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Key Points:
- Suspended sediment yield in temperate mountain catchments was a function of annual hydrology and geomorphic setting
- Physiography (variability of watershed slope) predicted overall suspended sediment behavior
- Sites with high slope variability had higher suspended sediment yields and were more reactive to disturbances (e.g., storms and forest management)

Supporting Information:
- Supporting Information S1

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Relative Influence of Landscape Variables and Discharge on Suspended Sediment Yields in Temperate Mountain Catchments

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Abstract Suspended sediment is an important regulator of stream habitat quality but notoriously difficult to predict and regulate. This difficulty arises because of high natural variability in suspended sediment yield in space and time. Here we quantified associations between suspended sediment yields and discharge, watershed setting (i.e., physiography and lithology), and disturbance history for 10 temperate mountain watersheds (8.5–6,242 ha) in the U.S. Pacific Northwest (H.J. Andrews Long-Term Ecological Research, LTER) over an ~60-year period. Annual suspended sediment yields varied almost 4 orders of magnitude across space and time. A linear mixed effects model indicated that much of the variation in yields could be explained by the random effect of site (conditional R^2 = 0.74) with additional variation explained by the fixed effects (marginal R^2 = 0.67) of cumulative annual discharge ($p < 0.001$) and the variability (standard deviation) of watershed slope ($p < 0.001$). Two annual sediment yield data points were model outliers, that each occurred within a decade after forest management activities and a large-magnitude storm event at sites with high variability of catchment slope. Other sites had low sediment yields for a range of conditions, including management or flood disturbance. Taken together, our study shows that watersheds with high slope variability have higher suspended sediment yields and may be more vulnerable to increases in sediment yields following disturbances.

1. Introduction

Suspended sediment transport is a natural process that has the potential to impact water quality (Bilotta & Brazier, 2008; Binkley & Brown, 1993; Brown & Binkley, 1994; Wood & Armitage, 1997), aquatic habitat (Kemp et al., 2011; Suttle et al., 2004), and landscape evolution (Milliman & Meade, 1983; Milliman & Syvitski, 1992). However, suspended sediment is notoriously variable in space and time, creating difficulties for the development of predictive models (Croke & Hairsine, 2006; Gomi et al., 2005). This has also created challenges for developing suitable Total Maximum Daily Loads (TMDLs) for sediment, which may be used to estimate background sediment yields and develop regionally specific water quality standards (Borah et al., 2006).

This is an important challenge in regions where forests and forest harvesting remain important for the economy. For example, forests in the temperate U.S. Pacific Northwest (PNW), including Oregon, Washington, and British Columbia, remain top timber producers in North America and local economies are heavily dependent on the forest products sector (Oregon Forest Resources Institute, 2017; State of Oregon, 2017). Forest management in these states/provinces has often been associated with increased sediment yields (Binkley & Brown, 1993; Brown & Binkley, 1994; Croke & Hairsine, 2006; Gomi et al., 2005). However, determining the background spatial and temporal patterns of suspended sediment, as well as the response to disturbances, remains difficult (Beschta, 1978; Fredriksen, 1970; Harris & Williams, 1971; Luce & Black, 1999).

There have been many studies in the PNW illustrating increased suspended sediment yields associated with forest management activities, including forest harvesting and road building. The Alsea Paired Watershed Study in Oregon was an important study that investigated the effects of clearcutting with and without riparian buffers, road building, and slash burning (Beschta, 1978; Brown & Krygier, 1971). Annual sediment yields increased ~2.8 times following intensive forest management practices (Beschta, 1978). Likewise, annual suspended sediment yields in the H.J. Andrews Experimental Forest (Oregon) were at least 12 times greater in watersheds that were clearcut and impacted by roads compared to the forested reference watershed (Grant & Wolff, 1991). Increases in both bed load and suspended sediment yield at the H.J. Andrews were attributed to harvest-related activities (Fredriksen, 1970; Grant & Wolff, 1991; Swanson & Fredriksen, 1982; Swanson & Jones, 2002). These studies and others (e.g., Beschta, 1978) provided critical knowledge that resulted in changes in forest practices in the PNW and elsewhere particularly aimed at mitigating impacts on sediment production and stream temperature (Hairston-Strang et al., 2008). However, there was no relationship between forest harvesting and increased suspended sediment yields in other studies, including the Alsea Watershed Study Revisited (Hatten et al., 2018), Middle Santiam River (Sullivan, 1985), Coyote Creek (Harr & McCorison, 1979), and Bull Run Watershed (Harr & Fredriksen, 1988; Rinella, 1987). In many cases, changes in forest practices that include smaller harvest areas and retention of riparian buffers have reduced the relationship between forest harvesting and increased suspended sediment yields compared to historical practices (Klein et al., 2012; Reiter et al., 2009; Terrell et al., 2011; Warrick et al., 2013). However, contemporary practices have not always been effective—others have continued to observe elevated suspended sediment after forest harvesting, even with the use of contemporary best management practices (Arthur et al., 1998; Bywater-Reyes et al., 2017; Wear et al., 2013).

The variability in response to forest harvesting may be due, in part, to the multitude of variables that influence suspended sediment yields. For example, catchment lithology, physiography, land cover, land use, and hydrologic conditions may all impact suspended sediment (Croke & Hairsine, 2006; Larsen et al., 2014; Mueller et al., 2016; Preston et al., 2011; Roman et al., 2012; Syvitski & Milliman, 2007; Wise & O'Connor, 2016). However, the majority of studies assessing suspended sediment yields rarely emphasize more than a few potential variables, partly because of limited spatial and temporal resolution of data sets. For example, Wise and O'Connor (2016) considered the association between sediment yields and lithology, physiography, and annual precipitation for Oregon. Land management and potential temporal trends in hydrologic conditions were excluded from the analysis by adjusting results relative to a fixed time period. Similarly, Bathurst and Iroumé (2014) analyzed the suspended sediment response to harvesting for 51 paired sites worldwide. They attributed most of the variability in sediment response across these sites to differences in the magnitude of ground disturbance or the occurrence of extreme storm events. However, variability in site lithologic or physiographic characteristics was not included in their analysis. Another recent study also showed that the variability in suspended sediment yield after contemporary forest practices was related to catchment lithology and physiography (Bywater-Reyes et al., 2017). The association of extreme hydrologic events and suspended sediment yield has been highlighted in other cases (Abbott et al., 2017; Grant & Wolff, 1991; Kao & Milliman, 2008; McBroom et al., 2003; Rainato et al., 2017; Swank et al., 2001; Wemple et al., 2001). However, generally, climate has had a secondary association with suspended sediment yields relative to catchment physiography, lithology, and land management (Milliman & Syvitski, 1992; Summerfield & Hulton, 1994; Syvitski & Milliman, 2007).

To improve our ability to predict suspended sediment yields, we must quantify how sediment yields vary with respect to catchment setting (e.g., lithology and physiography), discharge (annual and event-based), and disturbance history. In this paper, we use a temperate catchment in mountainous terrain with an exceptional spatial and temporal resolution of suspended sediment data to answer the following questions:

1. What is the relative association between discharge and catchment setting (i.e., lithology and physiography) and suspended sediment yields over an ~60-year period?
2. Is there an association between historical forest management activities (i.e., forest harvesting and road building) or extreme hydrologic events and the spatial and temporal trends in suspended sediment yield?

