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Potential and actual geomorphic complexity of restored headwater streams in northern Sweden

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ABSTRACT

Stream restoration usually relies on ecological theories presuming that increased habitat heterogeneity leads to higher biodiversity. However, to test this hypothesis a quantitative metric of overall geomorphic complexity is needed. We quantified geomorphic complexity using 29 metrics over five dimensions (sediment distribution, longitudinal profile, cross section, planform, and instream wood) of headwater streams in northern Sweden. We examined reaches with four different restoration statuses after a century of timber floating (channelized, restored, demonstration restored, and unimpacted) to determine (1) whether restoration increases complexity in all dimensions, (2) whether a complexity gradient can be quantified and which metrics can serve as proxies for the gradient, and (3) levels of potential complexity based on large-scale controls (drainage area, glacial legacy sediment, valley slope, valley confinement, old-growth forest/buffer zone, and beaver activity). We found a significantly higher complexity in unimpacted and demonstration restoration sites than in channelized sites in all five dimensions except the cross section (based on the two metrics quantifying variability in the cross section). Multivariate analyses were able to elucidate an apparent complexity gradient driven by three complexity metrics: longitudinal roughness, sediment sorting, and cross section chain and tape ratio. The large-scale factors of valley and channel gradient as well as median grain size, along with restoration status, drive differences in complexity composition. Restoring a reach to its potential complexity is beneficial in regions without reference systems or sufficient data to model flow and sediment processes. Unimpacted and demonstration restoration reaches displayed not only more intrareach variability than channelized reaches but also greater interreach heterogeneity in complexity composition, which supports a focus on reach-scale controls on potential complexity and a landscape-scale view on restoration.

1. Introduction

1.1. Background

Ecological theory presumes that increases in habitat heterogeneity will lead to greater biodiversity (Kerr and Packer, 1997; Palmer et al., 2010), which is often used as a measure of ecosystem health and resilience (Chapin et al., 2000; Young, 2000). Therefore, restoration of degraded aquatic and riparian environments often involves measures to increase geomorphic complexity, under the assumption that increased heterogeneity in geomorphic forms and structure will increase the number of species supported through niche diversification and provision of habitat for various life stages and behaviors (Elosegi et al., 2010). However, restoring riverine ecosystems by increasing geomorphic complexity has had mixed success, especially where stream degradation is a function of catchment-scale anthropogenic impacts rather than direct modification of the channel and/or floodplain (Pretty et al., 2003; Palmer et al., 2010).

Biodiversity has been explicitly linked to several specific aspects of fluvial complexity (Ward and Tockner, 2001; Elosegi et al., 2010). At the microhabitat scale, diversity in invertebrate taxa increases with varying grain size, as specific taxa require a specific range of sediment grain sizes (Vinson and Hawkins, 1998). At the reach scale, fish diversity is tied to several factors, including the diversity of bedform features, gravel bars, and bank types, as well as instream wood structures because various fish species require different habitats throughout their life cycle (Schlosser and Angermeier, 1995). At the catchment scale, the variation and spatial organization of process domains (sensu Montgomery, 1999), which describe local disturbance regimes that govern aquatic and riparian community organization, determine large-scale species diversity (Nilsson et al., 1989). Species respond differently to disturbance regimes, which are governed by local processes, such as hillslope sediment contributions, flooding magnitude and frequency, and channel migration or avulsions (Montgomery, 1999; Polvi et al., 2011). Therefore, logically it should follow that if it is possible to restore, or at least increase, complexity at a given spatial scale, restoration should positively affect diversity of taxa at that scale.

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Within the field of geomorphology, the term 'complexity' has been used in various contexts, either to explain theories of complex behavior or to describe and quantify the degree of heterogeneity exhibited in morphologies. The theories and processes that explain complex-systems research include ideas on how processes interact, self-organize, and can be deduced: chaos theory shows that simple, nonlinear interactions can lead to dynamic behavior; self-organizing patterns (including fractals) lead to internal events causing abrupt shifts in the system or cause large external signals to be drowned out by the internal feedbacks or self-organization; and self-organization and feedbacks affect both directions of spatial scales, implying that the most fundamental scale for analysis may not be the smallest scale (Murray et al., 2009). Morphologic complexity is most often discussed in relation to connections to either (i) restoration after anthropogenic impacts, because human impacts to many geomorphic systems have directly or indirectly created a simplified system (e.g., Wohl, 2001), or (ii) ecological processes, because heterogeneity in landscapes and landscape processes leads to habitat and thus species diversity, which may even induce feedbacks for geomorphic processes (Palmer et al., 2010; Polvi and Wohl, 2012).

Traditionally, in the field of geomorphology, fluvial forms and processes have been characterized using the average or trend, such as reporting the bed gradient when characterizing the longitudinal profile or the median grain size to describe the sediment size distribution, whereas describing complexity involves separating the noise from the signal by quantifying the variability around the trend. Complexity metrics have been used to describe transient storage and uptake of nutrients or organic matter (Gooseff et al., 2007; Baker et al., 2012), relate stream morphology to land use (Gooseff et al., 2007; Laub et al., 2012), and quantify anthropogenic degradation or evaluate restoration (Bartley and Rutherfurd, 2005; Lepori et al., 2005; Rayburg and Neave, 2008; Jähnig et al., 2009; Laub et al., 2012). Previous studies have characterized metrics of geomorphic variability, usually focusing on those thought to be most related to the response variable measured (e.g., nutrient retention, degree of urbanization, or species abundance), based on several spatial dimensions, including the longitudinal profile, cross section, sediment size distribution, and planform.

