Riverscape mapping and hyperscale analysis of the sediment links concept

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ABSTRACT

Longitudinal patterns in channel complexity play an important role in our understanding of fluvial systems. The spatial scales over which external controls such as tributaries, landslides and debris flows, alter channel form and influence the broader basin-wide trends in channel form. Channel complexity across a basin has important implications for how we conceptualize basin-wide trends in channel form such as downstream hydraulic geometry and the sediment links concept. This study takes a hyperscale approach to mapping channel morphology across 200 km of the Rogue River in Southwest Oregon - that is high-resolution data over large spatial extents allowing analysis to be conducted simultaneously at and across multiple spatial scales. Using a sUAS and digital photosieving we measured gravels on exposed gravel bars for the study area. We also measured thalweg depth in the field using a singlebeam echo sounder. Slope and channel width were derived using existing GIS datasets. We used these data to create a hyperscale view of the Rogue River examining the impact of tributary and non-tributary sediment links. We used a statistical approach to determine if changes in channel form were truly unique in the context of larger-scale channel variability. Our findings show inconsistent statistical significance of the identified lateral sediment sources (LSS) between variables - e.g. a statistically significant change in slope would not necessarily correlate with an increase in unit stream power. There were many LSS which triggered statistically significant changes to channel form. We used hyperscale graphs to reveal the complexity and spatial trends associated with the relationships between a given sediment link and channel form. The results of this study illustrate the complexity with which sediment links impact channel form and the distances below a given sediment link that a detectable signal exists, if a detectable signal exists.

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1. Introduction

Fluvial geomorphology has a long history of using broad conceptual frameworks to characterize watershed scale trends such as downstream hydraulic geometry (Leopold and Maddock, 1953), the river continuum concept (Vanstone et al., 1980), channel-reach morphology (Montgomery and Buffington, 1997) and the sediment links concept (Rice, 1998). As described by Fonstad and Marcus (2010) and Carbonneau et al. (2012), increasing data resolution continues to illustrate a far more complex geomorphic and hydrologic landscape. Despite this, gradual, basin-wide trends continue to be referenced as the “expected” pattern against which morphologic alterations are judged. The Rosgen classification scheme (Rosgen, 1994), a common basis for guiding fluvial restoration projects, relies on smoothly varying trends in channel form. Many landscape evolution models also rely on smoothly varying trends. This approach can have high accuracy for very generalized basin-wide descriptions of channel form in fine-grained alluvial valleys where autogenic processes dominate and external controls are minimal. However, these generalized trends do not accurately predict the spatial heterogeneity seen across the diversity of channel forms in existence at the resolution we can now quantify (Rice et al., 2001; Fonstad and Marcus, 2010). What is more frequently observed from measurements of channel width, depth, and particle size distribution is a far noisier signal. Local variability in channel form dominates at small scales, making the gradual, longitudinal, basin-wide trends more complicated than watershed scale conceptual models predict.

Characterizations such as channel-reach morphology (Montgomery and Buffington, 1997) and the river continuum concept (Vanstone et al., 1980) seek to address the heterogeneous nature of rivers by identifying geomorphically unique sections within the broader river. However, within these sections there remains the idealized downstream hydraulic geometry relation-
ships. The sediment links concept (Rice, 1998; Rice and Church, 1998) is a variation on downstream hydraulic geometry (Leopold and Maddock, 1953) that does not rely on characterizing the channel type morphology as a function of its distance from the basin divide. Instead of a continuous downstream fining from the upper to lower watershed, the sediment links concept suggests that the pattern of downstream fining may be periodically interrupted by local sources of new material (e.g., an underlying glacial deposit, landslides, bank failure) or discharge from tributaries referred to as lateral sediment sources (LSS). The sediment links concept does not suggest that all LSS will trigger discontinuity in trends of downstream hydraulic geometry. Instead, it seeks to identify basic characteristics that may offer predictive capabilities for channel discontinuities. There are two processes by which new material may cause an interruption in the process of downstream fining: (1) the new material deposited into the channel is of a sufficient size as to disrupt the pattern of downstream fining in the mainstem (e.g., it is larger than that in the mainstem). The addition of new material could be infrequent but deliver large quantities (e.g., landslide) or is delivered with a frequency such that it is a continuous source that is constantly delivering new material (e.g., tributaries or bank failure) or (2) in the case of a tributary, it has a sufficient discharge such that the transport capacity downstream of the confluence increases with the additional discharge. The increase in transport capacity is such that clast sizes that could not be transported upstream of the confluence are mobilized, leaving larger clasts, relative to those upstream, in the channel. Either scenario will result in an increase in gravel sizes at the confluence and potentially an increase in slope locally (Leopold et al., 1992; Knighton, 1998).

A primary challenge in reconciling basin-wide conceptual river models and more quantitative, location-specific observations is the fundamental disparity in the spatial extent and resolution of the observation. As the spatial scale of observation increases, local variability in channel morphology is missed or “smoothed out” and generalized longitudinal trends become more obvious. However, as spatial scales decrease to the scale of individual gravels and near-continuous width and depth measurements, local channel heterogeneity makes large-scale trends less and less apparent. A growing body of literature establishes the importance of the conceptual framework of riverscapes as holistic systems that exist simultaneously at scales from microhabitat to watershed (Fausch et al., 2002; Thorp et al., 2006, 2010; Carbonneau et al., 2012). Hyperscale analysis requires intensive, high-resolution data over large spatial extents so that analysis can be conducted simultaneously and across multiple spatial scales (Fonstad and Marcus, 2010).

Structure-from-Motion (SfM) and digital photosieving are tools that allow grain-by-grain measurement for entire gravel bars (Buscombe et al., 2010; Millidine et al., 2010; Chang and Chung, 2012; Langhammer et al., 2017; Woodget et al., 2018). This approach to data collection allows us to more efficiently characterize longitudinal trends in gravel sizes for all gravel bars in the study watershed. If one travels via the river, it is possible to sample gravel bars continuously rather than being limited to those that have road access, providing the opportunity to create a more complete picture of the variations in sediment and local morphology. We can integrate field data with high-resolution remote sensing datasets to create the spatially extensive and high-resolution data necessary to address questions concerning the longitudinal variation in width, depth, slope and the spatial pattern of sediment sizes within and between gravel bars. Observing patterns across spatial scales is not possible with discrete data sets. Hyperscale data are critical to examining the conceptual models that have been a foundation of fluvial geomorphology for decades to evaluate under what conditions they still provide useful insight into the process-form relationship.

This study integrates SfM, digital photosieving techniques, depth measured in the field, and remote sensing imagery to create a hyperscale data set for the Rogue River, a gravel bed river in the Pacific Northwest, USA. We consider all potential sediment sources in the study area, recognizing that some LSS may not create a quantifiable signal. In the context of the sediment links concept, we examine whether and how LSS and basin geology control gravel sizes and channel form by addressing the fundamental research question: How do tributary and hillslope sediment contributions influence channel form and particle size distributions? Specifically, we evaluate the following hypotheses:

- (H1) Tributaries will result in an increased gravel size at their confluence with the Rogue River.
- (H2) Non-tributary sediment sources will produce larger gravel sizes where they intersect the proximal channel compared with those gravel bars upstream.
- (H3) Tributary sediment sources will result in an increase in channel width and hillslope processes (e.g., debris flows and landslides) will trigger a decrease in channel width.
- (H4) Tributary and non-tributary sediment sources will generate an increase in slope.
- (H5) Channel depth will decrease locally at tributary and non-tributary sediment sources.

Our hypotheses come from previous studies and our understanding of the process-form relationship. The hypotheses concerning the size of gravels at LSS (H1 and H2) come from Rice (1998), with the understanding that not all tributaries will trigger morphologic discontinuities. Our prediction for the behavior of channel width (H3) derive from a process-form based approach. An increase in discharge at confluentes would trigger increased erosivity within the active channel suggesting an increase in width. The formation of small alluvial fans in the main stem decreases channel depth and may also lead to an increase in channel width (Leopold et al., 1992; Knighton, 1998). In contrast, the addition of large volumes of immobile cullum at hillslope derived sediment sources would likely decrease channel width. Our final hypotheses regarding slope and depth (H4 and H5) also follow from a process-form understanding. The accumulation of alluvial and colluvial material that are not transported downstream will eventually raise the elevation of the channel bottom, creating a decrease in channel depth (H5) and an increase in slope (H4).