2. H.J. Andrews Experimental Forest

The H.J. Andrews Experimental Forest (Figure 1) is a Long-Term Ecological Research (LTER) Network site, located within the Western Cascade Range of Oregon (H.J. Andrews Experimental Forest Long Term Ecological Research, 2017). The Andrews Forest was established in 1948 and is composed of 10 catchments ranging in size from 8.5 to 6,242 ha (Table 1) within the McKenzie River Basin (Swanson & Jones, 2002). All instrumented catchments are located within the Lookout Creek Watershed (LOOK), except for Watershed 1 (WS01) and WS09 that drain below the LOOK gauge and WS10 that drains to the adjacent Blue River (Figure 1).

The climate is marine temperate (Cfb Köppen-Geiger Classification, Kottek et al., 2006) with mean annual precipitation ranging from 2,200 to 2,600 mm. The majority of precipitation falls in winter months, whereas

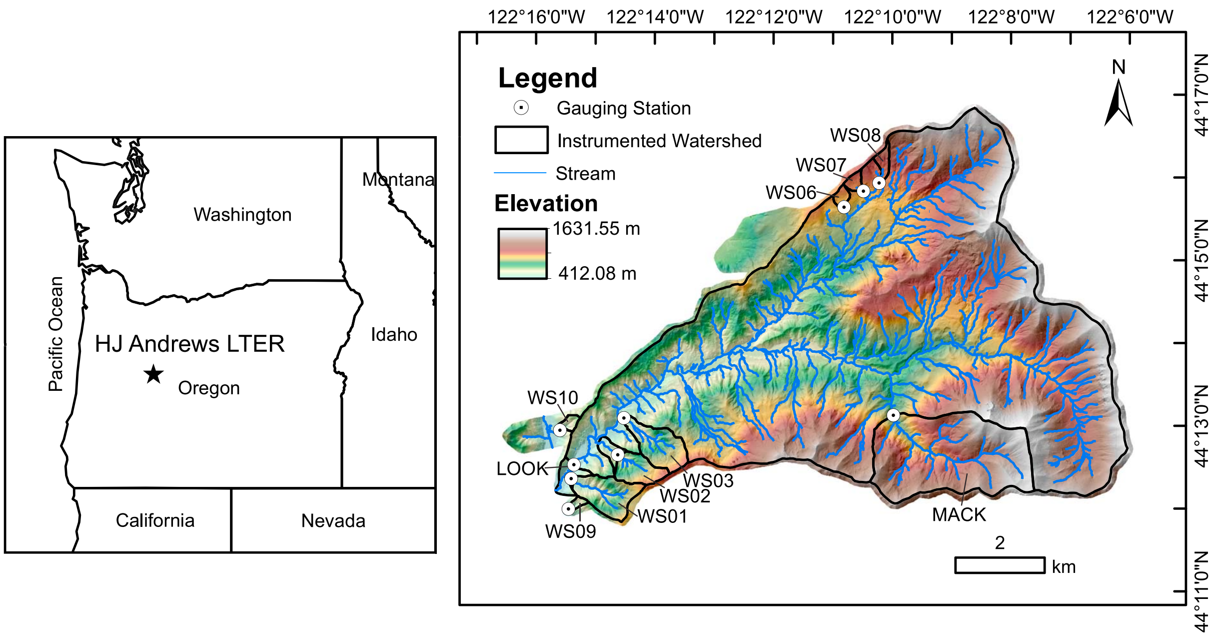

Figure 1. Map of the H.J. Andrews LTER and location within Oregon, including elevation, stream network, and location of gauging sites.

Table 1
Characteristics of Monitored Watersheds in the H.J. Andrews Forest

Watershed	Drainage area (ha)	Elevation range (m)	Mean slope (°)	Dominant lithology	Management history	Discharge[a] agency/ID	SSC data set	Suspended sediment record[d]
Lookout (LOOK)	6,242	421–1,627	21.9	All observed	25% patch-cut 1948–present	USGS 14161500	Composite[b] GSLOOK	2005–2015
Mack Creek (MACK)	581	755–1,626	25.8	Lava	Control; 12.9% harvest and road near drainage divide ridge	HJ Andrews GSWSMA	Composite[b] GSMACK	1971–2015
Watershed 1 (WS01)	96	439–1,027	30.7	Altered pyroclastics	100% clearcut 1962–1966; prescribed burned 1966	HJ Andrews GSWS01	Storm-based[c] and Composite[b] GSWS01	1956–1970, 1972–1988, 2003–2015
Watershed 2 (WS02)	60	545–1,079	28.0	Altered pyroclastics	Reference	HJ Andrews GSWS02	Storm-based[c] and Composite[b] GSWS02	1956–1970, 1972–2015
Watershed 3 (WS03)	101	471–1,080	27.7	Altered pyroclastics	1.5 km (6%) roads 1959; 25% clearcut in 3 patches 1962–1963; slash burned 1963; debris flows 1965 and 1996	HJ Andrews GSWS03	Storm-based[c]	1956–1970, 1972–1988
Watershed 6 (WS06)	13	878–1,029	14.1	Lava/tuff	100% clearcut 1974; broadcast burn 1975; road built 1976	HJ Andrews GSWS06	Composite[b] GSWS06	1972–1987, 2003–2015
Watershed 7 (WS07)	15.4	918–1,102	18.6	Lava	60% selective canopy removal 1974; broadcast burned 1975; remaining canopy removed 1984; thinned 2001	HJ Andrews GSWS07	Composite[b] GSWS07	1972–1987, 2002–2015
Watershed 8 (WS08)	21.4	962–1,182	14.5	Lava	Reference	HJ Andrews GSWS08	Composite[b] GSWS08	1972–1976, 1978–2015
Watershed 9 (WS09)	8.5	438–731	30.7	Altered pyroclastics	Reference	HJ Andrews GSWS09	Composite[b] GSWS09	1969–1971, 1974–2015
Watershed 10 (WS10)	10.2	461–679	30.2	Altered pyroclastics	100% clearcut 1975; debris flow 1986; 1996	HJ Andrews GSWS10	Composite[b] GSWS10	1971, 1973, 1975–2015

[a]Johnson and Rothacher (2016). [b]Johnson and Fredriksen (2017); suspended sediment concentration (SSC) samples were collected as three-week composites collected proportional to streamflow. [c]Jones and Grant (2003); suspended sediment concentration (SSC) samples were collected with vertically integrated storm-based grab samples 1958–1988 for WS1, WS2, and WS3; data previously used in Swanson and Fredriksen (1982) and Grant and Wolff (1991). [d]Suspended sediment reported for years with SSC samples and no more than four days of missing Q four SSC samples.

