SUSPENDED SEDIMENT YIELDS IN TRIBUTARIES OF ELK RIVER, HUMBOLDT COUNTY, CALIFORNIA

by

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SUMMARY

Suspended Sediment Yields in Tributaries of Elk River,
Humboldt County, California

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Turbidity threshold sampling methodology was used to estimate suspended sediment yields on three tributaries of Elk River during water year 2004. The three sampled watersheds are located in close proximity to one another and have similar physiographic parameters including size and lithology, yet differ in their management histories. The Little South Fork Elk River watershed is comprised of mostly undisturbed, mature forest; it had a suspended sediment yield of 6 tons/km^2. The Corrigan Creek watershed was first harvested in the 1950s and then experienced a second harvest entry only in its headwaters in the early 1990s; its suspended sediment yield was 59 tons/km^2. The South Branch North Fork Elk River watershed was first harvested in the 1970s and then experienced a second harvest entry throughout its entire watershed in the early 1990s. It had a suspended sediment yield of 121 tons/km^2 during water year 2004.

Particle size analysis showed that fine material (< 0.0635 mm) constituted 90 percent of the total suspended sediment load at South Branch North Fork Elk River and 87 percent of the total sediment load at Corrigan Creek. Fine material accounted for only 75 percent of the total sediment load at Little South Fork Elk River.

Suspended sediment load was estimated using a regression of the suspended sediment concentration to turbidity for individual storm events as well as for the whole year. Annual suspended sediment load estimates based on individual storm regression

have the potential to be more accurate than estimates based on annual regression because they capture variations in the suspended sediment – turbidity relationship. Variations in this relationship were observed for different storm events and also during certain components of individual storm events in this study. Differences between suspended sediment load estimates based on individual storm regression versus estimates based on annual storm regression were as large as 74 percent for individual storm load estimates and 16 percent for total annual load estimates. Variability in suspended sediment particle size, particle mineralogy, and organic content may explain the observed differences.

The severity of ill effects experienced by fish in the three streams was evaluated based on the models described by Newcombe and Jensen (1996). The observed doses (concentration × duration of exposure) of sediment in Corrigan Creek and South Branch North Fork Elk River are associated with ill effects including moderate physiological stress, moderate habitat degradation, and impaired homing in adult and juvenile salmonids, and 40-60% mortality in egg and larval stages. Fish in Little South Fork Elk River experienced lower doses of sediment that are associated with milder ill effects such as short-term reduction in feeding rate and feeding success of adult and juvenile salmonids, and major physiological stress and long-term reduction in feeding rate and feeding success of egg and larval stages.

This study examines variability in sediment yield and sediment dynamics of streams with similar physiographies and different management histories while exploring fluctuations in the suspended sediment – turbidity relationship and analyzing the potential effects of elevated sediment concentrations in these streams from a biological perspective.

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INTRODUCTION

Sediment yield is the total sediment outflow from a watershed per unit area over a specific period of time (e.g., $kg/km^2/yr$). The sediment load is the total amount of sediment discharge from a watershed and can be divided into two components: the suspended sediment load and the bed load. The suspended sediment load consists of fine particles such as silts, clays, and fine sands that are transported downstream in suspension. The bed load consists of larger particles such as coarse sands, gravels, cobbles, and boulders that are transported along the stream bottom. Sand-sized particles may be part of the suspended sediment load or the bed load depending on their mode of transport.

The sediment yield of a system is dependent on the geology, climate, vegetation, soils, topography, and land use of a watershed. The interaction of these variables determines not only the overall sediment yield, but also how the stream system moves and stores sediment and the resulting morphological characteristics of the stream system. Changes in any of these variables have the ability to alter the sediment regime of a stream system and thus alter the physical characteristics of the system. Potential changes in the physical characteristics of a stream include changes in: stream base level (e.g. aggradation or degradation), stream width, stream habitat units (e.g. increase or decrease in pool volume), stream sinuosity, bedforms (e.g. fining or coarsening of the stream bed), slope, and incision (Knighton 1998, Sullivan et al. 1987).

Of the factors that control the sediment yield of a system, climate and land use have the greatest potential for temporal fluctuation and are thus the factors that most commonly lead to changes in sediment regime and resultant changes in stream morphology. Reid (1993) cataloged numerous studies of sediment yield related to land use and found that sediment yields generally increased 2 to 50 times above background levels in response to road construction and logging. The highest increases were observed in systems that had poorly aligned road networks. Increases in sediment input can be larger at sites where landsliding is prevalent. Reid (1993) also observed that reduction in sediment yield was rapid after road use was discontinued and logged areas regenerated; yields measured more than five years after logging were typically less than five times greater than background levels.

The majority of watersheds on the north coast of California are listed as impaired due to excessive sediment under Section 303d of the Clean Water Act (Fitzgerald 2004). Increased sediment in streams can impact both the physical and biological function of stream systems. Salmonids are of particular concern in northern California because several threatened or endangered salmonids species are present in the region. Elevated sediment production can be detrimental to salmonids by reducing intergravel flow of oxygen to developing embryos and by entombing alevins (Hall and Lantz 1969, Phillips et al. 1975). High volumes of sediment can effectively reduce pool volume thereby decreasing rearing habitat for juvenile salmonids and resting pools for migrating adults (Lisle and Hilton 1992). Sedimentation can also interfere with the production and diversity of macrobenthic organisms, an important salmonid food source, by reducing hyporheic movement and eliminating macrobenthic rearing space (Spence et al. 1996).

Increased sediment loads in stream systems can lead to changes in stream channel morphology. Aggradation of the stream channel is a common response to increased sediment inputs. This can lead to a decrease in the volume of water that can be conveyed by the stream within its banks thereby affecting the magnitude and frequency of flood events (Knighton 1998). Channel aggradation leading to decreased channel capacity is of particular concern when there is commercial or residential development within the active flood zone.

Sediment levels are also a concern for drinking water quality. From a municipal perspective, high levels of sediment can make treatment of water to potable standards very difficult to impossible because the solids provide a medium for bacterial attachment and also serve as a protective barrier against the action of chlorine added for disinfection (Tchobanoglous and Schroeder 1985, United States General Accounting Office 1998). Private water users with shallow wells or direct diversions are rarely able to afford the technology necessary to treat heavily sediment-laden water, and their water supplies often become unusable when contaminated by high levels of sediment.

Total sediment load is important because it affects the physical nature of the stream system which in turn affects the stream biota. Many studies have addressed the adverse effects of suspended sediment on aquatic organisms and these studies suggest that the severity of the adverse effects is related to not just the total quantity of sediment or the instantaneous concentration of the sediment, but also to the duration of exposure to elevated sediment levels and also to the frequency of pollution episodes (Bisson and

Bilby 1982, Stober 1981). These studies show that adverse effects on salmonids increase with an increasing duration of exposure to elevated suspended sediment concentrations.

Duration of elevated sediment levels can also be very important because it can directly affect the quality and availability of potable water to private and municipal water users. Extended durations of highly elevated suspended sediment concentrations can cause depletion of supplies of treated drinking water and lead to shortages of potable water during periods where water quantity is abundant (United States General Accounting Office 1998).

Suspended sediment load and suspended sediment concentration duration in remote watersheds can be difficult to accurately measure given the complexities of collecting sediment data over a wide range of flow events and especially during large events when a majority of sediment is transported (Eads and Lewis 2002). Automated data collection of a parameter that can be continuously measured is necessary to effectively estimate suspended sediment loads in such systems.

Turbidity is a measure of the scattering of light by particles suspended in the water column. Turbidity can be measured on a quasi-continuous, high-frequency, time step basis, and this data can be easily stored on a data logging device for future collection. Turbidity data can then be related to the suspended sediment concentration of a limited number of physical sediment samples taken by an automated pump sampler when pre-selected turbidity thresholds are satisfied (Eads and Lewis 2002). The relationship of turbidity to suspended sediment concentration can then be applied to the continuous turbidity data to produce a continuous record of suspended sediment concentration (Lewis 2002). Unlike discharge controlled sampling systems, turbidity controlled sampling generates data for sediment pulses that may be unrelated to stream discharge, such as landslides and stream bank failures (Lewis and Eads 2001).

Turbidity is a useful surrogate for suspended sediment concentration; however, the most common unit of turbidity measurement (a Nephelometric Turbidity Unit or NTU) is not a standardized quantity and can vary widely among instruments and types of sediment (Davies-Colley and Smith 2001). Recently, efforts have been undertaken to create multiple new units of turbidity that are specific to the method by which a particular turbidity probe makes its measurement (Anderson 2004). Examples of the newly adopted units include Nephelometric Turbidity Ratio Unit (NTRU), Formazine Nephelometric Unit (FNU), Backscatter Unit (BU), Attenuation Unit (AU), and others.

The fact that turbidity measurements generated by different types of probes are not comparable and may not be recorded in the same units makes turbidity measurements on their own less meaningful. Continuous turbidity measurements become useful for the purpose of sediment load calculations when they can be correlated with physical suspended sediment samples. Use of this type of sampling methodology greatly improves the precision and utility of the data obtained.

In order to effectively manage watersheds to maintain beneficial uses it is important to understand how certain types of management activities can affect sediment dynamics. The purpose of this research is to gain insight into this relationship by observing sediment flux and sediment yield in three watersheds with similar physiography and different land-use histories. The data obtained from this study can then be used in conjunction with similar data from watersheds of varying physiography in order to better understand the role of management in watershed sediment dynamics.

The hypotheses to be tested in this study are: (a) the suspended sediment yield and the duration of elevated suspended sediment concentration increases with increasing degree of management, (b) the proportion of the suspended sediment load comprised of fine material (<0.0635 mm) increases with increasing degree of management, and (c) the sediment yield measured using individual storm regression of the suspended sediment concentration – turbidity relationship will produce different yields than estimates based on annual regression.

STUDY SITE

The three sampled watersheds are located in the Elk River watershed just south of Eureka, California (Figure 1). Elk River drains a 137 km^2 area extending from the western slope of the northern California Coast Range to Humboldt Bay. The lower watershed is divided into many private holdings and the primary land uses are agricultural and residential. A majority of the upper watershed is owned by the Pacific Lumber Company with the exception of the 30 km^2 Headwaters Forest Reserve that is publicly owned and managed by the United States Department of the Interior Bureau of Land Management.

