Quality and Quantity of Suspended Particles in Rivers: Continent-Scale Patterns in the United States

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ABSTRACT / Suspended solids or sediments can be pollutants in rivers, but they are also an important component of lotic food webs. Suspended sediment data for rivers were obtained from a United States–wide water quality database for 622 stations. Data for particulate nitrogen, suspended carbon, discharge, watershed area, land use, and population were also used. Stations were classified by United States Environmental Protection Agency ecoregions to assess relationships between terrestrial habitats and the quality and quantity of total suspended solids (TSS). Results indicate that nephelometric determinations of mean turbidity can be used to estimate mean suspended sediment values to within an order of magnitude ($r^2 = 0.89$). Water quality is often considered impaired above 80 mg TSS L^{-1}, and 35% of the stations examined during this study had mean values exceeding this level. Forested systems had substantially lower TSS and somewhat higher carbon-to-nitrogen ratios of suspended materials. The correlation between TSS and discharge was moderately well described by an exponential relationship, with the power of the exponent indicating potential acute sediment events in rivers. Mean sediment values and power of the exponent varied significantly with ecoregion, but TSS values were also influenced by land use practices and geomorphological characteristics. Results confirm that, based on current water quality standards, excessive suspended solids impair numerous rivers in the United States.

Suspended particles in rivers can compromise biotic integrity and degrade water quality, but they also represent an important part of the food webs and nutrient cycles of lotic ecosystems (Wood and Armitage 1997). Despite this dual role, limits on particulate material are usually based on turbidity, which does not account for particle quality or size. The United States Environmental Protection Agency (USEPA) reports that 13% of all rivers and 40% of impaired rivers assessed in 1998 were affected by sedimentation (United States Environmental Protection Agency 2000). Increased sediments can impair quality and lead to greater drinking water purification costs. Sediments can also reduce biotic integrity by interfering with growth and reproduction of valuable game fish, stressing endangered or threatened species, and extirpating sensitive invertebrate species (Berkman and Rabeni 1987, Cooper 1993, Waters 1995, Wood and Armitage 1997). Despite the pervasiveness of excessive sediments, and their integral nutritional role for filter-feeding invertebrates (Wallace and Merritt 1980, Wotton 1994), the relationship of sedimentation to food quality of suspended particles is not well established (except see Whiles and Dodds 2002).

To regulate sedimentation, concentration and composition of total suspended solids (TSS) must be related to various land uses. The USEPA adopted an ecoregion approach to deal with geographic variability when addressing water quality (Omernik 1987). However, it is not currently known whether there are relationships between ecoregions and suspended sediment quantity and quality.

The amount of TSS can vary substantially in rivers as a function of discharge. The most commonly used relationship between discharge (Q) and sediment concentration (C) is

$$C = aQ^b$$

where a is a constant, and b is the exponent. Thus, temporal variations in sediment concentrations can be ascribed to hydrologic variability (e.g., VanSickle and Beschta 1983). Mean concentrations are relevant to filter-feeding organisms using particulate material for food and when considering chronic exposure effects on

KEY WORDS: Ecoregions; Land use; Pollution; Seston; Suspended sediment; Turbidity; Water quality
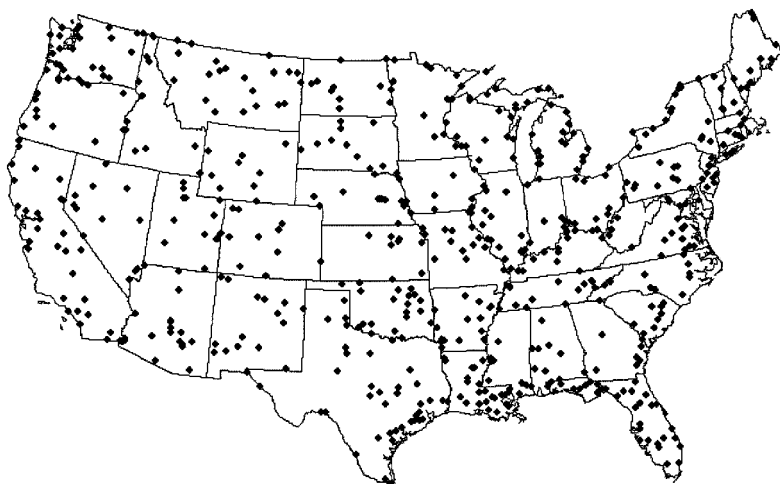
Figure 1. Sampling sites for total suspended sediments used in this analysis. Sites are part of the United States Geological Survey National Stream Water-Quality Monitoring Network.

biota. Maximum sediment concentrations are important when considering the probability of acute exposure effects. However, determination of maximum sediment concentration is difficult with direct manual sampling. For example, simple maxima from sites would be very sensitive to data from individual sites that had, by chance, been sampled during exceptional floods. The propensity of a system to have high sediment concentrations can be partially characterized by *b*, which can be considered as a flow-based index of potential spikes in sediment concentrations. Therefore, the power of the relationship (*b*) between concentration and discharge may be an indicator of acute effects, and the mean TSS can indicate chronic exposure. A system with a high value of *b* will be very prone to producing large increases in concentrations of TSS under increased discharge.

The overall objective of this study was to examine patterns regarding land cover and suspended sediment quantity and quality. This was accomplished by analyzing correlations within a database constructed from United States Geological Survey (USGS) data on rivers in the United States. We first used a correlation approach, because this is the most basic and general method available for data exploration. We then linked suspended sediment data (means and *b*) to the first three levels of the USEPA ecoregions to examine patterns of quality and quantity across different regions.

Methods

Data were compiled from the United States Geological Survey National Stream Water-Quality Monitoring Networks (WQN) derived from sampling sites (Figure 1) across the United States (Alexander and others 1996). These data sites included both those in the

National Stream Quality Accounting Network (~90% of data, NASQAN) and Hydrologic Benchmark Network (~10% of data stations, HBN). NASQAN sites were chosen at the outlets of major watersheds across the United States, and the HBN sites were chosen specifically as less culturally impacted (generally smaller) watersheds (Alexander and others 1998), and stand methods were used for ISS aanalyses (ASTM 1999) . Data were used from all stations with more than 10 data values for TSS from 1970 to 1983, with at least 75% of the data points taken between 1974 and 1978. Only 14 sites (2.2%) had less than 20 samples, and only 14% of the sites had less than 50 samples; the median number of samples per site was 89. Sampling frequency was 4 to 12 samples per year (generally monthly in the 1970s and quarterly in the 1980s), and there was a slight tendency across the data set for samples to be collected earlier in the calendar year (about 10% more per month in January to May than in June to December). Depth-and width-integrated sample-collection techniques were used to ensure adequate representation of the stream cross section (Alexander and others 1998), and standard methods were used for TSS analysis (ASTM 1999).