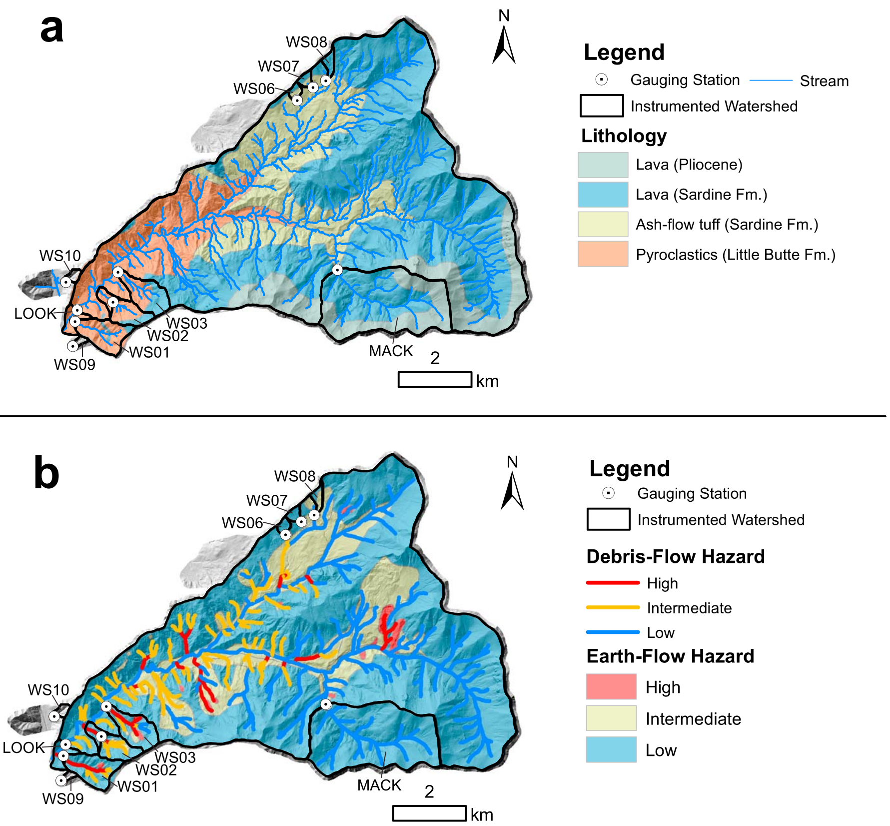

Figure 2. Maps of (a) lithology and (b) debris-flow and earthflow hazards.

summers are generally dry. Precipitation patterns vary with elevation, with higher elevation catchments (WS06, WS07, WS08, and Mack Creek [MACK]) receiving more precipitation as snow (H.J. Andrews LTER, 2017). Typical of Pacific Northwest watersheds, infiltration capacity generally exceeds precipitation intensity so that subsurface flow paths dominate runoff generation (Govindaraju et al., 2012; Johnson & Beschta, 1980; Swanson & Jones, 2002). The two largest flood events of record occurred in water years 1965 (30-year return period) and 1996 (60-year return period). Forests consist mostly of native conifers, dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) with some noble fir (*Abies procera*) and Pacific silver fir (*Abies amabilis*) at upper elevations (Swanson et al., 1998).

The instrumented catchments are located in different lithologic/geomorphic domains (Table 1). Landscape evolution of the H.J. Andrews has been associated with convergent mountain building of the Western Cascades (late Oligocene to early Miocene), together with glacial, hillslope, and fluvial geomorphic processes (Swanson & James, 1975). Lithology (Figure 2) generally varies with elevation, such that low-elevation regions are composed of hydrothermally altered pyroclastic flows (Little Butte Formation; Oligocene to lower Miocene), midelevation regions are often welded ash-flow tuff (Sardine Formation; Miocene), and higher-elevation regions are principally ridge-capping andesite lava flows (upper Sardine Formation and Pliocene flows; Swanson & Jones, 2002). Glaciation occurred at high elevation, leaving U-shaped valley morphologies within ridge-capping lava flows. Mass movements occur mainly within the Little Butte Formation and in portions of the Sardine Formation (Figure 2; Swanson & Jones, 2002). The altered pyroclastics of the Little Butte Formation are particularly prone to slope failures (Swanson & Dyrness, 1975). When separated by type, slow-moving earthflows have scarps within ridge-capping lava of the Sardine Formation (Swanson & Jones, 2002). Faster-moving debris flows are concentrated mostly within the altered pyroclastics of the Little Butte Formation but also occur in association with earthflows (Figure 2; Swanson & Dyrness, 1975; Swanson & James, 1975). WS01, WS02, WS03, WS09, and WS10 are underlain predominantly by altered pyroclastic flows, whereas WS06, WS07, and WS08 are underlain predominantly by lava flows. MACK is underlain by lava flows and was formerly glaciated (Figure 2).

3. Methods

Samples for determination of suspended sediment concentration (SSC) were collected using either vertically integrated storm-based grab samples (legacy data set; Jones & Grant, 2003) or discharge-proportional composite samples (nutrient data set; Johnson & Fredriksen, 2017). Composite samples were collected by H.J. Andrews LTER staff approximately every three weeks at the outlet of each catchment (Table 1). Discharge (Q) measurements for LOOK were managed by the U.S. Geological Survey (USGS; 14161500), while monitoring and measurements in all other flumes and weirs were managed by H.J. Andrews LTER (Table 1; Johnson & Rothacher, 2016).

For each SSC sample, we calculated suspended sediment load (Q_s) as the product of SSC and discharge (Q). As a result of the two different SSC sample collection methods, we used the following approaches to ensure that the two data sets were comparable. For legacy, storm-based samples, Q_s was calculated as the product of the SSC and the corresponding instantaneous Q for each sampling instance. We had to treat the composite sediment samples differently because the exact *SSC-Q* relationship was unknown. Thus, we calculated Q_s for these samples as the average of the product of the single, composite SSC and all the instantaneous (15-min) Q over the three-week collection period. This resulted in a Q-Q_s pair for each SSC sample, which we then used to derive rating curves (see below). Other approaches were considered to compute Q_s for the composite samples, including using the maximum and median discharge of the collection period, but the mean-value approach was found to produce results most consistent with the legacy samples and the values reported by H.J. Andrews LTER (Johnson & Fredriksen, 2017).

We calculated annual Q_s based on a rating-curve approach, whereby a relationship between Q_s and Q for each SSC sample was developed using a linear statistical model. We used a step-Akaike information criterion (AIC) approach for stepwise selection of model parameters (Hastie & Pregibon, 1992; Venables & Ripley, 2002) to develop relationships between log (Q_s) and log (Q), including the factors site, water year, and collection method. We considered all two-way interactions among the predictor variables. This allowed the rating curve to vary by site, year, and collection method. We then selected the model with the lowest AIC to predict daily Q_s based on mean-daily Q values for each site and the associated site-year rating curve. We corrected for collection method by making the prediction using the legacy/storm-based parameter estimate.

We divided Q_s values by catchment area to calculate daily sediment yields, then summed these values to calculate an annual sediment yield for each water year. As an error estimate, we considered the 95% confidence interval of the prediction. All sediment yields were log-transformed prior to model development. We then back-transformed estimated sediment yields for presentation and interpretation purposes. A smearing factor (Duan, 1983) was used in back-transformation to correct for log bias. We report sediment yields only for years with no more than four days of missing Q and at least four SSC samples per year (Table S1).

All statistical analyses were conducted in R (R Development Core Team, 2017), and figures were developed using the "ggplot2" package (Wickham, 2009).

3.1. Association Between Suspended Sediment Yield and Discharge or Catchment Setting

To determine the association between suspended sediment yield and discharge and/or catchment setting (i.e., lithology and physiography; question 1), we constructed candidate linear mixed effects models (Bates et al., 2015) to predict annual sediment yield (log-transformed to meet the normality assumption). We treated site as a random effect and included discharge and physiographic variables as fixed effects in candidate models. This enabled evaluation of the relationship between discharge and landscape characteristics with annual suspended sediment yield, accounting for site variability. We considered more complex random effects (e.g., including year or year-site interaction), but model performance was not improved (based on AIC; see below). We therefore retained the simpler random effects structure.

