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Measuring floodplain spatial patterns using continuous surface metrics at multiple scales

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ABSTRACT

Interactions between fluvial processes and floodplain ecosystems occur upon a floodplain surface that is often physically complex. Spatial patterns in floodplain topography have only recently been quantified over multiple scales, and discrepancies exist in how floodplain surfaces are perceived to be spatially organised. We measured spatial patterns in floodplain topography for pool 9 of the Upper Mississippi River, USA, using moving window analyses of eight surface metrics applied to a 1×1 m^2 DEM over multiple scales. The metrics used were *Range*, *SD*, *Skewness*, *Kurtosis*, *CV*, SD_{CURV}, *Rugosity*, and *Vol:Area*, and window sizes ranged from 10 to 1000 m in radius. Surface metric values were highly variable across the floodplain and revealed a high degree of spatial organisation in floodplain topography. Moran's I correlograms fit to the landscape of each metric at each window size revealed that patchiness existed at nearly all window sizes, but the strength and scale of patchiness changed within window size, suggesting that multiple scales of patchiness and patch structure exist in the topography of this floodplain. Scale thresholds in the spatial patterns were observed, particularly between the 50 and 100 m window sizes for all surface metrics and between the 500 and 750 m window sizes for most metrics. These threshold scales are ~ 15–20% and 150% of the main channel width (1–2% and 10–15% of the floodplain width), respectively. These thresholds may be related to structuring processes operating across distinct scale ranges. By coupling surface metrics, multi-scale analyses, and correlograms, quantifying floodplain topographic complexity is possible in ways that should assist in clarifying how floodplain ecosystems are structured.

1. Introduction

Floodplain topography interacts with the flow regime of rivers to influence spatial patterns of inundation, sedimentation, biogeochemical conditions, vegetation, and surface water–groundwater exchanges (Everson and Boucher, 1998; Thoms, 2003; Stanford et al., 2005; Alsdorf et al., 2007; Hamilton et al., 2007). Floodplains are areas of low relief within the riverine landscape, but their surface topography is often highly complex (Jones et al., 2008; Rayburg et al., 2009; Scown et al., in press), which is thought to contribute to their elevated biodiversity and productivity (Everson and Boucher, 1998; Ward et al., 2002b; Hamilton et al., 2007). 'Complexity' has been defined in terms of the number and diversity of parts or components, localised interactions and feedbacks among those parts or components, and the degree of spatial organisation—all of which contribute to the nonlinear character of complex systems (Simon, 1962; Levin, 1998; Phillips, 1999).

The topographic complexity of floodplains can be described, in part, by the heterogeneity and variability in elevation, slope, aspect, and curvature throughout the floodplain (Hoechstetter et al., 2008; Tarolli, 2014), as well as the spatial assemblage of morphological units created by these surface properties (Hamilton et al., 2007). However, topographic complexity is frequently poorly defined and quantified in floodplain research. Quantitative approaches to measuring the surface properties that contribute to topographic complexity in floodplains are required in order to evaluate floodplain complexity and its influence on geomorphological, hydraulic, and ecological processes.

Many approaches are available to quantify topography and topographic complexity. These have been applied, inter alia, to the analysis of landslides, hillslope processes, stream networks, river channel morphology, volcanoes, sea floors, coral reefs, and intertidal zones (Florinsky, 1998b; Pike, 2000; Walker et al., 2009; Brown et al., 2014; Legleiter, 2014a). Many utilise high-resolution digital elevation models (DEMs), particularly from remote sensing, to characterise topography based on relief, slope, aspect, and curvature (Evans, 1972; Zevenbergen and Thorne, 1987; Nogami, 1995; Florinsky, 1998a) or to classify topography into discrete landforms or morphological units (Iwahashi and Pike, 2007; Jones et al., 2007; Tarolli et al.,

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2012; Jasiewicz and Stepinski, 2013; Wyrick et al., 2014). Commonly, metrics that characterise surface patterns at each cell in the DEM, or within a delineated area, are employed to capture the overall surface topography. However, these metrics do not provide information on actual surface complexity (Wood, 1996; Scown et al., in press). Alternately, an extensive suite of surface metrics and geostatistical tools can be used in order to quantify the spatial variability, structure, and autocorrelation of topographic surfaces (see Table 1), although little attempt has yet been made to apply such approaches to floodplains (Scown et al., in press). Surface metrics are quantitative measures of continuous variables (McGarigal et al., 2009; Cushman et al., 2010). Environmental applications of surface metrics have occurred in mountainous regions (Nogami, 1995; Riley et al., 1999; Dorner et al., 2002; McGarigal et al., 2009; Iwahashi et al., 2012) or on the sea floor (McCormick, 1994; Brock et al., 2004; Wilson et al., 2007; Wedding et al., 2008; Walker et al., 2009; Zawada and Brock, 2009;

Table 1
Summary of selected surface metrics that have been used to measure topography and topographic complexity.

