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Key Points:
- Suspended sediment loads can coarsen or fine as a function of flow
- Gage analysis demonstrates that while sediment load fines with flow for some, high supply events, coarsening is more common
- Sediment capacity equations do not, generally, reproduce observed flow-gradation trends

Supporting Information:
- Supporting Information S1

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Flow Dependence of Suspended Sediment Gradations

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Abstract Suspended sediment loads can coarsen or fine as a function of flow. The flow-load gradation relationships can also vary nonmonotonically. This complex relationship between flow and load gradation complicates sediment model boundary condition selection and sediment rating curve analysis. This study analyzed flow-gradation data from 78 gages in the continental United States, exploring trends and tendencies in the flow-gradation relationships. Results were then compared to the flow-gradation trends generated by sediment capacity equations and a meta-analysis of sediment model data. Several systems, with abundant sediment supply fined with flow. However, most gage data and calibrated model inputs coarsened with flow. When nonmonotonic models were considered, one-third to one-half of the gages fit a second-order curve, coarsening over low-to-moderate flows (up to an average annual exceedance probability of ~30%) and fining over higher flows. The low-flow-coarsening trend was generally stronger than high-flow-fining trends. Many of these second-order trends demonstrated behavior more like "asymptotic coarsening." They coarsened until they reached a maximum physical grain size limit and gradation fined slightly or remained constant beyond the threshold flow. The dominance of flow-coarsening suggests most of the rivers surveyed (which included a bias toward large, regulated rivers) are supply limited. Supply limited (bed regulated) rivers tend to coarsen with flow, while capacity limited, high supply systems tend to fine with flow. Sediment capacity equations computed a variety of flow-gradation trends. Using transport functions to compute load-gradation model boundary conditions will often diverge from (or even invert) observed trends, especially in supply limited systems.

Plain Language Summary As river flow increases, the sediment load (the sand and silt the water transports) increases. Scientists and engineers try to compute relationships between flow and sediment load for a wide range of economic and environmental applications, like computing how long the river will take to fill a reservoir with sediment or if the river will burry or scour a salmon habitat restoration project. But the suspended sediment load includes particles of various size (from silt finer than 0.004 mm to coarse sand larger than 1 mm). So as the load increases, the mixture of grain sizes changes. The size of the load material can also influence economic and environmental decisions.

1. Introduction

Most sediment transport models subdivide sediment into size classes. These models compute transport parameters (e.g., fall velocity, transport capacity) by grain class. Therefore, most models require sediment flux at domain boundaries *by grain class*. Grain class specific boundary conditions increase the data burden for these models substantially.

Sediment models frequently use flow-load rating curves to specify total, dynamic sediment flux at the model boundaries. Multiple grain class models also force users to estimate sediment flux at the model boundaries by grain size. Therefore, when modelers define flow-load boundary conditions for multiple grain class models they must also define flow-gradation relationships that quantify how the load gradation changes with flow.

Developing a total flow-load rating curve can be challenging. The data are often rare, and when sufficient, they are always noisy. Flow does not explain all of the variability in the load data. Other processes like hysteresis, storm centering, and seasonality drive nonunique relationships between flow and sediment load. Intrastorm variability can also cause complex load gradation patterns over time (Walling et al., 2000).

However, despite these challenges, modelers often estimate load as a power function of flow, with reasonable success. Where no data exist, the flow-load relationship often becomes a calibration factor. Developing a flow-load relationship for a model boundary is not trivial, but is usually tractable. Estimating the flow-gradation (i.e., load fining or coarsening with flow) trend is much more difficult.

Many of the processes that complicate flow-load relationships also affect flow-gradation relationships. However, two additional factors make load-gradation relationships more difficult to estimate. First, sediment load-gradation data are rarer than concentrations or load measurements, requiring modelers to interpolate, extrapolate, or often, apply "engineering judgment" to fabricate gradational trends. Second, sediment gradation does not vary predictably with flow. While the magnitude of the sediment load almost always increases as a function of flow (with a few notable exceptions, López-Trazón et al., 2011; Piqué et al., 2014), load can coarsen or fine with flow. It can also remain relatively constant or vary nonmonotonically (Walling & Moorhead, 1989). Even when data are available, they can be complicated and difficult to distill into trends.

Modelers sometimes try to circumvent flow-load-gradation uncertainty by computing boundary sediment flux by grain class with transport capacity equations, using either internal model features (e.g., equilibrium load boundary) or external software (Sikonia, 1990; Yang, 1989). However, where data are abundant, observed trends do not always follow trends computed by capacity equations.

This study examines measured and computed flow-gradation relationships to provide a framework for estimating load-gradation trends at model boundaries when the data are scarce or absent. The study team analyzed and categorized the flow-gradation trends at 78 gages in the United States with suspended sediment gradation data over a range of flows. These results were then compared to flow-gradation trends computed by standard sediment capacity formulas.

2. Background

Suspended sediment gradations can fine or coarsen with flow (Figure 1). Two competing transport processes influence suspended flow-gradation trends: transport competence and transport capacity. Therefore, this study began with two simplified but competing hypotheses:

Hypothesis A—(↑) "The Coarsening Hypothesis": Gradation is directly related to flow. Suspended sediment coarsens as flow increases (Figure 1a).
Hypothesis B—(↓) "The Fining Hypothesis": Gradation is inversely related to flow. Suspended sediment fines as flow increases (Figure 1b).

The gradational evolution of total sediment load includes distinct but overlapping subprocess including bed load, suspended load, and wash load dynamics. This study analyzed depth integrated, suspended sediment samples, and assumed the reported "measured load" approximated suspended load. Therefore, while bed load gradation almost certainly varies with flow, this discussion and analysis focuses on suspended

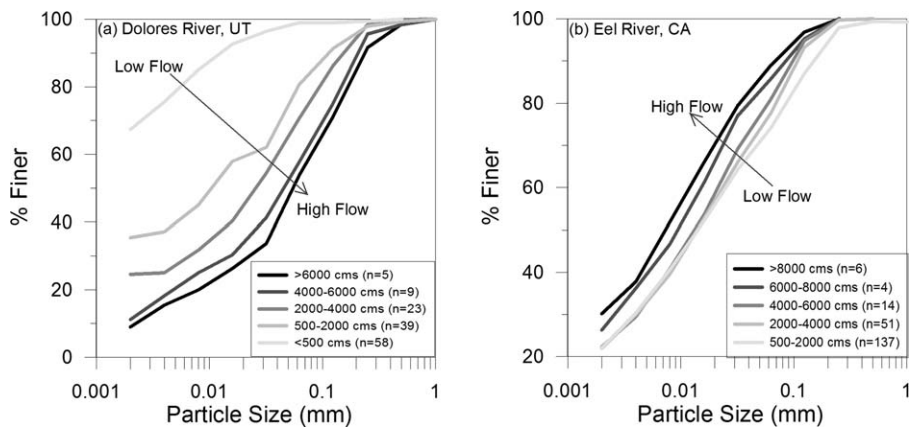

Figure 1. Suspended sediment gradations from two rivers averaged for five flow bands (where *n* indicates the number of gradation samples averaged for each flow). The Dolores River load coarsens (A↑) while the Eel River fines (B↓) with flow.

sediment gradations, including wash load components which are generally much less sensitive to flow than the suspended component of the bed material load.

2.1. Transport Competence and the Coarsening Hypothesis (A↑)

The coarsening hypothesis (A↑) is intuitive. Higher flows entrain coarser material. This direct relationship emerges from the "Transport Competence" principle. In sediment transport, a "competent" flow suspends a particular grain class. Grain class mobility in a graded bed is actually a complex, stochastic process (Andrews & Parker, 1987), but the principle that larger flows suspend larger particles may be the most intuitive and fundamental principle in sediment transport. Larger flows add coarse sediment to the suspended sediment load, which coarsen the suspended mixture. The coarsening hypothesis dominates the literature (Frostick et al., 1983; Grangeon et al., 2012; Horowitz, 1991; Lenzi & Marchi, 2000; Phillips & Walling, 2005). These studies suggest power functions can describes the relationship between flow and particle size. However, both monotonic hypotheses (coarsening A↑ and fining B↓) could also include linear and asymptotic relationships.

2.2. Transport Capacity and the Fining Hypothesis (B↓)

The fining hypothesis (B↓) emerges from the sediment capacity equations. Sediment capacity formulas tend to be nonlinear. These equations usually describe transport capacity as a power function of an excess mobility parameter (bed shear stress or stream power) and particle size. Larger flows disproportionately transport finer particles, increasing their concentration in the water column relative to coarser grain classes. Therefore, the computed capacity of fine particles increases faster with flow than the capacity of coarser particles, fining the suspended sediment mixture as flow increases (Hypothesis B↓).

2.3. Supply Side Factors

The competence-capacity dichotomy should control if the river has unlimited access to coarse and fine particles. However, sediment supply can control suspended sediment concentration and gradation. Supply limitation can reduce capacity-driven flow-fining. If the supply of finer sediment is limited, and cannot satisfy the higher capacity at high flows, supply limitation can neutralize the flow-fining effect of capacity.