As predictors in the linear mixed effects model, we included descriptive statistics of discharge and physiographic characteristics, as described below. The different descriptive statistics of discharge (normalized by dividing by drainage area) used to describe the magnitude and variability of discharge on an annual basis included maximum Q, maximum Q from the previous year, cumulative annual Q, median Q, and variance of Q. Physiographic characteristics included (slope, elevation, roughness, and index of sediment connectivity) for each watershed from a high-resolution light detection and ranging (LiDAR)-derived (1 m) digital elevation

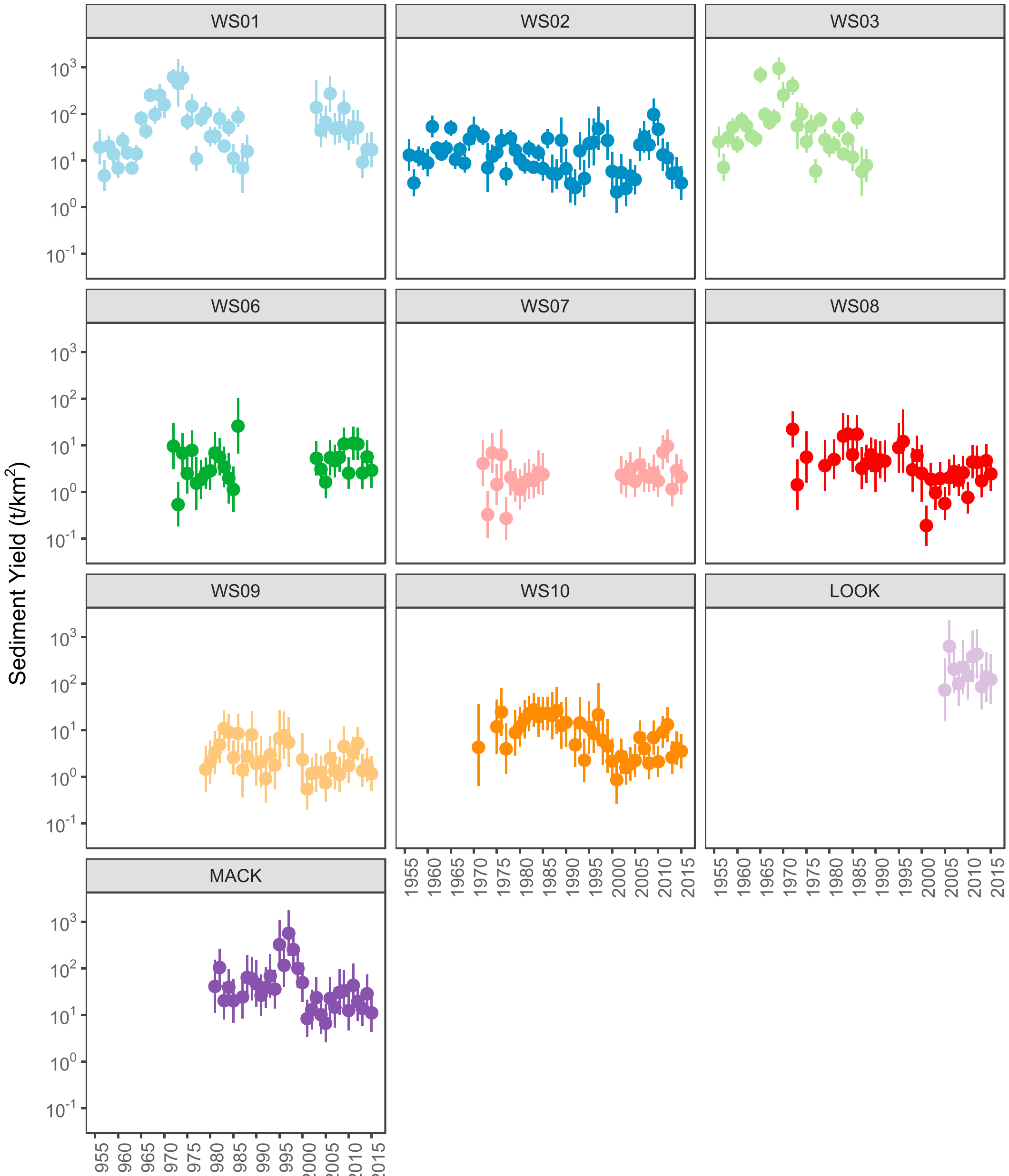

Figure 3. Annual suspended sediment yield by site with 95% confidence interval of prediction from rating curve shown. Yields vary 3 orders of magnitude across space and time.

model (Cavalli et al., 2013; Crema et al., 2015; Jenness et al., 2013; Spies, 2016). We selected these physiographic variables because they have previously been used to explain differences in suspended sediment yields across catchments in western Oregon (Bywater-Reyes et al., 2017). Briefly, relative elevation describes the shape of each watershed (hypsometry). As a roughness metric, topographic position index over a 10-m radius captures small-scale roughness features such as mounds, hummocks, swales, and gullies (Jenness et al., 2013; Majka et al., 2007). Index of sediment connectivity is a relative metric that considers how effectively up-stream topography is connected to downstream topography, which influences landscape sediment transport processes (Cavalli et al., 2013; Crema et al., 2015). To capture the entire distribution of values of each physiographic variable within each watershed, we considered statistical moments (mean, standard deviation, skewness, and kurtosis) of each variable. We additionally considered drainage area as a physiographic variable, as it has been found to be associated with suspended sediment yields in other studies (e.g., Church & Slaymaker, 1989).

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Table 2

Mean and Standard Deviation of Annual Suspended Sediment Yield at Each Site Using All Annual Yields, Showing Number and Type of Suspended Sediment Samples per Site[a]

Site	Mean annual sediment yield (t/km^2)	Median annual sediment yield (t/km^2)	Standard deviation (t/km^2)	SSC sample count	Sampling type
LOOK	231.3	147.9	141.8	136	Composite
MACK	67.7	31.9	17.0	420	Composite
WS01	97.1	48.0	205.5	1179 (976/203)	Storm-based/Composite
WS02	17.7	12.7	5.1	1278 (902/376)	Storm-based/Composite
WS03	108.2	42.7	2.2	1009	Storm-based
WS06	5.5	4.1	5.3	320	Composite
WS07	2.8	2.1	2.7	330	Composite
WS08	5.3	3.7	8.2	406	Composite
WS09	3.3	2.1	177.9	348	Composite
WS10	10.3	7.7	111.3	417	Composite

[a]See Table S1 for SSC by year and Table S3 for yields by year.

We used partial correlations between annual suspended sediment yields and the discharge and physiographic variables to determine predictor variables to include in the models (Rumsey, 2016). Because many of the discharge and physiographic variables were correlated with one another, we included only one discharge and one physiographic variable in each candidate model and compared more complex models to simpler models. We used a variance inflation factor (VIF) as a measure of multicollinearity often used as an indicator of poor regression coefficient estimation. Variables with VIF $>$ 5 were removed from candidate models (Neter et al., 1996).

We selected models based on AIC (Akaike, 1974) corrected for small sample size (AICc; Mazerolle, 2015). Models were considered plausible if their AICc value compared to the lowest AICc model (ΔAICc) was less than 3 (Richards, 2005). The relative importance of predictor variables was assessed by considering the change in response caused by a predictor if others were held at their midpoint (effect) with the "effects" package (Fox, 2003). Finally, we used a pseudo-R^2 for linear mixed-effect models that calculates conditional (random effect) and marginal (fixed effect) coefficients of determination ("MuMin" package; Barton, 2017) to assess model performance.

