated at high flow (which includes the active channel). We chose 40 plots to pilot the monitoring strategy as a means of balancing time constraints and the need for a sufficiently large dataset for statistical analyses.

The highest flow released from Cougar Dam over the duration of our study was 141.6 m^3/s. This discharge has a recurrence interval of 3.1 years, calculated using the period of record after dam construction (Moore, 2002). The geographic extent of the floodplain was mapped and divided into high flow wetted area, forest, and barren ground. In this study, we discuss only the area inundated during high flow. Regions of flow were not further stratified into back channels, main
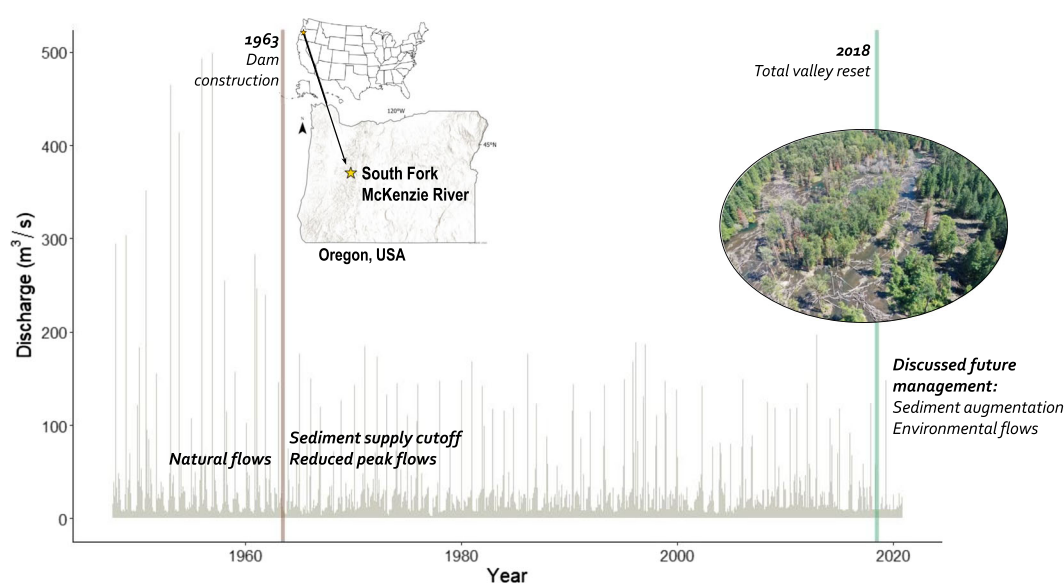

FIGURE 1 Flows at the South Fork McKenzie River (SFMR) (44.1596°N, 122.2864°W) before and after Cougar Dam construction in 1963. Phase I of the SFMR Floodplain Enhancement Project was implemented in 2018. The photograph of the SFMR in this figure was obtained from an October 2019 NBC16 Eugene news article by Kelsey Christensen

channels, flooded forest, for example, because the distribution of those potential strata is expected to change dramatically as the newly restored channel reaches a dynamic equilibrium over time. In total, 36 geomorphic in-stream plots were surveyed during the summer of 2019. The in-stream plots that were not surveyed in 2019 were either deemed unsafe for field measurements or unintentionally missed during our fieldwork. Due to limitations imposed in response to the COVID-19 pandemic, we were only able to resurvey 23 of the 36 plots during the summer of 2020 (Figure 2). The paired data from these 23 plots were used for statistical tests.

The design of the geomorphic monitoring plots was based on US Forest Service Forest Inventory and Analysis protocols (Bechtold & Patterson, 2005). We used a two-stage cluster sampling design in which geomorphic field plots are the primary sampling units and subplots within geomorphic field plots are secondary sampling units. Thus, each 42 m^2 hexagon was divided into four subplots: one center subplot, and three outer subplots, the centers of which are located 3 m from the center at azimuths 30°, 150°, and 270° (Figure 3). In the field, the survey team navigated to the center plot location using a 0.3 m horizontal accuracy EOS Arrow 100 GNSS receiver and used a tape and compass to determine the outer subplot locations. The design of four closely spaced subplots allows for analysis of spatial heterogeneity at multiple levels of proximity.

At each subplot we measured large wood volume, percent organic cover, water depth and velocity, canopy cover, and substrate (Table 2). Velocity was measured at both the surface and 60% depth

to identify differences between surface and deeper water. Water depth, velocity, and canopy cover were measured at the center of the subplot, and were expected to represent the average of the 3.14 m^2 area. Organic cover, large wood, and substrate measurements covered the entire subplot, and were measured via trained visual estimation, diameter and length measurements, and a random 10-clast sample, respectively. We chose these variables because they represent easily measured components of aquatic ecosystems (Baron et al., 2002). For example, canopy cover can provide shade which is often important in maintaining thermal refugia, may limit algal growth (Mosisch et al., 2001), and influences litterfall and particulate organic matter in the stream (Maguire, 1994). Substrate size determines physical habitat available for spawning (Tappel & Bjornn, 1983); large wood provides habitat structures and food resources (e.g., Fausch & Northcote, 1992; Wipfli & Baxter, 2010); organic cover provides energy sources to stream organisms (Tank et al., 2010); and water flow and its variability provide dissolved oxygen, habitat diversity, and connectivity (e.g., Pringle, 2001).