How, and at what spatial scales we characterize longitudinal trends in channel form is important for channel classification, hydraulic modeling and stream restoration. If too large a spatial scale is characterized, important complexity is lost. If the scale is too fine, it becomes challenging to relate longitudinal connectivity to morphologic connectivity. This research seeks to improve our understanding across spatial scales of the impact of LSS as controls on channel form.

2. Study area

To accurately assess the impact of tributary and non-tributary sediment sources on a fluvial system requires a river with a number of tributaries and some knowledge of where hillslope activity has impacted the active channel. The Rogue River is a characteristic gravel bed river in the Pacific Northwest, USA (Fig. 1) and flows through alluvial, metamorphic and sedimentary provinces (Fig. 2). Frequent gravel bars throughout the study area allowed us to map longitudinal trends in gravel sizes. The study area is comprised of an upper alluvial section with frequent gravel bars that flows over
Fig. 1. Rogue River watershed location in Oregon (upper left) and a detailed map of the study area. Gravel bar sample locations, tributaries and Grants Pass are also labeled. The GIS portion of the analysis is comprised of the darker blue streamline. Field work is approximated by the location of gravel bar samples.

Fig. 2. General geologic units of the Rogue River study area and the locations of gravel bars (circles), tributaries and non-tributary sediment sources (triangles) (Archuleta et al., 2017a).
mobile and cemented gravels with occasional bedrock outcrops. The lower portion is characterized by geologic lateral confinement with frequent bedrock outcrops controlling slope. Given the presence of in-channel bedrock and coarse gravels the majority of the study area is likely supply-limited, having the stream competence to move more material than is available (Jones et al., 2011). Tributary and non-tributary sediment sources occur throughout the study area, allowing us to examine their relationship with channel form in the context of downstream hydraulic geometry and changing geologic landscape.

The watershed is 13,350 km² and made up of four geologic provinces: The High Cascades (14%), the Western Cascades (16%), the Coast Range (1%) and the Klamath Mountains (56%) (Jones et al., 2011). Fig. 2 is a geologic map of the study area. Much of the broad valley floor the Rogue River flows through is comprised of Quaternary sedimentary deposits and landslides. In many places it is broken up by a number of metamorphosed and intruded igneous plutons, dikes and sills. Upstream of the old Gold Ray Dam site is an area of lacustrine deposits from the former Gold Ray dam roughly two river kilometers (RKM) long. The farther west one travels in the watershed, the less deformed and softer the Klamath terrain becomes, which suggests the potential for the delivery of more material from LSS.

In the eastern portion of the study area, the Rogue River valley is predominate alluvial and is bordered by harder volcanic and metamorphosed rocks. Downstream of the confluence with the Applegate River, the broad alluvial valley begins to narrow and the Rogue River becomes increasingly confined by ophiolite and sedimentary lithologies. The spatially varying river valley context exerts large-scale controls on channel morphology with important implications for watershed scale trends. There are eleven perennial streams in the study area, seven of which we consider large tributaries: the Illinois River (2550 km²), the Applegate River (1994 km²), Bear Creek (930 km²), Little Butte Creek (917 km²), Evans Creek (580 km²), Grave Creek (422 km²), and Jump-off Joe Creek (282 km²). There are an additional four small tributaries: Reece Creek (55 km²), Mule Creek (77 km²), Snider Creek (60.6 km²), and Galice Creek (61.9 km²). Tributaries entering the Rogue River east of the Applegate River (Evans Creek, Bear Creek, Snider Creek, and Little Butte Creek) originate in the older, more heavily metamorphosed portion of the Klamath Mountains suggesting less abrasion and therefore larger gravels.

From field observations and GIS we mapped fourteen non-tributary sediment sources including landslides, active bank erosion, and leftover hydraulic mining debris. All non-tributary LSS that intersect the active channel were included in this analysis. Channel forming flows are generated from winter frontal systems with base flows sustained by groundwater contributions from the upper Rogue River basin, supplemented by the only remaining dam, the William L. Jess Dam located 40 km upstream of the study area (Jones et al., 2011).

3. Methods

Downstream hydraulic geometry (Leopold and Maddock, 1953), the river continuum concept (Vannote et al., 1980) and channel reach morphology (Montgomery and Buffington, 1997) all suggest certain downstream trends in channel form, drawing large-scale trends from a series of discrete data points. To accurately improve our understanding of the heterogeneity in channel morphology requires a near-continuous longitudinal dataset. The goals of our field work were to collect the data necessary for computing particle size distributions and channel depth, and to make observations of unmapped, non-tributary sediment sources. We used a combination of remote sensing and field data to plot longitudinal patterns in channel form. Combined with gravel size measurements of all exposed gravel bars, we can examine the role LSS have on channel morphology and sediment size distribution across spatial scales.

3.1. Methodological approach

This study integrated aerial imagery, remote sensing, and field-based data. We used 10-m National Elevation Dataset (NED) and 1.2-m LiDAR data, aerial imagery from the National Agriculture Imagery Program (NAIP), soil maps from the U.S. Department of Agriculture (USDA), geologic maps from the Oregon Department of Geology and Mineral industries (DOGAMI) and 100-yr flood inundation maps from the Federal Emergency Management Agency (FEMA) (Archuleta et al., 2017a). We used these GIS data to digitize the active channel margin, extract channel slope, estimate the 2-yr return interval discharge and compute unit stream power. We collected aerial imagery using a DJI Phantom 3 UAV and a Nikon D5200 digital SLR camera. Depth data was collected using a SeaFloor System Hydrolite-TM single beam echo sounder paired with a Trimble Geo7X handheld data collector.

3.2. GIS processing

This study requires high resolution, spatially extensive data of multiple hydrogeomorphic variables to address the research question. Creating continuous maps of channel width and slope requires an approach that can be implemented at a basin-wide scale using all available data. GIS analysis for this study begins at the town of Shady Cove and ends downstream of the confluence with the Illinois River. Owing to the spacing of river access sites, field work began at Touvelle State Park near White City and ends at Illahe, upstream of the confluence with the Illinois River. Mapping of the active channel, corresponding with the bankfull width, was based predominately on NAIP imagery, relying on the presence of active, unvegetated gravels and the type and presence of vegetation along the channel margin. We supplemented this with breaks in bank slope from LiDAR and soils data, including those characterized by the USDA as river wash (Harrelson et al., 1994). We used the FEMA floodplain maps as a reference point. At no point does the bankfull channel margin cross the 100-yr floodplain, but in certain confined reaches they follow the same path. Distance downstream and channel width were derived from the digitized bankfull channel margin shapefile, converted to a four meter raster image, using the MATLAB program ChanGeom V0.3 (Fisher et al., 2012, 2013). ChanGeom computes a cumulative distance downstream based on pixel size centered within the rasterized active channel shapefile. Channel width is computed perpendicular to that center line at each pixel. The output of the ChanGeom program is a channel centerline and width measurement at every pixel. We extracted elevation at each centerline point from the NED data that we used to compute slope using a moving window. It is important that this window be large enough to capture elevation change in low-slope reaches without being so large as to smooth over small ripples and rapids. We built a semi-variogram to determine at what distance adjacent elevation values were no longer related, termed the range of the semi-variogram. This distance is derived from the range of the semi-variogram for elevation, where distances beyond 40 m no longer see spatial autocorrelation. We therefore used a 40-m window to compute slope. From our field observations we suspected that changes in slope, as a result of LSS, may be smoothed over given the window size for our slope computation and the subtle change in elevation at some ripples. Therefore, we digitized all named ripples and rapids in the study area based on Leidecker’s (2015) river guide book, which provides an independent source for the identification of channel slope breaks.
To identify non-tributary sediment sources, we used a combination of previously mapped landslides from DOGAMI and field observations. GIS mapped landslides were included only where they intersected the active channel. We added unmapped landslides and debris flows from field observations where hillslope scars were present and colluvium was noted within the bankfull channel. An area with eroding mining debris (RMK 113) and the two kilometers of bank erosion (RMK 50) through the lacustrine deposits upstream of the old Gold Ray Dam site also came from field observations.