3.2. Relationship Between Disturbance History and Suspended Sediment Yield

We assessed whether disturbance history improved our prediction of annual suspended sediment yields over the duration of the study period (question 2) in three ways. First, we included a factor in the linear mixed effects model (described in section 4.1) indicating whether a watershed has a history of any forest management activities or whether it is a reference watershed (Table 1). Second, we identified instances where the linear mixed effects model (section 4.1) substantially underpredicted suspended sediment yield by considering standardized residuals greater than 2.5 as indicative of model outliers (Rousseeuw & van Zomeren, 1990). After isolating events where the observed sediment yields were substantially greater than the model

Table 3

Partial Pearson Correlation Coefficients Between Annual Yield and Hydrologic Variables[a]*, With Those ≥0.50 Italicized*

	Log (sediment yield)	Cum Q	Med Q	Var Q	Min Q	Lag Q
Max Q	0.43	0.60	0.23	0.78	~~0.09~~	0.69
Lag Q	0.38	0.50	0.25	0.68	~~0.08~~	
Min Q	0.40	0.41	0.27	~~0.01~~		
Var Q	0.32	0.57	0.38			
Med Q	0.35	0.71				
Cum Q	0.50					

Note. All were significant ($p < 0.05$) unless indicated with strikethrough font. Annual yield was most strongly correlated with the annual maximum discharge. Many correlations among hydrologic variables were moderate (>0.50).
[a]Max = maximum; Lag = maximum from previous year; Min = minimum; Var = variance; Med = median; Cum = cumulative.

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Table 4
Partial Pearson Correlation Coefficients for Strongest Correlations Between the Mixed Model Site Coefficient (Fixed Effect) and Physiographic Variables[a]

	Log (sediment yield)	Rel elev SD	TPI SD	TPI skew	TPI kurt	Slope mean	Slope median	Slope SD	IC SD
Rel elev SD	0.70								
TPI SD	0.51	0.52							
TPI skew	0.36	0.49	−~~0.10~~						
TPI kurt	0.48	0.76	0.22	0.32					
Slope mean	0.32	0.36	0.82	−0.45	~~0.02~~				
Slope median	0.35	0.37	0.85	−0.42	~~0.03~~	1.00			
Slope SD	0.72	0.81	0.80	0.45	0.54	0.43	0.47		
IC SD	0.57	0.66	0.22	0.75	0.71	−0.27	−0.22	0.73	
Area	0.38	0.65	~~0.02~~	0.29	0.94	−0.10	−~~0.09~~	0.35	0.62

Note. Those ≥0.50 italicized. All were significant ($p < 0.05$) unless indicated with strikethrough font. The site coefficient was most strongly correlated with standard deviation of watershed slope. Many correlations among physiographic variables were moderate (>0.50).
[a]Rel elev SD = standard deviation of relative elevation; TPI SD = standard deviation of topographic position index; TPI skew = skewness of topographic position index; TPI kurt = kurtosis of topographic position index; slope SD = standard deviation of slope; IC SD = standard deviation of index of connectivity.

predictions, we evaluated whether the timing of these sediment events corresponded to the occurrence of known forest management activities (harvesting, road building, and slash burning) or high-flow events as indicated by peak-flow analysis. We acknowledge that our analytical approach is not as sensitive to detecting short-term management effects on sediment yields, relative to conventional paired watershed studies. However, the limited pretreatment observation period (0–6 years) for most study catchments reduced our ability to utilize a paired watershed approach given our broader spatial and temporal interests. Rather, with our approach, we aimed to investigate broad physiographic controls on suspended sediment yields over the long study period (~60 years).

Finally, as an additional line of inquiry concerning the regional sediment transport response to anthropogenic and natural disturbances, we considered changes in stage derived from comparing measured historic stage values (readNWISmeas function) to that predicted from the current rating curve (readNWISrating function; "dataRetribal" package; Hirsch & De Cicco, 2015) for LOOK. The difference in stage was interpreted as a relative bed-elevation change resulting from changes in scouring and deposition of material likely moved as bed load (Juracek, 2001; Juracek & Fitzpatrick, 2009). We used this change in stage as a continuous geomorphic record, likely correlated to sediment transport to augment the suspended sediment record that has gaps in space and time (Table 1).

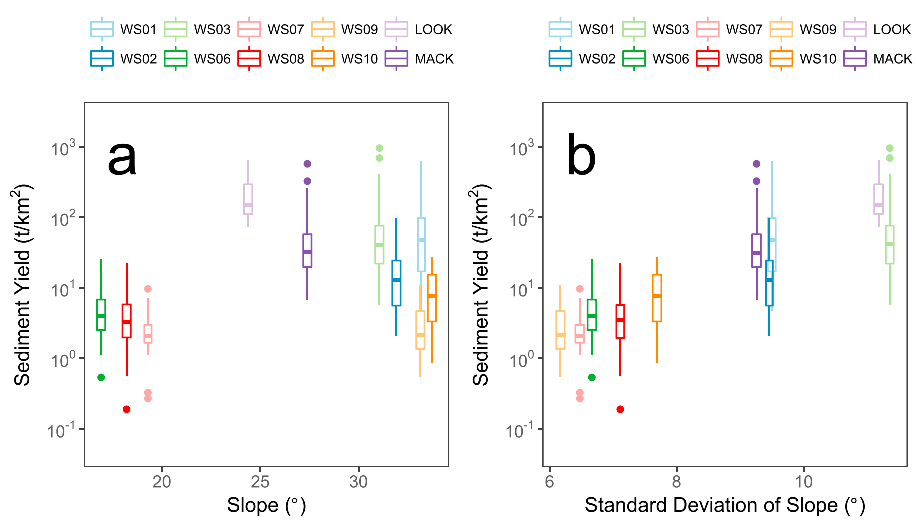

Figure 4. Box plots of annual sediment yield as a function of (a) mean watershed slope (°) and (b) standard deviation of watershed slope (°). Standard deviation of slope had a much stronger correlation with yield ($r = 0.72$, $p < 0.05$) compared to mean slope ($r = 0.32$, $p < 0.05$).

Table 5
AICc for the Top 10 Linear Mixed Effects Models and the Null Model Predicting Log (Sediment Yield) by Candidate Models That Included up to One Hydrologic Variable, One Physiographic Variable, and Whether the Watershed Had Been Managed

Model predictors	K	AICc	ΔAICc	AICc Wt	Cum. Wt	Log-likelihood
Cum Q + Slope SD	5	888.45	0	0.98	0.98	−439.14
Cum Q + Rel elev SD	5	896.55	8.1	0.02	1	−443.19
Cum Q + IC SD	5	902.51	14.06	0	1	−446.17
Cum Q + TPI kurt	5	905.57	17.12	0	1	−447.69
Cum Q + Area	5	907.77	19.32	0	1	−448.8
Cum Q + TPI skew	5	910.01	21.56	0	1	−449.92
Cum Q	4	910.96	22.51	0	1	−451.42
Cum Q + Manage	5	912.25	23.8	0	1	−451.04
Max Q + Slope SD	5	933.62	45.17	0	1	−461.72
Max Q + Rel elev SD	5	938.89	50.44	0	1	−464.36
Null	3	1020.93	132.48	0	1	−507.43

Note. All included site as a random effect. The number of estimated parameters (K), cumulative weight, and log likelihood are also shown.

4. Results

4.1. Association Between Suspended Sediment Yield and Annual Discharge or Catchment Setting

Across space and time, annual suspended sediment yields varied almost 4 orders of magnitude (Figure 3 and Tables S2 and S3). The highest annual yield (~953 t/km^2) was in WS03 in 1969, while the lowest yield (~0.2 t/km^2) was in WS08 in 2001. Despite the small study area, mean annual suspended sediment yields ranged widely from 2.8 to 231.3 t/km^2 across the 10 catchments of the H.J. Andrews Experimental Forest (Table 2). Likewise, variability by site ranged substantially, with LOOK, WS01, WS09, and WS10 having standard deviations of annual suspended sediment yields greater than 100 t/km^2 (Table 2).