The Elk River watershed is dominated by a maritime climate regime. Temperatures are moderate, and humidity remains high throughout the year. Summers are dry, and the rainy season (October through April) accounts for 90% of the total annual rainfall. The forested uplands of the Elk River watershed receive about 165 cm of precipitation per year (Hart-Crowser 2004).

Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) with Douglas-fir (*Pseudotsuga menziesii*), true fir (*Abies sp.*), Sitka spruce (*Picea stichensis*), western hemlock (*Tsuga heterophylla*), incense cedar (*Calocedrus decurrens*), western red cedar (*Thuja plicata*), and madrone (*Arbutus menziesii*) common in some locations. Deciduous trees are uncommon outside of riparian areas and some disturbed areas where a high degree of compaction or soil loss has occurred.

The watersheds are underlain mostly by rock units of the Quaternary/Tertiary Wildcat Group, which consists of poorly compacted sandstones, siltstones, and

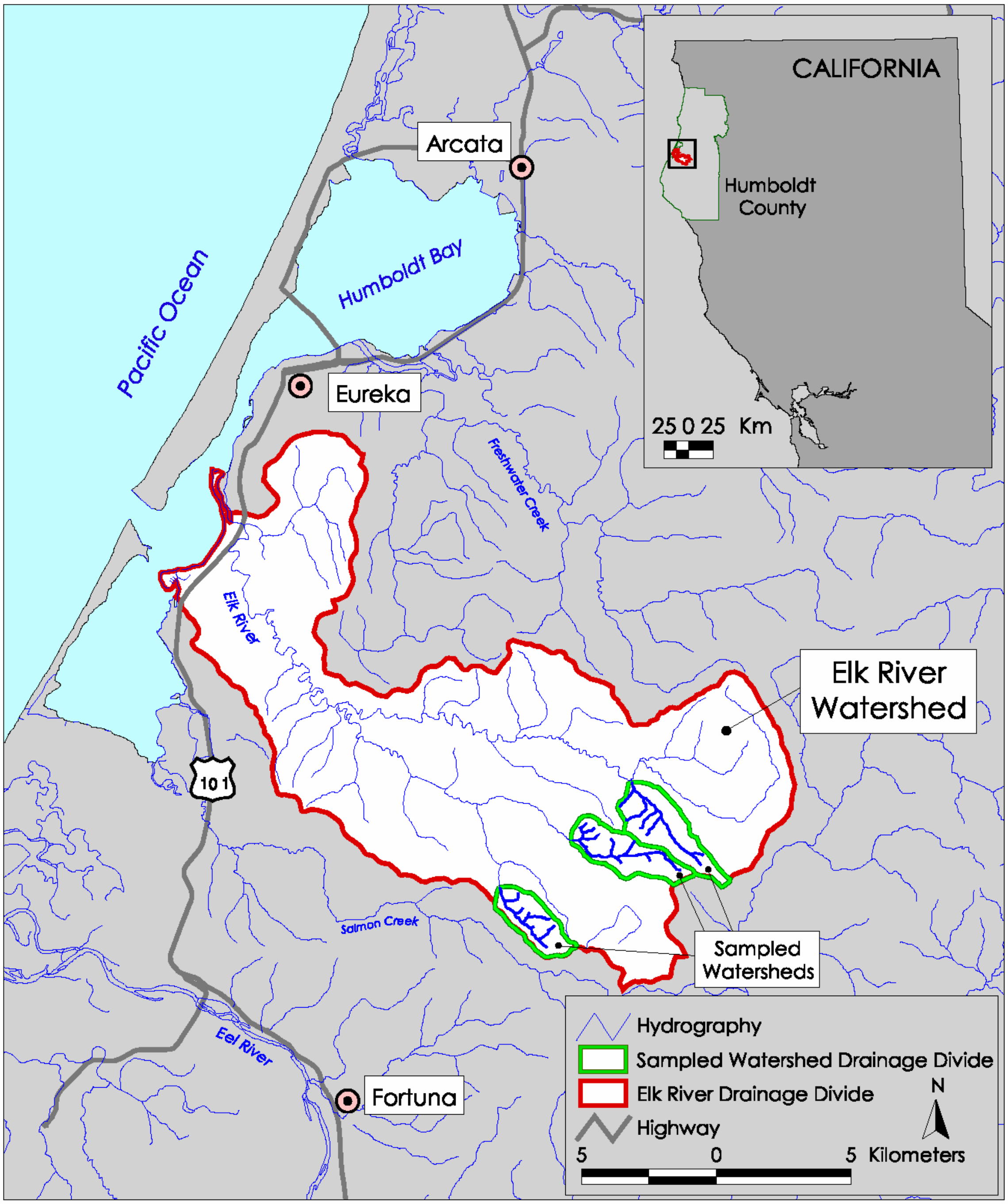

Figure 1. Elk River and sampled watersheds, Humboldt County, California.

mudstones that are highly susceptible to erosion where exposed (Knudsen 1993, McLaughlin et al. 2000). Stream channels draining areas underlain by Wildcat units are often dominated by silts and sands and have a high potential for suspended sediment loads (Hart - Crowser 2004).

Rock units of the Late Cretaceous Yager terrain are present in portions of the upper watershed, especially in stream channels and adjacent valley segments where the streams have incised through layers of Wildcat to expose the underlying Yager units. Yager units are substantially more cohesive and resistant to erosion than Wildcat units (Personal communication, J. Stallman 2004. Stillwater Sciences, 850 G Street, Arcata, CA 95521). They consist primarily of mudstones, siltstones, shales, graywackes, and some conglomerates (Knudsen 1993, McLaughlin et al. 2000). Stream channels that have down cut into the Yager units expose material ranging from well-consolidated bedrock to cobbles and gravel (Hart – Crowser 2004).

McLaughlin et al. (2000) mapped all three watersheds as consisting primarily of rock units of the Quaternary/Tertiary Wildcat Group with stream channels that have down cut into rock units of the Late Cretaceous Yager formation in some locations. Field reconnaissance and geologic consultation suggest that stream valley down cutting into the underlying Yager unit is more extensive than that mapped by McLaughlin et al. (2000) and that the proportion of stream channel that is cut into the Yager unit is similar for all three streams.

Locations of the three sampling stations in this study were selected such that the watersheds above the sampling locations were of similar physiography. All three watersheds have the same orientation to and are located the same distance from the ocean. This causes the watersheds to lie within the same isohyetal bands of average precipitation.

All three stream systems have similar watershed areas. The South Branch North Fork Elk River is the northern most system and drains an area of 4.9 km^2. Corrigan Creek drains an area of 4.0 km^2 and shares its northern watershed boundary with the southern boundary of the South Brach North Fork watershed. The Little South Fork Elk River drains an area of 3.1 km^2 and is located southwest of Corrigan Creek (Figure 2).

Lengths of stream channel per unit area that are designated as either Class 1 or Class 2 are also very similar (Figure 2). Class 1 and Class 2 designated stream channels are those that support fish or other aquatic species. South Branch North Fork Elk River has 1626 m/km^2 of Class 1 or Class 2 stream channel, Corrigan Creek has 1783 m/km^2, and Little South Fork Elk River has 1727 m/km^2 (Hart - Crowser 2004).

The primary difference between the three watersheds is their management histories. Most of the South Branch North Fork watershed was first harvested in the 1970s, though small areas were harvested in the 1940s and 1960s as well. A second harvest entry occurred throughout the entire watershed in the late 1980s and early 1990s consisting of partial cut and clear cut harvests with tractor yarding. The lower portion of the Corrigan Creek watershed was first harvested in the 1950s and the upper portion was

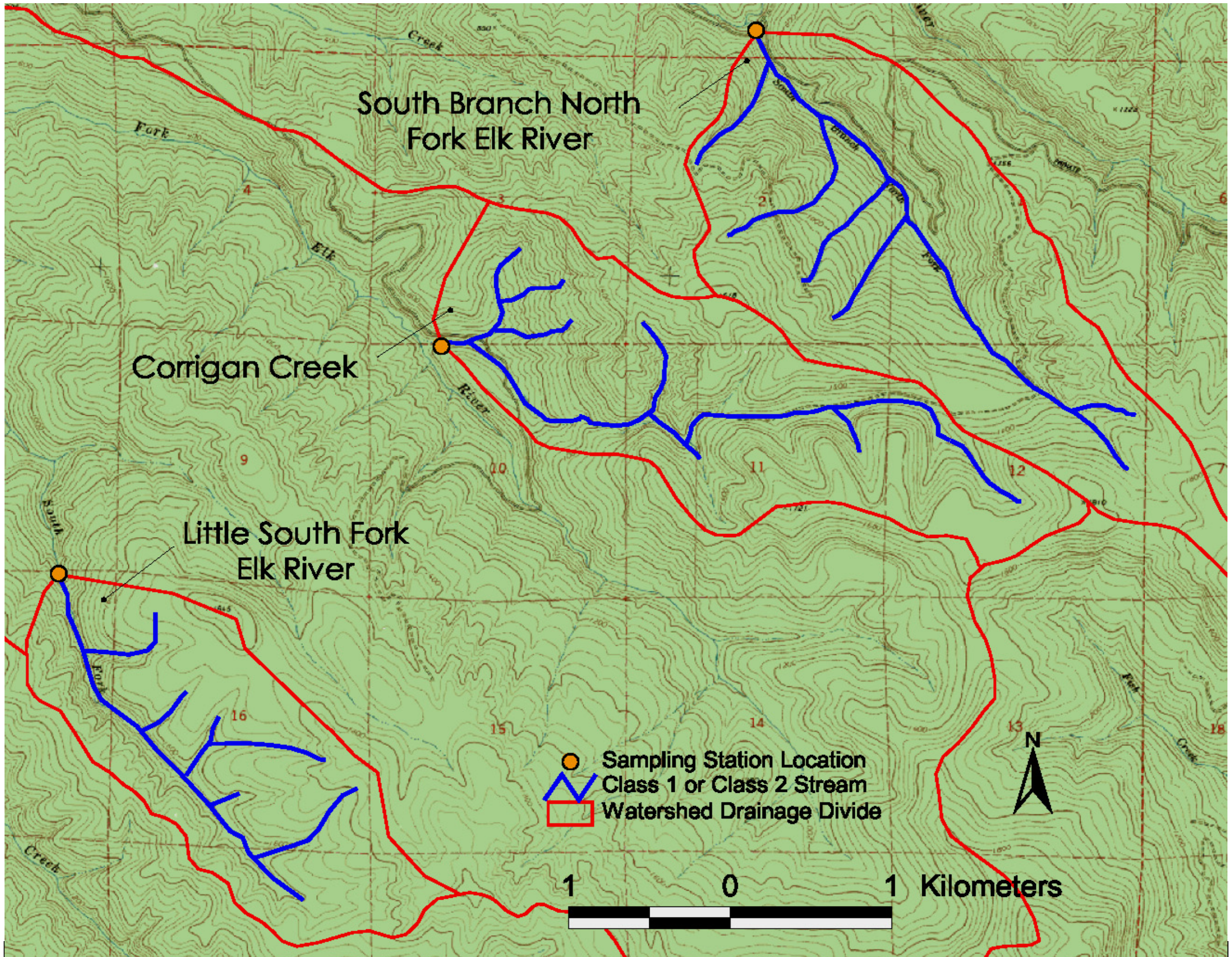

Figure 2. Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River watersheds and sampling station locations (extracted from McWhinney Creek 7.5- minute quad).