Surface metric	Indicates	Brief description	Selected references
Range	Magnitude of relief	Difference between the lowest and highest cells within a given extent.	Nogami (1995), Gadelmawla et al. (2002), Wilson et al. (2007), Walker et al. (2009)
Standard deviation (SD)	Variability about the mean	Standard deviation of surface heights. This metric is less sensitive than range as it accounts for all values not just the highest and lowest.	Evans (1972), Mark (1975), Gadelmawla et al. (2002), Glenn et al. (2006), Hoechstetter et al. (2008), McGarigal et al. (2009), Aberle et al. (2010)
Coefficient of variation (CV)	Variability relative to the mean	The standard deviation of surface heights divided by the mean. This metric is useful for low-lying areas where standard deviation is relatively low but small elevation changes are ecologically important.	McCormick (1994), Pollock et al. (1998)
Skewness	Peak and valley characteristics	The skewness of the distribution of surface heights. Positive skewness may indicate that the surface has high peaks or valleys filled in; negative skewness may indicate that peaks are flattened or deep valleys are present (McGarigal et al., 2009). In a geomorphological context, positive skewness may indicate sites of net deposition while negative skewness may indicate sites of net erosion.	Nogami (1995), Gadelmawla et al. (2002), McGarigal et al. (2009), Aberle et al. (2010)
Kurtosis	Landscape dominance or evenness	The kurtosis of the distribution of surface heights. High kurtosis may indicate the presence of a dominant height or height range equivalent to the 'landscape matrix' upon which peaks and valleys are superimposed; low kurtosis may reflect a more smoothed surface in which heights are more evenly distributed (McGarigal et al., 2009). This metric is similar to Nogami's (1995) *power* that measures the degree of concentration of elevations within a given extent.	Nogami (1995), Gadelmawla et al. (2002), McGarigal et al. (2009), Aberle et al. (2010)
Volume area ratio (Vol:Area)	Degree of dissection	The ratio between the volume of land above minimum elevation within a given extent and the volume created by multiplying the extent area with the range of surface heights within that extent. This metric is useful in determining the degree of dissection of a topographic surface as well as erosional and depositional stages of the landscape.	Nogami (1995)
Terrain ruggedness index (TRI)	Surface variability	Index of the absolute height difference between a cell and its eight neighbouring cells. This metric is similar to slope but indicates absolute not directional variability.	Riley et al. (1999), Wilson et al. (2007)
Standard deviation of curvature (SD_{CURV})	Convolutedness of the surface	The standard deviation of curvature across a surface. This metric may be useful in determining how variable curvature is across a surface and subsequently how convoluted or 'rough' that surface is. Surface roughness creates a diverse array of hydraulic and geomorphic conditions in floodplains. Standard deviations of slope and aspect have also been used.	McCormick (1994), Everson and Boucher (1998), McGarigal et al. (2009), Tarolli et al. (2012)
Rugosity	Surface roughness	The ratio between the actual surface area and that of a flat plane occupying the same *x*, *y* extent. This indicates surface roughness or convolutedness. Actual surface area is also important in many ecosystems when competition for space is a key structuring process and may be particularly relevant for densely vegetated floodplains such as that of the Amazon (Salo et al., 1986).	Hobson (1972), Nogami (1995), Jenness (2004), Kuffner et al. (2007), Wilson et al. (2007), Wedding et al. (2008), McGarigal et al. (2009), Walker et al. (2009), Friedman et al. (2012)
Texture	Density of pits and peaks	The density of pits and peaks across the surface. This metric is calculated as the number of pits and peaks within a given radius of each cell and first requires the identification of pits and peaks. This metric is similar to Hobson's (1972) *bump frequency distribution* that incorporates the number of peaks within an area and their magnitude.	Hobson (1972), Iwahashi and Pike (2007)
Fractal dimension	Geometric complexity of the surface	The fractal dimension of a surface can range between 2 and 3. A surface with a fractal dimension of 2 is a flat plane, while a surface with a fractal dimension approaching 3 is so convoluted that it almost fills the entire volume of its *x*, *y*, *z* extent. There are numerous techniques for measuring the fractal dimension of a surface, each with varying accuracy (Zhou and Lam, 2005).	Clarke (1986), Dubuc et al. (1989), Moore et al. (1991), Wood (1996), Zhou and Lam (2005), Wilson et al. (2007), Zawada and Brock (2009), Zawada et al. (2010)
Entropy	Diversity and variability in surface heights	The amount of uncertainty associated with predicting the height of a cell selected at random from all cells within the surface. Shannon entropy is likely the most appropriate calculation of entropy for topographical applications; however, other probability-related metrics are also available (Musick and Grover, 1990).	Musick and Grover (1990), Nogami (1995), Wood (1996), Phillips (2006)
Surface variogram	Spatial autocorrelation, spatial lags	The variogram of a topographic surface plots the change in variance of sampled surface heights against distance between sample locations. This metric can be calculated along uni- or omni-directional transects or within an area and is quantified by various parameters of the variogram plot (Legleiter, 2014a). Similar metrics have been referred to as *divergence index* and *variance staircase*.	Mark and Aronson (1984), Turner et al. (1990), Mertes et al. (1995), Wood (1996), Lane (2000), Dorner et al. (2002), Phillips (2006), Wilson et al. (2007), Legleiter (2014a)