An identical set of measurements was collected at each of the four subplots. However, we slightly modified the field sampling protocol in 2020, adding the large wood measurements in all three of the outer subplots. Previously, these data were only collected in the central subplot (Figure 3, Table 2). At each 1 m radius subplot, we measured canopy cover with a modified 17-point spherical densiometer in each cardinal direction; water depth with an engineer's rule; velocity at the surface and 60% flow depth using a Marsh–McBirney one-
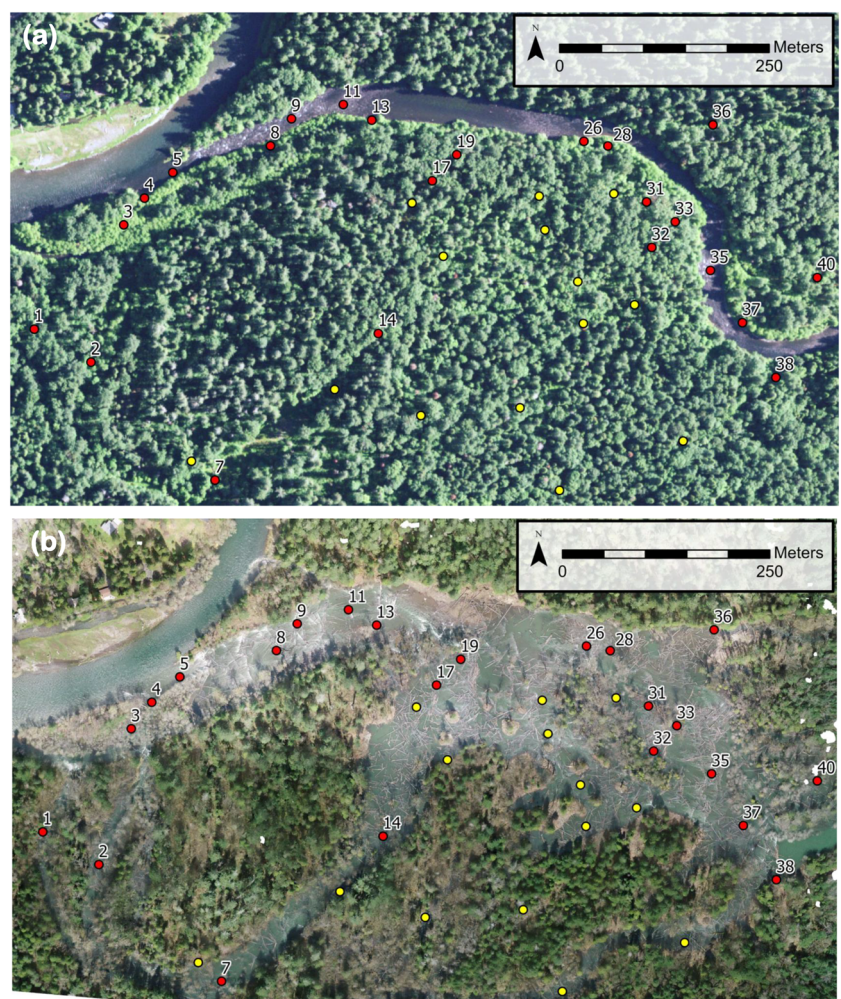

FIGURE 2 (a) Pre-restoration 2016 NAIP imagery with geomorphic plot locations. (b) Drone imagery captured during a high flow event in April 2019 of Phase 1 of the South Fork McKenzie River (Scott, 2019). Geomorphic field plots measured in both 2019 and 2020 are red and labeled with plot numbers. Yellow plots were measured only in 2019 but may be surveyed in future monitoring strategy iterations
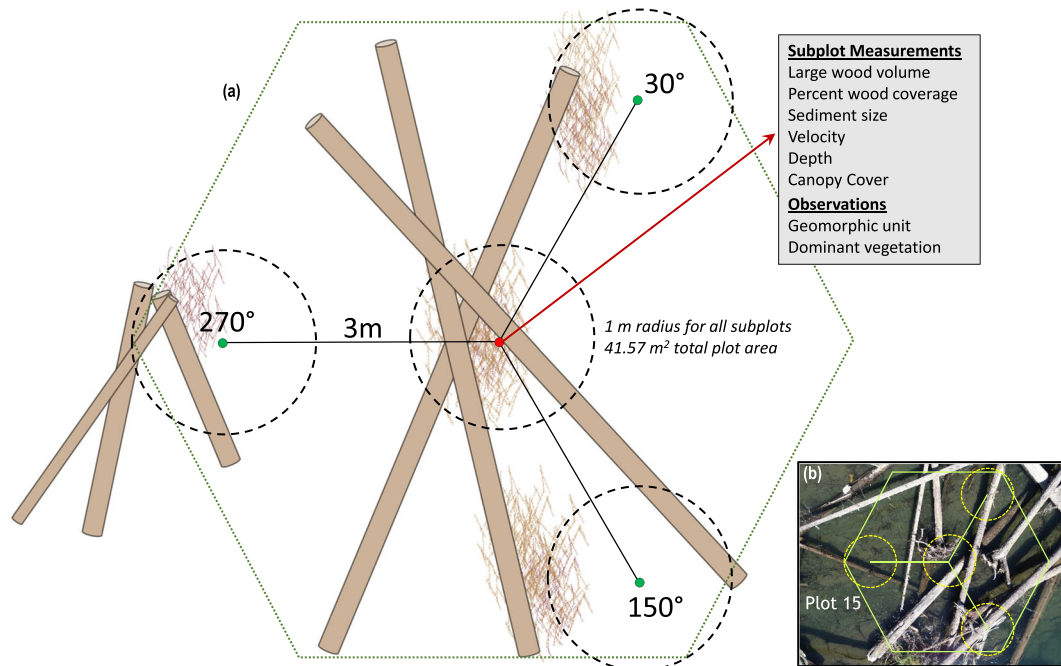
FIGURE 3 (a) Layout of geomorphic field plot. Outer subplots are distributed around the center subplot at 30°, 150°, and 270° azimuths. (b) A photograph example of a geomorphic field plot with overlay of plot design

dimensional (1D) velocimeter; the size of each piece of large wood that intersected the plot, using a metric tape for piece diameter and TruPulse 360° laser range finder for piece length; and sediment size via gravelometer with 10 randomly selected clasts per subplot (Table 2). Because field surveys took place in July–August 2019 and August 31–September 4, 2020, we expect there to be no change in canopy due to seasonal differences.