first harvested in the 1970s. The upper portion experienced a second harvest entry in the late 1980s and early 1990s consisting of partial cut and clear cut harvests with tractor yarding. The lower portion of the watershed has not experienced a second harvest entry. The area above the Little South Fork Elk River sampling station has never been harvested and consists entirely of late successional, old-growth redwood forest. There were plans to conduct harvest activities in this area and a 1.6 kilometer section of road was constructed from the southern boundary of the upper watershed running adjacent to the stream channel in the early 1990s. This area of the Little South Fork watershed was included in the Bureau of Land Management's purchase of the Headwaters Forest Reserve in the mid 1990s. The road was subsequently decommissioned and a complete slope restoration including excavation of stream crossings and recontouring of hillslopes was completed in 2003.

MATERIALS AND METHODS

Turbidity Threshold Sampling

The USDA Forest Service Redwood Sciences Laboratory in Arcata, California has developed a methodology to improve the accuracy and efficiency of suspended sediment load estimations. The turbidity threshold sampling (TTS) method uses real-time turbidity measurements to control an automated pumping sampler to collect physical suspended sediment samples over a range of turbidity values while attempting to sample all significant turbidity peaks (Lewis and Eads 2001).

The sampling thresholds are determined for each individual stream based on the range of turbidity values that are expected. These thresholds should be selected so that even small storms produce an adequate number of samples to allow creation of a relationship between suspended sediment concentration and turbidity that can be used to estimate suspended sediment concentration for the entirety of the individual storm event. The set of thresholds must also accommodate the upper limits of turbidity for a stream and be distributed such that the full range of turbidities can be sampled for a large event without exceeding 24 samples, the number of samples that the pump sampler is able to accommodate. Spacing thresholds in such a manner that their square roots are evenly spaced helps assure that both small and large events are adequately sampled (Lewis 1996). In order to improve sample coverage, different sets of thresholds are used when the turbidity is rising and falling. The number of thresholds used when the turbidity is falling is typically fifty percent greater than the number used when the turbidity is rising since the falling limb of the hydrograph is generally longer. In order to avoid sampling of turbidity spikes that may be due to non-storm-related factors (e.g., fouling of the probe or stream biota such as fish or insects), a particular threshold must be exceeded for two sampling intervals (10 minutes each) before a pump sample is collected. A user defined time period must also pass before a threshold can be reused. Sampling thresholds were adjusted numerous times at each station during the study period in order maximize sample coverage and efficiency.

Station Location

Stations were constructed at locations on the streams that made them suitable for sediment sampling and stream gaging. At the sampling location, the stream should be deep enough to fully submerge the turbidity probe at all flows. Pools are generally not suitable because sediment tends to settle there in a non-uniform manner depending on flow levels. Riffles can create a great deal of turbulence which also leads to non-uniform sediment transport depending on flow. The ideal location is a run that has relatively uniform and moderate depth, width, and bed material. This is also the ideal location to conduct stream discharge measurements. In the absence of an installed flume or weir, it is necessary to find a location that has a natural downstream control such as a log or a rock weir that serves to maintain the stage – discharge relationship throughout the range of flows. Additionally, it is desirable to find a location where a bridge can be constructed nearby for discharge measurements and depth integrated samples at discharges too large to wade. The sampling stations were constructed at locations that met these requirements on all three streams (Figures 3, 4, 5).

Station Equipment

The three suspended sediment sampling stations that were installed on Elk River all use the turbidity threshold sampling program to govern their sampling regime. The three sites all have different thresholds because of differences in turbidity ranges. All three sites use identical sampling instrumentation. Turbidity is measured using a Forest Technology Systems DTS-12 turbidity probe. Under revised standards released by the United States Geological Survey, the units of measure for the DTS-12 are Formazine Nephelometric Units (FNU) (Anderson 2004). The DTS-12 also measures water temperature.

The turbidity probe hangs from an articulated boom that hinges laterally and downstream (Figure 6). This type of articulation allows the probe to be easily displaced by logs and other debris transported during storm events without damage to the turbidity probe. The probe returns to its previous depth once the debris has passed. An articulating boom also allows the turbidity probe to move vertically in the stream channel in response to increasing and decreasing stream flow. The typical low-flow position of the turbidity probe is often less than 15 centimeters above the stream bed in order to ensure that the probe is fully submerged. As stream flow increases, drag generated by the probe and submerged portion of the boom causes the probe to be pushed further up in the water column. This movement avoids collision with the larger particles and rocks that

Figure 3. Sampling station located on Corrigan Creek.

Figure 4. Sampling station located on Little South Fork Elk River.

Figure 5. Sampling station located on South Branch North Fork Elk River.

Figure 6. Bank mounted sampling boom articulating downstream during a high flow event on Corrigan Creek.

move along the stream bed during storm events and also helps to ensure that the turbidities measured during storm events are those of the suspended load and not of the bed load. The probe can also be manually raised or lowered in response to changing flow levels. The bases of the booms at Corrigan Creek and South Branch North Fork are bank mounted whereas the boom at Little South Fork is bridge mounted (Figure 3, 4, 5, 6). Both types of installation allow the probe to articulate in the same manner. The particular installation used was determined by site-specific considerations.

An ISCO 3700 pump sampler is located in a small shed near each stream. The pump sampler can accommodate 24 water samples. The 500 mL sample bottles are filled with approximately 350 mL of stream water when a pump sample is triggered. The water is drawn through a 0.635 cm diameter vinyl tube that passes through the boom arm. The intake is located approximately 3 cm below the front of the turbidity probe.

A Druck 1830 pressure transducer is used to monitor the water surface elevation (stage) of the stream. The pressure transducer is mounted in a 2.5 cm pipe with a perforated cap on the end to allow water in. The end of this pipe is submerged at all flows and is connected to rebar that is driven into the stream bed near the turbidity probe. This must be a fixed installation, as any movement would alter the stage reading. Each site is also equipped with a staff gage that allows a visual estimation of the water stage. The staff gage is important because it provides a cross reference to determine if the pressure transducer is functioning properly.

The turbidity probe, the pump sampler, and the pressure transducer are all connected to a Campbell CR10X data logger which is housed inside a water proof case that is installed inside of the shed. A laptop computer was used to interface with the data logger, download data, and check data quality. Due to difficult access, an analog phone modem was installed at the Little South Fork site to permit remote monitoring of data and to determine when a station visit was necessary. A solar panel was installed there in order to power the site without having to transport batteries. A tipping bucket rain gage was also installed at the Little South Fork site in mid-February, 2004.

Station Visits

Sites were visited during and after major storm events in order to resupply bottles, download data, check for proper functionality, clear debris interfering with the turbidity probe or pump sampler intake, clean turbidity probe optics, and conduct stream discharge measurements. Discharge was measured according to the velocity – area method (Dingman 2002) using a Marsh-McBurney Flo-Mate electronic velocity meter to measure flow velocity. Time allowing, a second discharge measurement was taken for quality control purposes. Of the 5 quality control discharge measurements that were taken, none had a difference greater than 7 percent of the original measurement, and the average margin of difference was 4.6 percent.

All three sites have one designated low flow cross-section at which all measurements were taken. Each site also has a bridge from which discharge and depth-integrated measurements could be taken at very high flows. Field forms were completed and notes were taken during each site visit. Depth-integrated sediment samples were collected using a DH-48 sediment sampler during some station visits.

Lab Procedure

Collected bottles were appropriately labeled and stored in boxes until they could be processed. Lab procedures for measuring suspended sediment concentration in samples followed procedures detailed in Standard Methods for the Examination for Water and Waste Water (American Public Health Association 1992). In addition to standard suspended sediment sampling procedure, all samples were first passed through a 0.0635 mm sieve to separate sands from the remaining sediments. The samples were then passed through a 1 µm (0.001 mm) pore size filter to determine the weight of fine particles (silts and clays). Every third consecutive sample whose field turbidity was greater than 200 FNU was also first passed through four additional sieves (1000, 500, 250, and 125 µm) in order to gain an appreciation for the size distribution of sediments in high concentration samples. Turbidity was measured for all lab samples using a Hach 2100 N laboratory turbidity meter. Lab turbidity data was used to cross reference field turbidity measurements in order to ensure field data quality.

Sampling Period

All three stations were instrumented in the fall of 2003. Sampling began on different dates at each of the three stations, but all were fully functioning before the first storm event on December 6, 2003. To make data comparison more meaningful, all results are reported for the period of overlapping data from the three sites: November 26, 2003 through June 16, 2004. The precipitation total for this time period was 4.5 cm (6 percent) higher than the historical mean rainfall for the same period based on data from the National Weather Service rainfall station in Eureka, California for 54 years of data (Western Regional Climate Center 2005).

