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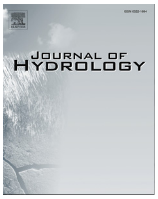

Research papers

Geology and geomorphology control suspended sediment yield and modulate increases following timber harvest in temperate headwater streams

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ABSTRACT

Suspended sediment transport is an important contributor to ecologic and geomorphic functions of streams. However, it is challenging to generalize predictions of sediment yield because it is influenced by many factors. In this study, we quantified the relevance of natural controls (e.g., geology, catchment physiography) on suspended sediment yield (SSY) in headwater streams managed for timber harvest. We collected and analyzed six years of data from 10 sites (five headwater sub-catchments and five watershed outlets) in the Trask River Watershed (western Oregon, United States). We used generalized least squares regression models to investigate how the parameters of the SSY rating curve varied as a function of catchment setting, and whether the setting modulated the SSY response to forest harvesting. Results indicated that the highest intercepts (α) of the power relation between unit discharge and SSY were associated with sites underlain primarily by friable rocks (e.g., sedimentary formations). The greatest increases in SSY after forest harvesting (up to an order of magnitude) also occurred at sites underlain by the more friable lithologies. In contrast, basins underlain by resistant lithologies (intrusive rocks) had lower SSY and were more resilient to management-related increases in SSY. As such, the impact of forest management activities (e.g., use of forested buffers; building of new roads) on the variability in SSY was primarily contingent on catchment lithology. Sites with higher SSY, or harvest-related increases in SSY, also generally had a) lower mean elevation and slope, b) greater landscape roughness, and c) lower sediment connectivity. We used principal component analysis (PCA) to further explore the relationship between SSY and several basin physiographic variables. The PCA clearly separated sites underlain by friable geologic units from those underlain by resistant lithologies. Results are consistent with greater rates of weathering and supply of sediment to headwater streams in catchments with more friable lithologies, and limited sediment supply in catchments underlain by resistant lithologies. We hypothesize that a similar framework may aid in predicting the overall SSY of a catchment as well as its susceptibility to increases in SSY following forest harvesting.

1. Introduction

Mountainous headwater streams may disproportionally contribute to global sediment discharge (Kao and Milliman, 2008; Milliman et al., 1999; Milliman and Syvitski, 1992), particularly if impacted by land-use practices that often increase fine sediment transport and deposition (Binkley and Brown, 1993; Croke and Hairsine, 2006; Gomi et al., 2005; Montgomery, 2007; Sofia et al., 2016; Tarolli and Sofia, 2016). Fine sediment can negatively impact fishes and other aquatic ecosystem elements (Kemp et al., 2011; Suttle et al., 2004) and degrade water quality (Brown and Binkley, 1994; Wood and Armitage, 1997). It is, therefore, considered a pollutant under the United States (US) Clean Water Act. In the western US, where mountainous regions of the temperate Pacific Northwest (PNW) are targeted for timber harvesting activities, the Environmental Protection Agency has classified >70% of streams as water-quality impaired—~19,000 km of streams are threatened by sediment pollution in Oregon alone (United States Environmental Protection Agency, 2016). Despite this, Total Maximum Daily Loads (TMDLs) for suspended sediment have not been defined in many states, including Oregon. As such, deciphering the relative controls on suspended sediment transport in mountainous headwater streams may be particularly crucial for understanding both local effects important for water quality standards in

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timber-dependent economies (Haynes, 2003; Prestemon et al., 2015) as well as mass flux of material on a broader scale.

In an effort to quantify the impact of forest practices on fine sediment dynamics in temperate headwater catchments, an early paired-watershed study (Alsea Watershed Study in Oregon) compared 1960's forest harvesting practices that included clearcutting and burning of slash to forest management practices that retained riparian vegetation along streams as buffers (Beschta, 1978; Brown and Krygier, 1971). This study became the prime example of the environmental consequences of unregulated logging, as annual sediment yields increased up to 500% in the more heavily disturbed catchment (Beschta, 1978). In part based of these findings, contemporary forest management practices now limit slash burning, harvest size, and harvest frequency, while requiring riparian buffers to be retained around streams (e.g., Oregon's Forest Protection Laws). The principal objectives of these regulations is to mediate increased sediment yields to streams and regulate stream temperatures. A number of paired-watershed studies have since occurred to assess the efficacy of *modern* forest practices on limiting suspended sediment yields (SSY). The conclusions of these studies have been mixed (Binkley and Brown, 1993; Gomi et al., 2005) showing increases (i.e., Macdonald et al., 2003), decreases (i.e., Grant and Wolff, 1991), and no changes (i.e., Hotta et al., 2007) in SSY, hindering generalization concerning controls on sediment flux rates in catchments impacted by contemporary forest management activities.