There are five USGS discharge gates on the Rogue River, two of which are within the study area, two upstream of the study area, and one just downstream of the study area. We used the log-Pearson Type III method to estimate the 2-yr return interval flood for all five gates (Bedient and Huber, 2002). We built a second-degree polynomial regression equation where drainage area at each gate is used to estimate the 2-yr return interval discharge at that gate \( R^2 = 0.99 \). For this study, we take the 2-yr flood event to be the channel forming flow – that is, the flow that channel width, depth and gravel sizes are adjusted to (Wolman and Miller, 1960; Knighton, 1998; Stock and Montgomery, 1999). From the ten-meter NED data we computed a flow accumulation raster that we applied the polynomial equation to, generating a computed discharge at every pixel along the channel based on the size of the contributing area at that pixel. From the above variables we computed unit stream power \( \omega \) to provide a physically-based estimate of sediment competence (Bagnold, 1966; Phillips, 1989), where \( \omega \) represents unit stream power, \( p \) is the density of water, \( g \) is the gravitational constant, \( Q \) is discharge, \( S \) is slope and \( W \) is channel width.

\[
\omega = \frac{pQgS}{W}
\]  

(1)

The result of the GIS data processing is a spatial dataset with a point every four meters containing the northing and easting, distance downstream (km), elevation (m), channel width (m), channel slope (m/m), \( Q \), discharge (m³/s) and unit stream power (W/m²).

### 3.3. Field data

Field work took place over nine days, in three trips, traveling a total of 200 km of the Rogue River. We traveled during dam-controlled summer low flows of approximately 32.5 m³/s (95% exceedance) to maximize the number and size of exposed gravel bars. We stopped at each gravel bar and photographed all unvegetated portions of the gravel bar that we used to generate orthophotographs. Every attempt was made to travel in the channel thalweg so that depth data from the echo sounder represented the deepest point in the channel. However, this was not always possible because of rapids and other obstacles. The echo sounder and Geo7X recorded a point every five seconds comprised of channel depth, northing, easting, and elevation. Initial study design anticipated using the field collected GPS elevation data for water surface slope and channel elevation maps, but poor precision in the Z direction (i.e., with elevation points changing by as many as 100 m between adjacent measurements) made this impossible. Depth measurements could not be accurately tied to an elevation datum; therefore, depth is a relative depth model (RDM). We can, however, still use the RDM to address our hypothesis that depth will decrease at LSS (H5). The RDM still illustrates the distinction of pool-riffle sequences in the bathymetry even without being able to tie the channel bottom to an absolute elevation above sea level. The lack of elevation datum also means that it impossible to compute water surface elevations, and therefore slope, based on the depth data.

Airspace and land management allow for the flight of UAVs from the beginning of the field work portion of the study area at Touvelle State Park to the confluence of Grave Creek. For all exposed gravel bars in this reach, aerial imagery was collected using a DJI Phantom 3 UAV. From Grave Creek to the end of the study area at Illahee, the Rogue River flows through a designated Wild and Scenic River corridor that prohibits UAV operation. For gravel bars within this reach, we walked the bars taking photographs with a Nikon D5200 DSLR on a telescoping pole.

All gravel bars were photographed from heights between four and ten meters above ground level, for both photographic platforms, giving a horizontal and vertical ground resolution of 0.4 cm or better. Camera height for a given gravel bar was chosen based on visual estimations of the gravel sizes present, ensuring that individual clasts were clearly visible based on the point of view screen. Each gravel bar was processed using Agisoft PhotoScan Professional, 2018 (now Metashape), generating a sparse point cloud, dense point cloud and georeferenced orthophotograph for each gravel bar following well established best practice (Westoby et al., 2012; Fonstad et al., 2013; James and Robson, 2014; Carbonneau and Dietrich, 2017). All gravel bars were exported as GeoTIFFs with one-centimeter resolution to standardize analytical scale between gravel bars. For the UAV based imagery we relied on direct georeferencing the orthophotographs as small ranges of uncertainty in absolute gravel bar location were deemed acceptable in exchange for the more efficient data collection in the field (i.e., not having to survey ground control points at each bar) (Carbonneau and Dietrich, 2017). The gravel bars photographed using camera-on-a-pole had ground control points taken using the Trimble Geo7X so that they could be georeferenced. It took between 30 and 200 photographs to capture a gravel bar depending on the size of the bar and camera height necessary to capture gravels.

We analyzed gravel bar orthophotographs using BASEGRAIN 2.2, which is implemented in MATLAB. A number of alternative approaches are available for digital photosieving including the Digital Grain Size Project (DGS) (Buscombe, 2013) and SediNet (Buscombe, 2019). Initial study design sought to examine spatial trends in individual gravel sizes within a gravel bar – an output available in BASEGRAIN but not DGS. BASEGRAIN works as a progressive edge detection algorithm that iteratively turns clasts to white and the shadowed interstitial spaces black, and converts the white raster area to individual vector polygons. It then computes the A axis, B axis, area, and orientation for each identified gravel, exporting these measurements as tabular data (Detert and Weitbrecht, 2012; Detert and Weitbrecht, 2013). Small gravel bars (<15 m²) were processed as a single image. Large gravel bars (>15 m²) were broken into a series of adjacent, non-overlapping 15 m by 15 m tiles. This was done to increase the processing efficiency of BASEGRAIN. We used the parameterization recommendations in the BASEGRAIN documentation concerning image processing thresholds at each of the five steps (Detert and Weitbrecht, 2012; Detert and Weitbrecht, 2013). Before processing each image, vegetation and fines were masked. After processing, the user can examine the partitioned image and mask, merge or split clasts based on their visual analysis of the image (see Fig. 3). After processing, the 15 m sample data tables were combined so that each gravel bar had a single table with all gravel data. From the data tables containing the size of all identified and measured gravels at a single bar, we computed the D₁₀, D₅₀ and D₅₄. As a sensitivity analysis to the user-input portions of BASEGRAIN, two research assistants each processed 21 of the gravel bars. The gravel bar metrics were also compared to hand sampling of gravel bars conducted by the USGS in 2011 (Jones et al., 2011) on duplicated gravel bars.
Having traveled a number of rivers we have observed that riffles and rapids frequently occur at tributary confluences and places where hillslope activity interacts with the channel. Riffles and rapids are a hydraulic indicator of an increase in channel slope and or roughness (Leopold et al., 1992; Knighton, 1998). We include the point location of all named rivers and rapids in the study area as an alternative indication of a break in channel slope that may not be quantifiable from our statistical analysis.

4. Results

Our research on the Rogue River reveals a complex sediment landscape. Commonly observed longitudinal trends like downstream hydraulic geometry (Leopold and Maddock, 1953) do not appear in any of the variables measured (Fig. 5). For the entire study, the downstream hydraulic geometry relation scaling exponent for width is below the expected range of 0.3–0.5 for alluvial channels (Gran and Montgomery, 2001). Relative depth and slope both vary at short spatial scales with little to no lasting downstream impact due to LSS. Width and unit stream power both have sub-reaches with higher spatial autocorrelation broken up by sub-reaches with high spatial variability. Discharge increases smoothly between tributaries, with abrupt jumps in discharge commensurate with the size of the tributary. However, the increase in discharge does not appear to correlate with changes to the other geomorphic variables (Fig. 5). The downstream plot of $D_{84}$ show some reaches between LSS exhibit downstream fining (RKM 134 and 113) but these trends are subtle and are not clear in the plot of $D_{50}$ (Fig. 5). Many of the tributary and non-tributary sediment sources we identified produced a statistically significant geomorphic signal when compared to the study area median. However, statistical significance was not always caused by the geomorphic change we hypothesized, such as a significant high slope value at a landslide caused by a bedrock outcrop rather than colluvial deposition. In many cases a significant change in a variable that failed to reject a hypothesis did not indicate that other related variables at that location were significant (Fig. 6).