Data Quality

Due to the remote location of the sampling stations, some data loss was unavoidable. Data loss was typically caused by loss of battery power or insufficient data logger memory. In one instance, a tree fell on the sampling station. Stage and turbidity data for periods of lost data were reconstructed by generating regression relationships with the remaining two sites during periods of proper functionality. These data were identified in the processed data file. Fortunately, no data were lost during any of the major storm events. Subsequent analysis showed that stage and turbidity data reconstructed from the other two sites accounted for a total of 2.4 percent of the sediment load at Little South Fork Elk River. Reconstructed data accounted for only 0.06 percent of the load at Corrigan Creek and 0.9 percent of the load at South Branch North Fork.

Data loss also occurred during very short periods of time when the battery was disconnected for station service, when obviously erroneous stage or turbidity readings were registered during site work, or when the sensors were fouled by aquatic biota. These data were identified in the processed data files and replaced by linear interpolation from the point of last known valid data to the point where valid data resumed. Linear change is expected over the very short intervals typical of this type of data loss. Data restored by linear interpolation accounted for less than 0.01 percent of the total sediment load at each of the three sites.

Depth-Integrated Samples

Pumped sediment samples are taken from a fixed intake located approximately 3 cm below the upstream end of the turbidity probe. Sediment concentration can vary with depth and distance across the stream cross section. Depth-integrated samples were taken in order to calibrate the point samples to the cross-sectional mean sediment concentration. There were considerable differences between point samples and depth-integrated samples on numerous occasions. Unfortunately there was an inadequate number of samples (5 at Corrigan Creek, 7 at Little South Fork, and 10 at South Branch North Fork) to separate sampling error from bias and to justify adjustment of the load estimates. Increasing the frequency of depth integrated samples taken in future years should allow development of a stronger relationship of point to cross sectional sediment discharge that may improve the accuracy of suspended sediment load estimates.

Suspended Sediment Concentration - Turbidity Relationship

Annual suspended sediment load estimates based on turbidity are potentially sensitive to the regression model used to describe the relationship between turbidity and suspended sediment concentration. A linear model is generally adequate to describe most of the relationship, but problems are often encountered at the lower end of the relationship. There can be a significant amount of suspended material that is finer than the 1 µm filter pore size that was used to filter the sediment samples (Gippel 1989, Personal Communication, J. Lewis 2005. Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata, CA 95521). In addition, there tends to be a higher percentage of organic particles at low suspended sediment concentrations (Madej 2005). Organic particles have a lower specific gravity than mineral particles and therefore produce higher turbidity values for a given mass (Gippel 1995). These factors can also lower the amount of suspended sediment that is measured for a given turbidity and cause linear plots of the relationship to have an intercept less than zero, thereby underestimating the suspended sediment load.

Quadratic models typically fit the data better than linear models, but problems similar to the linear model are encountered at the lower end of the relationship. Regression relationships using both of these models can be forced through the origin, but the quality of fit to the complete data set can suffer as a consequence. Using a best-fit quadratic relationship with a negative intercept produced a 29,346 kg smaller sediment load estimate versus a quadratic relationship forced through the origin on the South Branch North Fork data. This is a difference of approximately five percent of the total estimate.

A loess model predicts a y value for a set of equally spaced points covering the range of observed data, based on a weighted regression. It fits local first or second degree polynomials instead of forcing a simple model to fit all of the data in a sample

(Cleveland and Devlin 1988). A loess model is flexible and useful for complex data sets that have unusual points of inflection. This model solves the problem of negative predictions from models that cannot accommodate curvature near the origin. The drawback of the loess model is that it does not generate a predictive formula that can be compared to other data sets or extrapolated past the range of available data. When the loess model was used in this study, linear extrapolation was used to extend the model short distances above and below the range of the existing turbidity and suspended sediment data.

Any points that appeared to be outside the normal range of data on the suspended sediment – turbidity plots were examined to determine their validity. Plots of turbidity versus time in the range of the questionable samples were analyzed for any abnormal spikes. Particle size composition of these samples was also examined for abnormally high sand fractions. All sediment samples were determined to be valid.

RESULTS

Stage - Discharge Rating Equations

In order to make accurate suspended sediment load estimates it is important to generate a valid rating equation that describes the relationship between river stage (measured by the pressure transducer) and discharge (computed using the velocity - area method) at each gaging station. One stage and one turbidity reading are recorded by the sampling equipment at each site every 10 minutes. Linear changed in these parameters is assumed between sampling intervals. The 10 minute stream discharge computed from actual stage measurements and the rating curve is multiplied by the associated suspended sediment concentration to yield a 10 minute suspended sediment flux. These values are then summed to produce a storm or annual suspended sediment load.

Each site had between 6 and 8 discharge measurements that were used to generate the stage - discharge relationship. Due to the rapid response of the small watersheds involved in this study and the lengthy travel time to each of the sites, it was particularly difficult to obtain discharge measurements near the peaks of large storms. In addition, Elk River Road floods during large storm events making access to the sites difficult or impossible during periods of peak discharge. For these reasons it was necessary to extrapolate the stage - discharge rating curves beyond the range of discharge measurements that were obtained.

Hydraulic formulas and relationships were used in order to extend the rating curves to the level of the highest observed flows. Measurements of the water surface slope during elevated discharges were obtained in the vicinity of the gaging sites and the stream bed profile at the fixed cross sections used to collect discharge measurements was mapped. The stage of peak flows during the study period was recorded by the pressure transducer and then related to specific points at the cross sections being measured. The width, average depth, and area of flow during peak flows at the individual cross sections was then determined. Based on these parameters, the Manning equation (Knighton 1998) was used to calculate discharge at the highest recorded stages. The form of the Manning equation used is:

$$Q = (1.49/n)*R^{2/3}S^{1/2}*A$$

where:

Q = discharge (meters^3/second),

R = hydraulic radius ~ mean depth (meters),

S = water surface slope (meters/meters),

A = cross sectional area (meters^2), and

n = coefficient of roughness

The coefficient of roughness (n), however, is not a fixed value and tends to decrease as flow depth increases and proportional energy losses due to boundary friction decrease (Thorne and Zevenbergen 1985). Energy losses due to boundary friction are eventually completely overcome as flow volume increases and n subsequently remains constant. This holds true as long as the stream remains within its banks and does not rise onto the floodplain. None of the three streams rose above the banks during the study period.

Values of *n* computed from actual gaging measurements were plotted against mean depth to observe the trend in lowering of *n* values with an increase in mean depth. Such a plot for Corrigan Creek (Figure 7) shows that as mean depth increases, the coefficient of roughness decreases until the mean depth exceeds 0.3 meters, at which point *n* remains constant at 0.035. Therefore, an *n* value of 0.035 was used to calculate a discharge of 3.00 m^3/sec at the highest recorded stage at Corrigan Creek.

An identical plot was created for Little South Fork Elk River (Figure 8). Due to bedrock and large scale roughness elements present in the channel at the cross section location, the initial coefficient of roughness values were much higher. This coupled with the lack of discharge measurements at high stages (access to the Little South Fork Elk River site requires a three hour hike in addition to the hour and a half drive required to access the other two sites), explains why this relationship didn't exhibit the asymptotic behavior that was observed at Corrigan Creek. Extrapolation of the observed relationship to the predicted mean depth at the highest observed flow (0.81 meters) yielded a roughness coefficient of approximately 0.075. This value is consistent with values observed for streams of similar size and bed material (Barnes 1967) and yielded a peak flow of 2.92 m^3/second at Little South Fork Elk River.

Hydraulic geometry relationships are the resulting power function derived from plotting mean depth, width, and area of flow against discharge. These relationships can be useful in extrapolating the peak discharge of a stream. The discharge plotted against area yielded a peak flow of 3.14 m^3/second at Little South Fork Elk River and the

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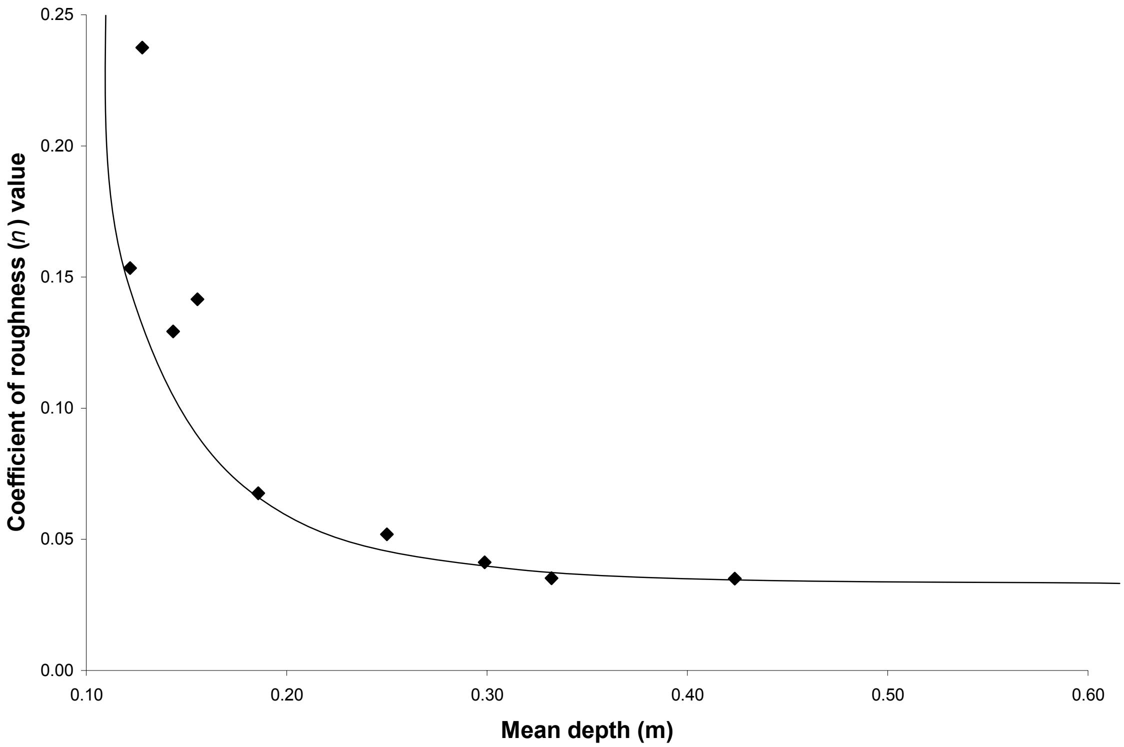

Figure 7. Computed coefficient of roughness (*n*) values against mean depth for discharge measurements at Corrigan Creek.