Storm centering can also increase sediment eroded from portions of the watershed with distinct geology or land use giving sediment loads different gradation signatures (Bogen, 1992). Tributaries with distinct suspended sediment gradations (Costigan et al., 2014; Davis et al., 2014; Rubin & Topping, 2001; Wood et al., 2015) or the relative contributions of watershed, bank, catchment slope, and bed sources (Grangeon et al., 2012; Lenzi & Marchi, 2000; Slattery & Burt, 1997; Wood et al., 2015) for different flows can also affect suspended sediment gradations. Walling and Moorhead (1989) suggested that supply factors are built into flow-gradation trends, since larger flows draw sediment from larger areas, introducing a "sediment latency" effect. Larger storms—which deliver more sediment—also transport sediment longer distances between the source and the river. Longer watershed transport pathways tend to deliver finer sediment, since the coarse material deposits en route. Finally, Rubin and Topping (2001) argued that bed evolution ("bed regulation") drives classical supply limited hysteresis, which also coarsens the suspended sediment load on the rising limb of a hydrograph.

Therefore, supply side processes also introduce competing effects, supporting both hypotheses. Supply limitation and bed regulation moderate capacity-driven fining, supporting the coarsening hypothesis. However "sediment latency," delivers finer sediment from farther reaches of the watershed during larger storms, support the fining hypothesis. The competing transport and supply processes affecting load coarsening and fining are summarized in Table 1. With multiple, competing processes in play, nonmonotonic relationships between flow and gradation are easy to imagine.

Table 1
Competing Processes That Cause Sediment Loads to Fine or Coarsen on the Transport and Supply Sides of Continuity

	Coarsening hypothesis (A↑)	Fining hypothesis (B↓)
Transport processes	Competence	Capacity
Supply processes	Supply limitation	Source latency

2.4. Nonmonotonic Relationships

The competing processes summarized in Table 1 suggest the initial dichotomy between monotonic coarsening (A↑) or fining (B↓) hypotheses over-simplifies the potential trends. Nothing limits flow-gradation response to monotonic behavior. Competence could dominate over low flows and capacity over the higher flows, giving the suspended sediment gradation a second-order (or higher) relationship with flow (Figure 2). Alternately, capacity could dominate the system, making the suspended load fine with flow, until supply limitation

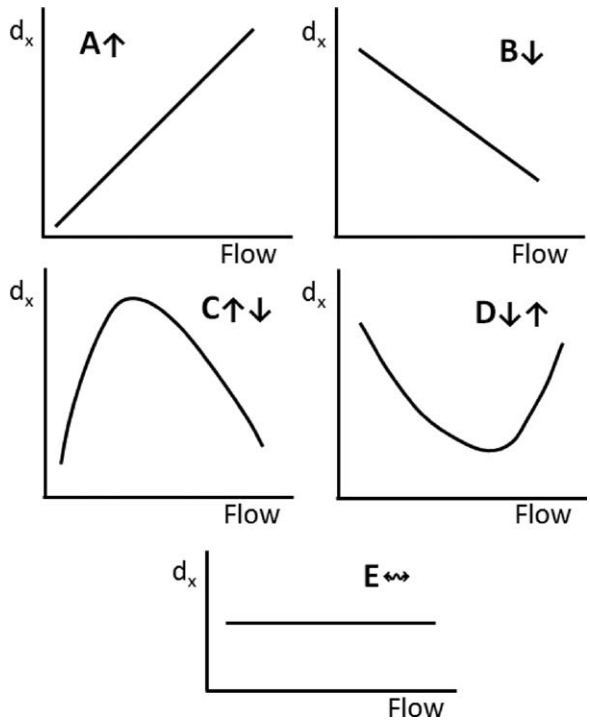

Figure 2. Five load-gradation relationship considered, including monotonic (A↑ and B↓) and nonmonotonic (C↑↓ and D↓↑) relationships and flow-independence (E↔).

favored competence-driven coarsening at higher flows. Finally, some systems may have no significant flow dependence or the interactions of these processes could produce data so noisy that flow-independence becomes the best assumption.

Therefore, after the study evaluated the first two hypotheses (monotonic coarsening and fining), the analysis expanded to include three corollary hypotheses:

Hypothesis C—(↑↓) "The Coarsening-Fining Nonmonotonic Hypothesis": Gradation coarsens with flow for low flows then fines with flow for large flows.
Hypothesis D—(↓↑) "The Fining-Coarsening Nonmonotonic Hypothesis": Gradation fines with flow for low flows then coarsens with flow for large flows.
Hypothesis E—(↔) "The Flow-Independence Hypothesis": Load gradation is either insensitive to flow or its relationship to flow is too complex to establish reliably.

These hypotheses are assigned notations A to E and symbols (↑, ↓, ↑↓, ↓↑, ↔) to simplify results. The idealized relationships between flow and a representative grain size percentile (d_x, which, in this study was the d_{85}) are depicted in Figure 2.

This study started with the a priori hypothesis that capacity effects dominate competence effects, so the data should generally support the fining hypothesis, Hypothesis B (↓), with some supply limited outliers (e.g., those directly downstream of dams) which would fit the coarsening hypothesis (A↑). The data did not support this hypothesis.

3. Methods

This study inferred flow-gradation trends from depth integrated, suspended sediment measurements at 78 US Geologic Survey (USGS) sediment gages in the United States. These gages were then categorized based on the hypotheses described above. First, the analyses were limited to the monotonic hypotheses. Second, the nonmonotonic models were included, and the gages were sorted between the five hypotheses in Figure 2. The results from these gages were then compared to the flow-gradation trends generated by several sediment capacity equations.

3.1. Data Analysis

3.1.1. Flow-Gradation Data Set

This study mined the USGS water quality database for gages with substantial suspended sediment gradation data. The following search parameters identified promising gages: "Suspended sediment," "fall diameter," "% <0.002 mm," "% <1 mm" (data codes 70337 to 70346), >1,000 water quality samples (U.S. Geological Survey, 2014). This search compiled graded suspended sediment measurements. These data were collected with depth-integrated samplers which include both wash load and the suspended component of the bed material load but exclude bed load. This distinction is important, because suspended-bed material load varies with flow while wash load does not. Excluding the bed load also mutes competence-driven flow-coarsening which should be most obvious in bed load transport. Additionally, the fine sediment samples used in this study were measured in deionized water with disassociated samples, reporting "absolute" particles size rather than "effective" particle size. The effective particle size measures the size of transporting particles in situ, accounting for the actual size of composite particles, transported as aggregates and flocs, instead of breaking them into their component parts (Walling & Woodward, 2000).

This search produced 92 data sets with 4 to 3,919 suspended sediment gradation curves. The analysis and discussion was limited to 78 gages with 10 or more load-gradation curves (median curves = 138, average = 377). Table 2 lists the gages analyzed and includes summary flow statistics.

Table 2
Gages With Load-Gradation Data, the Number of Observations, and the Flow Parameters Associated With the Gradation Samples