We photographed 60 gravel bars in the study area using the UAV or camera-on-a-pole, each gravel bar requiring 30 to 200 photographs to capture. SIM processing generated usable orthophotographs for 55 gravel bars. Of the five bars we could not use, one had clast sizes that were too small to detect, two had vegetation that prevented gravels from being clearly distinguishable, and two suffered from poor photogrammetric alignment and were therefore unreliable. Comparisons to gravels bars hand sampled by the USGS in 2011 (Jones et al., 2011) suggests that the BASEGRAIN analysis is an acceptably reliable method for analyzing gravel sizes. Based on the single factor ANOVA test, the two sampling approaches (USGS and BASEGRAIN) are statistically derived from the same group as indicated by a large p-value. We computed a p-value of 0.65 in comparing the $D_{16}$, $D_{50}$ and $D_{84}$ computed by BASEGRAIN to the values reported by the USGS at the same gravel bars. When we only considered the $D_{50}$ and $D_{84}$ in the comparison, the p-value increased to 0.98, suggesting that the two size distributions are statistically from the same population. Knowing that BASEGRAIN is limited in its ability to detect the smallest class sizes, based on image resolution, we only considered the $D_{50}$ and $D_{84}$ in our analysis. Depth measurements exist for the 200 km of field-based study area except for a 20-km section beginning at RKM 104 caused by a sensor error.

Not all tributary and non-tributary sediment sources will generate a quantifiable change in channel morphology (Rice, 1998; Rice and Church, 1998). Here we test all potential sediment sources in the study area for the presence of a geomorphic signal indicating a discontinuity in downstream hydraulic geometry. We also

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**Fig. 3.** Comparison images of a portion of gravel bar ‘MidValley.14’. On the left is the partitioned image from BaseGrain. Blue lines show the location of the a and b axes used in the computation. The right image shows the original photograph of the same area.

**Fig. 4.** An example of the sampling method for the statistical analysis looking at the confluence of Galice Creek and the Rogue River. The black rectangle shows the extent of an 80-meter sample, here sampling active-channel widths. The selection of width values here will be compared to all width values.

3.4. Analysis

Analysis of the hydrogeomorphic variables width, slope, unit stream power and relative depth relied on the non-parametric 1-tailed Kruskal-Wallis H test. A test area consisted of the data for a single variable adjacent to the identified sediment source, plus those values extending one mean channel width (80 m) downstream of the source. An 80-m window was chosen as the average distance of the range from semi-variogram plots for each of the variables except slope (as explained in Section 3.2). See Fig. 4 for a sampling example. A sample was then tested against all values for the study area.

As an external check of the accuracy of BASEGRAIN, we compared the $D_{16}$, $D_{50}$ and $D_{84}$ values we computed against hand-sampled USGS results from 2011 using single factor ANOVA. Gravel bar spatiality was analyzed using Getis-Ord General G to determine whether gravel bars were randomly distributed within the study area. Size based clustering of gravel bars was analyzed using Getis-Ord $G^*_c$ (Getis and Ord, 1992).
applied the empirical model (Eq. (2)) derived by Rice (1998) to provide some context for which tributaries are likely to produce a geomorphic discontinuity.

\[
P = \frac{e^{(8.68 + 6.08X_1 + 10.04X_2)}}{1 + e^{(8.68 + 6.08X_1 + 10.04X_2)}}
\] (2)

In Eq. (2), \(X_1 = \log(A_t/A_m)\) and \(X_2 = \log(0.14(A_t/A_m)^{-0.51})\), where \(A_t\) refers to the area of the tributary watershed and \(A_m\) refers to the watershed area of the mainstem. Based on the probability equation by Rice (1998), which relates the relative drainage areas of the tributaries and mainstem, there is a low probability of any tributary producing a geomorphic discontinuity (Table 1). We then take a form-process approach in an attempt to better understand when and why an LSS may or may not produce a quantifiable signal. We analyzed the impacts of tributary and non-tributary sediment sources on a variety of hydrogeomorphic variables. The results of that analysis, in the context of our hypotheses, are presented below.
Table 1
The probability that a given tributary will result in a geomorphic discontinuity based on the empirical equation developed by Rice (1998). The Rogue River watershed area ($A_w$) is 13,350 km$^2$.

<table>
<thead>
<tr>
<th>Tributary Name</th>
<th>Watershed Area (km$^2$)</th>
<th>$A_1/A_2$</th>
<th>$X_1$</th>
<th>$X_2$</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois River</td>
<td>2550</td>
<td>0.19</td>
<td>−0.72</td>
<td>−0.49</td>
<td>0.36</td>
</tr>
<tr>
<td>Applegate River</td>
<td>1994</td>
<td>0.15</td>
<td>−0.83</td>
<td>−0.43</td>
<td>0.34</td>
</tr>
<tr>
<td>Bear Creek</td>
<td>930</td>
<td>0.07</td>
<td>−1.16</td>
<td>−0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>Little Butte Creek</td>
<td>917</td>
<td>0.07</td>
<td>−1.16</td>
<td>−0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>Evans Creek</td>
<td>580</td>
<td>0.04</td>
<td>−1.36</td>
<td>−0.16</td>
<td>0.23</td>
</tr>
<tr>
<td>Grave Creek</td>
<td>422</td>
<td>0.03</td>
<td>−1.50</td>
<td>−0.09</td>
<td>0.21</td>
</tr>
<tr>
<td>Jump-off Joe Creek</td>
<td>282</td>
<td>0.02</td>
<td>−1.68</td>
<td>0.00</td>
<td>0.18</td>
</tr>
<tr>
<td>Reece Creek</td>
<td>55</td>
<td>0.00</td>
<td>−2.39</td>
<td>0.36</td>
<td>0.10</td>
</tr>
<tr>
<td>Mule Creek</td>
<td>77</td>
<td>0.01</td>
<td>−2.24</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>Snider Creek</td>
<td>60.6</td>
<td>0.00</td>
<td>−2.34</td>
<td>0.34</td>
<td>0.11</td>
</tr>
<tr>
<td>Galice Creek</td>
<td>61.9</td>
<td>0.00</td>
<td>−2.33</td>
<td>0.34</td>
<td>0.11</td>
</tr>
</tbody>
</table>

4.1. (H1) Tributaries will result in an increased gravel size at their confluence with the Rogue River

Only three of the tributaries have a gravel bar located at the confluence with the Rogue River and have gravel sizes larger than those at the nearest upstream gravel bars; the sign of a significant LSS according to Rice (1998). Evans Creek, Galice Creek, and Mule Creek all have $D_{50}$ and $D_{95}$ sizes larger than the closest upstream gravel bar. The Applegate River, Bear Creek, and Grave Creek all have gravel bars at the confluence with the Rogue River but gravel bars are smaller than those upstream. Reece Creek, Little Butte Creek, Snider Creek, and Jump-off Joe Creek do not have gravel bars at the confluence. The Illinois River does have a gravel bar at the confluence but gravel size measurements do not exist for those gravel bars. Table 2 shows the sizes of each gravel bar in the study area.

4.2. (H2) Non-tributary sediment sources will have larger gravel sizes at the exposed gravel bar where they intersect the active channel

Most non-tributary sediment sources do not have an associated gravel bar. The active bank erosion at RKM 50, the debris at the Flanagan Mine at RKM 113, the landslide at RKM 142, and the landslide complex at RKM 203 all have associated gravel bars. Of those, only the Flanagan Mine results in gravel sizes larger than those at upstream gravel bars. The remaining ten non-tributary sediment sources do not have a gravel bar in close proximity (Table 2).

4.3. (H3) Tributary sediment sources will result in an increase in channel width and hillslope processes will trigger a decrease in channel width

All tributaries that exhibited a statistically significant change in width did so as a predicted increase in width (Table 3). Evans Creek, Jump-off Joe Creek, and Galice Creek confluences do not have mainstem widths that are statistically different than the median for the study area. The statistical results of non-tributary LSS are less clearly defined. The active cut bank and Flanagan Mine debris both show a significantly high width, as do the landslides at RKM 196 and RKM 211. The remaining five statistically significant landslides are all significantly narrower than the median. An additional five landslides do not have a significant impact on channel width.

4.4. (H4) Tributary and non-tributary sediment sources will generate an increase in slope

Eight of the eleven tributary confluences have a slope that is significantly different than the median study area slope with 95% confidence. However, not all of those eight are caused by slopes that are steeper than the study area median slope, as hypothesized. Bear Creek, Grave Creek, and the Illinois River all have slope values that are statistically lower than the median slope. Reece Creek, Little Butte Creek, Evans Creek, Galice Creek, and Mule Creek are all significantly steeper than the median slope. Snider Creek, Jump-off Joe Creek, and Mule Creek do not have a slope that is statistically different than the median. In addition to the statistical test we used, the presence or absence of named riffles and rapids can be used as a method for identifying locations with a local increase in slope. The only creek with a statistically high slope but no named riffle at the confluence is Little Butte Creek. The remaining seven tributaries with statistically significant slopes (high and low) all have a named riffle or rapid at the confluence.