Associated values of latitude, longitude, drainage area, population (1990), land cover in 1987 (percentage urban, cropland, pasture, forest, range, farmland [agricultural land not in crop, pasture or range categories] or other), were taken from the data set. Values measured from samples and measurements taken simultaneously with TSS included turbidity (nephelometric turbidity units, NTU), discharge, temperature, dissolved nitrogen, total nitrogen, and suspended carbon (TSC). Not all of these additional values were available for every date and every station. The abstracted data set included 59,820 individual sampling

events and was used to calculate suspended nitrogen (TSN = total nitrogen − dissolved nitrogen) and C:N of suspended particles (TSC/TSN) for each date with values available.

An average data point for any individual variable at a specific station was only created when more than 10 values were available. If more than 10 values were not available, a "missing" value was assigned for that particular mean value for that station. This was the case for up to 32% of the mean values for any particular variable; TSN and TSC values were not available for many stations. Any obvious outliers (mean values from a station for a variable that was more than two times greater than the next smallest value or less than one half of the next largest values) were assigned missing values. This step was necessary because it was difficult to determine whether the outliers were caused by analytical error, data entry error, or unusual conditions at the site, although less than 1% of the data were removed using these criteria. However, removal of outliers and removal of station means for variables where there were fewer than 10 observations resulted in a different number of stations with means for each variable. The range encompassed a maximum of 622 individual stations with TSS values to the minimum of 420 stations with C:N data.

The relationship between sediment concentration and discharge was also determined for each station to assess the likelihood of acute exposure from high-sediment events. In this case, the relationship between log discharge and log sediment concentration was examined using regression analysis (VanSickle and Beschta 1983) for those stations that had more than 20 values for both discharge and TSS. Where the regression was not significant ($p > 0.05$) for b, the power of the relationship, a "missing" code was assigned for any further analyses of factors influencing b.

The ecoregion of each sampling site was derived from maps produced by the National Health and Environmental Effects Research Laboratory of the USEPA for Levels I, II, and III (Omernik 1987, Commission for Environmental Cooperation 1997). These ecoregions are based on land use, soils, land surface form, and potential natural vegetation. In the United States, there are a total of 9 level I ecoregions, 32 level II ecoregions, and 78 level III ecoregions.

Correlations were explored using the nonparametric Kendall τ procedure to avoid problems with any nonnormal data distributions. The relationship between log TSS and log NTU was fit with a linear regression. Analysis of variance followed by Fisher's LSD test ($p < 0.05$) was used to compare TSS (mean and b) across ecoregions. In analysis of variance, only ecore-

gions with data from 10 or more stations were used, and TSS and b were distributed normally. Means and regressions for each station were calculated using SAS (version 8.2, SAS Institute, Cary, NC). All additional statistical procedures were performed using Statistica 5.5 (Statsoft, Tulsa, OK), except the two-dimensional Kolmogorov-Smirnov (2dKS) bivariate breakpoint analysis (Garvey and others 1998) that was conducted using code provided by J. Garvey, Southern Illinois University, Carbondale.

Results

Site-specific means for TSS varied more than three orders of magnitude across sites (Figure 2) and correlated well with turbidity (NTU, Table 1, Figure 2A). Regression analysis of NTU and total suspended solids (TSS) yielded the following relationship:

$$\log_{10} \text{TSS (mg/L)} = 0.606 + 0.960*(\log_{10} \text{NTU}) \quad r^2 = 0.89 \quad (1)$$

The median value of TSS was 63 mg/L (Figure 3A). Nonparametric 2dKS analysis (Garvey and others 1998) suggested a breakpoint in TSS values with a forest cover of 17%, and that the highest values for TSS concentration occur below 20% forest cover (Figure 4C). When only samples that had more than 33% forest cover were included (as a conservative indicator of relatively undisturbed and vegetated watersheds), there were fewer high (e.g., >100 mg/L) TSS concentration values, and the median value was 15 mg/L, about one fourth of the median for the entire data set including sites with little forest cover (Figure 3B).

Suspended sediments were only moderately correlated with TSC and TSN ($\tau = 0.58$ and 0.51 respectively, Figures 2B, C), suggesting that inorganic materials (i.e. TSS-TSC) have a significant influence on TSS. Stated another way, carbon was not highly correlated with total sediment concentrations; thus the inorganic component varied significantly and independently from carbon. Although total suspended sediments ranged across nearly four orders of magnitude, TSC and TSN ranged approximately two and less than two orders of magnitude, respectively (Figures 2B, C).