Gage #	River (gage location)	*n*	Q_{min} (m^3/s)	Q_{max} (m^3/s)	$Q_{10\%}$ (m^3/s)	$Q_{1\%}$ (m^3/s)	Q_{max}/Q_{10}	Watershed area (km^2)
11179000	Alameda Creek (Niles)	69	0.3	266	423	792	0.63	1,639
9364500	Animas River (Farmington)	303	3.1	282	295	468	0.96	3,522
7146500	Arkansas River (Arkansas City)	97	23.2	844	1674	3341	0.5	93,514
7137500	Arkansas River (Coolidge)	45	2.8	104	361	2741	0.29	65,812
6437000	Belle Fourche River (Sturgis)	65	4.8	183	420	1222	0.44	15,076
6279500	Bighorn River (Kane)	173	18.7	586	556	782	1.05	40,823
6885500	Black Vermillion River (Frankfort)	81	3.4	202	665	1489	0.3	1,062
13213000	Boise River (Parmia)	43	14.8	163	277	448	0.59	10,116
1481000	Brandywine Creek (Chadds Ford)	47	0.0	207	400	737	0.52	743
7227500	Canadian River (Amarillo)	23	0.9	18				50,362
7228500	Canadian River (Bridgeport)	12	7.1	198	1494	3006	0.13	65,465
9402500	Colorado River (Grand Canyon)	100	44.2	1549	3070	7311	0.5	366,742
9380000	Colorado River (Lees Ferry)	381	63.7	3058	3102	7502	0.99	289,561
9180500	Colorado River (Cisco)	403	28.3	1371	1726	2659	0.79	62,419
14243000	Cowlitz River (Castle Rock)	232	104.8	1815	2408	3214	0.75	5,796
4208000	Cuyahoga River (Independence)	75	10.8	345	419	656	0.82	1,831
9180000	Dolores River (Cisco)	134	3.5	150	337	690	0.44	11,862
11465200	Dry Creek (Geyserville)	139	1.3	535	618	1691	0.87	420
12472350	DW 272 A Drain (Royal Camp)	21	0.1	0.5				8
7327440	East Bitter Creek (Tabler)	63	0.2	45	98	147	0.46	91
11477000	Eel River (Scotia)	307	45.6	10647	9128	17010	1.17	8,063
7304500	Elk Creek(Hobart)	23	1.0	121	410	1260	0.3	1,422
9474000	Gila River (Kelvin)	144	0.3	680	1039	4793	0.65	46,648
9315000	Green River (Green)	402	1.7	1243	1288	1865	0.97	116,161
3308500	Green River (Munfordville)	17	88.1	544	1310	2262	0.42	3,867
9217000	Green River (Green River)	42	15.9	259	398	611	0.65	36,260
9261000	Green River (Jensen)	231	19.8	748	820	1108	0.91	65,786
9152500	Gunnison River (Grand Junction)	61		345	655	1103	0.53	20,520
7277700	Hickahala River (Senatobia)	21	54.1	453	449	694	1.01	313
10336700	Incline Creek (Crystal Bay)	19	0.2	1.2	2.4	5.8	0.48	18
5465500	Iowa River (Wapello)	43	117.5	3002	2117	3236	1.42	32,375
1567000	Juniata River (Newport)	62	126.9	2512	2378	4607	1.06	8,687
6892350	Kansas River (Desoto)	1397	24.1	2438	3212	4600	0.76	154,767
6887500	Kansas River (Wamego)	312	75.3	1886	2613	7030	0.72	143,175
7144100	L Arkansas River (Sedgwick)	17	9.0	340	478	573	0.71	3,017
9260000	Little Snake River (Lily)	182	0.1	142	247	372	0.58	10,448
7327490	Little Washita River (Ninnekah)	146	0.5	213	297	978	0.72	539
4193500	Maumee River (Waterville)	76	202.2	3200	2441	3793	1.31	16,395
6934500	Missouri River (Hermann)	3676						
6610000	Missouri River (Omaha)	1656	416.3	5437	4240	8398	1.28	836,048
6818000	Missouri River (St. Joseph)	3156						
6893000	Missouri River (Kansas City)	3919	623.0	3483	9012	16791	0.39	1,253,813
6807000	Missouri River (Nebraska City)	1851	617.3	6060	5026	8397	1.21	1,061,895
6486000	Missouri River (Sioux City)	1577	404.9	5324	3885	7930	1.37	814,810
1357500	Mohawk River (Cohoes)	18	648.5	3143	2789	4283	1.13	8,935
7301500	North Fork Red River (Carter)	43	0.0	240	546	1209	0.44	5,019
14241100	North Fork Toutle River (Kid Valley)	292	10.2	555	704	1529	0.79	736
2448000	Noxubee River (Macon)	14	3.5	368	963	2247	0.38	1,989
9382000	Paria River (Lees Ferry)	188	0.3	94	246	505	0.38	3,652
8396500	Pecos River (Artesia)	311	0.1	125	435	1975	0.29	39,627
5427948	Pheasant Branch (Middleton)	14	0.7	12	22	37	0.54	44
6805500	Platte River (Louisville)	194	34.8	2322	2855	5328	0.81	183,889
1646580	Potomac River (Chain Bridge)	29	125.7	9005				29,966
12101500	Puyallup (Puyallup)	33						
6856600	Republican River (Clay Center)	119	1.9	782	1031	3295	0.76	44,139
8330000	Rio Grande (Albuquerque)	635	0.8	187	310	503	0.6	37,555
8313000	Rio Grande (Otowi Bridge)	336	0.1	345	414	726	0.83	37,037

Table 2. *(continued)*

Gage #	River (gage location)	n	Q_{min} (m^3/s)	Q_{max} (m^3/s)	$Q_{10\%}$ (m^3/s)	$Q_{1\%}$ (m^3/s)	Q_{max}/Q_{10}	Watershed area (km^2)
8332010	Rio Grande Floodway (Bernardo)	535	30.6	214				49,805
8358400	Rio Grande Floodway (San Marcial)	345	0.1	178	184	259	0.97	71,743
8353000	Rio Puerco (Bernardo)	548	0.0	169	222	568	0.76	16,110
11467000	Russian River (Guerneville)	145	2.5	2008	2303	3066	0.87	3,465
11447500	Sacramento River (Sacramento)		268.7	2798	2886	3174	0.97	60,883
11377100	Sacramento River (Red Bluff)	31	232.2	2812	4812	8034	0.58	23,051
11303500	San Joaquin River (Vernalis)	261	1.7	1181	1102	3128	1.07	35,058
9368000	San Juan River (Shiprock)	311	2.7	345	660	1594	0.52	33,411
9379500	San Juan River (Bluff)	1019	26.3	660	811	1863	0.81	59,570
6877600	Smoky Hill River (Enterprise)	152	5.5	1201	1015	2831	1.18	49,883
10336698	Third Creek (Crystal Bay)	37	0.1	3.2	3.6	6.0	0.88	16
14242690	Toutle River (Castle Rock)	88	8.4	1699				1,323
14242580	Toutle River (Tower Road)	241	13.9	985	1159	1757	0.85	1,285
2436500	Town Creek (Nettleton)	44	17.2	719	1510	3144	0.48	1,606
9415000	Virgin River (Littlefield)	242	2.2	91	439	1370	0.21	13,183
7328100	Washita River (Alex)	225	17.0	264	755	2108	0.35	12,398
7326500	Washita River (Anadarko)	138	16.0	311	2245	554	0.14	9,469
6452000	White River (Oacoma)	153	0.3	399	773	1652	0.52	25,535
5427970	Willow Creek (Madison)	20	0.2	44	21	22	2.1	8
6329500	Yellowstone River (Sidney)	94	130.3	1733	2884	4336	0.6	177,134

A d_{85} was computed for each gradation curve from each gage, where the data were sufficient to compute this parameter. The d_{85} is the 85th percentile grain size, which means that 85% of the sample mass is finer than the d_{85}. The study experimented with other summary response variables (e.g., the median) and fit distributions to these gradation curves, to represent them with more complex response variables. However, these approaches were more prone to data biases than the d_{85} (see data bias discussion in the supporting information) and did not differ substantially from the d_{85} analyses.

3.1.2. Statistical Methods

The gage gradation analysis applied three statistical methods to identify monotonic and nonmonotonic trends from the gradation data at the 78 gages. Code was developed in the statistical software R, to transform the d_{85} data and the "% finer than 63 microns" data and regress these against flow, choosing the zeroth-order, first-order, or second-order model that fit these data best. This study assumed that any model higher than a second-order polynomial is probably over fit to the data quality and precision. Therefore, model testing was constrained to the best fit of the five trends in Figure 2. Then the d_{85}s were binned, averaged, and plotted by flow exceedance probability. These three analyses each compensated for different data biases (see supporting information). Therefore, their results are presented together to identify the dominant trends.

3.1.2.1. Method 1: Q-d_{85}

The gradation curves from each gage were summarized as paired Q-d_{85} data. The response variable (d_{85}) was transformed with the Box and Cox (1964) transformation, to improve normality and homoscedasticity of the residuals.

R code fit zero (constant) and first-order (linear) polynomial models to the transformed Q-d_{85} data set from each gage. Because the data were transformed, a first-order fit can represent nonlinear, monotonic trends. Then the minimum AIC fit was selected from the five monotonic and nonmonotonic models. The top plots in Figure 3 include examples of the Q-d_{85} analysis for fining (right) and coarsening (left) gages. The minimum AIC fits are plotted for just the monotonic models (dashed line) and all models (solid line) are included for both cases.

3.1.2.2. Method 2: Q-Fine %

Some of the gradation data truncated the percent-finer data at the 63 μm, sand-silt boundary. Occasionally these truncated gradation curves did not include enough data to compute a d_{85} (e.g., if 90% of the sediment was finer than 63 μm). Excluding these curves could introduce bias (see extended discussion in the supporting information). To mitigate the curve truncation bias, the flow associated with each gradation was