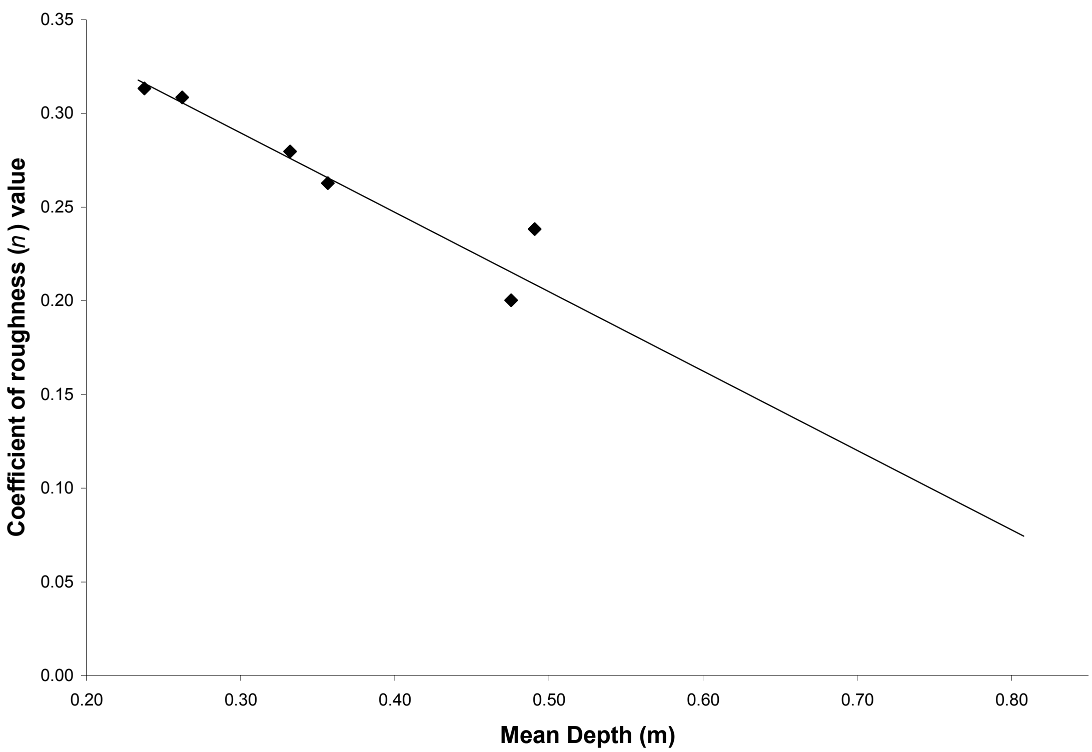

Figure 8. Computed coefficient of roughness (*n*) values against mean depth for discharge measurements at Little South Fork Elk River.

discharge plotted against the mean depth yielded a peak flow of 2.69 m^3/second. These values are roughly consistent with the peak flow estimates derived from the Manning equation.

At South Branch North Fork Elk River, there was a discharge measurement taken at a high flow that was only 0.12 meters below the highest recorded stage. The pressure transducer and staff plate were subsequently moved to a more appropriate sampling location during the summer of 2004. For these reasons, no hydraulic calculations were needed or used to predict the peak flow at this site. The rating curve was linearly extrapolated a short distance above the highest discharge measurement in order to generate the necessary peak flow data.

None of the rating curves for the three gaging locations were adequately fit by a conventional power function. There was reasonable agreement at the lower end of the curves, but peak flows were significantly over-predicted. The rating data for each of the three streams was divided into three ranges of data which were fit very well by linear regression; therefore, combinations of three linear functions were used to generate a rating curve at each of the three sites (Figures 9, 10, 11). Loess plots fit to the discharge measurement points showed very good agreement with the three linear function method, but were not used for discharge calculations because of the ease with which linear functions could be compared and altered to accommodate future potential shifts in the stage-discharge relationship. A segmented regression could also be used to combine the three linear relationships for each stream into a single continuous function (Draper and

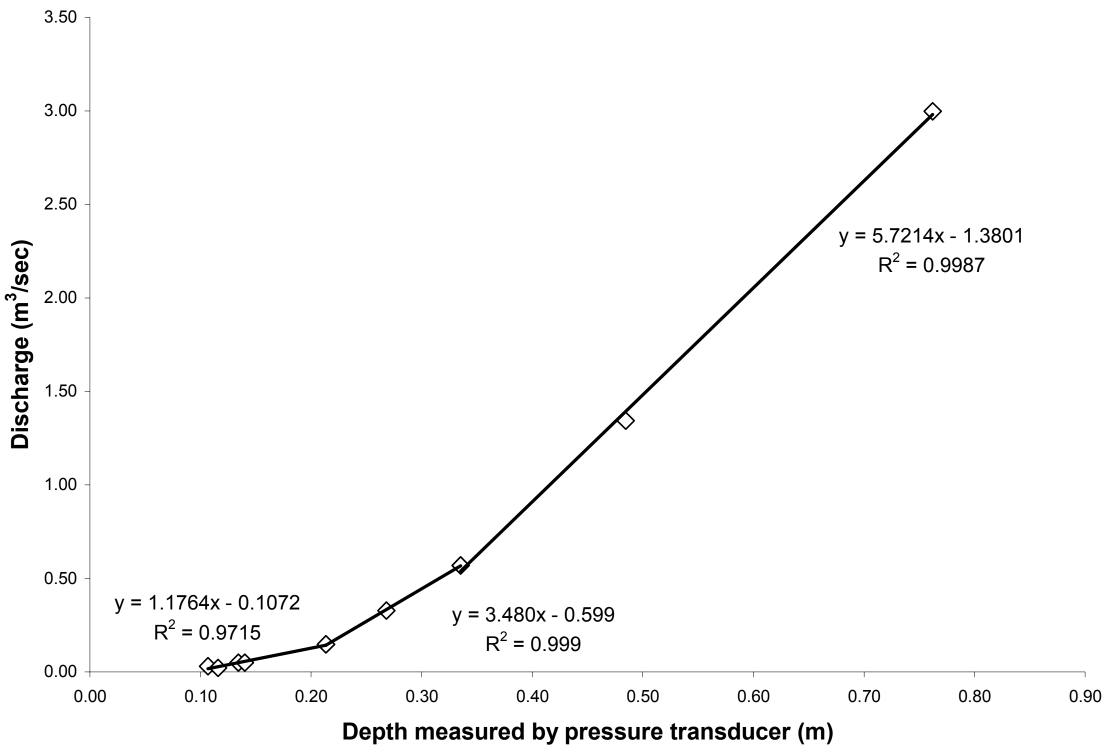

Figure 9. Three part linear discharge rating curve for Corrigan Creek.

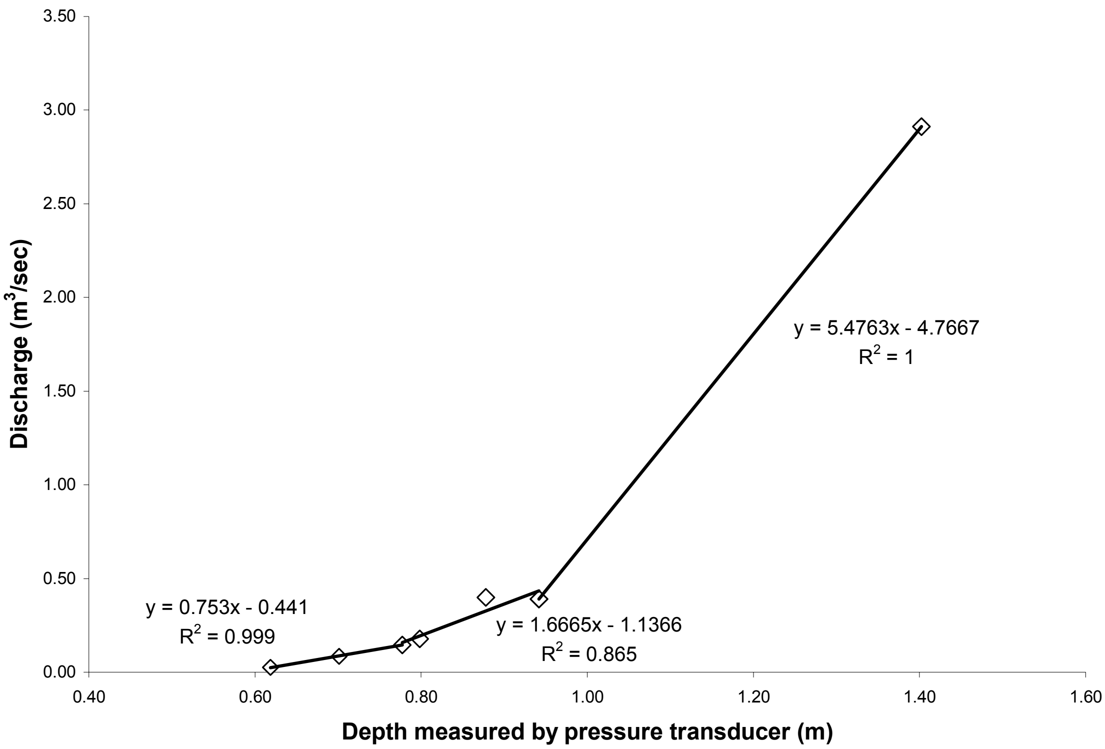

Figure 10. Three part linear discharge rating curve for Little South Fork Elk River.