Considering only land use categories, TSS was significantly and most strongly correlated with percentage of forest cover (negative correlation), followed by percentage of rangeland and cropland cover (positive correlations). The percentage of urban area in a watershed was negatively correlated with TSS (Figure 4, Table 1) primarily because watersheds with more than 5% urban area had no mean values of TSS above 500 mg/L.
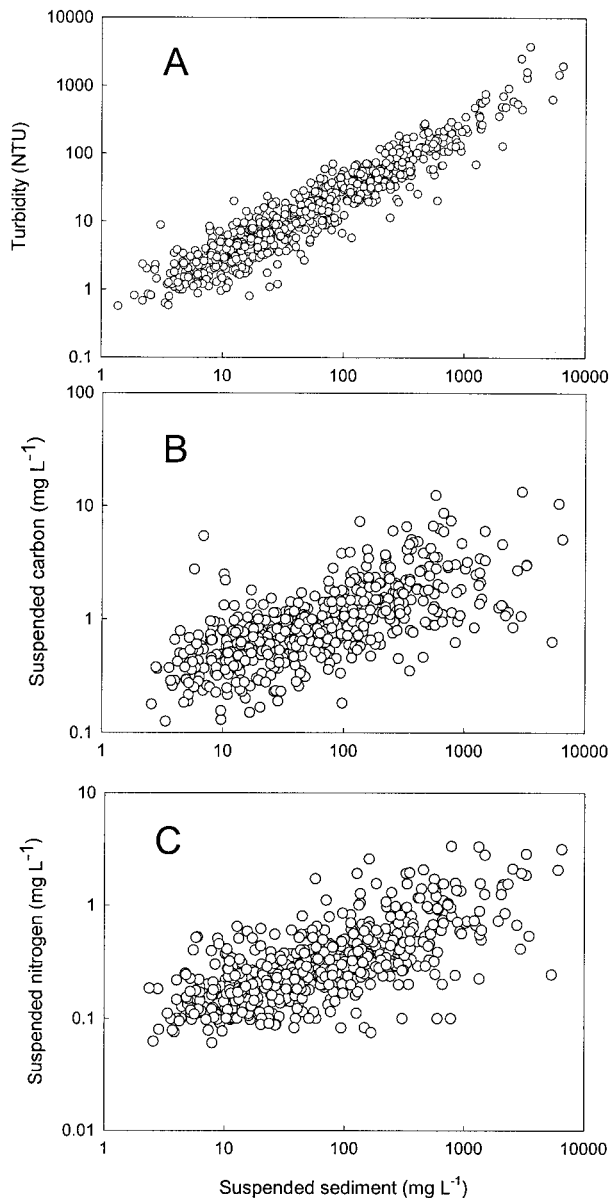
Figure 2. Relationships between suspended sediment and turbidity (**A**), suspended carbon (**B**), and suspended nitrogen (**C**). Each point is a site-specific mean.

Latitude had a significant, but weak effect, whereas longitude had a stronger effect, with sites further west having higher TSS concentrations. Highly urban sites are more prevalent in the Eastern United States, so we tried to control for latitude (dry region) effects on the urban–TSS correlation by only analyzing data east of −94°. There still was a significant negative correlation between percent urban land use in the watershed and TSS in the moister sites found in the Midwest and the Eastern United States. This correlation could still be confounded by the fact that highly urban sites are not likely to have a substantial proportion of cropland.

The exponential relationship between discharge and TSS (b) was significant for 489 of 619 stations. The r^2 values ranged from 0.01 to 0.91 with a median r^2 of 0.35, indicating that discharge generally was only moderately successful in predicting TSS at many sites. The power of the exponential relationship between discharge and TSS (b) was correlated with fewer variables than was mean TSS (Table 1). Mean TSS, b, and longitude were all positively correlated. Land cover and several other physical and chemical parameters were significantly correlated with mean TSS, but did not have Kendall τ values of more than 0.14 (Table 1).

At ecoregion level I, higher TSS values were associated with the North American Deserts and the Great Plains (Figure 5), sites with greater values for longitude. Analysis of variance indicated that Northern Forest sites had significantly lower TSS than most other sites, followed by Eastern Temperate Forest sites, patterns that were consistent with the trend of lower TSS with more forest cover. Power (b) varied significantly by ecoregion level I (ANOVA, $p < 0.00001$), with the highest values in the Marine West Coast Forest region. North American Deserts had the highest mean TSS, but intermediate values of b.

Variance at ecoregion level II was evident even within ecoregion level I regions (Figure 6). As was true for level I ecoregions, the relationship between ecoregion and b varied from that between ecoregion and mean TSS, but was still significant (ANOVA, $p < 0.0001$).

At ecoregion level III, there were also significant differences in TSS across regions (ANOVA, $p < 0.0001$), with the greatest TSS found in regions dominated by cropland agriculture, the Northwestern Glaciated Plains, followed by the Northwestern Great Plains, and then the Southern and Central California region (Figure 7). As with the level I ecoregion analyses, there was poor correspondence between patterns of TSS and b across level III ecoregions.

Carbon:nitrogen values, which can be used as indicators of particle quality (e.g., food quality for organisms feeding on particulate material), were examined, but there were no factors that were significantly correlated with C:N that had Kendall τ values of more than 0.14. However, when C:N data were analyzed by level-I ecoregions, C:N values were significantly greater (about 50%) in the Northern Forests than all other ecoregions (Fisher's LSD, $p < 0.002$, data not shown), suggesting a moderate ecoregion effect on differences in land use that correspond to large-scale ecoregions.

Table 1. Correlations among variables related to suspended sediment quantity and quality[a]

	Turbidity (NTU)		Suspended sediment		Suspended carbon		Suspended nitrogen		Sediment vs. discharge, power (b)		Inorganic sediment	
	τ	N	τ	N	τ	N	τ	N	τ	N	τ	N
Longitude	0.17	633	0.22	622			0.17	584	0.15	618	0.24	522
Drainage area	0.29	613	0.29	602	0.18	509	0.24	565			0.25	503
Population (1990)	−0.15	542	−0.18	533							−0.17	483
% Urban	−0.20	551	−0.24	542			−0.13	525			−0.23	492
% Cropland	0.18	551	0.16	542	0.27	498	0.21	525			0.16	492
% Pasture												
% Forest	−0.33	551	−0.37	542	−0.26	498	−0.39	525			−0.37	492
% Range	0.31	551	0.35	542	0.18	498	0.31	525			0.36	492
% Farm					0.14	498						
% Other	−0.16	551			−0.21	498						
Discharge												
Temperature	0.17	632										
Turbidity			0.79	622	0.53	527	0.50	584			0.79	522
Sediment					0.53	522	0.51	579	0.29	618	0.99	522
TSC							0.49	526			0.52	522
TSN											0.53	522

[a]Only correlations with nonparametric Kendall $\tau > 0.14$ are listed. All listed correlations are highly significant ($p < 1 \times 10^{-7}$).
NTU: nephelometric turbidity units; TSC: total suspended carbon; TSN: total suspended nitrogen.

Suspended carbon was most strongly related to percentage cropland and forest (Figure 8, Table 1), and TSN was most strongly related to percentage forest and rangeland (Figure 9, Table 1). Correlations were consistent in sign and magnitude for TSC and TSN, with a stronger influence of percentage forest on TSN than TSC. The proportion of organic carbon in TSS decreased with increasing drainage area and increased with greater cover of cropland and forested area (Figure 10).