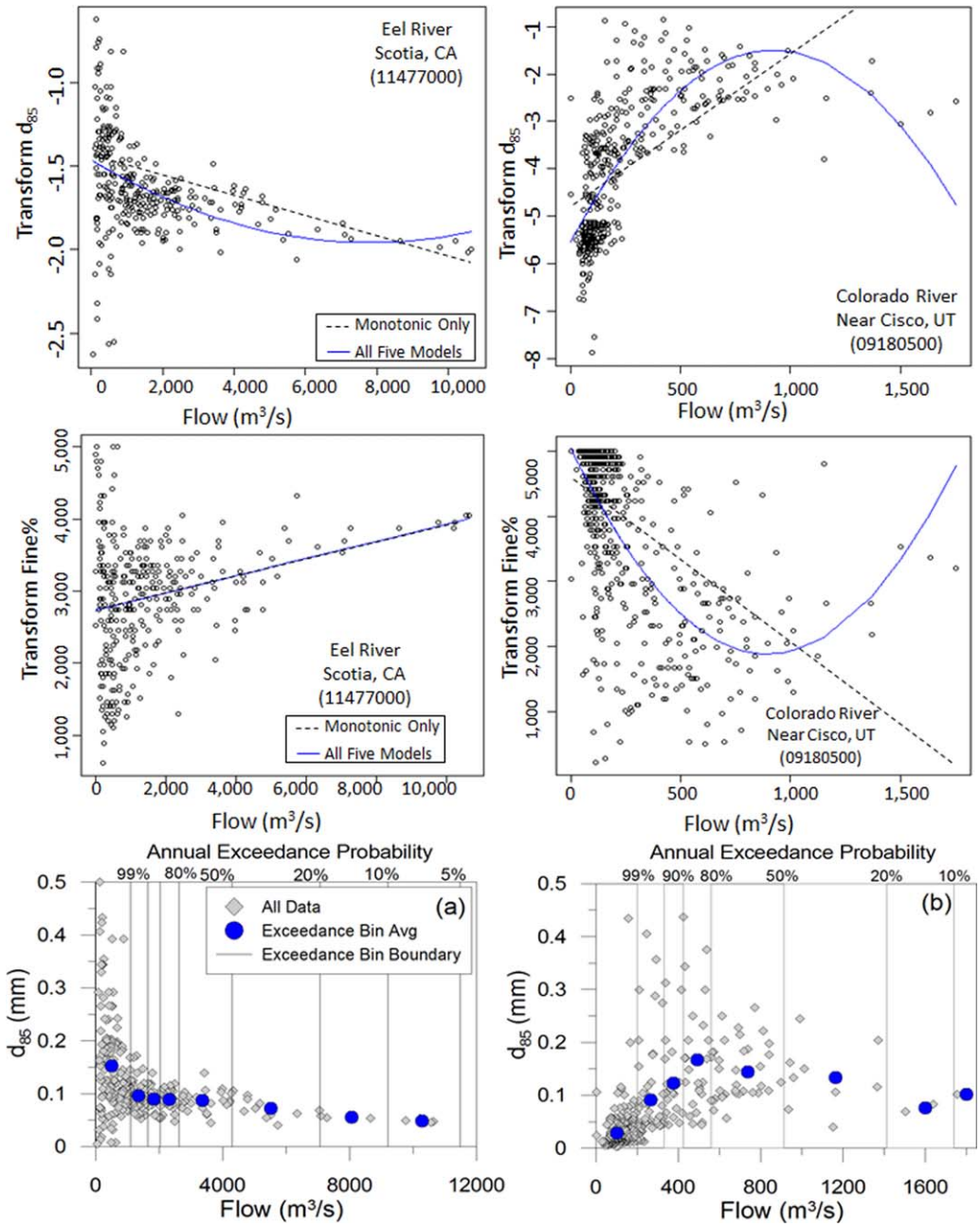

Figure 3. The three statistical analysis applied to the (left) Eel and (right) Colorado. The top and middle figures plot the best fit from just the monotonic models (dotted line) and from all five models (solid line) for the d_{85} and *Fine-%* analyses. The bottom figures plot the d_{85} and the exceedance probability bins with bin averages. The *y* axes of the top four plots are the Box and Cox (1964) transformations of the dependent variables. The transformations make the model errors more normally distributed, and in the process, more homoscedastic.

also paired with the percentage of the sample finer than 63 μm ("*Fine %*"). Regressing flow against Fine % also expanded the data set because many gages had concentration measurements that only included the sand-silt split percentages. Therefore the Q-Fine % analysis included all flows with percent-fine measurements. The analysis proceeded precisely as the previous method, except the *Fine %* replaced the d_{85} as the response variable. Figure 3 includes the Q-Fine % analyses (middle) using data from the same gages.

3.1.2.3. Method 2: Q_{EP}-$d_{85(bin\text{-}avg)}$

The gradation data were collected, disproportionally, at low flows. To address this low-flow bias a third analysis subdivided and averaged gradation data into normalized flow bins. Turowski et al. (2010) used a similar

approach to manage a similar, low-flow data bias in their analysis of the flow dependence of bed load percentage. The binned approach gives similar weight to the rare, large, events, and abundant, small events. This weighting reflects the assumptions of flow-gradation rating curves, but binning data violates regression assumptions, ruling out objective model fits, and leaving the curve analysis to subjective, gestalt analysis.

Flow bins were determined by annual exceedance probabilities (AEP) instead of absolute flow (U. S Army Corps of Engineers, 2010; U.S. Interagency Advisory Committee on Water Data, 1982). The AEP is the likelihood of equaling or exceeding a flow threshold in any given year. Because the gages selected include a large range of contributing areas and flow regimes, binning gradation data by exceedance probabilities provided a meaningful way to compare the relative flow magnitude across different systems (e.g., it makes more sense to compare the 10% events in different systems than the 100 m^3/s flow).

Once the Q-d_{85} data were converted to AEP-d_{85} data, they were divided into 10 exceedance probability bins from >99% to <2%. The d_{85}'s in each bin were averaged, and the average d_{85} for each bin was plotted against the geometric mean of exceedance probability (Figure 3). These plots were then examined visually to determine which monotonic model described them best (coarsening: A↑, fining: B↓, or independence: E↔). Then, they were reanalyzed to include the nonmonotonic hypotheses.

3.2. Gradational Trends Computed From Sediment Capacity Equations

This study also explored the flow-gradation response computed by several common sediment capacity equations. This analysis included four transport capacity functions that partitioned suspended and bed load and four total load functions. Partitioned capacity functions included: Toffaleti (1968), van Rijn (2007a, 2007b) the version of Einstein (1950) documented in Thomas et al. (2002), and the multiple-grain class formulation of Bagnold (1977) described in van Niekerk et al. (1992). Total load functions included Ackers and White (1973), Laursen-Copeland (Laursen, 1958; Thomas et al., 2002), Engelund and Hansen (1967), and Yang (1989), as documented in U.S. Army Corps of Engineers (USACE) (2016). The Hydrologic Engineering Center's River Analysis System (HEC-RAS) (Gibson et al., 2006; USACE, 2016) generated Toffaleti and all total load results and the Sediment Analysis Module (SAM) (Thomas et al., 2002) applied Einstein (1950). MATLAB code was developed for Bagnold (1977) and van Rijn (2007a, 2007b).

The functions computed capacity by grain class for a range of flows (0.03–300 m^3/s) in a rectangular (300 m long to 50 m wide) channel with a 0.0005 slope. The idealized channel included a bed gradation that spanned most of the sand range, including equal portions (25%) of all four classic sand grain classes (Very Fine Sand (VFS) = 0.088 mm, Fine Sand (FS) = 0.18 mm, Medium Sand (MS) = 0.354, and Coarse Sand (CS) = 0.707 mm). Hydrodynamic and sediment parameters were selected to keep Rouse numbers smaller than 2.5 (the approximate threshold for suspended conditions) for most grain classes at most flows and for all grain classes at the higher flows.

Two problems confound comparisons between the computed and measured flow-gradation relationships. First, sediment capacity equations are limited to sand sizes and coarser, excluding wash load in most systems. The measured data include wash load. Second, the measured data exclude bed load while the total load capacity equations not only include bed load but often include suspended algorithms designed with the same basic conceptual framework as bed load functions. Total load functions are likely to emphasize or exaggerate competence effects and cannot be compared directly to the suspended data presented. Therefore, results were stratified by the transport assumption (suspended-bed or total) in order to compare suspended results to suspended data and to examine how the equation assumptions affect load-gradation relationships.

4. Results

4.1. Gage Analysis

The coarsening hypothesis (A↑) dominated the monotonic results and the coarsening-fining (C↑↓) hypothesis emerged when all five models were considered. Results from the six analyses (i.e., the Q-d_{85}, Q-Fine%, and $Q_{(EP)}$-$d_{85(bin\text{-}avg)}$ are plotted by statistical method in Figure 4. (Individual gage results are included in the supporting information.) Figure 4a includes the results for the monotonic analysis and Figure 4b distributes the 78 gages based on the best fit from all five hypotheses.

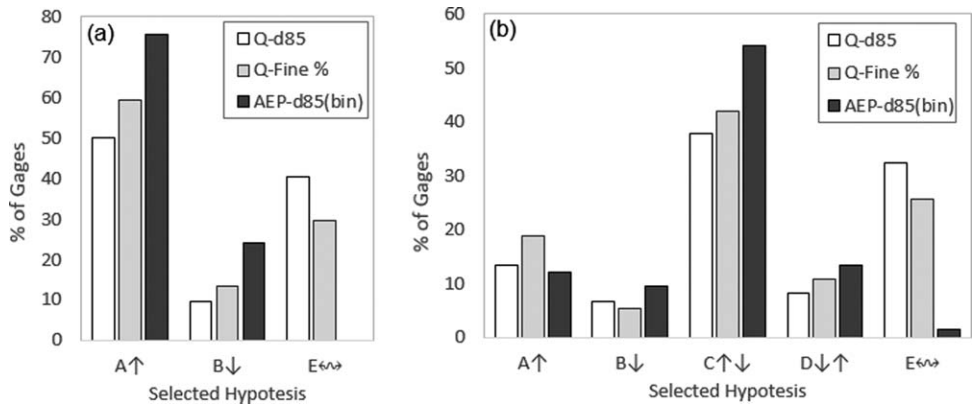

Figure 4. Proportion of gages associated with each basic model based on the three analysis methods (a) limiting hypotheses to monotonic options and (b) including second-order, nonmonotonic options (C↑↓ and D↓↑).

Between the monotonic models (Figure 4a) coarsening (A↑) dominated fining (B↓). Gages coarsened 3–4 times more often trends than they fined. Statistical analyses found no significant trend at 25–37% of the gages, suggesting flow-independence. The overall result was independent of the statistical analysis. Coarsening was far more common than fining.