Although geomorphologists, and even most laypeople, can qualitatively discern stream reaches with various degrees of complexity, two difficulties remain: (i) quantifying an overall reach-scale level of complexity for streams, and (ii) comparing levels of complexity between reaches with different levels of potential complexity based on valley and basin controls. Various studies have quantified complexity in various dimensions for specific purposes, either relating it to a particular species or a discrete disturbance (e.g., Bartley and Rutherfurd, 2005), but few have attempted to integrate the degree of complexity for all dimensions over an entire reach. Laub et al. (2012) attempted to but were unable to quantify a gradient of complexity for urban, forested, and restored streams in Maryland and Colorado, USA. Streams from a similar geographic location with similar land use had most similar complexity metrics, but each type of stream reach was more complex than the others for at least one complexity metric. Comparisons of complexity between different physiographic regions and with various land uses may be hindered by differences in potential complexity of a given reach. For example, a reach within a confined valley with low gradient hillslopes will not be able to form multithread channels nor will it receive colluvial inputs of large boulders, reducing the possible potential complexity. Differences in gradients of complexity may be explained by different controlling geomorphic factors, such as sediment sources, biotic interactions, and channel mobility. Direct and indirect anthropogenic history, such as channel modification and land use, can also affect reach-scale complexity; however, larger landscape-scale controls, which can take centuries or more to adjust, will determine a reach's potential complexity. An understanding of potential complexity is particularly important where appropriate reference conditions are not available for anthropogenically degraded stream reaches and where restoration measures seek to increase complexity for the sake of fish habitat and biodiversity. We argue that restoration and evaluation of complexity in streams with reach-scale, in-channel modifications require consideration of larger scale controls—and thus an assessment of the differences in natural potential complexity between reaches.

1.2. Large-scale controls on channel form and complexity

We identify six large-scale controls, specific to northern Sweden, yet applicable to many other regions, that have varying effects on the different dimensions of fluvial complexity: drainage area, glacial legacy sediment, valley slope, valley confinement, old-growth forest/buffer zone, and beaver activity. In order to conceptually determine the potential complexity of a given reach, we present the effects of increasing the magnitude of each large-scale control on each complexity dimension (Table 1). Because an increase in a large-scale control may have differing effects on each of the five complexity dimensions (sediment distribution, longitudinal, cross section, planform, instream wood), determining each effect separately is important. Increasing the magnitude of each of these large-scale controls does not always show the same directional change in complexity in each dimension and can even show mixed results depending on magnitude of effect or other interacting effects (Table 1). For example, an increase in valley confinement increases fluvial complexity for the longitudinal profile, cross section, sediment distribution, and instream wood, but decreases complexity in the planform dimension; whereas an increase in beaver activity and thus dams will increase complexity in the longitudinal profile and planform but show mixed effects in the cross section, sediment distribution, and instream wood dimensions. However, the directionality or linearity of the effect may not be the same for all settings. In the semialluvial setting of northern Sweden, an increase in valley gradient will lead to an increase in longitudinal complexity; however, in purely alluvial settings this may not be the case as channels transition through the plane bed bedform.

1.3. Objectives

The objectives of our study were (i) to determine whether different dimensions of complexity (sediment distribution, longitudinal, cross section, planform, instream wood) or specific complexity metrics respond equally to reach-scale restoration in northern Sweden, (ii) to examine whether an overall gradient of instream complexity can be quantified for stream reaches with different levels of restoration in a forested catchment after a century of timber floating caused irrevocable in-channel modifications, and (iii) to analyze the larger scale (catchment- and reach-scale) controls on the observed gradient of instream complexity and present a relative model of potential complexity for the reaches studied. These objectives will serve to assist in setting and carrying out stream restoration goals. Although we do not present ecological data here, we discuss the results in terms of relating geomorphic complexity to biodiversity.

2. Regional setting

2.1. Climatic, geologic, and geomorphic setting

Our study reaches are located along tributaries of the Vindel River, which is a free-flowing river (i.e., unimpacted by hydropower or other large dams), flowing from the Scandes mountains, along the Swedish–Norwegian border, southeast toward the Gulf of Bothnia in the Baltic Sea. The Vindel River has a drainage area of ~12,500 km^2 at the confluence with the Ume River, 20 km northwest of the city of Umeå. The landscape of northern Sweden is geologically old, with the Cambrian-aged Caledonides forming the headwaters of most rivers, and the eastern portion of northern Sweden consisting of erosion surfaces and deposits from continental glaciation (Fredén, 1994). Because the bedrock in the Vindel River catchment consists mostly of Precambrian granites and metamorphic rocks and the landscape has fairly low relief (~200–600 m asl; Fredén, 1994), the landscape produces quite low