Discussion

Water that exceeds suspended solids levels allowed by law is more expensive to treat because removal of sediments by filtration uses energy and materials in proportion to the amounts that must be removed. Drinking water regulations in the United States require that water not exceed 5 NTU. According to Equation 1 from our study, 5 NTU corresponds to 19 mg L^{-1} TSS, and mean values of TSS from more than 60% of the rivers in our analysis exceeded this value. These data provide further evidence that many of the rivers in this country exceed water-quality criteria for TSS, which could lead to reduced biological integrity and increased drinking water treatment costs.

Regulations on the amount of TSS allowed in rivers vary across the United States. In some states, 10 mg/L TSS is considered too high; fisheries may be harmed above 80 mg/L, and waters more than 400 mg/L provide poor fish habitat (Waters 1995). Negative impacts of suspended sediments on fish include smothering eggs, interfering with respiration, limiting visibility for sight feeders, and loss of habitat and prey communities (Berkman and Rabeni 1987, Wood and Armitage 1997). Most of the average TSS concentrations in the large data set we examined exceeded 10 mg/L, ~35% exceeded 80 mg/L, and ~10% exceeded 400 mg/L. Hence, it is likely that there are substantial numbers of rivers where chronic exposure to TSS harms fish communities.

Other vital components of stream ecosystems, including primary producers and invertebrate communities, are also sensitive to increased TSS (Wood and Armitage 1997). Suspended sediments can adversely affect benthic organisms indirectly through sedimentation and decreased habitat quality, but there is also evidence for direct effects resulting in abrasion, increased drift, and mortality. For example, Cooper (1988) found that TSS values greater than 200 mg/L resulted in elevated mortality of some sessile stream invertebrates, and Culp and others (1986) found that elevated levels of TSS resulted in catastrophic drift of stream invertebrates.

It is more difficult and expensive to directly measure TSS with gravimetric techniques than it is to determine turbidity by nephelometry (NTU). Thus, it would be beneficial to know whether NTU values can be used to
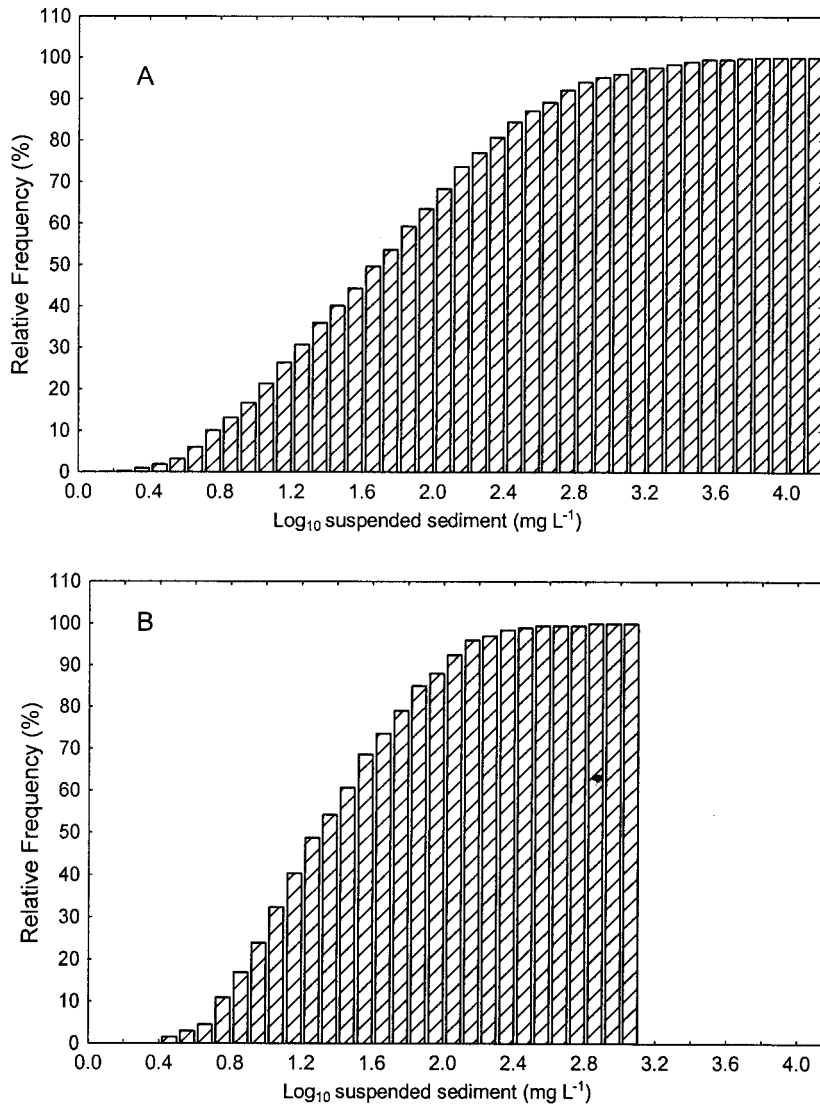
Figure 3. Cumulative frequency plots of suspended sediment for all USGS stations (**A**), and for the subset of USGS stations with watersheds with greater than 33% forest cover (**B**).

accurately estimate TSS concentrations. Earhart (1984) demonstrated site-specific correlations between TSS and NTU values. The relationships reported by Earhart (1984) between NTU and TSS were less variable than those reported in this paper, but held only for specific sites over narrow concentrations of TSS. Variability in the TSS–NTU relationships in our analysis is probably related to differences in size, composition, and refractive index of particles (Earhart 1984). However, our results do indicate that mean NTU can be used to estimate mean TSS within an order of magnitude. Although an order of magnitude may seem like a wide range, Figure 1 illustrates that TSS can vary over three orders of magnitude across systems.

Large data sets, such as those analyzed here, allow for increased generalization (Lettenmaier and others 1991), but have a corresponding increase in variance. This variance may be linked to the variety of sites that are sampled, as well as variation in how samples were collected and analyzed. For example, there are currently more efficient sampling strategies to link discharge and sediment loading (Thomas and Lewis 1993, Thomas and Lewis 1995) than were used by the USGS. Thus, sampling used in the analysis may have been biased and decreased the ability to correlate watershed factors with TSS concentrations or could have led to spurious correlations (e.g., if high discharge events were more likely to be sampled in Western regions).