Annual suspended sediment yield was moderately to strongly correlated with many discharge (Table 3) and physiographic (Table 4) variables. The variable most strongly correlated with annual suspended sediment yield (Table 4) was the standard deviation of watershed slope ($r = 0.72$, $p < 0.05$; Figure 4b). Standard deviation of slope was strongly correlated with standard deviation of relative elevation and standard deviation of TPI—a roughness metric and standard deviation of index of connectivity. Standard deviation of relative elevation had the second strongest correlation with yield ($r = 0.70$, $p < 0.05$). Annual suspended sediment yield was only moderately correlated with slope ($r = 0.32$, $p < 0.05$; Table 4 and Figure 4a). Similarly, suspended sediment yields were poorly correlated with drainage area ($r = 0.38$; $p < 0.05$) relative to several other physiographic variables (Table 4). For discharge characteristics, annual suspended sediment yield was most strongly correlated (Table 3) with cumulative annual Q ($r = 0.50$, $p < 0.05$) that was, in turn, correlated with most other hydrologic variables (most >0.50).

Table 6
Mean Hydrologic and Physiographic Variables by Watershed, Showing Those That Appear in the Top 10 Linear Mixed Effects Models (Table 5)

Site	Cum Q (m)	Max Q (cm/day)	Slope SD (°)	IC SD	Rel elev SD (m)	TPI skew (m)	TPI kurt (m)
LOOK	1.68	9.16	11.18	0.46	264.71	−0.21	74.99
MACK	1.81	8.07	9.26	0.36	177.67	−0.32	21.46
WS01	1.41	9.16	9.50	0.34	122.98	−0.70	8.80
WS02	1.34	6.62	9.46	0.33	112.56	−0.85	11.00
WS03	1.34	6.59	11.36	0.39	136.73	−0.60	23.44
WS06	1.57	6.90	6.66	0.35	32.18	−0.50	6.86
WS07	1.06	5.21	6.47	0.33	40.60	−0.69	9.31
WS08	1.13	6.21	7.11	0.34	44.51	−0.89	8.36
WS09	1.27	6.75	6.17	0.26	69.14	−1.76	9.97
WS10	1.51	8.86	7.69	0.30	54.41	−2.25	11.36

Table 7
Linear Mixed Effects Model Results[a] Predicting Log

Parameter	Estimate	Standard error	*t* value
Random effects[b]			
Site:WS01	0.59	0.12	NA
Site:WS02	−0.50	0.11	NA
Site:WS03	−0.44	0.14	NA
Site:WS06	−0.12	0.15	NA
Site:WS07	0.05	0.15	NA
Site:WS08	0.02	0.13	NA
Site:WS09	0.09	0.13	NA
Site:WS10	−0.14	0.13	NA
Site:LOOK	0.41	0.21	NA
Site:MACK	0.04	0.13	NA
Fixed effects[c]			
Intercept	−4.92	0.64	−7.74
Cum *Q*	1.33	0.11	11.64
Slope SD	0.65	0.07	8.97

Note. Annual suspended sediment yield (t/km^2) by cumulative annual *Q* (m; Cum *Q*) and standard deviation of watershed slope (°; slope SD) with a random site effect.
[a]AICc = 896.84; 346 observations from 10 groups. [b]Conditional R^2 = 0.73. [c]Marginal R^2 = 0.67; $p < 0.0001$ for all fixed effects.

The best-supported model of those considered (lowest AICc; Table 5) for predicting the log of annual suspended sediment yield (t/km^2) included cumulative annual *Q* (m) and standard deviation of watershed slope (°). Eight of the top 10 models included a hydrologic variable and a physiographic variable (Tables 5 and 6), strongly suggesting that both should be included to predict annual suspended sediment yields. For example, ~67% of the variation in annual suspended sediment yield was explained by the fixed effects in the top model (minimum AICc), whereas ~74% of the variation was explained by the random effect (Table 7). In this model, the relative importance of standard deviation of watershed slope was slightly greater than cumulative annual *Q* (Figure 5), as indicated by the effect each had on sediment yield when the other was held constant. However, when the 95% confidence interval of each was considered, the effects were indistinguishable over the range of observations.

4.2. Association Between Suspended Sediment Yield and Forest Management Activities or Extreme Hydrologic Events

In the linear mixed-effects candidate models, the eighth model included cumulative annual discharge and the factor “manage” that considered forest management history, with ΔAICc = 23.8 compared to the best-supported model (Table 5). This indicated the statistical strength of the model was not improved by the addition of a coarse variable indicating forest management history. The observed annual suspended sediment yields versus the predicted annual yields (Figure 6) show only a few data points outside the 95% prediction interval for the top linear mixed effects model. Of these, only two would be considered outliers based on their standardized residuals. These include the suspended sediment yield from WS03 in 1969 (953 t/km^2 compared to a prediction of 73 t/km^2) and WS01 in 1973 (457 t/km^2 compared to a prediction of 21 t/km^2). Both of these watersheds were managed in the decade prior to the outliers and experienced the second largest storm of record after management (1965). Other managed watersheds (e.g., WS06, WS07, and WS10) had no outliers. WS06 was managed between 1974 and 1976 (100% clearcut, broadcast burn, road building), while WS07 was managed in 1974–1975, 1984, and 2001 (selective canopy removal, broadcast burn, and thinned). No sediment increases were evident in either catchment, with the exception of a slight increase in 1976 (Figure 7a and Table S3). No direct comparisons (e.g., paired-watershed analysis) were possible with the reference (WS08) because it lacked 1974–1976

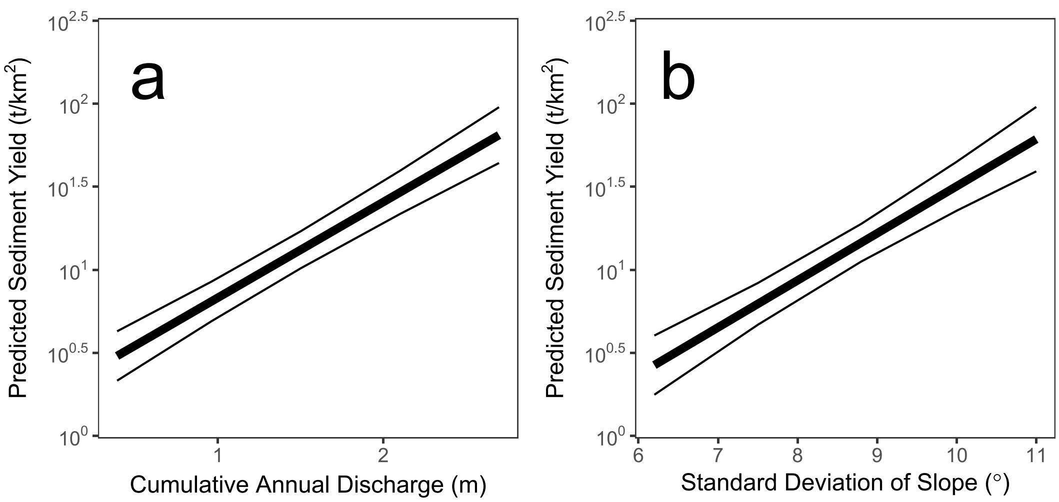

Figure 5. Linear mixed effects model results showing the fixed effect of (a) cumulative annual discharge and (b) standard deviation of watershed slope on annual sediment yield when the variability from site was accounted for (random effect), with 95% confidence interval of model shown. Each effect has approximately the same influence on sediment yield over the range of observed values.