The impacts of land-management on SSY are generally a function of both sediment supply and transport capacity. However, thresholds for fine-sediment motion are met frequently in most systems, often rendering sediment supply the limiting factor (Church, 2002; Paustian and Beschta, 1979). Sediment supply generally varies across landscapes depending on factors associated with catchment setting, such as climate, physiography, and geology, or disturbance history (Buss et al., 2017; Croke and Hairsine, 2006; Gomi et al., 2005; Hicks et al., 1996; Johnstone and Hilley, 2014; Montgomery, 1999; Montgomery and Brandon, 2002; O'Byrne, 1967; O'Connor et al., 2014). For instance, SSY was greater in more erodible (e.g., sedimentary and volcanics) lithologies compared to more resistant lithologies in Western Oregon and northwestern California (Wise and O'Connor, 2016), the Idaho Rocky Mountains (Mueller et al., 2016; Mueller and Pitlick, 2013), Wyoming (Colby et al., 1956), and in New Zealand (Hicks et al., 1996). However, following high severity disturbances like wildfire, the potential role of lithology may be greatly reduced relative to the fine-sediment supply associated with the disturbance (Moody et al., 2008; Wise and O'Connor, 2016).

Factors such as physiography and land management affect SSY, but the relative influence of these in relation to other controls is less clear. In a global analysis of large rivers, Syvitski and Milliman (2007) found that geologic and physiographic variables explained the majority of variance in long-term SSY among sites (65%), whereas climate and land use accounted for 14% and 16%, respectively. In a setting of uniform lithology, Klein et al. (2012) found that harvest intensity and drainage area best predicted 10% turbidity exceedance levels (indicative of chronic turbidity), whereas physiographic variables did not improve the prediction. For Washington streams draining managed forests of the PNW, turbidity (a proxy for suspended sediment transport) was correlated with geologic province, independent of forest management practices (Reiter et al., 2009). Thus, evidence suggests that both basin characteristics (lithology and physiographic conditions) and land management influence SSY. Furthermore, interdependencies between catchment setting and the response of SSY to land management activities may exist. For example, in North Westland catchments of New Zealand, O'Loughlin and Pearce (1976) found the most substantial increases in SSY occurred following forest removal in catchments underlain by easily erodible sedimentary formations.

The purpose of this research was to examine the relative influence of basin setting (lithology and basin physiographic variables) and forest management on SSY in temperate headwater catchments. Specifically, we analysed 6 years of data from a watershed, which included harvested and unharvested sub-catchments and was underlain by heterogeneous lithologies, to achieve the following objectives:

1. Quantify how suspended sediment yield varies by catchment setting in forested headwater catchments;
2. Determine whether contemporary forest management practices impact annual suspended sediment yield in forested headwater catchments;
3. Determine whether there are natural catchment settings that result in different levels of vulnerability or resilience to increases in suspended sediment yield associated with disturbances (e.g., harvest activities).

These objectives provide the structural subheadings used in the following Methods, Results, and Discussion sections.

2. Background

2.1. Trask River Watershed Study

We used data from the the Trask River Watershed Study (TRWS) of Oregon's Watersheds Research Cooperative (WRC; http://watershedsresearch.org/). The WRC studies were established to investigate the impact of contemporary forest management practices on biological, chemical, and physical water quality, including fine-sediment transport. TRWS is located in the northern Oregon Coast Range, occupying ~25 km^2 on the East Fork South Fork Trask River in the Wilson-Trask-Nestucca Watershed, which drains to the Pacific Ocean at Tillamook Bay (Fig. 1). The TRWS used a nested, paired-watershed approach. The study area is composed of four larger catchments: Pothole (PH), Gus Creek (GC), Upper Main (UM), and Rock Creek (RCK), with each encompassing several smaller sub-catchments (Fig. 1). Three of these larger catchments (PH, GC, and UM) included harvested sub-catchments, while one catchment (RCK) remained unharvested as a reference (Table 1). We used data from 10 sites, which had continuous records of discharge and suspended sediment across the period of interest, including five headwater sub-catchments and five watershed outlets.

Baseline data collection began in water year 2010 and continued through water year 2015, with road upgrades (July–August 2011) and harvest (May–November 2012) occurring in the middle of the study period. In particular, new roads were built July through August 2011 in the UM (UM1 and UM2) and GC (GC3) watersheds (Table 1). No new roads were built in the PH watershed; however, upgrades on existing roads occurred throughout the TRWS (August 2011). Road densities were similar for all watersheds, with UM2 and GC3 having slightly higher densities (Table 1). Harvest treatments of study sub-watersheds consisted of clearcuts (UM2 and GC3) and a clearcut with buffers (50 ft; ~15 m; PH4) that were conducted May–November 2012. Depending on the slope, headwater sub-catchments were harvested using different contemporary techniques, including ground-based and cable logging (Table 1).

Forests in the TRWS are dominated by second-growth Douglas-fir (*Pseudotsuga menziesii*), with populations of red alder (*Alnus rubra*) primarily located in riparian areas. The entire watershed has been subjected to a combination of historic fires (Tillamook