When the analyses included second-order, nonmonotonic relationships (Figure 4b) the coarsening-fining model (C↑↓) emerged as the most common trend. The three analyses selected this model for 38–54% of the gages. The exceedance probability approach ($Q_{(EP)}$-$d_{85(bin\text{-}avg)}$), which emphasized the importance of rare, high flow, data, associated over half the gages with the coarsening-fining (C↑↓) hypothesis.

Because the exceedance probability ($Q_{(EP)}$-$d_{85(bin)}$) analysis normalized gradation and flow, these curves could be plotted together. All of the $Q_{(EP)}$-$d_{85(bin)}$ curves categorized as coarsening-fining (C↑↓) and fining (B↓) are plotted together with average curves in Figure 5. The average coarsening-fining curve (C↑↓) (Figure 5a) transitioned from coarsening to fining around a 30% annual exceedance probability (approximately a "3.3 year" recurrence interval). The average fining (B↓) curve (Figure 5a) actually includes a minor coarsening trend between the two lowest flow bins, which could be evidence of a minor, competence-driven coarsening trend below the 95% exceedance probability.

Results were stratified by contributing area, flow (AEPs), and various gradation metrics (see supporting information). None of these analyses produced statistically significant trends. However, mapping results to explore geographic distributions proved more instructive. Figure 6 maps the monotonic results (from the $Q_{(EP)}$-$d_{85(bin\text{-}avg)}$ analysis) and a map of the four-model analysis is included in Figure 7. These maps illustrate the dominance of the coarsening (A↑) and coarsening-fining (C↑↓) tends. In Figure 7, most of the large rivers in the mountainous west and southwest, including gages in and downstream of the Rocky and Sierra Nevada mountains, fit the coarsening-fining model (C↑↓), with a couple monotonic coarsening gages. These included most of the gages on the Colorado, Sacramento, and Rio Grande systems.

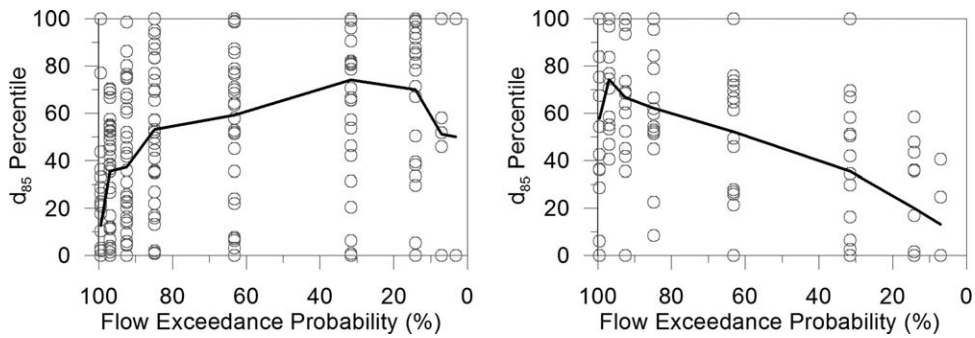

Figure 5. Compiled results from the Q_{AEP}-$d_{85(bin\text{-}avg)}$ analysis. Results for the C(↑↓) gages plotted together on the left and the B(↓) plots on the right.

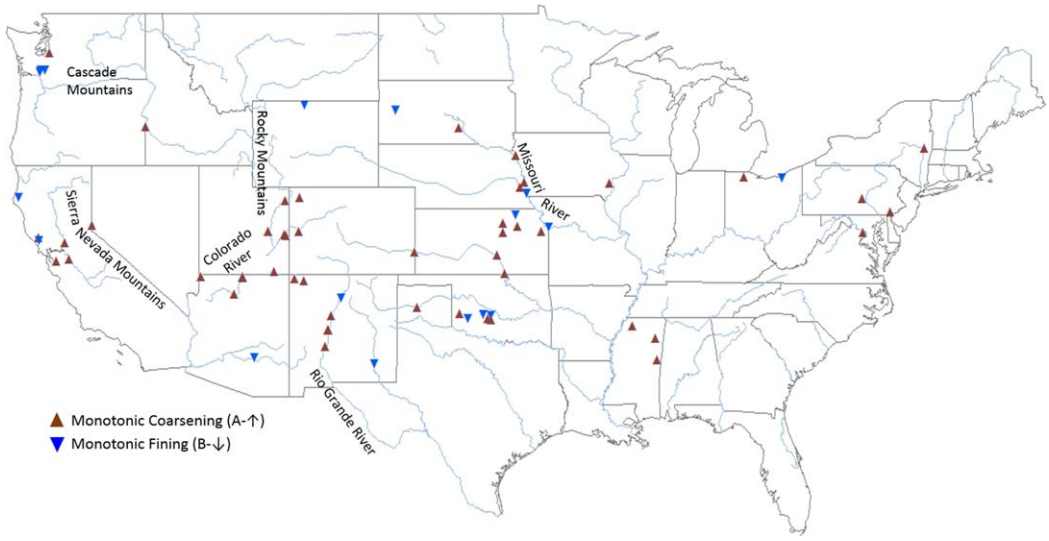

Figure 6. Map of monotonic model associations from the $Q_{(EP)}$-$d_{85(bin\text{-}avg)}$ analyses summarized in Figure 4a. Coarsening is much more common than fining.

Rivers in the flatter, central region of the country, with substantial loess loads, were more diverse. Plains gages were more likely to coarsen monotonically, even when second-order models were considered. Excluding the Missouri River, these gages were approximately evenly split between A (↑) and C (↑↓), with a couple examples of both B (↓) and D (↓↑). Most of the D (↓↑) gages fell along the lower Missouri River.

Monotonic fining gages (B↓), on the other hand, clustered in the Cascade and Coast ranges of the Pacific Northwest, including three gages in the Cowlitz-Toutle watershed in Southwestern Washington and the Eel and Russian Rivers along the California coast range. Data were sparse in the Northeast and Southeast. However, A (↑) and C (↑↓) gages still dominated these regions and the monotonic results (Figure 6) indicate general coarsening. It is worth noting that geographic trends mainly reflect physiographic similarities between rivers and do not necessarily characterize regional hydraulic conditions.

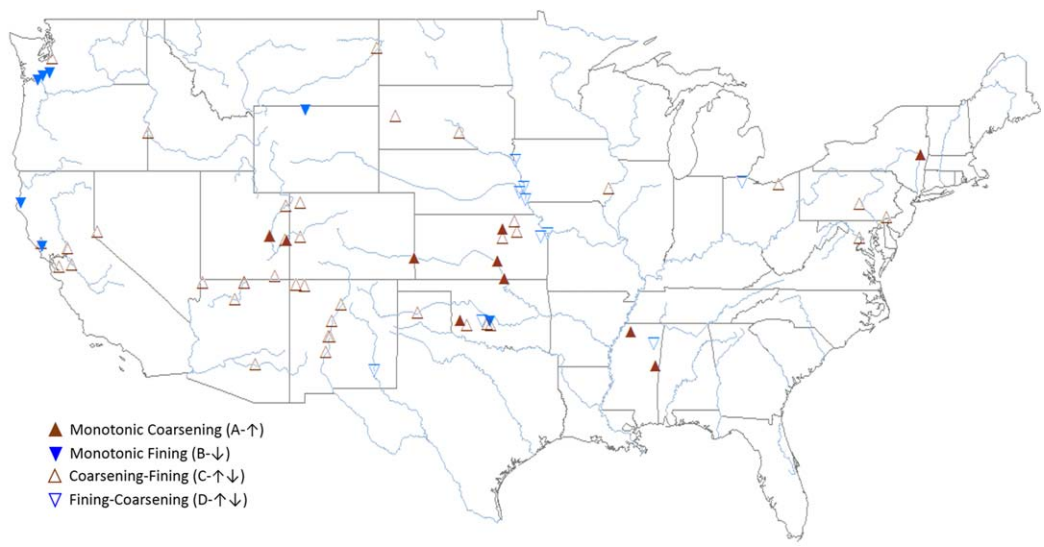

Figure 7. Map of the four model associations from the $Q_{(EP)}$-$d_{85(bin\text{-}avg)}$ analyses summarized in Figure 4b. Coarsening (A↑) and coarsening-fining (C↑↓) gages dominate the map, particularly the large regulated rivers of the mountainous west with monotonic fining gages (B↓) clustering in the high supply, unregulated rivers in the Pacific Northwest. Most of the fining-coarsening gages are along the Missouri River (D↓↑), likely because of the supply limitation of the 2011 event.