3.1 | Data analysis

3.1.1 | Quantifying geomorphic change

We used the survey package in R to estimate site-scale means and variances for canopy cover, organic cover, median grain size, water velocity, and water depth that account for our two-stage (plot and subplot) cluster sampling design (Lohr, 1999; Lumley, 2020). Cluster sampling design-based t-tests were used to assess significant differences in site-scale summary statistics. For wood volume, only the center subplots were compared because the outer subplots were not measured in 2019; thus, a paired Welch two sample t-test was used to estimate change in mean wood volume per plot.

Water depth and velocity were scaled according to the discharge on the day they were measured using the equation in Table 3 to account for potential differences due to discharge (discharges averaged 9.3 $m^3 s^{-1}$ during measurements in 2019 and 14.2 $m^3 s^{-1}$ during 2020, Supporting Information Tables S2–S4). We used the Pearson correlation coefficient to evaluate whether wood volume and organic cover were changing as a function of location of plot within the study reach, and an F test to compare variance in velocity.

We used the non-parametric, matched-pairs Wilcoxon Signed Rank Test, adapted for clustered data, to determine significant differences in grain size between the 2 years of measurement. This test was conducted using all the measured sediment clast sizes, with

10 clasts per subplot and totaling 40 clasts per plot and run with the clusrank package in R (Jiang et al., 2017).

We used Gaussian Mixture Modeling with the mclust package in R to separate the sediment distribution for each year into separate fine and coarse distributions (Scrucca et al., 2016). Welch two sample t-tests were performed on the coarse and fine distributions separately to determine significant differences between years. Substrate was also separated into categorical classes of silt, sand, gravel, cobble, and boulder, and frequencies of each class were calculated for each of the 23 plots measured in both years.

3.1.2 | Heterogeneity

Floodplain spatial heterogeneity is well established as an important component of biologically and geomorphically functioning river corridors (e.g., Zeug & Winemiller, 2008; Bellmore et al., 2015; Wohl, 2016; Camara dos Reis et al., 2019). However, methods of measuring floodplain heterogeneity are inconsistent in the literature (Wohl, 2016). We used the intra-class correlation coefficient, also called the intra-cluster correlation coefficient (ICC), to assess the correlation among subplots within a plot compared to the correlation between plots throughout the entire site. We expect subplots within a plot to be highly correlated and we are interested in the magnitude of change in similarity after a year of adjustment. The equation for ICC is from Lohr (1999) and was implemented using the fishmethods package in R (Nelson, 2014, 2019):

$$\text{ICC} = 1 - \frac{M}{M-1} \frac{\text{SSW}}{\text{SSTO}} \qquad (1)$$

where M is the number of secondary sampling units in each primary sampling unit, SSW is the sum of squares within a cluster and SSTO is the sum of squares total. As ICC approaches 1, elements within a

TABLE 2 Measurement methods for on-the-ground plots at South Fork McKenzie River

Category	Location	Measurement technique
Large wood (> 10 cm diameter, > 1 m length)	Center subplot, 2019 All subplots (2020)	• Measure diameter within subplot area of each piece with diameter tape • Measure length with tape or laser range finder
Organic cover: percentage area covered by large wood, fine wood, and particulate organic matter	All four subplots	• Estimate visually *Note: Field technicians must train their eyes on a control area beforehand*
Water depth	All four subplots	• Measure with tape at each subplot center. Note if dry.
Water velocity	All four subplots at surface and 60% depth	• Measure velocity in maximum flow direction with Marsh–McBirney velocimeter
Water temperature	One sensor per plot	• Tie HOBO temperature sensor to log or other stable object at plot center. Take photograph, global positioning system (GPS) point, and location description
Canopy cover	All four subplots	• Average four densiometer readings, one for each cardinal direction
GPS location	All four subplots at center	• Record GPS points within 0.3 m accuracy (used Arrow GNSS receiver)
Sediment	All four subplots	• Measure *b*-axis of 10 randomly selected clasts per subplot with a gravelometer.

cluster are more homogenous and contribute little to the efficiency of the clustered sampling design compared to a simple random sample. Changes in ICC over 2 years are used to assess whether plots are becoming more homogenous with site adjustment. Wood volume is not included in this comparison because wood volume was only measured in the center subplots in 2019 and therefore has only one measurement per plot. We use the cluster-sampling adjusted variance calculated with the survey package in R (Lumley, 2020) to examine differences in entire site scale heterogeneity for each measured variable.

We also used the ICC to assess heterogeneity at the intermediate inter-plot scale. Plots were combined with their nearest neighbor and evaluated as grouped clusters, with a total number of eight combined subplots. From all possible pairs of plots, potential combinations were identified based on minimum distances between plots, and pairs for analysis were chosen based on judgment of similar geomorphic conditions. Five of the 23 plots were left out due to distance of > 100 m away from their nearest neighbor, or due to their nearest neighbors having already been accounted for within a pair of plots, leading to nine pairs input into the ICC calculation.

We recorded the geomorphic unit at each subplot based on our observed surroundings. We then input these field-determined geomorphic units to the Gini–Simpson diversity index to quantify an integral representation of overall site diversity (Simpson, 1949):

$$\text{SIDI} = 1 - \sum_{i=1}^{m} P_i^2 \qquad (2)$$

where P_i is the proportion of the landscape occupied by each patch type. Simpson's diversity index (SIDI) represents the probability that any two plots measured would be different patch types. We intend this to show a simple example of how to use a biological heterogeneity metric in a geomorphic context.