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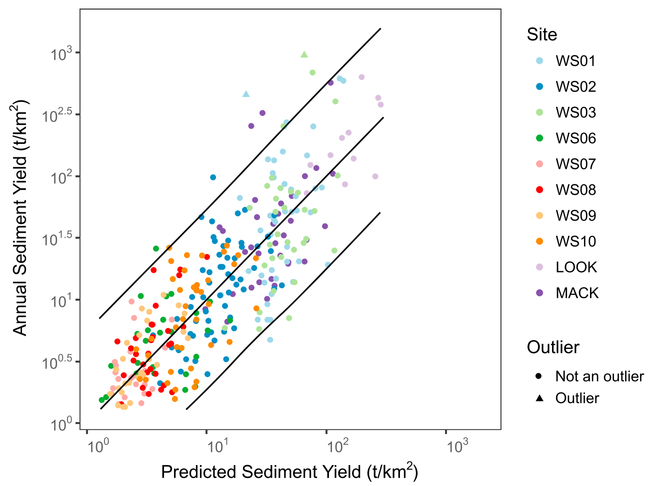

Figure 6. Annual sediment yield as a function of linear-mixed-effects-model predicted sediment yield, with the 95% prediction interval shown. Only two annual yields were considered outliers (triangles) where yields were much greater than expected from the model. These include WS03 (1969) and WS01 (1973).

data. WS10 was clearcut in 1975 and had SSY of 12 t/km^2 in 1975, 25 t/km^2 in 1976, and 4 t/km^2 in 1977. The reference for WS10 (WS09) had missing data during this time—as such, a direct comparison was again not possible (Figure 7b). If there were increased suspended sediment yields following forest management activities for these previously unstudied watersheds, they were not evident in the annual time series (Figure 7).

The bed elevation record at LOOK supports the notion that extreme hydrologic events were major drivers of sediment transport and channel geometry. Comparisons of manual stage measurements to predicted stage from the current rating curve at LOOK indicate changes in stream bed elevation following the 1965 flood, with a relative increase of ~0.2 m (Figure 8). Bed elevation stabilized until ~1985 and recovered to 1964 levels by ~1990. The 1996 flood resulted in an ~0.3-m increase in bed elevation for LOOK with a period of recovery lasting until ~2010 and finally values that were comparable to preflood conditions (1964, 1990 values) by 2016. These data indicate that bed-elevation changes in the larger LOOK watershed that integrate anthropogenic and natural disturbance are controlled by large flood events. The largest magnitude changes in bed elevation, and therefore sediment movement, generally occurred after floods with ≥30-year return intervals. This suggests for the H.J. Andrews that trends in sediment transport are driven by the hydrologic conditions and physiographic setting.

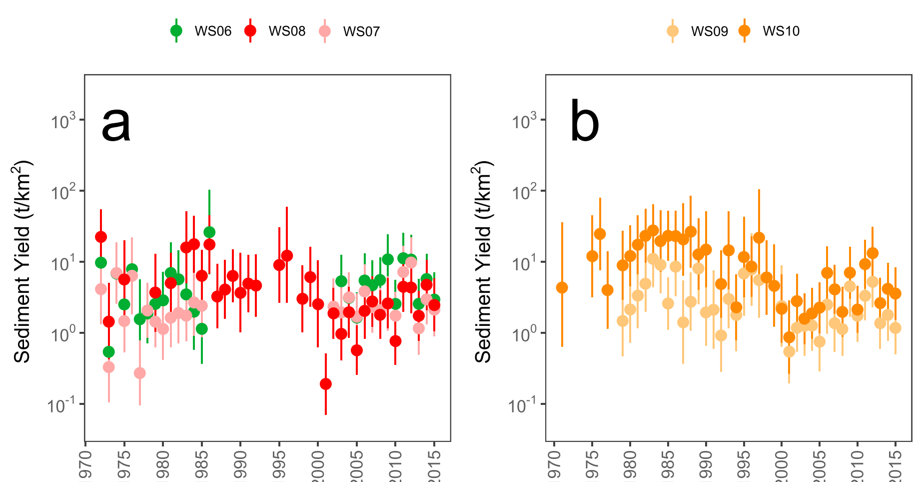

Figure 7. Sediment yields with 95% confidence intervals for (a) WS06, WS07, and WS08 and (b) WS09 and WS10. WS06 was managed 1974–1976, WS07 was managed 1974–1975 and 1984 and 2001, and WS10 was managed 1975. These watersheds have no outliers in the predicted sediment yields (Figure 6).

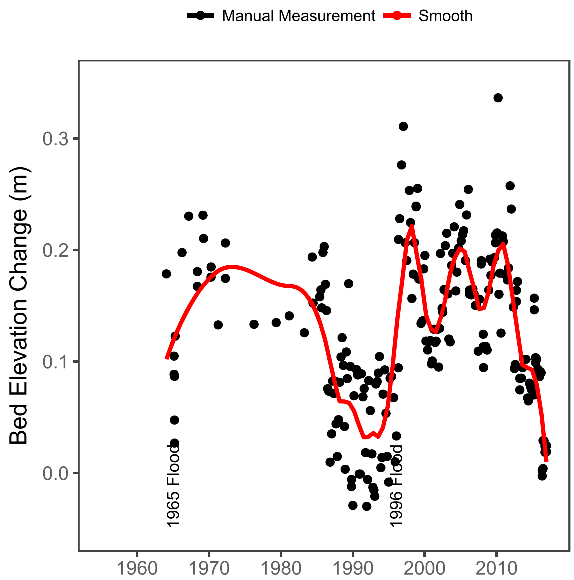

Figure 8. Change in streambed elevation at Lookout Creek (LOOK) from 1960 to 2016, illustrating the importance of infrequent, high streamflow events for suspended sediment yields.

5. Discussion

In this study, we assessed the relative association between discharge and catchment physiography and suspended sediment yield using a spatially and temporally (~60 years) robust data set from the H.J. Andrews Experimental Forest, a PNW LTER Network site. Additionally, we assessed whether the effects of historical forest disturbances explain the variance in annual sediment yields over an ~60-year period.

5.1. Association Between Suspended Sediment Yield and Watershed Hydrology or Physiography

Our principal finding was that watershed physiography (i.e., standard deviation or variability of watershed slope), combined with cumulative annual discharge, explained 67% of the variation in annual sediment yield across the ~60-year data set. However, sediment yields varied widely across space and time, with mean annual yields ranging from 2.8 to 231.3 t/km^2. Sediment yields also varied immensely within individual years, from virtually no export (WS08; 2001) to 953 t/km^2 (WS03; 1969).

Variability in watershed slope was the best predictor of annual suspended sediment yield relative to other physiographic variables. Interestingly, suspended sediment yields were only moderately correlated with drainage area in our study. Previous studies have illustrated increasing suspended sediment yields with increasing area drained for small watersheds, with a decreasing trend thereafter (Church & Slaymaker, 1989). Our analysis, similarly, showed a positive correlation between suspended sediment yield and drainage area for our small (<10,000 ha) catchments (Table 4). As in the case of Church and Slaymaker (1989), this positive relationship could be indicative of increasing sediment entrained from storage in or near the stream channel with increasing drainage area. However, in our study this relationship may also be associated with a greater occurrence of debris-flows in catchments of intermediate size (WS01, WS02, and WS03) compared to the smaller catchments (WS06, WS07, and WS08).