Some specific practices that lead to increased sedimentation in rivers and streams are well known. Waters (1995) includes agricultural activities (cropland and livestock grazing), forestry, mining, urban develop-
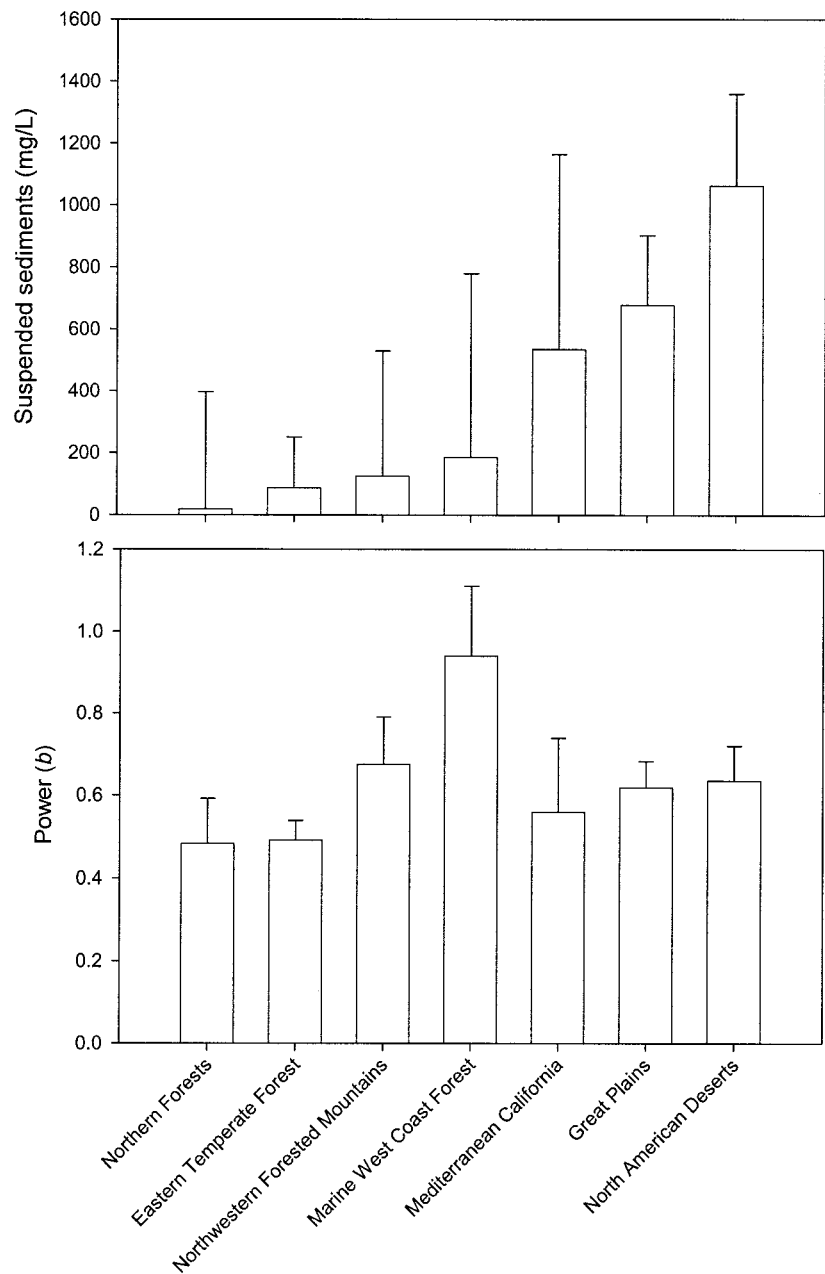
Figure 4. Suspended sediment as a function of watershed drainage area (**A**), percentage urban area (**B**), percentage forested area (**C**), and percentage cropland (does not include rangeland) area (**D**). Each point is a site-specific mean.

ment, and stream bank erosion as activities likely to encourage sedimentation. For example, it is obvious that there is substantial localized sediment input after heavy rains in areas where there is disturbed cropland or new construction and no riparian vegetative buffer. The relative impacts of small-scale processes and sources across the landscape are not as clear. Agriculture has been implicated as the primary source of sedimentation, with forestry having less of a large-scale impact (Wood and Armitage 1997).

We expected the percentage of urban area to be positively correlated with TSS in rivers because we assumed urban development led to increased inputs of particulates via storm water and sewage inputs, as well as increased erosion. For example, Pozo and others (1993) found higher concentrations of suspended particles, particularly organic constituents, associated with sewage effluent from urban development in a Spanish river. In contrast, our results suggest that urbanization leads to decreased sediment delivery to streams and
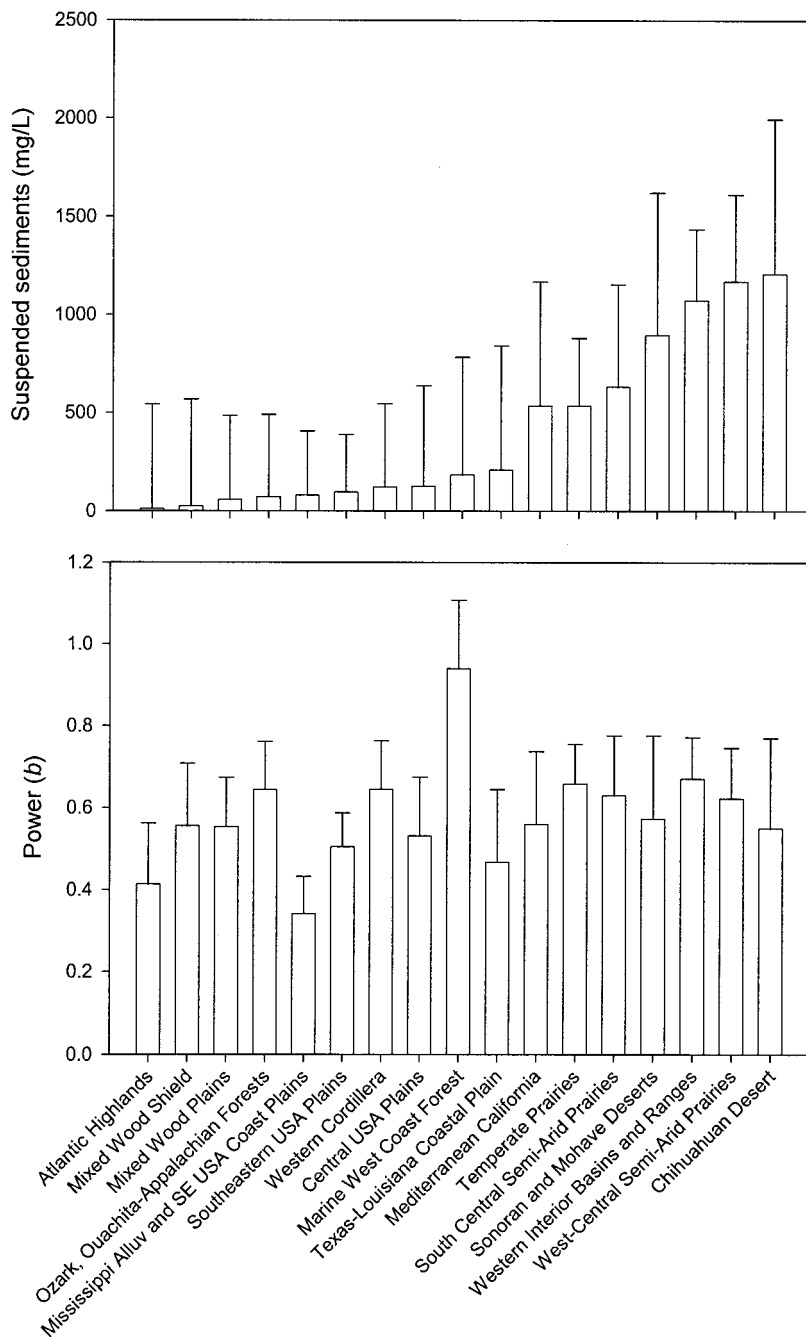
Figure 5. Mean suspended sediments and power (**b**) of the relationship between discharge and concentration by EPA level I ecoregions. Error bars = 95% confidence interval.