In summary, we used ICC to assess spatial heterogeneity at the intra-plot and intermediate inter-plot scales, variance to assess site inter-plot spatial scales, and SIDI to assess integrated spatial heterogeneity at the site inter-plot scale.

3.1.3 | Evaluation of the monitoring strategy

We used categorical sediment data in a non-parametric difference test, and power analysis to evaluate the number of geomorphic field plots needed to optimize the field monitoring strategy presented here. Due to the size-based categorical nature of the sediment size classes measured in subplots, ordinal logistic regression with a random effect for plot was conducted using the mgcv package in R (Wood, 2011). The random effect accounts for correlation among observations in the same plot. Difference detection for sediment classes relies on a contrast of likelihoods of whether an observation falls within the same category in 2019 versus 2020 and is approximated by a modified Friedman's test. A non-parametric power analysis was conducted by simulating sediment data for an experimental number of plots (*n*) and repeating an ordered logistic regression model fit 100 times for each non-parametric modified Friedman's test of *n* plots for each year. The statistical power (%) at the $p \leq 0.05$ level is the proportion of iterations that detected a significant contrast between 2019 and 2020 data. Data were simulated by random draws of 2019 and 2020 observations, where randomness was weighted by the distribution of the categories for each year. This analysis is expected to be a conservative representation of power because random sampling error was introduced by taking a random draw from the population of the original model's residuals and applying the residual to the simulated observation, thus moving the observation up or down *i* category levels as determined by the randomly drawn residual. Random draw was appropriate because residuals were normally distributed about zero.

TABLE 3 Estimates for the mean values of measured variables 2019–2020 and associated standard error

Variable	2019	2020	Significant change?
Canopy cover (%)	40 ± 6	26 ± 6	Yes ($p < 0.0001$)
Organic cover (%)	20 ± 3	23 ± 4	No ($p = 0.33$)
Wood volume, center subplot (m³)	2.8 ± 0.4	2.4 ± 0.3	No ($p = 0.40$)
Median grain size (mm)	37 ± 8	33 ± 8	No ($p = 0.37$)
Wilcoxon Signed Rank Test			Yes ($p < 0.0001$)
Water velocity at surface (m/s)[a]	0.16 ± 0.04	0.16 ± 0.04	No ($p = 0.98$)
Water velocity at 60% depth (m/s)[a]	0.15 ± 0.04	0.14 ± 0.03	No ($p = 0.67$)
Water depth (cm)[a]	26.4 ± 4.6	23.0 ± 3.8	No ($p = 0.19$)

[a]Water depth and velocity are scaled according to discharge at the time of measurement using $\left(\frac{x}{Q_{survey}}\right) \times Q_{avg}$, where Q_{avg} is the average discharge between the survey times for each measurement. Dry plots are included in parameter estimates for depth and velocity.
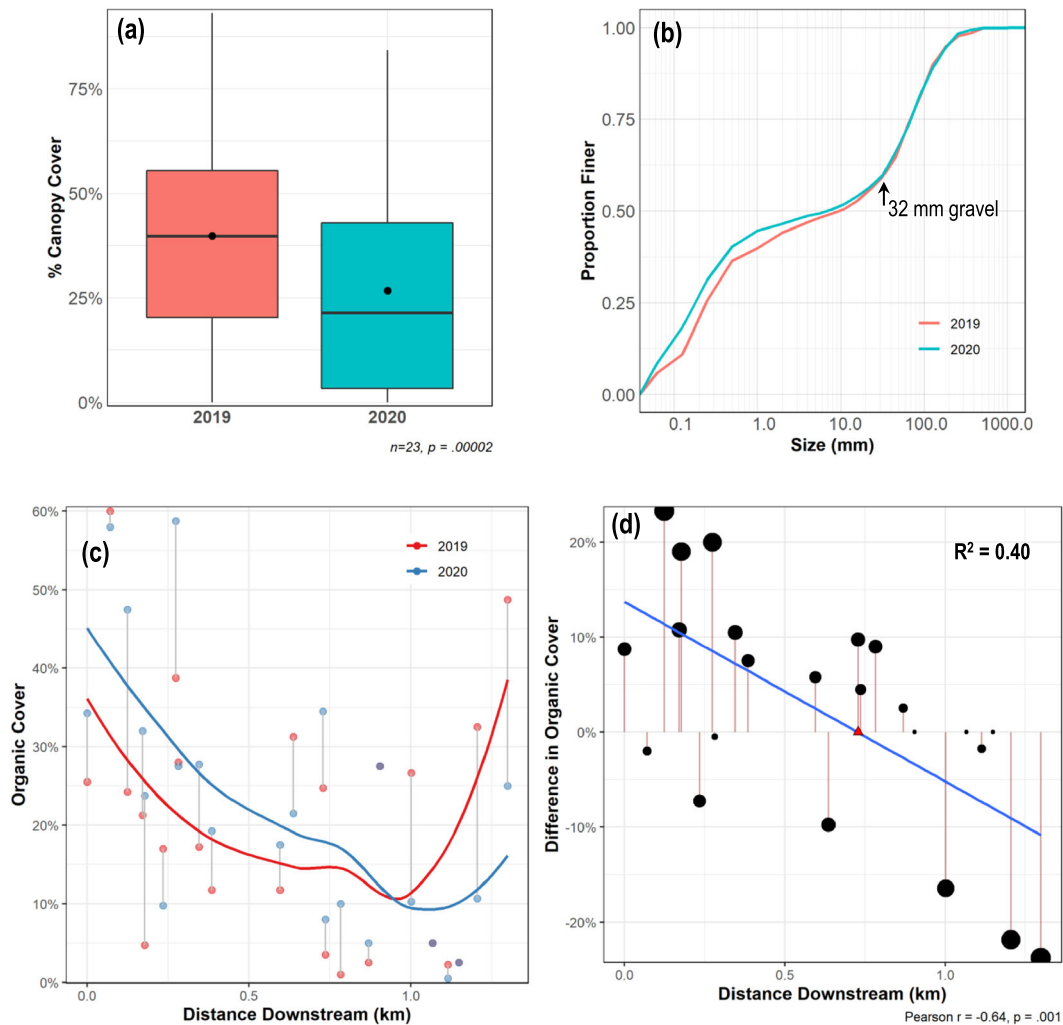