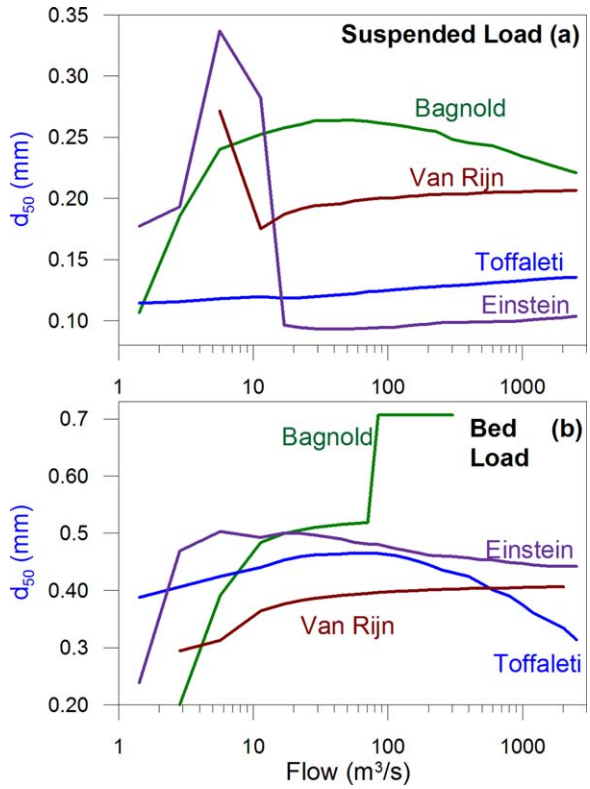

Figure 8. Flow-gradation relationships for four transport capacity functions that separate transport by (top, a) suspended and (bottom, b) bed load processes.

4.2. Flow-Gradation Relationships Computed With Capacity Equations

The computational analysis investigated the interaction between competence and capacity in the common sediment capacity equations. This analysis examined two types of transport capacity functions: (1) algorithms that separated suspended and bed load computations, and (2) total load functions, which compute bulk transport capacity, considering suspended load and bed load together. The sediment capacity functions that partition suspended sediment from bed load can be compared to the suspended sediment data analyzed above. However, while the flow-gradation trends from the total load function are not directly comparable to the data, they are commonly used to develop sediment model boundary conditions and are included.

The flow-gradation response of the partitioned capacity equations is included in Figure 8 and the total load results are plotted in Figure 9. The computational analysis generated Q-d_{50} responses as diverse as the gage observations, including curves that reflect most of the hypotheses in Figure 2. The suspended load gradations computed by some suspended equations (Einstein and van Rijn) vary substantially at low transport, as grain-classes shift between bed and suspended load, introducing gradational nonlinearities. However, all suspended load functions except Bagnold coarsen slightly (at approximately the same rate) at the higher flows (>20 m^3/s). These suspended gradation responses do not reflect any of the dominant flow-gradation trends in the gage data.

Bagnold, which includes an excess mobility approach, has the same basic coarsening-fining trend (C↑↓) as the three excess mobility total-load functions (Acker-White, Yang, and Laursen-Copeland). The Bagnold and Ackers White curves are plotted with the transport potential computed for each grain class in Figure 10. In both cases, new grain classes are entrained as flow increases over the low-flow range, driving a low-flow, competence-driven, coarsening phase. Then at higher flows, the capacity of the smaller grain classes grows nonlinearly, driving flow-fining. In Engelund and Hansen (1967) transport scales to grain size, making the computed total load gradation to flow.

Total load capacity calculations include bed load, confounding comparison to the gage data. Bed load emphasizes the competence-driven flow-coarsening at lower flows and most total load equations fine at higher flows as capacity effects dominate. The bed load components of the partitioned functions are included in Figure 8. These capacity functions all include competence-driven coarsening at low flows, and either increase monotonically over the whole flow range, switch to a high-flow-fining phase as coarser grain-classes transition to suspended load. The analysis was repeated with pure bed load functions (Meyer-Peter & Müller, 1948; Wilcock & Crowe, 2003), which both coarsened strongly over the flow range (see supporting information).

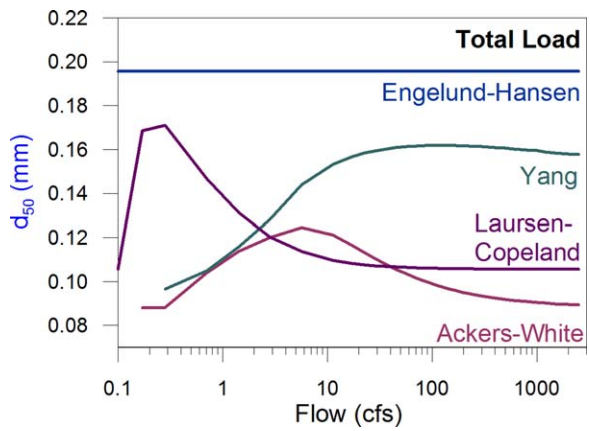

Figure 9. Flow-gradation relationships for four total load sediment capacity functions.

Transport capacity equations also assume unlimited sediment supply. This assumption does not describe many rivers, and confounds comparison to the measured data.

5. Discussion

5.1. Meta-Analysis Comparison With Published Trends

The study hypothesis predicted that capacity effects would dominate competence effects, causing most gages to fine with flow. The gage

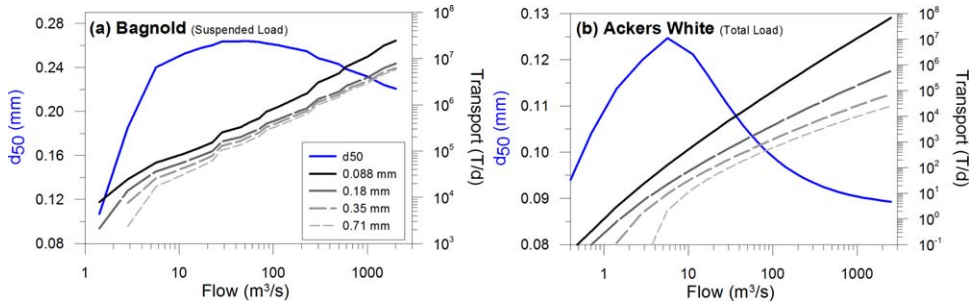

Figure 10. Computed transport by grain class and the median grain size (d_{50}) of transported sediment over a range of flows with two excess mobility functions (a) the suspended component of Bagnold (1977) and (b) Ackers and White (1973)—a total load function—for a four grain class mixture.

analysis results did not broadly support this hypothesis. The monotonic results can be summarized in two statements:

1. Flow-gradation trends vary between systems and can fine or coarsen with flow.
2. Most gages coarsened with flow.

Table 3
Gradation Trends Inferred From Published Data and Narrative Descriptions

River	Trend	Reference
Exe River at Pixton, Stoodleigh, and Thorverton, UK	A↑	Walling and Moorhead (1989)
Culm River at Rewe, UK	A↑	Walling and Moorhead (1989)
Eel River, CA, USA	A↑	Brown and Ritter (1971)[a]
Rio Puerco, NM, USA	A↑	Nordin (1963)[a]
Upper Tees, UK	A↑	Carling (1983)[a]
Scott Run, VA, USA	A↑	Vice et al. (1969)[a]
Wuding River, China	A↑	Long and Qian (1986)[a]
River Swale at Catterick, UK	A↑	Walling et al. (2000)
Sandusky River, OH(Ballville), USA	A↑	Evans et al. (2002)
River Ure at Westwick Lock, UK	A↑	Walling et al. (2000)
Galabre, France	A↑	Grangeon et al. (2012)
River Zagozdzonka, Poland	A↑	Hejduk and Banasik (2010)
Il Kimere, Kenya	A↑	Frostick et al. (1983)
Kootenai, MT,[b] USA	A↑	Wood et al. (2015)
Colorado River (1996 Grand Canyon flood Experiment), USA	A↑	Rubin and Topping (2001)
Rio Cordon, Italy	A↑	Lenzi and Marchi (2000)
Madeira, Brazil	A↑	PCE (2013)
Jackmoor Brook, UK	B↓	Walling and Moorhead (1989)
Creedy River at Crowley, UK	B↓	Walling and Moorhead (1989)
Clyst River at Clyst Honiton, UK	B↓	Walling and Moorhead (1989)
Niobrara River, NB, USA	B↓	Coby and Hembree (1955)[a]
Niobrara River, NB (Spencer), USA	B↓	Gibson and Boyd (2016)
Lower Kansas River, KS, USA	B↓	Mundorff and Scott (1964)[a]
Blue Ridge, GA, USA	B↓	Kennedy (1964)[a]
River Swale at Leckby Grange, UK	B↓	Walling et al. (2000)
River Stour, UK	B↓	Slattery and Burt (1997)
Dart River at Bickleigh, UK	C↑↓	Walling and Moorhead (1989)
Clyde River, Scotland	E↜	Fleming and Poodle (1955)[a]
Vermilion River, Manitoba, Canada	E↜	Environment Canada (1975)[a]
River Ouse at Skelton,[c] UK	E↜	Walling et al. (2000)

[a]Cited in Walling and Moorhead (1989).
[b]R-LODEST correlated load with quadratic flow, seasonality and the relative component of flow from Libby Dam.
[c]d_{50} constant and % finer than 0.004 decreases with flow.

Both of these findings align with other published results. A compilation of flow-gradation trends inferred from other literature is included in Table 3.

Walling and collaborators (Stone & Walling, 1997; Walling et al., 1992; Walling & He, 1998) inferred flow-gradation relationships from floodplain deposit thickness and measured suspended sediment size in small-to-moderate area watersheds in the United Kingdom. Walling and Moorhead (1989) augmented these measurements with data from several large rivers in various geomorphic settings around the world. Many of the relationships in Table 3 come from this work. These studies found more flow-fining than the gage results above, but still reported more coarsening sites than fining sites.