rivers, probably because there is more cover (pavement, buildings) and bare soil is rare (e.g., lawns and paved areas cover soil and reduce erosion). Alternatively, the large spatial scale of our analysis may have "diluted" the impacts of urbanization (e.g., urban point source impacts may quickly attenuate with downstream distance) or caused spurious spatial effects (e.g., urbanization could have been lower in drier regions that were more prone to sedimentation).

Although suspended particulates are often viewed as pollutants, they are also important components of energy flow and nutrient cycling in rivers, representing the primary food resource for a great variety of filter-feeding organisms including numerous invertebrates and some fishes (Wallace and Merritt 1980, Wotton 1994). As a result, the nutritional quality of particles is also of interest. Whiles and Dodds (2002) showed that suburban development led to higher (e.g., up to 50%
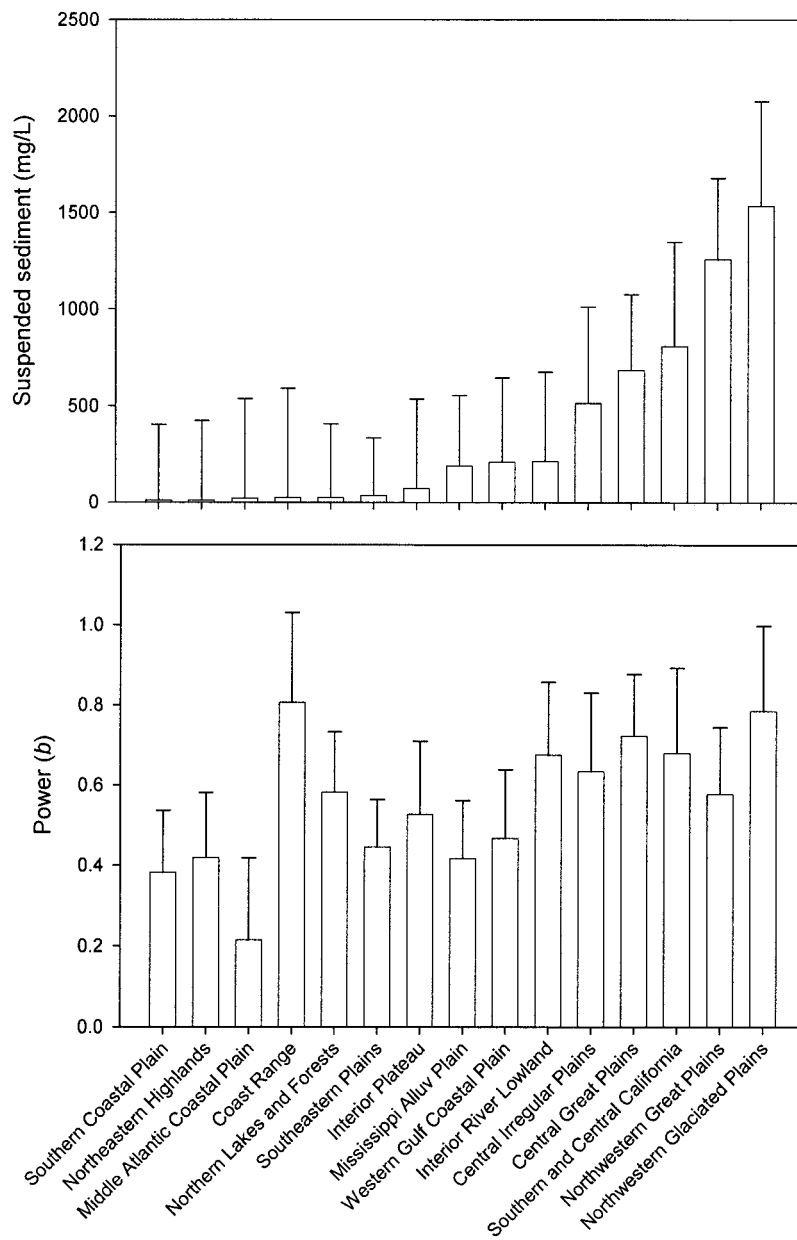
Figure 6. Mean suspended sediments and power (**b**) of the relationship between discharge and concentration by EPA level II ecoregions. Error bars = 95% confidence interval.

higher than similar, undisturbed systems) concentrations of suspended particles in headwater streams, and these particles were also of lower quality (e.g., higher C:N) compared to nearby undisturbed systems. For this study, we examined the quality of suspended particles with two indices, percent carbon and C:N, and found very few consistent patterns, suggesting that the scale of this investigation was not appropriate for detecting general patterns of quality. The greater input of leaf materials (high C:N) expected in forested areas may have driven the significantly higher C:N in ecoregion level I Northern Forest.