FIGURE 4 (a) Change in canopy cover from 2019 to 2020. Canopy cover was the only significant change with a parametric cluster-sampling adjusted two-sample *t*-test ($p = 1e-5$) and thus is the only variable shown. Dots represent the mean for each year. (b) Empirical cumulative distribution showing grain size converging for 2 years for sizes above 32 mm. Non-parametric tests indicate fining between 2019 and 2020. (c) Organic cover, or percent plot area covered by organic matter, in 2019 and 2020. Colored dots represent 2019 (red) or 2020 (blue) organic cover at each plot, and colored lines show locally weighted smooth (loess) curves of best fit. Vertical lines connect the same plots for different years. (d) Trend in downstream organic cover change. With distance downstream, the change in organic cover decreases ($R^2 = 0.40$, $p = 0.001$). Vertical line segments connect the magnitude of change for each plot to 0, and a red triangle shows the model-predicted value of 0 change in organic cover

4 | RESULTS

We initially present results in the context of overall changes with time in individual variables at the restoration site and then evaluate changes in the three spatial scales of heterogeneity.

4.1 | Geomorphic change

Canopy cover decreased significantly from 2019 to 2020 according to the clustered Welch two-sample *t*-tests (Figure 4a). Aside from the non-parametric test for sediment described later in this section,

no other measured variables experienced statistically significant changes over the two measurement years. However, there was a significant negative correlation between organic cover and distance downstream in 2020 as well as a significant negative correlation between change in organic cover and distance downstream between 2019 and 2020 (Figure 4c,d). With increasing distance downstream, organic cover in 2020 decreased, and the change in organic cover between the 2 years transitioned from positive to negative, indicating that measured locations gained organic material upstream and lost material downstream. Of the 23 plots, 12 experienced a relative increase in organic cover, eight decreased, and three remained unchanged. The positive increases in organic cover occurred within plots upstream of plots 9, 11, 13, and 14, which cluster in longitudinal position near the linear model-estimated value of zero change (728 m, Figure 4d). This location aligns with a downstream slope increase in the path of the historic main channel, observable in post-treatment high flow aerial imagery (Scott, 2019). Due to a limited number of plots in the higher gradient area, we did not observe a significant trend in velocity with downstream distance. This longitudinal position also coincides with the entrance to a previously dry channel that contains plots 7, 2, and 1, which experienced the largest decreases in organic cover. There is no correlation between canopy cover change and distance downstream, nor is there a correlation between canopy cover change and organic cover change.

Results for significant differences in sediment using the non-parametric test were obtained from tests of the total sediment dataset and from the compiled medians of each set of 10 clasts per subplot ($p < 0.001$ for the entire dataset and the dataset of subplot medians). The non-parametric test does detect sufficient evidence to conclude that there is a significant difference in grain size between 2019 and 2020 (Table 3).

Cumulative distribution function (CDF) plots for each year show lower proportions of substrate smaller than 32 mm (coarse gravel and finer) in 2019 compared to 2020 (Figure 4c). Fine sediment increased significantly ($p = 0.01$) in 2020 compared to 2019 when bimodal distributions were split into coarse and fine distributions. When analyzed as categorical classes, a 3% increase of sand was measured in 2020, balanced by a relative decrease in cobbles and boulders (Table S1).

4.2 | Heterogeneity

The ICC increased for all variables in the intra-plot analyses between 2019 and 2020, except for organic cover (Table 4), indicating that canopy cover, substrate, water velocity, and water depth became more spatially homogeneous at the intra-plot scale. This supports our first hypothesis.

Our second hypothesis regarding intermediate-scale inter-plot heterogeneity is partially supported. The ICC for organic cover, sediment size, and water depth decreased from 2019 to 2020, suggesting that the spatial heterogeneity of these variables increased at distances up to 100 m between the paired plots (Table 4). The ICC of the paired plots was smaller than the intra-plot ICC, indicating that among-plot heterogeneity was greater than within-plot heterogeneity in both years for all variables except sediment size in 2019 and organic cover in 2020. For these, heterogeneity is higher when examined at the intra-plot scale.

Site-scale heterogeneity increased for organic cover and sediment size (Table 4). However, confidence intervals for variance estimates all overlapped and thus only show qualitative evidence for trends over the 2 years. SIDI shows an overall decrease in diversity from 0.89 in 2019 to 0.74 in 2020. This number represents the probability that two randomly chosen plots will be different habitat types and depend on similarity of reported geomorphic units during the field surveys. The decrease in overall diversity suggests that the entire restoration reach has also become more spatially homogeneous with time, which contradicts our third hypothesis.

4.3 | Evaluation of the monitoring strategy

We detected fining in categorical sediment classes between 2019 and 2020 ($p = 0.01$). Using the same test over multiple iterations, we found that the non-parametric power analysis with categorical sediment data reaches 80% power at 60 plots (Figure 5). Based on sediment data alone, 60 plots each year are required to ensure > 80% statistical power to detect a change in sediment size. With the current study design of 40 plots, we achieve 67% power to detect differences in substrate classes.