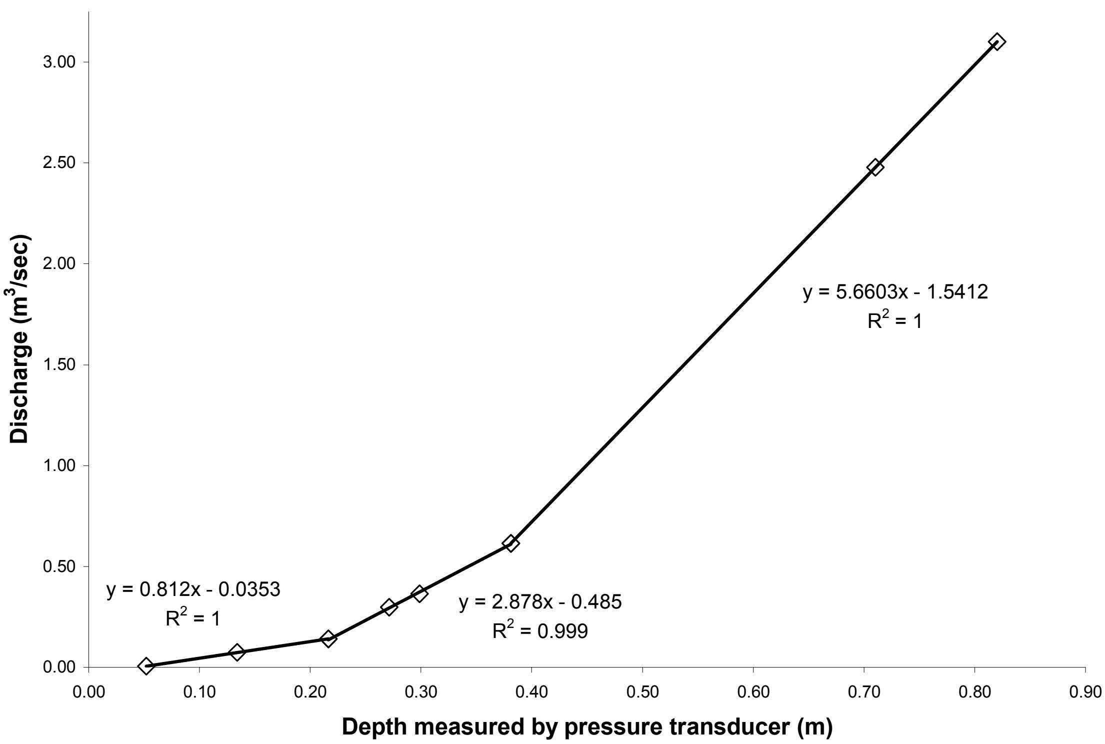

Figure 11. Three part linear discharge rating curve for South Branch North Fork Elk River.

Smith 1981). This method is suggested when creating future discharge rating curves for these sites.

Suspended Sediment Yield Estimates

A loess model was used to relate suspended sediment concentration to turbidity for the complete set of samples taken during water year 2004 at each of the 3 sites (Figures 12, 13, 14). Figures 15, 16, and 17 are the same plots with ranges constrained to 80 mg/l and 80 FNU (the range of the Little South Fork data) for comparison of the lower end of the suspended sediment – turbidity relationship. Differences in the user-defined sampling thresholds accounted for differences in the distribution of sediment samples. Little South Fork Elk River had the lowest range of turbidity values which allowed the use of low sampling thresholds (below 20 FNU). South Branch North Fork had high turbidities which necessitated use of more thresholds at elevated turbidities and allowed for very few samples below 20 FNU. Corrigan Creek had moderate turbidities which allowed for an intermediate level of sampling below 20 FNU. Specifications about the type of loess model used and the statistics associated with each of the loess plots are detailed in Table 1.

The loess model was used in conjunction with the three part linear stage - discharge rating equations for the three sites (Figures 9, 10, 11) to generate suspended sediment load estimates for each site using the R statistics software. The predicted ten minute suspended sediment concentration (mg/L) was multiplied by the predicted ten minute stream discharge (m^3/sec) and converted to produce a ten minute suspended

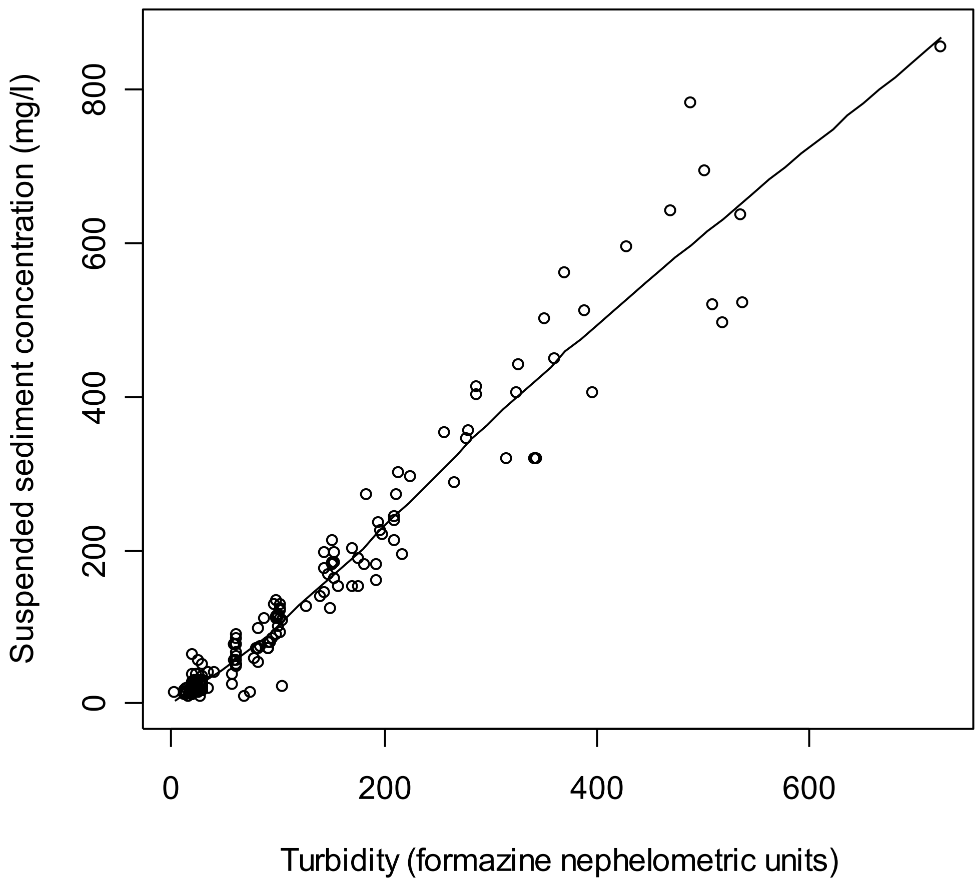

Figure 12. Loess plot of suspended sediment concentration against turbidity for Corrigan Creek.

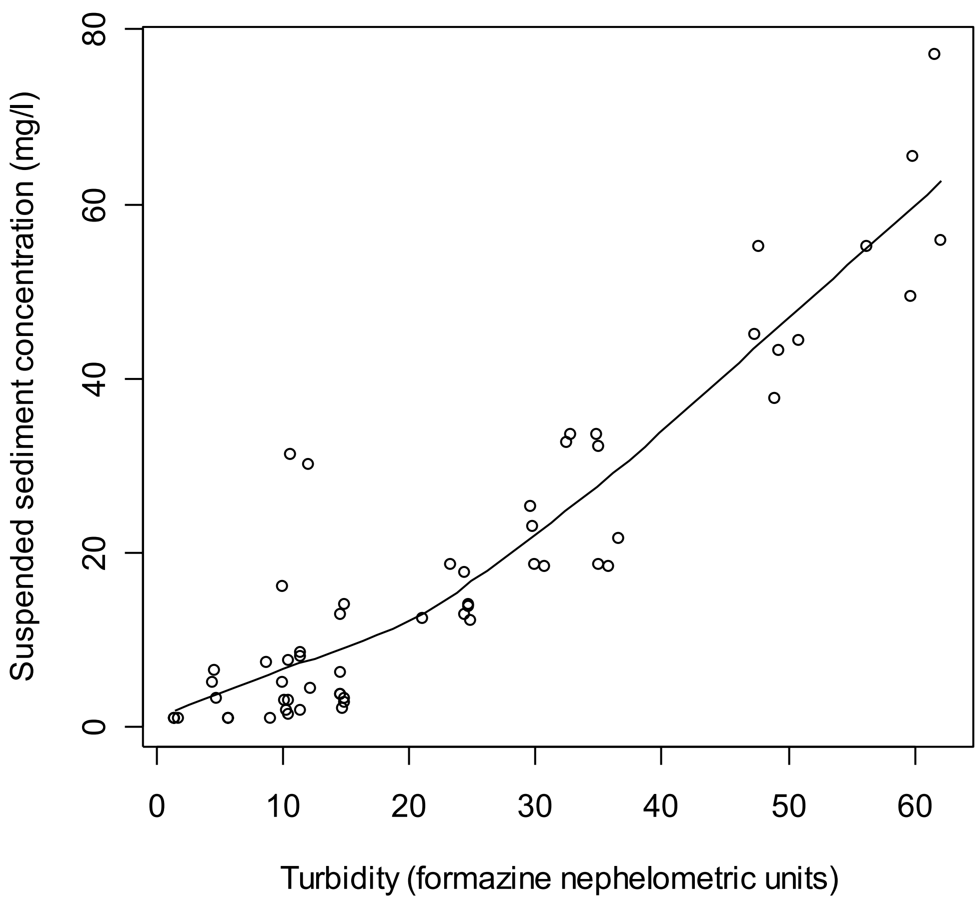

Figure 13. Loess plot of suspended sediment concentration against turbidity for Little South Fork Elk River.