Results from reservoir stratigraphy also demonstrate both trends. Evans et al. (2002) correlated gravel lenses in the Ballville Reservoir with historic flood events, indicating flow-coarsening (A↑) driven by bed load dynamics. However, Gibson and Boyd (2016a, 2016b) found flood debris associated with cohesive layers in the otherwise sand sediment in Spencer Reservoir, indicating flow-fining (B↓) driven by wash load with agricultural sources.

A higher percentage of these published studies found flow-fining trends than the gage analysis in section 4.1. However, the literature also corroborates the two major findings of this study: the diversity of flow-gradation relationships and the dominance of coarsening.

The higher proportion of fining systems in the literature than in the gage analysis may reflect sample bias which, could offer some insight on the processes. The gage analysis in this study was biased toward large, dammed, US, rivers that often drain mountainous watersheds while the literature includes many smaller, lower gradient, European watersheds, including several in the UK (which, like Michigan in the US, has geographical limits on maximum watershed size). The sediment latency hypothesis came out of the UK, based on analysis of

Table 4
Summary of Flow-Gradation Curves Used to Parameterize Sediment Models

River	Trend	Model
Argandab River, Afghanistan	A↑	Gibson and Pridal (2015)
Euclid Creek, USA	A↑	Gibson (2001)
Tuttle Creek, USA	A↑	Shelley and Gibson (2015)
Russian River, USA	A↑	Gibson (2010); Gibson and Nelson (2016)
Cuyahoga River, USA	A↑	Gibson (2002)
Ontonagon River, USA	A↑	Creech et al. (2010)
Clark Fork/Blackfoot, USA	A↑	WEST Consultants (2003)
Mississippi (at Vicksburg), USA	A↑	Copeland and Lombard (2009)
Mississippi (at Tarbert Landing), USA	A↑	Thomas (1994)
Granite Reservoir, USA	A↑	G. Teesdale (personal communication, 2012)
Upper Truckee River, USA	A↑	ENTRIX (2008)
Susquehanna River, USA	A↑	Hainly et al. (1995)
Lower Mud River, USA	A↑	WEST Consultants (2003)
Platte River, USA	A↑	Tetra Tech (2015a)
White River, USA	A↑	USACE (2016)
11 Middle Rio Grande Tributaries, USA	A↑	Tetra Tech (2013)
Sheyenne River, ND, USA	A↑	U.S. Army Corps of Engineers (USACE) (2012); Gibson and Nelson (2016)
Muskegon River, USA	A↑	Gibson (2017)
Lower Puyallup River, USA	A↑	Gibson et al. (2017)
Cajon Wash, USA	A↑[a]	M. Teal (personal communication, 2016)
Muskegon River, MI (Big Rapids), USA	A↑[a]	Gibson (2017)
Chulitna, Yentna & Talkeetna Rivers, USA	A↑[a]	Tetra Tech (2015b)
Puyallup River, USA	B↓[b]	Sikonia (1990)
Cowlitz River, USA	B↓	Gibson et al. (2010)
Hillside Arroyo, USA	B↓	Tetra Tech (2013)
Sacramento River, USA	B↓	NHC and MBH (2011)
Niobrara River, USA	B↓	WEST Consultants (2010); Gibson and Boyd (2016)
Kootenai River, USA/Canada	C↑↓	M. Price (personal communication, 2016)
Lower Missouri, USA	D↓↑[c]	Shelley and Gibson (2015)
San Lorenzo River, USA	D ↓↑	Copeland (1986)
Susitna River, USA	D↓↑	Tetra Tech (2015b)
São Francisco River, Brazil	E↜	USACE-CODEVASF (2013); Creech (2014)
Puyallup River, WA, USA	E↜	Wardman et al. (2009)
Rio Grande River (Cochiti Reservoir), USA	E↜[d]	Davis et al. (2014)

[a]Some A↑ had curves add bed load material for the higher flows, but the suspended component did not vary with flow, making the suspended sediment essentially E↜.
[b]Load gradations computed with an earlier version of BAGS (Pitlick et al., 2009).
[c]Under most flow conditions the load fined with flow but flood of record [2011] suspended sediment concentration decreased over time and sediment load coarsened.
[d]The gradations of each tributary were constant with flow, but one tributary was finer than the other. Therefore, the load-gradation relationship in the reservoir was sensitive to the relative tributary flow.

these smaller, agricultural, watersheds, which may suggest that flow-fining is more common in these watersheds where supply limitation is less pronounced.

5.2. Meta-Analysis Comparison of With Model Parameters

Multiple grain class sediment transport models require users to specify flow-gradation relationships at domain boundaries. Measurements rarely support this data requirement. Modelers usually infer flow-gradation relationships from limited data (including data sources not included in the statistical analysis above) or adjust the flow-gradation inputs during calibration to match prototype response. When these data are not available or are scarce, models form their best conceptual, geomorphic model about how the load gradation varies with flow. Therefore, these model inputs also represent an additional line of either direct (based on data), indirect (calibrated to other observed data), or qualitative evidence. Table 4 categorizes the flow-gradation relationship from several of these models into the five flow-gradation hypotheses. On the whole, these results align with the gage data and published trends. Results include instances of fining and coarsening, with more of the latter (at a ratio of approximately 4:1).

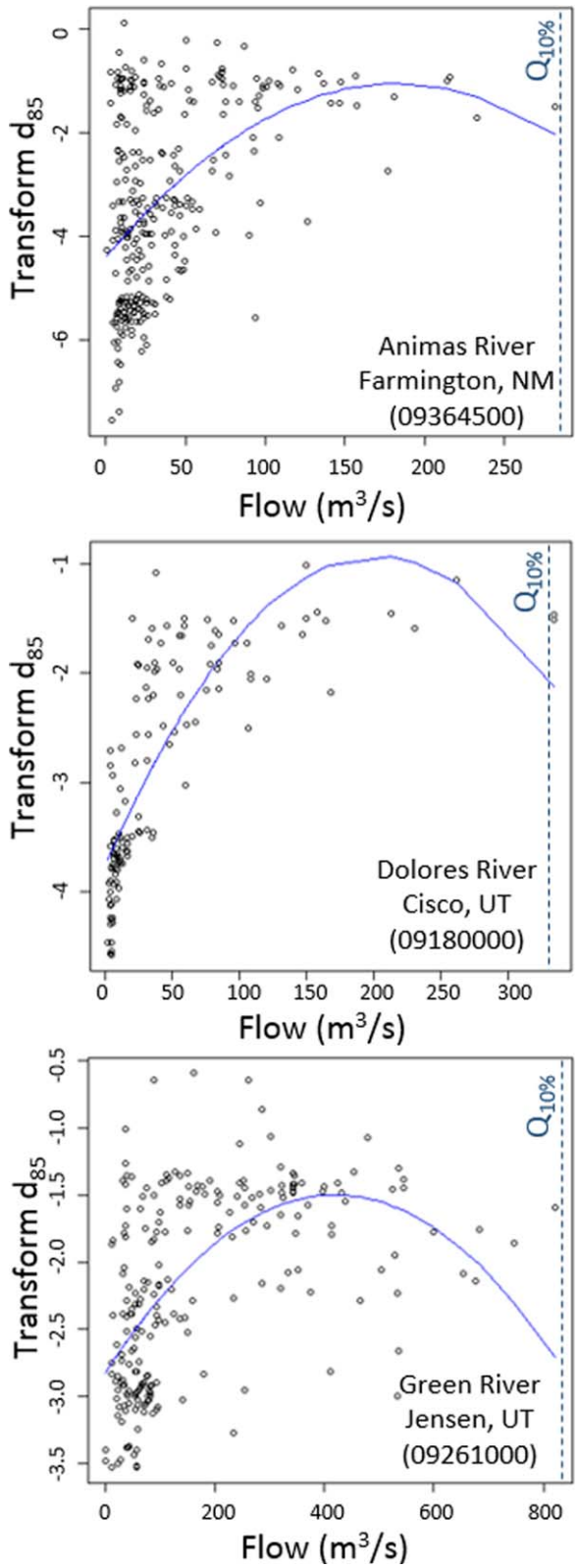

Figure 11. Three examples of the second-order coarsening-fining trends large, western rivers, which could be classified as "asymptotic coarsening."

5.3. Dominance of Asymptotic Flow-Coarsening and Supply Limitation

Flow-coarsening dominated study results (Figures 4a and 6) when trends were limited to monotonic options (zero- and first-order regressions). The coarsening-fining trend (C↑↓) was the most common nonmonotonic model, particularly for large Western rivers. However, at most coarsening-fining (C↑↓) gages, the coarsening phase was much more pronounced than the fining phase. Three, representative coarsening-fining (C↑↓) gages—from large, Western, United States, rivers—are included in Figure 11 (see also, Colorado River gage in Figure 3). These data are plotted with the 10% annual exceedance flow for scale. These gages follow a similar pattern. The coarsening trend usually approaches a practical upper limit instead of transitioning into a definitive fining trend. At least six other gages shared the asymptotic coarsening pattern of the gages in Figure 11. These gages coarsen over flows approaching approximately 1/3rd of the 10% annual exceedance flow (corresponding to the 30% AEP transition between coarsening and fining in Figure 5).

The flow-gradation relationship in these systems seems more sensitive to supply side factors than the competence-capacity dichotomy. An "asymptotic coarsening" model—where the bed gradation enforces a practical upper bound on the suspended gradation—may describe these observations better than a competence-capacity-driven coarsening-fining model C (↑↓).