TABLE 4 Intra-class correlation coefficients (ICCs) showing similarity between subplots within a geomorphic plot for 2019 and 2020 at two scales, standard deviation (SD) of measured variables (units in Table 3), Gini–Simpson Diversity Index, and observed trends; plus signs indicate an increase in heterogeneity and minus signs show a decrease during the monitoring period

Variable[a]	10 m intra plot scale			100 m inter-plot scale			Site scale		
	ICC 2019	ICC 2020	Trend	ICC 2019	ICC 2020	Trend	SD 2019	SD 2020	Trend
Canopy cover	0.67	0.89	−	0.49	0.59	−	0.30	0.28	−
Organic cover	0.45	0.28	+	0.40	0.34	+	0.20	0.24	+
Sediment size	0.15	0.32	−	0.27	0.21	+	46	51	+
Water velocity, surface	0.64	0.75	−	0.16	0.27	−	0.22	0.20	−
Water velocity, subsurface	0.63	0.69	−	0.16	0.29	−	0.21	0.18	−
Water depth	0.59	0.67	−	0.22	0.19	+	26	21	−
Gini–Simpson Diversity Index							0.89	0.74	−

[a]Wood volume is not included due to the single sample per plot in 2019.
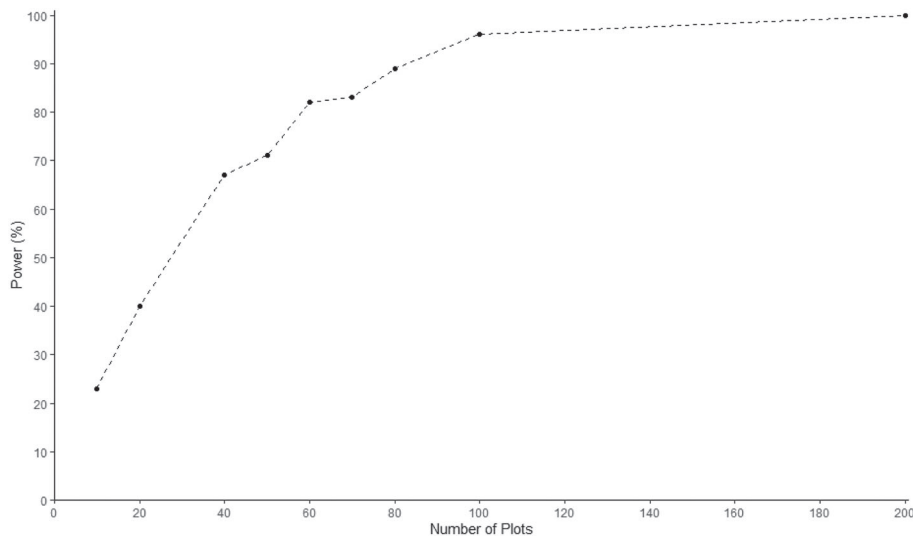
FIGURE 5   Results of non-parametric power analysis with 100 iterations of a model fit to categorical sediment data

5 | DISCUSSION

Two years of data from the geomorphic plot monitoring design allowed us to assess site adjustments immediately after the restoration was completed and to evaluate the monitoring strategy and its efficiency.

5.1 | Geomorphic change and connectivity

Between 2019 and 2020 we observed a 35% loss of tree canopy cover. Surveys were completed in July–August 2019 and August 31–September 4, 2020, so canopy cover decrease due to seasonal change alone is unlikely. We did observe many dead trees as well as many newly toppled trees in 2020, which likely explained the loss of canopy cover. There are multiple potential causes. Channel filling raised water levels across the entire floodplain of the SFMR, including persistent rises in the water table and flooding in many areas, killing many large trees. Also, large areas of the site were opened during the restoration, leaving remaining trees more exposed to the wind. Finally, flooding and high water tables might have softened the soils so that trees were less wind-firm after restoration. In most streams, newly recruited large wood can foster feedbacks, increasing sediment deposition and channel–floodplain connectivity (Collins et al., 2012; Sear et al., 2010), but the number of trees that fell between 2019 and 2020 was small relative to the thousands of large wood pieces added during the restoration, so we expect newly recruited wood had little impact. This is supported by our plot measurements which did not show a significant change in large wood volume or organic cover when averaged across the entire site. It is likely, however, that these losses in canopy cover led to less shade, which could increase primary production of algae, potentially enhancing food web richness and complexity (e.g., McNeely et al., 2007).

Coarse particulate organic matter (CPOM) can be a critical foundation to the foodweb, supporting primary consumers (Tank et al., 2010). The SFMR is a large, poorly shaded river, and the restoration greatly expanded the wetted area and perhaps changed the relative importance of allochthonous versus autochthonous CPOM. However, we see strong changes in organic cover with flow distance through the restoration site. Our data suggest that CPOM is efficiently trapped in the upper portion of the study area but lost in the lower portion of the study area. Between construction in 2018, and consecutive years of measurement in 2019 and 2020, organic material deposited before restoration on dry forest floor was inundated, reworked, and transported, especially in the reactivated secondary channel in the southern portion of the restoration site. Longitudinal connectivity of CPOM has thus decreased within the upstream portion of the study area and increased in the downstream portion. The explanation for this difference in CPOM retention between the upstream and downstream portions of the study area is not known but could involve the steeper gradient of the downstream portion or the more efficient transport of CPOM within the reactivated secondary channel in the downstream portion.