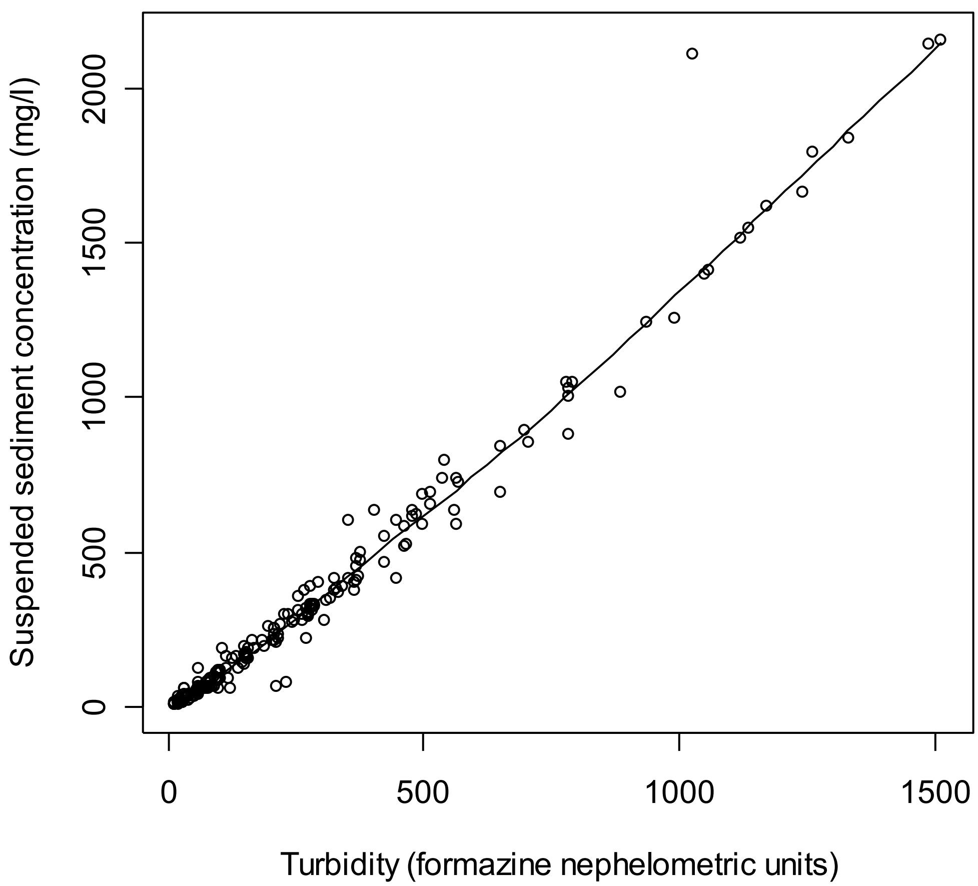

Figure 14. Loess plot of suspended sediment concentration against turbidity for South Branch North Fork Elk River.

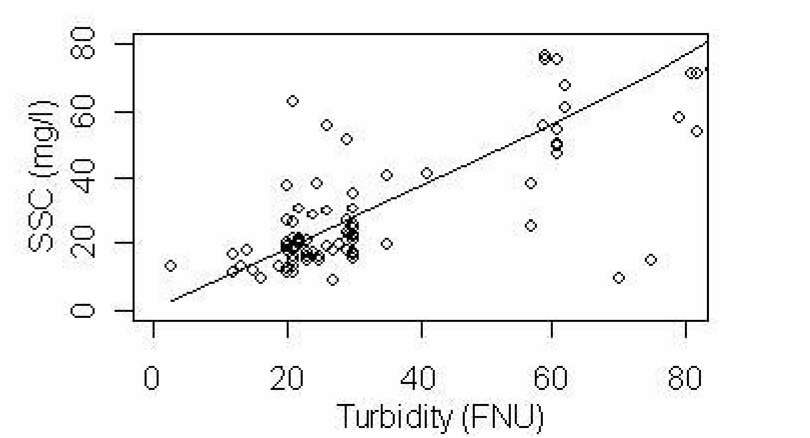

Figure 15. Low range of loess plot of suspended sediment concentration against turbidity for Corrigan Creek.

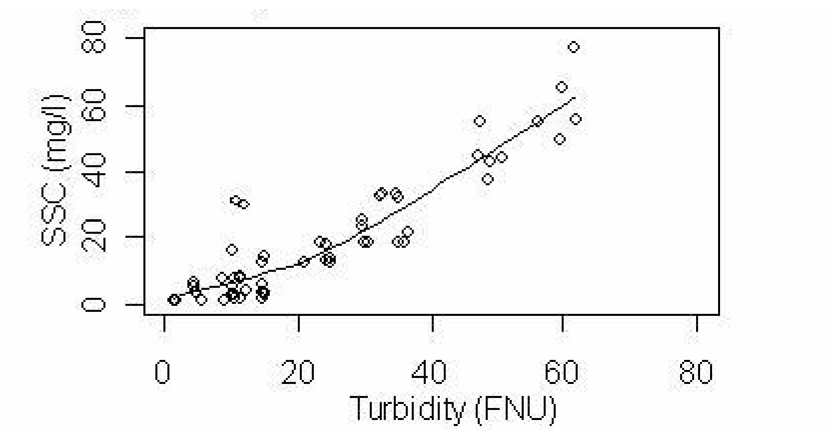

Figure 16. Low range of loess plot of suspended sediment concentration against turbidity for Little South Fork Elk River.

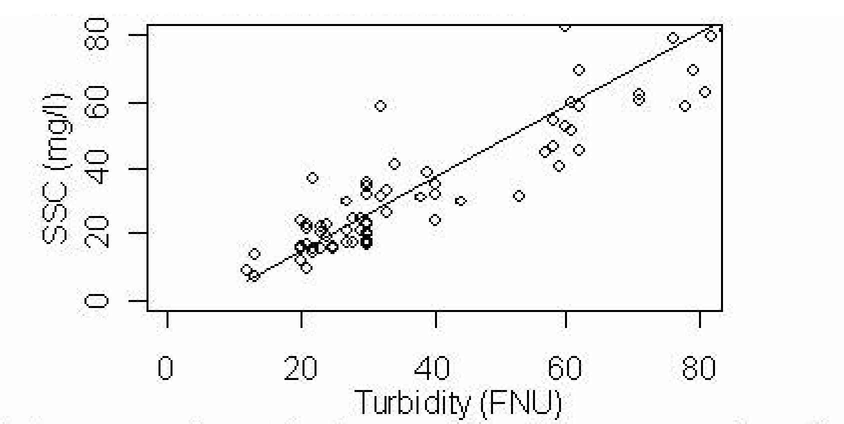

Figure 17. Low range of loess plot of suspended sediment concentration against turbidity for South Branch North Fork Elk River.

Table 1. Statistics for loess plots of suspended sediment against turbidity.

	Corrigan Creek	Little South Fork Elk River	South Branch North Fork Elk River
Plot type	Loess	Loess	Loess
Family	Gaussian	Gaussian	Gaussian
Degree	1	1	1
Span	0.67	0.67	0.67
Number of Observations	168	59	213
Residual Standard Error	36.81	7.13	65.31
Linear Extrapolation Above (mg/L)	724.00	62.16	1515.00
Linear Extrapolation Below (mg/L)	2.59	1.37	12.00

sediment discharge (kg). The entire set of 10 minute suspended sediment discharges was then summed to produce a total suspended sediment load estimate for each site. The estimated sediment load was adjusted for the drainage area above each of the stations to obtain a normalized suspended sediment yield in metric tons/km^2/year. The estimated suspended sediment yield at Little South Fork Elk River was 6.6 tons/km^2. The yield at Corrigan Creek was 55.1 tons/km^2 and the yield at South Branch North Fork Elk was 122.2 tons/km^2. These data, including the total stream discharges are summarized in Table 2.

Another method to estimate annual suspended sediment yield is to use the relationship between suspended sediment concentration and turbidity for each individual storm event to generate sediment loads for that event. This method can be of particular utility when there is a poor annual relationship between turbidity and suspended sediment concentration or when the particle sizes or composition cause the relationship to shift during different storm events or different periods of the year. Differences in rock and soil mineralogy, particle size, and the abundance of organic sediment can cause differences in the light scattering properties of the transported material and can vary the suspended sediment concentration to turbidity relationship (Gippel 1989, Gippel 1995).

The eight largest storms of water year 2004 were analyzed using individual storm regressions to generate individual storm loads. These storm events accounted for a very large percentage of the total suspended sediment load at all three sites and contributed considerably more sediment to the total load than smaller events. A storm event was

Table 2. Summary of data for overlapping sample period.

For Period of Record 11/26/03 07:20 - 06/16/04 14:50			
	Corrigan Creek	Little South Fork Elk River	South Branch North Fork Elk River
Total Discharge (m^3)	2,287,908	1,671,682	3,716,323
Watershed Area (km^2)	4.01	3.11	4.92
Unit Area Discharge (m^3/km^2)	569,914	537,867	755,200
Total Suspended Sediment Load (tons) From Annual Regression	221.1	20.4	601.5
Total Suspended Sediment Load (tons) From Individual Storm Regressions	237.1	18.0	594.7
Difference Between Estimates (tons)	16.0	-2.4	-6.8
Total Suspended Sediment Yield (tons/km^2) From Annual Regression	55.1	6.6	122.2
Total Suspended Sediment Yield (tons/km^2) From Individual Storm Regressions	59.1	5.8	120.8
Difference Between Estimates (tons/km^2)	4.0	-0.8	-1.4
Difference as a Percent of Individual Storm Regressions Estimate	6.7	-13.5	-1.1

defined as an extended period of increased stage and turbidity. A storm event concluded when the turbidity was no longer decreasing at an appreciable rate or when another storm event began.

A linear model was used for this portion of the analysis because of the limited number of points available for each storm event and the acceptability of the fit of linear functions to this data. Some storms were divided into several regressions when it appeared that there were numerous distinct relationships. In particular, different relationships were observed during some storms when turbidity was rising and falling.

Individual storm estimates obtained by this method are presented in Table 3. This table also contains the r^2 value, residual standard error, and coefficient of variation for each individual storm plot. The coefficient of variation is a statistical representation of the precision of an estimate. The coefficient of variation represented as a percentage is defined as: $100 \times \text{variance}^{0.5}$/ estimated total load, where variance of the estimate is calculated as per Lewis (1996). When there are two distinct regressions to describe the turbidity – suspended sediment concentration relationship for an individual storm event, the coefficient of variation represented as a percentage is:

$100 \times ((\text{variance}_1 + \text{variance}_2)^{0.5}) / (\text{estimated total load}_1 + \text{estimated total load}_2)$

(Lewis 1996). Table 4 compares individual storm estimates generated by a loess model of the annual suspended sediment to turbidity relationship with estimates based on storm-wise linear regressions accompanied by the upper and lower boundaries of the 95% confidence interval for storm-wise linear regression estimates.

Table 3. Statistics for suspended sediment load estimates of eight largest storms of water year 2004 based on storm-wise linear regressions between suspended sediment concentration and turbidity.