Rubin and Topping (2001) observed flow-coarsening on the Colorado River during the managed flood in 1996 with pronounced load hysteresis, characteristic of supply limitation. They proposed several bed regulation hypotheses to explain coarsening in supply limited systems. In supply limited systems, particularly downstream of dams, most of the transported sediment comes from the bed. The bed cannot satisfy the high fine capacities that drive flow-fining. Therefore, competence (and preferential transport due to bed regulation) causes load coarsening over a wider range of flows in supply limited systems until it hits a physical upper limit or entrains finer floodplain sediment. Most of the large rivers in the Western United States are highly regulated and many were supply limited before the dams. Widespread supply limitation can explain the prevalence of coarsening in these systems.

5.4. High Supply Fining: The Exception That Suggests the Rule

Monotonic fining gages (B↓) clustered in the Pacific Northwest (Cascade Mountains) in the Cowlitz-Toutle system and the Eel and Russian Rivers (Figure 7). These are all high supply systems with modest-to-no flow regulation, and therefore, support to the initial flow-fining hypothesis (Figure 12).

The Cowlitz, Toutle, and North Toutle may be the least supply limited rivers in the continental United States. They are downstream of Mount St. Helens, which introduced 3.5 billion tons of sediment into their watersheds in 1980. All three rivers have significant fining trends from all six analyses (Figure 12). The other fining (B↓) rivers in the Northwest (the Eel (Figure 3) and Russian) are also coarse-bed, high-gradient rivers with high sediment loads. The Eel is entirely unregulated and the permanent Russian River dams are limited to the upper

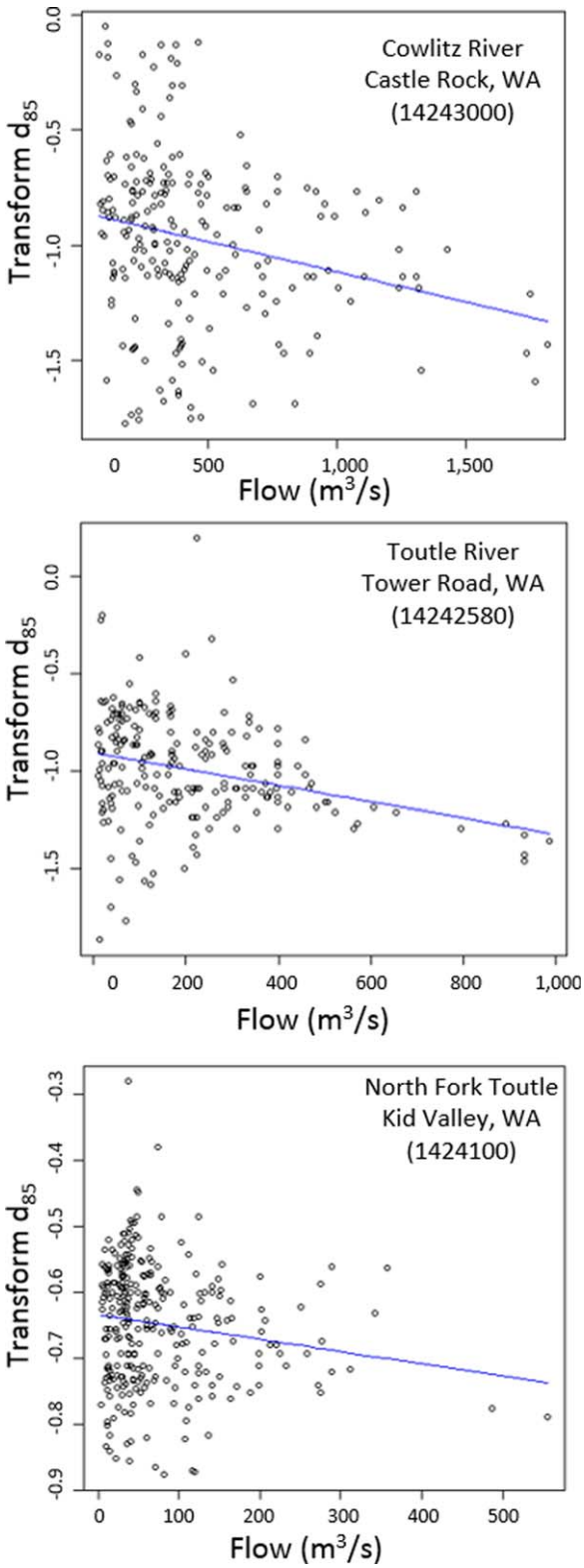

Figure 12. Fining in volcanic supply, Pacific Northwest Rivers.

regions of the river. These rivers are not strongly supply limited and therefore fine with flow.

Capacity effects overwhelmed competence effects on the Cowlitz-Toutle gages. Including bed load measurements would probably introduce competence-driven coarsening effects as higher shears entrain gravel and cobble (as Montgomery et al., 1999 observed in another volcanic supply systems). However, capacity-driven fining dominates suspended transport.

These fining (B↓) gages were the exception that suggest the rule. These high supply Northwestern gages support the a priori flow-fining hypothesis for nonsupply limited conditions. Therefore, the dominant coarsening (A↑), asymptotic coarsening, or coarsening-fining trends (C↑↓) that coarsen more than they fine are probably driven by supply side effects (e.g., dam driven supply limitation). However, the supply limitation that drives coarsening is widespread enough to make it the dominant process.

5.5. Implications for Transport Function Based Boundary Conditions

Some of the excess mobility transport capacity equations (particularly the total load equations) align, prima facie, with the dominant coarsening-fining trend, (C↑↓) or asymptotic-coarsening trend, coarsening over low flows with a less pronounced (or minor) fining trend over the high flows. However, the capacity equations did not all follow this trend and most of the suspended load equations computed minor fining for most of the flow range. Most of the low flow-coarsening in the excess mobility equations (both partitioned and total load) came from bed load effects, which are not reflected in the gage data. Therefore, the suspended load equations (Figure 8a), which shared the load-process assumptions of the gage measurements, provide the best comparison to the data analyzed. These suspended sediment computations did not reproduce the dominant gage trends. The variability in the capacity equations (in shape and magnitude) and the divergence of the suspended equation trends from the suspended data trends, suggest that these equations are not likely to predict gradational responses at model boundaries well.

Boundary conditions computed with sediment capacity equations also assume unlimited supply. But supply side constraints appear to drive the flow-gradation trends in most of the rivers analyzed. Therefore, capacity based, flow-gradation boundary conditions are poorly posed more often than not. Flow-gradation relationships should be developed based on the best data available. Where data are sparse or absent, modelers should develop a working monotonic hypothesis for the suspended component of the boundary loads: flow-fining in capacity limited systems and flow-coarsening in supply limited systems. This hypothesis should be evaluated as part of the model calibration and validation process.

6. Conclusions

Flow-gradation relationships are complex, including examples of flow-fining, flow-coarsening, and more complicated, nonmonotonic responses. Some of this complexity arises because flow does not account for all of

the load-gradation variability. However, sediment transport modelers usually define their sediment boundary conditions with flow-load and flow-gradation trends, even (especially) when data are sparse. Therefore, modelers must understand the processes that drive flow-gradation trends.

The 78 gages analyzed in this study included examples of all five flow-gradation trends hypothesized (Figure 2). The high supply (including volcanic supply) rivers in the Pacific Northwest followed the hypothesized flow-fining prediction (B↓). However, flow-coarsening (A↑) was more common than flow-fining (B↓) by a ratio of around 3:1. The literature review turned up a lower ratio (1.5:1) and the model parameter review returned a higher ratio (4:1), but the meta-analyses supported both the diversity of the flow-gradation trends and the dominance of coarsening. The literature review may have included more flow-fining because it included more, smaller, agricultural watersheds which were not as influenced by supply limitation effects.

When the analysis expanded to include nonmonotonic analyses, the coarsening-fining trend (C↑↓) was most common, including a third to a half of the gages depending on the analysis. This coarsening-fining trend was most common in the large rivers in the American Plains and West. However, the coarsening trend in these gages was much more pronounced than the fining trend. Therefore, the dominant nonlinear trend was described as "asymptotic coarsening" (A↑-E↜) or "asymmetrical coarsening-fining" (C↑↓). Because high supply rivers in the Northwest supported the initial fining hypothesis, these widespread coarsening trends are likely supply side effects (e.g., dam related supply limitation). The prevalence flow-coarsening suggest supply limitation or bed scale dynamics (like those described by Rubin & Topping, 2001) often influence flow-gradation trends. These results were not based on random samples and include substantial biases. They tend to reflect large rivers with good sediment data and historic sediment concerns. However, they demonstrate the importance of supply on gradational trends.

Finally, the sediment capacity equations also generated diverse flow-gradation trends and most flow-coarsening computed by the suspended equations was minor compared to the measured data, over most of the flow range. The suspended capacity equations did not broadly reflect the gage data and reflect supply unlimited conditions. Therefore, sediment-model boundary conditions based on transport equations are often poorly posed. The flow-gradation relationship must be developed using the best data, system analysis, and intuition that account for the relative contributions of competence and capacity, local influences (e.g., loess loads and glacial settings), and supply limitation.

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