We do not see a pattern of fining substrate similar to that of accumulating organic cover at upstream plots. Organic material transported from upstream, especially material mobilized by upstream restoration, was likely trapped at the surface by placed large wood pieces and constructed log jams, while fine sediment carried in suspension downstream is distributed throughout the site. Substrate fining over 2 years since construction aligns with the goal of providing more suitable habitat for fish. Salmonids require gravel for rearing and spawning (Keeley & Slaney, 1996). Although the proportion of gravels did not significantly increase, the proportion of gravel in both years is higher than the proportion of cobbles and boulders, providing more spawning opportunity than the primarily boulder-bedded condition prior to restoration. We assume that the increase in sand is temporary and associated with disturbance from restoration activities upstream, based on the increased sand proportion, our field observations of Phase I during upstream construction, and direct observation of construction activity in Phase II. In a connectivity context, longitudinal connectivity of fine sediment has decreased, allowing local deposition of fine sediment and creating spawning habitat.

5.2 | Heterogeneity and connectivity

ICCs with intra-plot and intermediate-scale inter-plot data reveal changes in spatial heterogeneity and provide evidence that, at a scale of tens of meters, habitat is stabilizing in a pattern that reflects local-scale controls. The channel restoration and regrading of the valley

floor by heavy equipment destroyed the previous armor layer and fill materials mixed deeper sediment layers and floodplain surface sediment so that the as-built restored surface was much finer textured. The restoration was completed in late summer of 2018 and our first post-restoration measurements were collected in 2019, after winter high flows had already started reworking the sediment. Local processes have continued to rework this sediment and our plot data reflect the changes that occurred between 2019 and 2020.

Initial disturbance via construction and rewatering of the floodplain also altered the boundaries of dry forest and fluvial process domains. Heterogeneity decreased at the intra-plot scale for all the metrics we measured except organic cover. At the intermediate-scale, heterogeneity increased for organic cover, substrate, and water depth. Organic cover and substrate also had increased variance when calculated for the entire site. These increases in diversity reflect promising trends in local-scale habitat availability for organisms throughout multiple life cycle stages. At the site-scale, measured by SIDI, we recorded an overall decrease in heterogeneity. Some geomorphic units, such as flooded forest and flooded meadow, may change to different geomorphic units as inundated vegetation dies, sediment is deposited, and wood aggregates into log jams, forming islands and more secondary channels. In contrast, we expect dry areas outside of the wetted channel study area to become more diverse as the elevated water table, and therefore increased subsurface hydrologic connectivity, interact with topographic lows in the forested floodplain and form wetlands.

Qualitative observations suggest that restoration activities at the study site have altered connectivity. The direct addition of substantial large wood and the resulting formation of an anastomosing channel planform have reduced longitudinal connectivity within the channel. Removal of artificial levees and regrading of channel and floodplain surfaces have increased lateral connectivity. The combined effects of more in-channel obstructions from large wood and the greater inundated surface area have likely increased vertical connectivity. These changes to 3D connectivity better represent natural conditions in river corridors of this region prior to intensive human alteration starting in the 19th century (Collins & Montgomery, 2002; Sedell & Froggatt, 1984).

5.3 | Evaluation of the monitoring strategy

The monitoring protocols we developed for the SFMR were intended to serve as a pilot that could be modified to better capture geomorphic change and complexity and to allow monitoring of other ecological and remotely sensed metrics. Having evaluated the first set of monitoring results using these protocols, we consider it useful to present the results of the initial monitoring protocol and our recommended changes because Stage 0 restoration is becoming increasingly common and other investigators may face the same uncertainties and period of "experimentation" in designing monitoring protocols.

The described monitoring approach is necessary to inform adaptive management that may influence future intervention on the site and future implementation of the Stage 0 restoration approach in other locations. Additionally, monitoring of this nature facilitates an assessment of post-restoration site evolution, and potentially pre- to post-restoration change if timed appropriately. Cost and time-feasible monitoring allows documentation of short- and long-term temporal change of multiple aspects (e.g., wood retention, sediment size, channel planform, etc.) of the post-restoration site. Stage 0 restoration produces a spatially extensive post-restoration site that is much more complex than pre-restoration conditions and can be more complex than applications of previous restoration styles (e.g., Rosgen), and so requires a monitoring approach that is more capable of capturing the spatio-temporal heterogeneity of these different aspects than more conventional approaches designed around single threaded stream systems. We recognize that the monitoring approach presented here has room for improvement, but think it is important to share with the broader scientific community in effort to begin the process of establishing best practices for Stage 0 restoration monitoring through replication, repetition, expansion to new sites and regions, and inspiration of new methods.

This protocol in particular is designed to complement a suite of remote sensing methods where similar measurements can be obtained from UAVs (i.e., drones) and subsequently calibrated using field measurements. Once calibrated, future iterations of remote monitoring can be implemented in a low-cost, time-efficient manner with seasonal or annual frequency adapted to local needs. In the meantime, field-based monitoring methods that aim to eliminate bias and capture spatial heterogeneity are useful in the initial evaluation of large-scale projects such as the one described at SFMR.

Based on our power analysis and the results from the ICC analysis, we suggest that simple random sampling might provide a better alternative than the two-stage cluster sampling design we employed here. Having a single plot (or a single subplot within a plot) is reasonable because of the relative homogeneity we observed within clusters when compared to heterogeneity throughout the site. This modification would also increase statistical power for determining changes through time, because, for the same effort, field crews could substantially increase the number of plots sampled. For example, a sample size of $n = 60$ plots with only one subplot per plot would provide a balance of statistical viability and field feasibility. However, the tradeoff for replacing clustered plots with single subplots is a limited ability to capture small-scale heterogeneity.