Only two non-tributary sediment sources have mainstem slopes that are not statistically significant, both of which are landslides. Four non-tributary sediment sources have a significantly high slope and eight have a significantly low slope, as compared to the median slope (Table 3). Not all significant high slope, non-tributary sediment sources are necessarily a result of channel-modifying coluvium (see Section 5.3).

4.5. (H5) Channel depth will decrease locally at all sediment sources

None of the depth measurements samples were statistically significantly different compared to the median depth. However, our more detailed exploration of this dataset in the Discussion section proposes a relationship between changes in depth and LSS in certain locations.

4.6. Hyperscale analysis

Hyperscale graphs (Figs. 8–11) offer new ways to analyze and interpret fluvial features at watershed to gravel bar extents (Fonstad and Marcus, 2010; Dietrich and Carbonneau, 2019). Hyperscale graphs display the correlation between two variables using all possible window sizes to compute each correlation using code implemented in Python (Dietrich and Carbonneau, 2019). Here, we use color to show the Pearson’s correlation coefficient between two variables. Along the x-axis is distance downstream. The y-axis represents the size of the moving window used to compute the correlation coefficient (Dietrich, 2016a). Large window sizes should reveal general, basin-scale trends in how the two variables change through space relative to each other. At smaller window sizes the impact of local controls on the channel dominate the pattern. In the context of downstream hydraulic geometry we would expect width to have a generally positive correlation with discharge as the channel responds to increasing stream competence, and slope to have a generally negative correlation as relief decreases (Leopold and Maddock, 1953).

Fig. 8 shows the correlation between channel width and estimated discharge at the channel forming flow. At window sizes above 120 km it exhibits the opposite trend as predicted by down-
stream hydraulic geometry, a general decrease in channel width with increasing discharge expressed as a weak negative correlation between the two. This is a function of the generally narrow channel as the Rogue River passes through the Klamath Mountains and Coast Range in the lower half of the study area. At window sizes between 30 km and 120 km changes in valley geometry appear. The upper portion of the watershed displays the trend in correlation we would expect from a confined reach where volcanic rocks confine the channel (Fig. 2) and is represented by a weak negative correlation shaded green. At around RKM 60 the Rogue River enters the wider alluvial valley where width generally increases with increasing discharge, displayed in red, indicating a positive correlation coefficient. Above this point, geologic confinements prevent the predicted trend of a downstream increase in channel width. As the Rogue River flows out of the alluvial section, channel width decreases downstream (RKM 100) as the river flows into and through the geologically confining Klamath Mountains. As the Rogue River approaches the coast (RKM 180), the valley begins to widen moving downstream. Within these window sizes the relationship between channel width and discharge appears to be independent of tributary contributions, suggesting that geology is still the primary control.

At window sizes under 10 km (Fig. 9) we would expect to see the influences of LSS and single-point geologic controls. Where channel form is a function of downstream hydraulic geometry we should also see some evidence at these spatial scales. Tributaries that join the Rogue River in the alluvial portion of the study area trend to be associated with a positive correlation between channel width
The table below shows the statistical output for all of the tributaries and landslides for all hydrogeomorphic variables. We take a p-value < 0.05 to indicate a statistically significant result as compared to the study area median value.

<table>
<thead>
<tr>
<th>RKM</th>
<th>Name</th>
<th>Tributaries - Width</th>
<th>tribus- Width</th>
<th>Tributaries - USP</th>
<th>Tributaries - Slope</th>
<th>Tributaries - RDM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>f-test</td>
<td>p-value</td>
<td>f-test</td>
<td>p-value</td>
<td>f-test</td>
</tr>
<tr>
<td>30.172</td>
<td>Reece Creek</td>
<td>42.4648</td>
<td>0.0000</td>
<td>34.8996</td>
<td>0.0000</td>
<td>10.3433</td>
</tr>
<tr>
<td>40.8470</td>
<td>Little Butte Creek</td>
<td>32.1138</td>
<td>0.0000</td>
<td>21.6222</td>
<td>0.0000</td>
<td>6.4899</td>
</tr>
<tr>
<td>46.9198</td>
<td>Snider Creek</td>
<td>63.7348</td>
<td>0.0000</td>
<td>30.9205</td>
<td>0.0000</td>
<td>3.3870</td>
</tr>
<tr>
<td>49.8309</td>
<td>Bear Creek</td>
<td>13.1801</td>
<td>0.0003</td>
<td>34.3002</td>
<td>0.0000</td>
<td>31.9361</td>
</tr>
<tr>
<td>77.2360</td>
<td>Evans Creek</td>
<td>2.0568</td>
<td>0.1515</td>
<td>35.1559</td>
<td>0.0000</td>
<td>41.3773</td>
</tr>
<tr>
<td>103.7830</td>
<td>Applegate River</td>
<td>187.3628</td>
<td>0.0000</td>
<td>12.2517</td>
<td>0.0005</td>
<td>74.6202</td>
</tr>
<tr>
<td>122.8440</td>
<td>Jump-off Joe Creek</td>
<td>3.7009</td>
<td>0.0054</td>
<td>2.2563</td>
<td>0.1331</td>
<td>0.1989</td>
</tr>
<tr>
<td>134.9150</td>
<td>Galice Creek</td>
<td>0.2738</td>
<td>0.6006</td>
<td>15.8866</td>
<td>0.0001</td>
<td>15.1132</td>
</tr>
<tr>
<td>148.0730</td>
<td>Grave Creek</td>
<td>30.8438</td>
<td>0.0000</td>
<td>71.8310</td>
<td>0.0000</td>
<td>83.7539</td>
</tr>
<tr>
<td>181.4670</td>
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<td>21.2692</td>
<td>0.0000</td>
<td>11.3884</td>
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<td>1.4064</td>
</tr>
<tr>
<td>216.8100</td>
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<td>48.5746</td>
<td>0.0000</td>
<td>39.0889</td>
<td>0.0000</td>
<td>95.9994</td>
</tr>
</tbody>
</table>

The table above shows the statistical output for all of the tributaries and landslides for all hydrogeomorphic variables. We take a p-value < 0.05 to indicate a statistically significant result as compared to the study area median value. The bank erosion at RKM 50 also shows a positive correlation between width and discharge. Landslides should result in a negative correlation coefficient, driving a decrease in channel width regardless of discharge. Many of the landslides occur where there is a statistically insignificant correlation between width and discharge in the hyperscale graph indicated by a gap in the graph. Some, such as the landslides at RKM 82, 87 and 203 occur at places with a clear negative correlation coefficient between width and discharge indicating a localized narrowing of the channel. In general, the impact of this narrowing on the correlation does not extend beyond window sizes of 10 km. Additional notable signals in Fig. 9 occur at RKM 5 and 17. The increase in width at RKM 5 is attributable to an unvegetated mid-channel bar. At RKM 17 an unvegetated point bar in an area with agricultural use suggests the increase in active channel width generating the large, positive values.

The graph of slope and discharge (Fig. 10) also exhibits a trend running opposite to that of downstream hydraulic geometry at window sizes greater than 130 km. At window sizes between 30 km and 130 km, the middle alluvial portion of the study area shows a weak positive correlation between slope and discharge. This runs counter to downstream hydraulic geometry and the trends seen in the hyperscale graph of width and discharge. In the upper portion of the study area the mid-sized correlation coefficient window sizes show a patchwork of the expected negative correlation between slope and discharge. The impact of particularly low slope areas, such as at RKM 50, influence average slopes at these larger window sizes. In the downstream portion of the study area, average slope decreases as the Rogue River leaves the Coast Range generating the expected negative correlation between slope and discharge.