Ecoregions are seeing increased use in ecosystem management (Bryce and others 1999), particularly to guide monitoring of surface waters (e.g., Pan and others 2000). Categorizing individual sampling sites to ecoregions can be problematic because water quality in rivers is a function of the entire watershed above that point (Omernik and Bailey 1997). Hence, a given watershed may encompass several ecoregions, and consideration of all ecoregions in the watershed above a specific location may improve management of water quality (Griffith and others 1999). We did not assess this effect because we did not know how to appropri-
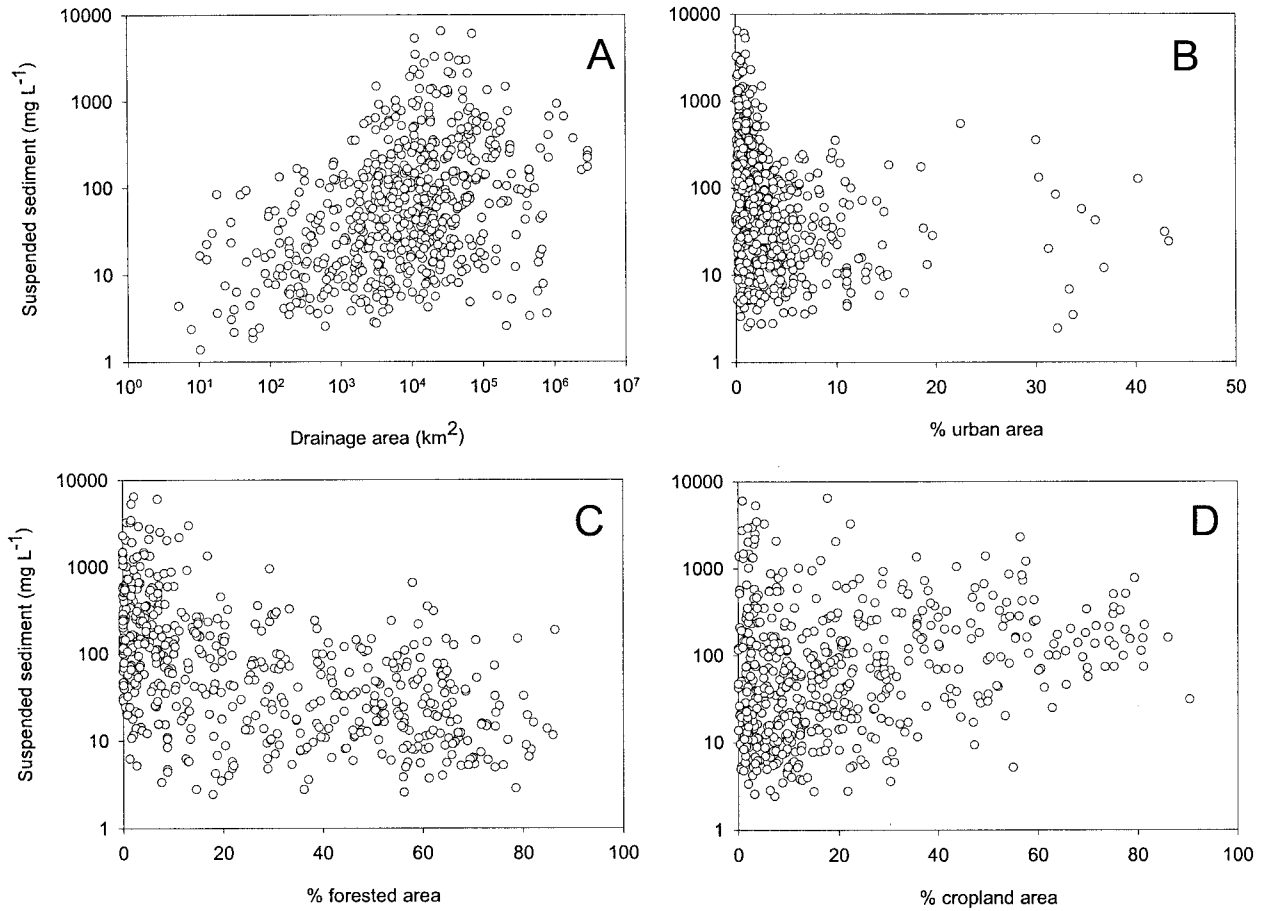
Figure 7. Mean suspended sediments and power (**b**) of the relationship between discharge and concentration by EPA level III ecoregions. Error bars = 95% confidence interval.
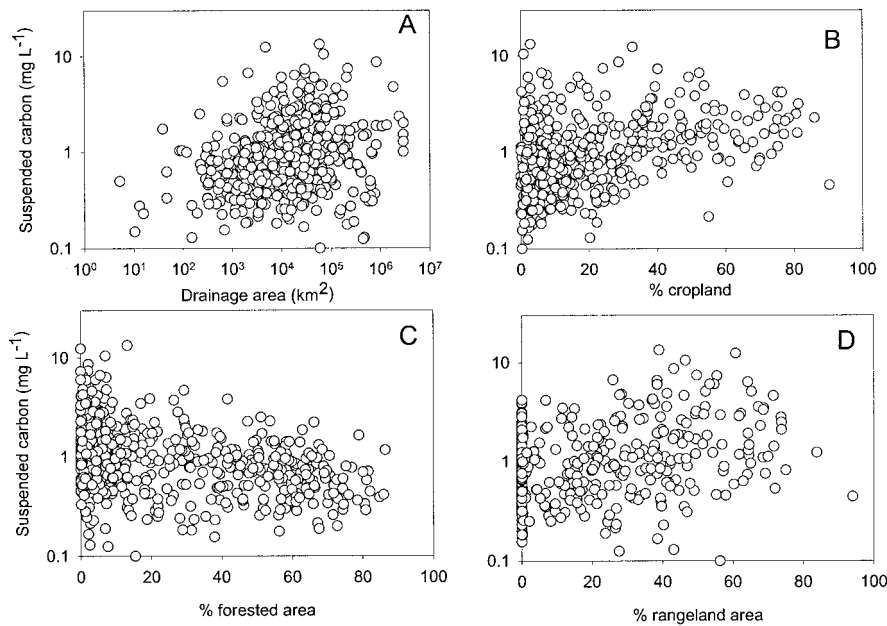

Figure 8. Suspended carbon as a function of watershed drainage area (**A**), percentage cropland area (**B**), percentage forested area (**C**), and percentage rangeland area (**D**). Each point is a site-specific mean.