Future iterations of field plots at the SFMR could incorporate the following changes to address potential shortcomings in the design: (1) a larger subset, or the entire sample size, of the original 40 plots can be measured in order to increase statistical power, and if possible more plots will be added; (2) flow direction can be added to the hydraulic measurements to gain insight about primary flow paths and potential for incision and island formation; and (3) geomorphic units can be selected from a preexisting list to better estimate large-scale heterogeneity. We also find it appropriate to move forward with measurements of only surface velocity due to the large sample size ($n = 184$) used to establish the linear regression of surface velocity and velocity at 60% depth. Use of surface velocity measurements can be used directly to calibrate estimated velocity from video footage, and the linear regression can be used to predict velocity deeper in the water column.

5.4 | Long-term channel adjustment

In designing this study, we were less motivated by pre- and post-restoration assessment, and more motivated to establish a method to

capture post-restoration baseline conditions in the earliest stages of adjustment toward a retentive and complex floodplain. Acquisition of pre-restoration and reference site plot data of the type described here would greatly strengthen the ability to assess the effects of restoration. We anticipate subsequent uses of this strategy at the SFMR to assess resilience to current and future disturbances, such as forest fire. Within 1 week after 2020 field measurements, the Holiday Farm Fire burned over 700 km^2 in the McKenzie River watershed, including the SFMR Floodplain Restoration Project outlined in this study.

We have described the short-term, small-scale river adjustments that occur immediately after construction associated with restoration (Erwin et al., 2016). Larger-scale progressive adjustments over many years could maintain a dynamically stable channel or could result in changes indicating that a channel was not properly designed for the flow regime and sediment supply (Brierley & Fryirs, 2016; Erwin et al., 2016). At the SFMR site, we assume that spatial heterogeneity will continue to decrease within plots but increase between plots and at the scale of the entire site as a result of gradual redistribution of large wood by higher flows and associated spatial organization of hydraulics and sediment transport. The timespan over which these adjustments will occur largely depends on external disturbances including (i) high flows that influence wood transport and deposition and (ii) wildfires that influence wood recruitment and retention. Because the site is below a dam and has regulated flows, redistribution of wood will likely occur more slowly than under a natural flow regime. The frequency and severity of wildfires, however, seem to be increasing with climate warming, suggesting an acceleration of wildfire-induced wood dynamics. In the best-case scenario, the river corridor will continue to adjust to a multithread channel with high lateral and vertical hydrologic connectivity, limited longitudinal sediment connectivity, and high habitat diversity. In the worst-case scenario(s), (i) the introduced large wood would all be transported downstream and the restoration-induced heterogeneity would be lost, (ii) insufficient flow would result in gradual filling and terrestrialization of newly created secondary channels, or (iii) insufficient sediment supply would limit retention of substrate grain sizes suitable for salmon spawning. We consider these scenarios unlikely because of (i) limited peak flows downstream from the dam, (ii) sufficient flow to maintain some sediment transport and a multithread channel planform, and (iii) continuing introduction of finer sediments through lateral channel movement.

Process-based restoration is most likely to prove successful if matched with process-based management that is informed through spatially representative monitoring for at least several years post-restoration. Opportunities for process-based management at the SFMR may be relatively limited by the large dam and flood-control reservoir located only a few kilometers upstream. Thus, the degree to which historic natural processes can be restored will depend on the degree to which sediment augmentation and environmental flows can also be restored (Beechie et al., 2010; Poff et al., 1997). However, within the human-generated constraints, the project implementation at the SFMR utilizes maximum valley space and available sediment, wood, and water resources to create a more heterogeneous and laterally connected river corridor. The restored configuration of the river corridor is likely to be persistent and resilient to diverse disturbances because of the higher floodplain water table and surface inundation (resilient to wildfire and drought) and the much greater cross-sectional area and hydraulic roughness of channels (resilient to floods). Analogous to dam removal projects and associated studies, restoration efforts of this type and scale should be targets for scientific research (Bellmore et al., 2017). Restoration toward Stage 0 conditions offers a unique opportunity to adapt post-project management efforts with modern monitoring techniques.

6 | CONCLUSION

The monitoring strategy described here used a randomized two-stage cluster sampling design to ensure unbiased location of study plots while also maximizing observation of habitat types across the site. Habitat complexity increases potential for biotic diversity and resilience (Bellmore et al., 2015; Uno & Pneh, 2020), so geomorphic monitoring should be paired with biotic sampling and water quality monitoring to assess holistic success of stream restoration project designs. The geomorphic plot design is matched with a suite of additional monitoring efforts at the study site that are not discussed in this article but include biotic counts, a food web analysis, and seasonal remote sensing data collection.

Our conclusions that spatial heterogeneity is increasing at intermediate spatial scales, but not within individual plots or across the entire restoration site, are limited by the lack of pre-restoration data and by the short timeframe (2 years) of monitoring. Qualitative assessments of site condition suggest an increase in intermediate- and site-scale spatial heterogeneity relative to conditions prior to restoration and we expect these trends to continue with time. Decreased longitudinal connectivity and increased lateral and vertical connectivity have likely improved floodplain function and habitat conditions since restoration and we expect these trends to continue.

AUTHOR CONTRIBUTIONS
Sarah Hinshaw collected the data, analyzed the data, wrote the initial draft, and edited the manuscript. Ellen Wohl reviewed and edited the manuscript, and offered conceptual knowledge that contributed to interpretations of the findings. Jonathan D. Burnett and Steve Wondzell conceptualized the initial research motivations and acquired funding. Jonathan D. Burnett and Sarah Hinshaw developed the methodology, and Jonathan Burnett analyzed a portion of the data. Ellen Wohl, Jonathan Burnett, and Steve Wondzell offered supervision during the data collection and writing processes.

DATA AVAILABILITY STATEMENT
Data can be made available to the public in the supplementary online information.

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