At window sizes under 10 km (Fig. 11) the influence of tributary and non-tributary sediment sources and local geologic control (such as bedrock grade control) are apparent. This is most notable at locations where landslides interact with the channel such as at RKM 87, 121, 142, 148 and 203. Some, but not all of the tributaries exhibit an increase in slope while others have the opposite relationship with slope. Evans Creek (RKM 77), the Applegate River (RKM 103) and Galice Creek (RKM 134) all exhibit a positive correlation indicating a local increase in slope. Jump-off Joe Creek (RKM 122) and Mule Creek (RKM 181) exhibit a negative correlation; a local decrease in slope. At the scale of single pixels there is pattern of alternating positive and negative values. Carbonneau et al. (2012) suggest that this is potentially a function of the pool-riffle sequence. The black lines in Fig. 11 show the location of named riffles and rapids in the study area. Some of these agree with the sequence of positive (high slope) and negative (low slope) correlations in the hyperscale graph, but not all. In some locations such as between RKM 50 and 110 there is good overall agreement between locations with named riffles and rapids and local increases in slope. In other areas, between RKM 150 and the end of the study area, there appears to still be a correlation, but it is not strong enough to be visible in more than the first few rows – the smallest window sizes of 10-100 m.

5. Discussion

The Rogue River presents a hydrogeomorphic landscape with high spatial variability that runs opposite the conceptual model for changes in geomorphic properties proposed by downstream hydraulic geometry (Leopold and Madow, 1953), represents a sediment landscape with different external controls than the sediment links concept (Rice, 1998), and is less conducive to reach-specific characterization than channel-reach morphology (Montgomery and Buffington, 1997). For the entire study, the downstream hydraulic geometry relation scaling exponent for width is below the expected range of 0.3-0.5 for alluvial channels.
(Gran and Montgomery, 2001). When dividing the study area into geologically similar reaches, those that are characterized by alluvial processes do exhibit scaling exponents in-like with those expected by downstream hydraulic geometry: specifically, the area upstream of Bear Creek, and the area beginning just downstream of Grants Pass and ending at Jump-off Joe Creek. This suggests that the reason for the lack of characteristic downstream hydraulic geometry is those reaches that are geologically confined. These alluvial reaches are also where we see the clearest signals of geomorphically significant LSS expressed in gravel sizes. The geologically confined sections where the expected patterns of downstream hydraulic geometry are not present also have more narrow channels and higher slopes.

In the Rogue River, LSS appear to exert a quantitative control on many of the hydrogeomorphic variables we examined. However, variability within the channel is not entirely explained through the LSS. Rice (1998) and others (Ferguson et al., 2006) suggest that tributary area relative to the main channel is a good predictor for the presence of a statistically meaningful LSS based on the metric of an increase in gravel sizes. Nevertheless, we find that gravel size does not act as a reliable indicator of a sustaining source of sediment, regardless of tributary watershed area. In the Rogue River different LSS seem to be highlighted by different hydrogeomorphic variables – width in some places, slope in others – and some do not appear to exert a quantifiable control on channel form. Our findings show that the identification of geomorphically meaningful LSS in the Rogue River must be considered in the context of the multiple hydrogeomorphic variables that can be used to quantify channel form. This suggests that to successfully identify important LSS for the Rogue River, and likely other similar rivers, measuring a suite of hydrogeomorphic variables is important. No single variable was a consistent indicator of a meaningful LSS. Instead, different hydrogeomorphic variables exhibited a statistically meaningful change at likely sediment sources inconsistently, suggesting that in the Rogue River enduring sediment sources do not create consistent geomorphic signals. We also suggest that the historic anthropogenic context is important to understand the presence or absence of a geomorphic signal associated with an LSS (James, 1999; James and Marcus, 2006). Human activity has the potential to increase the size and volume of sediment contributions to the channel and modify channel width such that there is not suitable room for gravel bar development. The historical role of anthropogenic activity is discussed further in Section 5.5. In the Rogue River some of the heterogeneity in channel form and gravel sizes can be explained in the context of downstream hydraulic geometry, LSS, anthropogenic activity and geology, but much of it remains unexplained.

We found statistical evidence of geomorphic discontinuities at certain tributaries and for some geomorphic variables, despite the low probability of a geomorphic discontinuity as predicted in Table 1. A number of reasons likely exist for the lack of agreement between the predicted model and statistical analysis found here. We view the variable basin geology and the history of anthropogenic activity as primary reasons why the predictive model did not perform better. The original paper by Rice (1998) explores two study areas with relatively low anthropogenic disturbance and similar geology. As such, they find watershed area to be the dominate predictor for geomorphic discontinuity, where watershed area serves as a proxy for discharge, stream power, and therefore the ability of a tributary to deliver sediment. The mixed geology of our study area and history of mining suggest that watershed area is likely not the best predictor for the presence of a geomorphic discontinuity. The discrepancy at Galice Creek highlights this, with the lowest probability of a geomorphic discontinuity and one of the most statistically significant geomorphic discontinuities in slope of the study area.

5.1. Digital photosieving calibration

We show that BASEGRAIN does an acceptable job computing gravel sizes, as compared to the 2011 study by the USGS (Jones et al., 2011), which used traditional hand-sampling techniques and produces a far more complete data set requiring less time in the field as compared to hand counting. Our statistical analysis showed no difference between the D50 and D84 populations generated using the different methods. However, the use of BASEGRAIN does present some challenges. Any given clast must be comprised of a certain number of pixels for the processing algorithm to positively identify it and compute its size. Additionally, there must be sufficient contrast between individual clasts and the interstitial spaces for accurate distinction between any two adjacent grains. Poor contrast could have the effect of over estimating gravel sizes because unique particles would be lumped together. For all but five gravel bars, we were able to control both potential sources of error with proper study design. Overlapping clasts, such as imbrication, are not possible to control with proper study design. Overlapping clasts would cause a systematic decrease in the size of any given gravel. We recognize that this has the potential to create inaccurate data, but our comparison with the USGS study suggests that it was not an issue on the Rogue River. We believe that for many applications accepting a marginal decrease in the level of precision in exchange for the clear increase in data resolution and spatial scale is desirable in those studies where environmental factors are appropriate for implementation of BASEGRAIN or other digital photosieving techniques.

5.2. Spatial patterns of gravel bars

Gravel bars in the Rogue River do not exhibit clustering in their spatial distribution throughout the watershed. However, both D50 and D84 sizes reveal some statistically significant size-based clustering of large gravel sizes at the gravel bars between RKM 187 and 198 (Fig. 5), an area with no identified LSS. Within the context of the sediment links concept, we would expect that at important sediment sources there would be a lack of size-based clustering as the sudden increase in gravel size would be much different than the gravels upstream. Immediately downstream of a new LSS some size-based clustering would be evident as the gravel sizes between the adjacent bars would likely be similar because any size decrease would be a function of the gradual in-channel fining processes. However, this expectation was not met. Patterns of downstream fining along the Rogue River are not present at the reach scale, nor are they reliably present between adjacent sediment sources.

The D84 and D50 values for the gravel bar at RKM 193 are notably higher than those upstream and downstream. This gravel bar immediately follows a short, narrow reach and the large size might be related to the sudden drop in unit stream power associated with an increase in width. However, this direct relationship is not present at other locations in the study area. At RKM 164 the D50 and D84 values also appear anomalously large. This bar consists of predominantly sands with interspersed cobbles. It is possible that the lack of measurable grains across the smaller size thresholds has resulted in a grain size distribution that is positively skewed, therefore giving anomalously large D50 and D84 sizes. In the Rogue River, gravel sizes appear to be more a function of local conditions such as sediment supply, geologic composition, and the local channel form as it relates to shear stresses and transport rates. The downstream patterns of gravel sizes in the Rogue River are not generally explained by continuous downstream fining, discontinuous LSS, or some combination of these principles (Fig. 5).
5.3. Sediment links concept

In his original paper Rice (1998) describes tributaries as continuously depositing new material in the mainstem resulting in a persistent geomorphic signal from the LSS. These systems must therefore be transport limited, with more material of a large enough size that not all of it can be mobilized during channel forming flow events. Conversely, landslides are interpreted as discrete events with the geomorphic signal diminishing over time. In supply limited systems such as the Rogue River, a geomorphic signal caused by deposition at tributary confluences is less likely to occur because a flow event in a tributary of sufficient magnitude to deposit material into the Rogue River is likely to occur when discharge in the Rogue River is sufficient to immediately transport the material downstream. This suggests that tributaries generate temporally transient, timebound geomorphic signals. This is supported by our findings at most of the tributary confluences. The most notable geomorphic evidence of LSS in the Rogue River were at landslide deposits where the size of hillslope material greatly exceeded the transport capacity of the Rogue River. While some finer material associated with landslides and debris flows is transported downstream, the largest clasts remain in-channel and create many of the geomorphic signals expected at an LSS, most notably a local increase in slope. The hillslope sediment sources therefore exist as enduring, timeless geomorphic signals – the geomorphic evidence enduring through time. Fig. 6 illustrates a conceptual model of the relationship between a lateral sediment source, transport capacity, and time.