Figure 9. Suspended nitrogen as a function of watershed drainage area (**A**), percentage cropland area (**B**), percentage forested area (**C**), and percentage rangeland area (**D**). Each point is a site-specific mean.
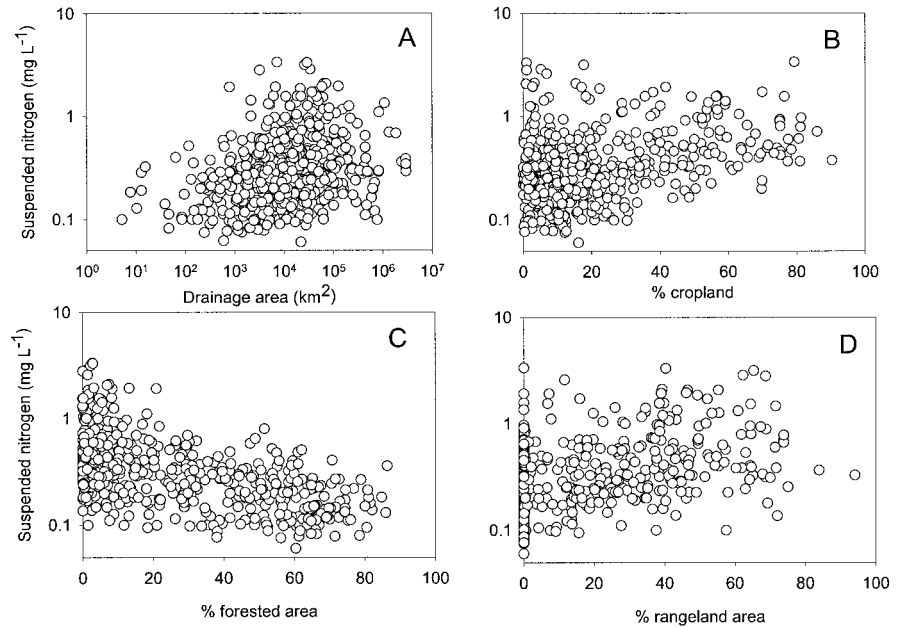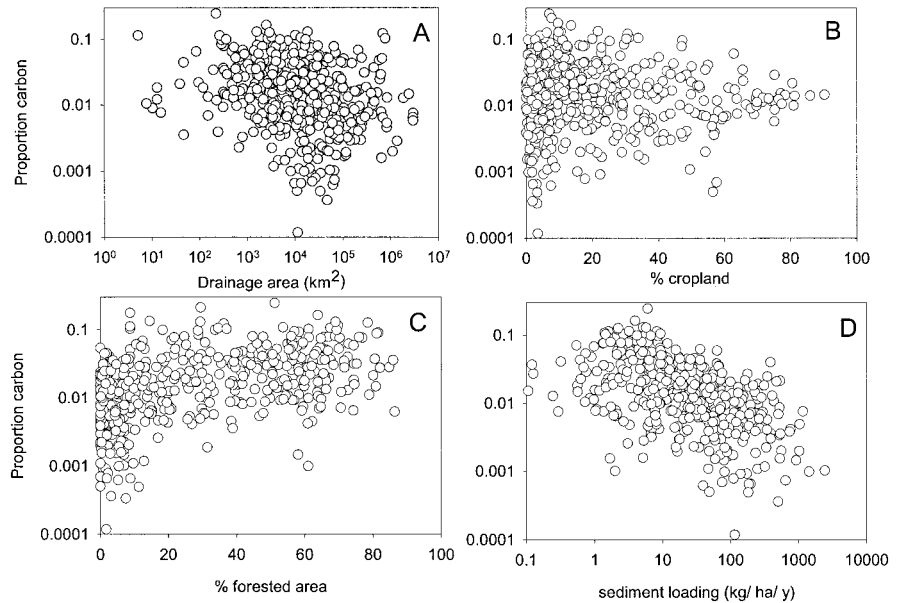

Figure 10. Proportion of suspended carbon (suspended carbon/suspended sediment) as a function of watershed drainage area (**A**), percentage cropland area (**B**), percentage forested area (**C**), and sediment loading (kg/ha/y) (**D**). Each point is a site-specific mean.

ately weight the influence of upstream ecoregions. Future investigations of this issue will improve ecoregion-based water quality management efforts. Our study did demonstrate significant relationships between ecoregions and mean TSS and TSS-discharge functions (*b*). In particular, there tended to be greater mean TSS in drier ecoregions. Some other factors that could be related to ecoregions were not well correlated with sediment quality or quantity. For example, temperature and longitude had a weak relationship with suspended

sediment quality and quantity. However, there was also an apparent effect of ecoregion on C:N of particles.

Our results suggest that an ecoregion approach to assessment and management of suspended sediment quality and quantity may have merit, but region-specific information should also be considered. For example, riparian zones (Hubbard and others 1990) and road placement may be very important in sediment yields (Rice and Lewis 1991). These effects are not discernable in the large-scale data sets we used. Within each

ecoregion, relatively pristine reference sites could form a baseline for the ecoregion (assuming pristine or relatively undisturbed sites remain). Our results suggest that factors such as vegetative cover, precipitation, soil type, or geology may need to be considered when regulating TSS, and that forested regions may naturally have lower concentrations and different quality of TSS than drier areas.

In conclusion, based on current water quality standards and assuming the sites we analyzed are representative of rivers in the United States, a substantial proportion of rivers in the United States have TSS concentrations that exceed existing standards and such levels may threaten biotic integrity and increase the costs of drinking water treatment. Large-scale land cover patterns are related to suspended sediment quantity and quality. For example, forested ecoregions tend to have higher carbon content in suspended sediments. Therefore, a landscape approach, including both ecoregion and anthropogenic factors, should be considered when determining what baseline levels of TSS are expected and are obtainable.

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