As with drainage area, mean watershed slope is often linked to sediment transport but with little quantitative evidence (Barreiro-Lostres et al., 2017; Montgomery & Brandon, 2002; Swanson et al., 1986). Here slope was only one of many physiographic variables that were moderately correlated with yields. Our best physiographic predictor, variability of watershed slope, is likely a proxy for many processes, encompassing multiple catchment characteristics. In the literature, there is evidence that changes in relief—related to variability in slope—can increase erosion rates and sediment delivery, especially in steep, high-relief watersheds (Ahnert, 1970; Montgomery & Brandon, 2002). Standard deviation of relative elevation (e.g., relief) had, in fact, the second strongest correlation with yield after standard deviation of slope in our study, illustrating a potential process linkage between variability in slope and sediment transport processes. Watersheds (LOOK, MACK, WS01, WS02, and WS03) with a high standard deviation of watershed slope (>9°) also had high relief (variation in relative elevation; Table 6), and relatively high mean slopes, and the largest drainage areas (Table 1). Three of these watersheds (WS01, WS02, and WS03) have incised V-shaped valleys (Figure 1) and high debris-flow hazards coupled to the stream network (Figure 2), a characteristic that would also be captured by standard deviation of slope. MACK, although located in relatively stable terrain and lithology, was formerly glaciated. Such areas often have high sediment yields in the Cascades (Jaeger et al., 2017). LOOK, the largest watershed, has ample locations for sediment storage that may be remobilized during high-flow events.

The standard deviation of slope was furthermore strongly correlated with standard deviation of TPI—a roughness metric. Bywater-Reyes et al. (2017) found similar results in watersheds located in the Oregon Coast Range (PNW, USA) with suspended sediment yield varying as a function of variability in slope and a terrain roughness metric similar to standard deviation of TPI used here. Bywater-Reyes et al. (2017) argued that the association between yields and landscape roughness metrics is likely a result of roughness being a proxy for sediment supply. Bywater-Reyes et al. (2017) found a peculiar association between high index of sediment connectivity and *lower* suspended sediment yields. Here some highly connected watersheds (e.g., WS01, WS02, and WS03) had high sediment yields, whereas for others there was no consistent relationship between the index of connectivity and sediment yields. This is likely because watersheds must have both supply of material as well as the ability to transport it, a condition not necessarily met by high connectivity alone.

5.2. Association Between Suspended Sediment Yield and Historical Forest Management or Extreme Hydrologic Events

In our study, the effects of historical forest management activities on the variation in annual suspended sediment yield were not evident, which was, in part, related to the resolution of the available data. For example, our analysis indicated little to no association between forest management history and increased suspended sediment yields in WS06, WS07, and WS10. However, a classic paired-watershed study was not possible given the lack of predisturbance data in the corresponding reference sites (WS08 and WS09). When the hydrologic and physiographic context of the data set was accounted for in our linear mixed-effects model, only two annual sediment yield data points were outliers, occurring for WS01 and WS03 within a decade after management. Grant and Wolff (1991) documented increased suspended sediment yields for WS01 and WS03 up to approximately nine years following the combined occurrence of forest management practices and the 1965 flood event, consistent with the time frame during which we detected outliers at these sites. Conditions at WS01 and WS03 were particularly vulnerable given the timing of the 1965 storm in relation to extreme management conditions (clearcutting in WS01 and poorly built roads in WS03).

Suspended sediment yield dynamics were likely also exacerbated by the particular physiography of these catchments. Both WS01 and WS03 have high standard deviation of slope in comparison to the other managed watersheds for which there were no outliers and limited or no related increased suspended sediment yields detected here, although the records do not extend back to include the 1965 flood event, nor were they managed during that time. For the record available, two watersheds with low variability in slope (WS06 and WS10) had low annual sediment yields (Table 2), despite a history of active forest harvesting (100% clearcut) and occurrence of the 1996 flood (recorded in WS10). Similarly, WS06, WS07, and WS08 had consistently low sediment yields, even following the 1996 flood event. Moreover, substantial forest harvesting, broadcast burning, and road building occurred in both WS06 and WS07 over the period of study. Physiographically, WS06 and WS07 had characteristically low variability in watershed slope. Thus, the lack of large sediment yield events illustrates the association between physiography and watershed resiliency to erosion and sediment delivery following both natural and anthropogenic disturbances.

The extent to which the results hold beyond the H.J. Andrews Experimental Forest is unclear and outside the scope of this study. However, consideration of catchment physiography could provide insights into the mixed responses of SSCs and yields following contemporary forest harvesting (Binkley & Brown, 1993; Gomi et al., 2005). For example, suspended sediment has been shown to increase (Grant & Wolff, 1991), decrease (Macdonald et al., 2003), or to remain unchanged (Hotta et al., 2007) following contemporary forest management practices. However, our results, and others, indicate that catchment physiography, as well as lithology, is important for prediction of watersheds most vulnerable to disturbance-related increases in suspended sediment (Bywater-Reyes et al., 2017).

While outliers in suspended sediment yield occurred in watersheds with high variability in watershed slope or a history of forest management, they were also coincident with large magnitude storm events. Whereas the specifics of disturbance from forest management practices in WS01 and WS03 influenced the source and magnitude of sediment exports, Grant and Wolff (1991) also emphasized the role of episodic events, such as debris flows, in controlling exports of sediment from 1958 to 1988 in WS01, WS02, and WS03. Earlier studies at the H.J. Andrews have also noted the importance of large floods as drivers of high sediment export (Caine & Swanson, 1989; Swanson et al., 1998; Swanson & Jones, 2002). In a global analysis incorporating observations from 51 temperate catchments, Bathurst and Iroumé (2014) attributed the greatest increases in suspended sediment yield in managed watersheds to extensive ground disturbance or extreme events, consistent with the findings here. Swank et al. (2001) considered long-term (~20 years) suspended sediment yields for an Appalachian watershed influenced by road building and logging and also found an association between sediment yield and extreme storm events. Likewise, in an ~30-year data set Rainato et al. (2017) found an association between years with large storm events and high sediment yields. The confounding influence of management history preceding the 1965 storm event, combined with missing records for the 1996 event, makes it difficult to decipher the relative influence of multiple factors on suspended sediment yields. However, as an additional line of evidence, the temporal changes in streambed elevation at LOOK support the notion that large storm events influence sediment transport at the H.J. Andrews (Figure 7).

The temporal variations in streambed elevation in LOOK after the 1996 flood (60-year return period) and the 1965 flood (30-year return period) were similar. However, the 1996 flood resulted in a greater magnitude of change in streambed elevation (~0.3 m aggradation) compared to the 1965 flood (~0.2 m aggradation). Similarly, the duration of increased bed-elevation lasted ~20 years after both the 1965 and 1996 floods, with a decline over an additional five years. Assuming a moderately strong correlation between bed load and suspended load in our study catchments (Mueller & Pitlick, 2013), we can infer that sediment yield in the Lookout watershed is principally associated with the frequency of large flood events. Our inference of the relative contribution of physiographic, hydrologic, and management both temporally a spatially in temperate catchments underscores the need for long-term hydrologic data (Tetzlaff et al., 2017).

6. Conclusion

Based on data from 10 watersheds, spanning ~60 years, we showed that catchment physiography (variability in slope) combined with cumulative annual discharge explained most of the observed variation in annual suspended sediment yield. The few anomalously high annual suspended sediment yields occurred in watersheds with high variability in slope and in the decade after forest management and a large flood event. Over the spatial and temporal scale considered, suspended sediment yield were most strongly associated with catchment physiography, discharge, and infrequent flood events. Our results suggest that physiographic characteristics could be used in the PNW to assess watershed vulnerability and/or resilience to erosion and sediment delivery in general, and following anthropogenic and natural disturbances. However, our study also illustrates the high variability in sediment yields in space and time. The factors associated with suspended sediment yield considered here should be tested more broadly to investigate their utility for forest managers and other regulators in setting baseline values for impact assessment and regulation development.

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