We enriched our analytical approach to identifying statistically high slopes through the inclusion of named riffles and rapid's. This is an alternative method for independently identifying the presence of high slopes that can help identify which sediment sources may be triggering an increase in slope; either through high magnitude, low frequency events or as a continuous source of sediment. This is important given the inconsistent relationship between the statistical variables in our study and challenges associated with relying purely on statistical analysis (Ziliak and McCloskey, 2008). One would expect that the tributary sediment sources that have a named feature and a local increase in slope value larger than the median are likely indicators of an enduring sediment source. The Applegate River, Evans Creek, and Galice Creek are good examples of this, with named hydraulic features associated with a statistically meaningful increase in channel slope. Despite the channel form evidence for active LSS, the gravel sizes at the Applegate River confluence are smaller than the reach average and represent a decrease in gravel size compared to gravel bars upstream and downstream. We propose that the lack of a sediment size spike at Bear Creek, Jump-off Joe Creek, and Grave Creek is owing to a combination of sediment storage occurring upstream of the confluence with the Rogue River and the downstream transport of deposited material by the Rogue River, thus removing geomorphic evidence of the LSS. Aerial imagery from NAIP show extensive portions of the tributary channel as alluvial and unvegetated. We hypothesize that these gravels are not entering the Rogue River because of deposition upstream of their confluence, with infrequent mobilization to the Rogue River occurring at flows sufficiently large that deposition does not occur in the main Rogue River. It is also possible that abrasion prior to entering the Rogue River results in gravels that are of a similar enough size that there is no discernable signal. Tributary sediment sources are therefore time-bound – the presence of a geomorphic signal is transient with respect to time and therefore may or may not be observable.

All the non-tributary sediment sources except four have a named riffle or rapid adjacent to where they intersect the active channel, which is confirmed with the statistical analysis of slope. However, when considering non-tributary sediment sources, we noticed that in-channel morphology does not always align with the sediment links hypothesis. The landslide at RKM 58.32 has a named hydraulic feature, a statistically steeper slope, and higher unit stream power. However, at this location the cause of the rapid is bedrock, not colluvium from field observations. Similarly, field observations suggest that the landslide at RKM 148.63 is caused by a combination of bedrock and hillslope deposits. This study cannot positively attribute a given gravel bar’s presence to the adjacent hillslope. Some landslides, such as the one at RKM 148.63 and RKM 142.16, have large angular midstream boulders with no evidence of alluvial transportation supporting the observation of a hillslope process LSS. Other bars adjacent to landslides do not.

Slope and the presence or absence of riffles and rapids should be linked, as riffles and rapids are defined, in part, by a local increase in slope. All of the LSS that have a named riffle have a significantly steep slope except for Little Butte Creek and the landslide at RKM 82.17, neither of which have a significant slope. However, not all LSS reveal a significantly high slope value as expected. The inconsistency between on-the-water identified hydraulic features and the statistical slope analysis is potentially related to how the USGS generates its 10-m elevation data and therefore how slopes were computed. Elevation data for the study area is based on the 1/3 arc-second DEM from the USGS. Vertical accuracy is based on the best available source data that, for the study area, is usually based on LiDAR. For a small portion of the study area beginning just downstream of Mule Creek and extending to the end of the field study area LiDAR data is unavailable and the elevation data was likely derived by the USGS using the 1:24,000 contour lines ([Archuleta et al., 2017b]). The rapids at LSS that either do not have a significant slope value compared to the median, or have a significantly low value, all have low relief through the riffle and tend to be less than 40 m long. Thus, the slope computation used in this study smooths the riffle to a low slope value that is not statistically different from the median, despite the fact that they are observable, named features.

5.4. Relative depth

The samples for the depth analysis were conducted in the same manner as the other hydrogeomorphic variables. With depth, these included the range of depths before, at, and after an LSS. The analytical approach was such that this range of values was tested for its statistical relationship with all observations, but within-sample variation was not analyzed. How depth changes at an LSS should reveal the presence of a pool-tail crest, suggesting a submerged delta deposit that may not be revealed based on channel slope or unit stream power. At Mule Creek there is a rapid decrease in depth at the confluence, indicative of a pool-tail crest ([Heitke et al., 2010]). The Mule Creek signal is important because it does not show up as a significant sediment source in any of the other hydrogeomorphic variables. At the Mule Creek confluence depth decreases by five meters compared to the pool upstream of the confluence (Fig. 5). The clear alluvial fan at the Rogue River’s edge suggests that the change in depth is an indication of a submerged delta and a potentially important source of sediment in the formation of the downstream gravel bar, which has a D50 of 55.3 mm and a D94 of 104.4, both of which are larger than the nearest upstream bar. This indicates that there are some sediment contributions that are not discernable from our methods.

5.5. Historic anthropogenic context

The Galice Creek confluence has statistically significant high unit stream power and high slope in the mainstem despite the small watershed area, which runs counter to the predictive model proposed by the sediment links concept. Hydraulic mining started at
the Old Channel Mine on Galice Creek in 1860 with written accounts claiming massive amounts of material being washed down daily (‘Galice Creek - Oregon Gold Locations, 2019’). Hydraulic mining likely delivered an abundance of material, oversized for the tributary, to the Rogue River. The notable rapid, high slope, and high unit stream power here are likely the legacy of the volume and size of material washed into the Rogue River during mining operations. Our analysis suggests that Galice Creek is a potentially important sediment source; however, the history of land use in the area calls the geomorphic evidence into question. The only section with an
apparent trend in downstream fining begins at Galice Creek (RKM 134.9) with gravel sizes fining consistently before increasing at the two landslides downstream of Grave Creek (RKM 148.62 and 153.64) (Fig. 5). Given the historical context of Galice Creek, we believe the downstream fining could be a function of the delivery of especially large material to the Rogue River as a byproduct of hydraulic mining (James, 1999). Galice Creek and the Flanagan Mine debris at RKM 113.63 (Fig. 5) have two of the largest D50 and D84 values of the LSS with an adjacent gravel bar. Galice Creek has an important history of hydraulic mining that is likely a key source of the size of material at its confluence with the Rogue River and the associated rapid. Likewise, the material from the Flanagan Mine are also comprised of larger material than would be frequently transported and appear to result in an in-channel increase in gravel size.

Based on the watershed area and geology of the Applegate River, we would expect it to produce a clear signal with an increase in gravel sizes and likely a riffle or rapid at its confluence with the Rogue River owing to the local increase in slope from the contribution of new alluvium. The statistically high slope and named riffle at the Applegate River ends just upstream of the modern confluence. Examining aerial imagery from 1939 (georectified using NAIP imagery), we see that the Applegate River used to meet the Rogue River just upstream of the riffle in question (Fig. 7). Since the 1939 imagery anthropogenic modification forced the Applegate River mouth downstream to its current location. This suggests that historically the Applegate River contributed enough material to form an alluvial deposit sufficient to create a riffle. Unfortunately, we do not have a good time constraint on when this shift occurred. Unlike at Galice Creek, which has a sediment signal because of human activity, the Applegate River may be missing the statistical high-
slope signal because of human activity moving the channel. We cannot know what the gravel sizes at the historic confluence of the Applegate River were, but at the bar upstream of the modern confluence adjacent to the historic confluence, D50 size is the same, and the D84 is slightly larger than the D50 and D84 at the modern confluence (Table 2).

The exaggerated signal at Gravel Creek, the buried alluvial deposit at Mule Creek, and the spatially disjointed signal at the Applegate River all suggest that observing physical evidence of meaningful LSS can be problematic. Channel modification and the overlying hydraulic conditions can enhance or hide a signal. The majority of the sediment sources in this study could not be consistently identified across all hydrogeomorphic variables measured. This challenge in signal identification is likely closely related to the challenges arising from readily available hyperscale data sets. As heterogeneity in a channel appears to increase with data resolution, what we think of as a geomorphic signal becomes harder to distinguish from natural variability, or noise. Frequently, observations of fluvial systems identify a variety of processes interacting at multiple spatial scales including sediment sources, sediment breaks, evidence of legacy events, and an overall patchwork of channel-forming process links (Carbonneau et al., 2012).

5.6. Additional geomorphic controls

The Applegate River and Grave Creek are the only large tributaries that have a gravel bar at the confluence and D84 and D50 values that are smaller than the reach average. Given the findings of Rice (1998) and the relative watershed sizes of these tributaries, we would expect both tributaries to trigger an increase in gravel sizes. The sub-basin geology of these tributaries is comprised pre-
dominately of softer, mixed sedimentary rock. Additionally, they both flow through their own depositional valley before entering the Rogue River. Jump-off Joe Creek is also large enough that we would expect an increase in gravel size associated with the sediment source, but the closest downstream gravel bar is roughly a kilometer away and the gravel sizes there are smaller than the study area average. Both suggest that the depositional environment before the confluence, and softer geology in the tributary watershed more prone to fining result in a sediment source that is not expressed in gravel size. However, given the similarity between tributary lithologies and mainstem lithology we do not believe that tributary sub-basin geology is playing a major role in channel morphology.

The previous discussion has examined the role of tributary and non-tributary sediment sources as external controls on channel morphology. However, autogenic processes also play a role in channel form. We see potential evidence of self-organized pool-riffle sequences in alluvial reaches. Sediment waves, or pulses, are also potentially playing a role in channel form (Sklar et al., 2009; Venditti et al., 2010). While not explicitly tested in this study, these processes likely have some explanatory role in the portion of channel heterogeneity not previously explained. Depth, particularly in the alluvial sub-reach downstream of the confluence with the Applegate River, appears to exhibit a semi-regular trend between relatively deep and shallow reaches with a spacing of 400–1000 m, roughly five to seven times the mean channel width (Leopold et al., 1992; Knighton, 1998). The hyperscale graph of slope (Fig. 9) shows a similar pattern for slope. At the smallest window sizes alternating positive and negative correlation values, indicate alternating high and low slope, have a similar spatial frequency as depth. Like depth, the section of the Rogue River where this trend is clearest is in the alluvial portion downstream of the Applegate River.

In coarse alluvial rivers sediment tends to disperse downstream rather than translate downstream maintaining the form of a wave (Sklar et al., 2009; Venditti et al., 2010). The deposition attributed to an LSS would increase bed elevation locally with the same effect on channel form as discussed at the end of Section 1. Between the spatially episodic hillslope and continuous tributary sediment delivery, processes of dispersion and translation of the sediment will diminish the initial signal – potentially rendering the wave (sediment source) undetectable. In-channel storage where channel width increases or slope decreases, and the potential of (de)synchronization at tributaries, could also complicate the sediment links concept (Gran and Czuba, 2017). This study showed that at many of the confluences channel width was high and slope was low, relative to the study area, suggesting that local storage of sediment may be occurring. In-channel storage may also account for the subtle clustering of larger gravel sizes between RKM 187 and 198. In addition to the dispersion and storage of sediment, the combined effects of multiple sediment contributions may also serve to enhance or depress the LSS signal.

5.7. Hyperscale graphs

The hyperscale graphs reveal the importance of the varying spatial extent of a given LSS relative to larger spatial scale geologic controls. The hyperscale graphs displaying the full range of correlation windows (Figs. 8 and 10) illustrate the relationship between larger-scale controls and their respective variables. Changes in the longitudinal relationship between any two variables appears to be
related to the broad scale geologic controls, a similar finding and interpretation to that by Dietrich (2016). These broad-scale trends provide useful insight into the spatial scales at which trends such as downstream hydraulic geometry persist.

At smaller scales of correlation (Figs. 9 and 11), the impact of local controls on channel form are more apparent. In Fig. 11 we would expect the presence of a pool-riffle channel form to be most apparent as the window size is small enough to not smooth over these channel forms. In some reaches such as between RKM 100 and RKM 160 there does appear to be a strong co-occurrence of named riffles and rapids (black lines) and local increases in slope (positive correlations). The distance over which the local increase in slope influences broader trends can be estimated by the vertical extent (y-axis) of the signal. The majority of the riffles and rapids with a positive correlation only exert a signal that is quantifiable at the smallest window sizes. We believe that these are likely true indicators of the pool-riffle sequence in sections where alluvial processes dominate. High slope areas, such as at RKM 150 (Figs. 10 and 11), which have a signal persisting beyond the 10 km window, indicate very high slope riffles and rapids that are more frequently a function of bedrock control. Because these rapids are of such high slope, their presence generates positive correlation coefficients at larger window sizes than those lower slope riffles and rapids. This interpretation of the pool-riffle sequence is similar to that by Carbonneau et al. (2012). At correlation windows below 10 km, the relationship between width and discharge appears dominated by large, seemingly isolated, changes in width. In some areas such as between RKM 65–80, width does not vary downstream (Fig. 5) so a relatively abrupt, small increase or decrease in width (RKM 68 and 72, respectively) would have a disproportionate impact on the hyperscale graph. This is because the correlation coefficient is computed using a smaller sample size and is therefore more sensitive to any change in width.

5.8. Future work

There are currently a number of promising digital photosieving techniques including BASEGRAIN (used in this study) (Detert and Weitbrecht, 2012), two by Buscombe (2013, 2019) and one by Carbonneau et al. (2004). As the application of digital photosieving becomes more prevalent it is increasingly important that direct comparisons between all digital photosieving techniques are made. A series of direct comparisons between analytic approaches will help illustrate any strengths or weaknesses in the different analytic approaches to digital photosieving. Understanding the different strengths and weaknesses of the various techniques, such as dealing with complicated lighting, vegetation, and wood, is important to ensure high quality data. A series of deliberate tests of these systems against the same dataset is therefore needed.

Gravels on exposed gravel bars are only mobilized at high flow events and it is therefore possible that they do not accurately represent the subtle variations in gravel size at LSS. Therefore, it would be advantageous to measure gravel sizes for the portion of the channel at, and adjacent to, the channel thalweg. Continuous measurement of gravel sizes would allow their inclusion in hyperscale graphs to help illustrate changes in gravel size moving downstream, providing a continuous picture of longitudinal changes in gravel sizes. In shallow, clear water streams this is potentially possible using underwater cameras, or by using aerial photography and adjusting for the refraction of light (Dietrich, 2016b). Direct measures of water surface elevations would also prove valuable. This would allow slope computations to occur at the same spatial scale as mea-

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Fig. 11. A close-up view of the 10 km and below window size examining the correlation between slope and discharge. The study area begins in the upper right, and flows right to left through each row. The black diagonal lines show the location of named riffles and rapids.
6. Conclusion

This study found that the impact of tributary and non-tributary sediment sources on channel morphology was highly varied, depending on sediment source type and hydrogeomorphic variable being examined. The lack of consistent correlation between any given variable and a change in channel morphology suggests that for the Rogue River, a predictive model of LSS as primary controls of channel morphology is not appropriate, although some sediment sources are evident. In the low-disturbance field sites used by Rice (1998), gravel size plays a key role in the identification of channel forming sediment sources. Local controls on the Rogue River and its tributaries, in concert with the history of mining and land use, generate a scenario where sediment sources may be expressed through some, but not necessarily all, of the hydrogeomorphic variables used here. Thus, measuring as suite of hydrogeomorphic variables is crucial to effectively characterizing the impact of LSS on channel form. Despite gravel size and tributary drainage area not being consistent indicators of meaningful LSS, as suggested by Rice (1998), we do find several interesting signals such as the role that historic anthropogenic activity appears to have in enhancing LSS signals, and submerged alluvial fan-like features as evidence of otherwise unapparent LSS.

As our ability to measure rivers over larger distances and at higher resolutions improves, this spatially extensive and intensive data can be used to deepen our understanding of channel morphology across spatial scales. The hyperscale approach taken here allows for the simultaneous study of basin-scale patterns and local processes. The relationship between localized, autogenic process on channel form can be observed in the context of basin-wide trends in channel morphology. This offers the potential to deepen our understanding of how a single sediment wave may behave and influence pool-riffle sequences, and what that means for larger spatial-scale patterns such as downstream fining between LSS.

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