Storm # and component	Date & Time Start	Date & Time End	Load Estimated Using Storm-Wise Linear Regression (kg)	Number of Sediment Samples	r^2	Residual Standard Error	Coefficient of Variation
			Corrigan Creek				
2	12/10/03 19:00	12/13/03 21:10	13,459	11	0.98	20.22	3.95
3 total	12/13/03 21:20	12/18/03 14:20	20,800	14	NA	NA	2.68
3 rising	12/13/03 21:20	12/14/03 1:00	5,953	4	1.00	10.03	1.59
3 falling	12/14/03 1:00	12/18/03 14:20	14,847	10	0.99	17.68	3.70
5 total	12/28/03 18:00	12/29/03 13:00	24,780	12	NA	NA	2.87
5 rising	12/28/03 18:00	12/29/03 6:10	8,275	5	1.00	11.59	1.83
5 falling	12/29/03 6:20	12/29/03 13:00	16,505	7	0.97	36.81	4.21
6	12/29/03 13:10	12/31/03 12:00	12,893	5	1.00	5.66	2.37
7	12/31/03 13:00	1/15/04 13:00	45,446	17	NA	NA	3.99
7rising	12/31/03 13:00	1/1/04 8:00	12,266	5	0.99	36.66	7.72
7falling	1/1/04 8:10	1/15/04 13:00	33,180	12	1.00	18.05	4.67
13	2/16/04 6:00	2/20/04 13:00	65,934	13	0.99	25.25	4.49
14	2/25/04 6:00	2/28/04 12:00	26,469	12	0.89	21.73	5.92
17	5/17/04 17:40	5/30/04 12:30	2,795	10	0.97	12.05	8.20
			Little South Fork Elk River				
2	12/10/03 19:00	12/13/03 21:10	1,378	9	0.94	4.79	7.59
3	12/13/03 21:20	12/18/03 14:20	1,770	6	0.98	3.83	9.88
5	12/28/03 18:00	12/29/03 13:00	1,519	6	0.89	6.53	9.41
6	12/29/03 13:10	12/31/03 12:00	1,727	4	0.96	1.80	5.93
7	12/31/03 13:00	1/15/04 13:00	3,246	8	0.97	4.62	14.47
13 total	2/16/04 6:00	2/20/04 13:00	4,734	10	NA	NA	7.86
13 rising	2/16/04 6:00	2/17/04 4:20	1,543	4	1.00	0.61	0.83
13 falling	2/17/04 4:30	2/20/04 13:00	3,191	6	0.93	2.27	11.66
14	2/25/04 6:00	2/28/04 12:00	1,243	4	1.00	0.34	2.51
17	5/17/04 17:40	5/30/04 12:30	109	3	0.45	8.78	87.61
			South Branch North Fork Elk River				
2	12/10/03 19:00	12/13/03 21:10	24,190	20	0.99	35.49	2.71
3 total	12/13/03 21:20	12/18/03 14:20	51,052	21	NA	NA	7.13
3 rising	12/13/03 21:20	12/13/03 23:20	8,552	5	0.96	184.25	8.14
3 falling	12/13/03 23:30	12/18/03 14:20	42,500	16	0.99	89.51	8.41
5	12/28/03 18:00	12/29/03 13:00	NA	0	0.00	0.00	0.00
6	12/29/03 13:10	12/31/03 12:00	25,679	11	0.88	76.46	13.71
7	12/31/03 13:00	1/15/04 13:00	102,301	27	0.99	40.83	2.64
13	2/16/04 6:00	2/20/04 13:00	191,348	44	0.98	53.33	2.54
14	2/25/04 6:00	2/28/04 12:00	85,977	16	0.93	25.06	3.50
17	5/17/04 17:40	5/30/04 12:30	NA	0	0.00	0.00	0.00

Table 4. Individual storm loads for the eight largest storms of water year 2004 estimated using storm-wise linear regression and loess annual regression of suspended sediment concentration against turbidity.

Storm #	Storm Load Estimated by Storm-Wise Linear Regression (kg)	Storm Load Estimated by Loess Annual Regression (kg)	Difference (kg)	Difference as a % of Estimate Using Storm-Wise Linear Regression	Coefficient of Variation for Storm-Wise Linear Regression	Lower Boundary of 95 % Confidence Interval for Storm-Wise Linear Regression (kg)	Upper Boundary of 95 % Confidence Interval for Storm-Wise Linear Regression (kg)
Corrigan Creek							
2	13,459	12,012	1,448	10.8	3.95	12,396	14,522
3	20,800	21,144	-344	-1.7	2.68	19,685	21,915
5	24,780	25,416	-636	-2.6	2.87	23,358	26,202
6	12,893	11,220	1,673	13.0	2.37	12,283	13,503
7	45,446	42,804	2,642	5.8	3.99	41,815	49,077
13	65,934	57,557	8,377	12.7	4.49	60,009	71,859
14	26,469	23,631	2,838	10.7	5.92	23,336	29,601
17	2,795	2,955	-160	-5.4	8.20	2,470	3,439
Total	209,781	193,784	15,996	7.6			
Little South Fork Elk River							
2	1,378	1,613	-235	-17.1	7.59	1,169	1,587
3	1,770	1,959	-189	-10.7	9.88	1,420	2,120
5	1,519	1,707	-188	-12.4	9.41	1,233	1,805
6	1,727	1,427	301	17.4	5.93	1,522	1,932
7	3,246	2,845	401	12.4	14.47	2,307	4,186
13	4,734	6,840	-2,106	-44.5	7.86	3,989	5,478
14	1,243	1,653	-410	-33.0	2.51	1,181	1,306
17	109	29	81	73.6	87.61	-82	301
Total	15,618	18,043	-2,426	-15.5			
South Branch North Fork Elk River							
2	24,190	22,232	1,958	8.1	2.7	22,879	25,502
3	51,052	53,276	-2,224	-4.4	7.1	43,773	58,331
5	No Data	65,239	NA	NA	NA	NA	NA
6	25,679	25,708	-29	-0.1	13.7	18,639	32,719
7	102,301	101,442	860	0.8	2.6	96,904	107,698
13	191,348	197,402	-6,054	-3.2	2.5	181,623	201,072
14	85,977	86,387	-410	-0.5	3.5	79,955	91,999
17	No Data	4,658	NA	NA	NA	NA	NA
Total	480,547	486,447	-5,899	-1.2			

The total sediment load generated by the eight largest storms as estimated by individual storm regression was added to the load estimated by annual regression for the remaining time periods. This produced an annual sediment yield estimate based on individual storm regression of 5.8 tons/km^2 at Little South Fork, 59.1 tons/km^2 at Corrigan Creek, and 120.1 tons/km^2 at South Branch North Fork (Table 2).

Figures 18, 19, and 20 are plots of the suspended sediment concentration against turbidity at all three sites. These plots contain the entire annual data set accompanied by a linear regression of this data. These plots also highlight several selected storm events and linear regressions of these events. There are obvious differences in the suspended sediment – turbidity relationships over the course of the year at Corrigan Creek (Figure 18) and Little South Fork Elk River (Figure 19). South Branch North Fork Elk River (Figure 20) shows very little variation in this relationship throughout the year.

Neither method appeared to consistently over predict or under predict the other method. Individual storm regression predicted an annual load of 2,430 kg less than annual regression predicted at Little South Fork Elk River and a load of 16,000 kg more than annual regression at Corrigan Creek (Table 4). These are considerable differences when accounting for the size of the total load, especially at Little South Fork Elk River where the difference amounted to 16 percent of the total annual load. At Corrigan Creek the difference amounted to 8 percent of the total annual load.

Annual regression predicted a load of 5,900 kg more than individual storm regression at South Branch North Fork Elk River which amounted to only one percent of

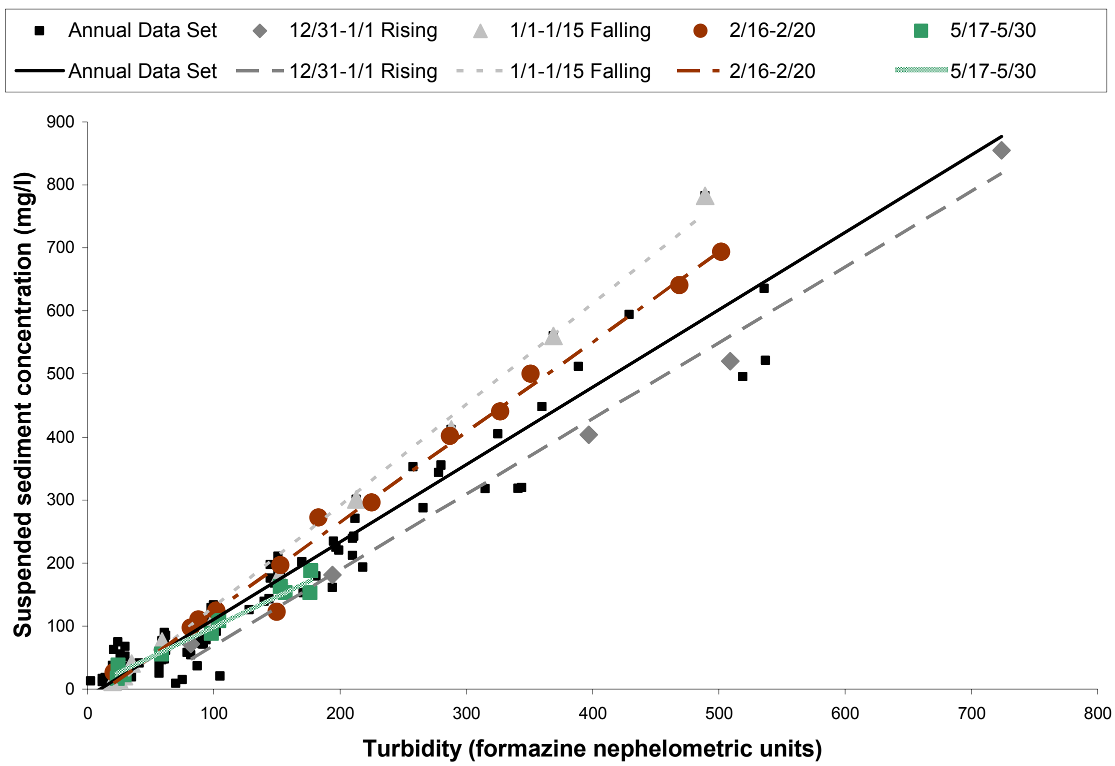

Figure 18. Suspended sediment concentration – turbidity relationship for annual data set and for selected storm events at Corrigan Creek.

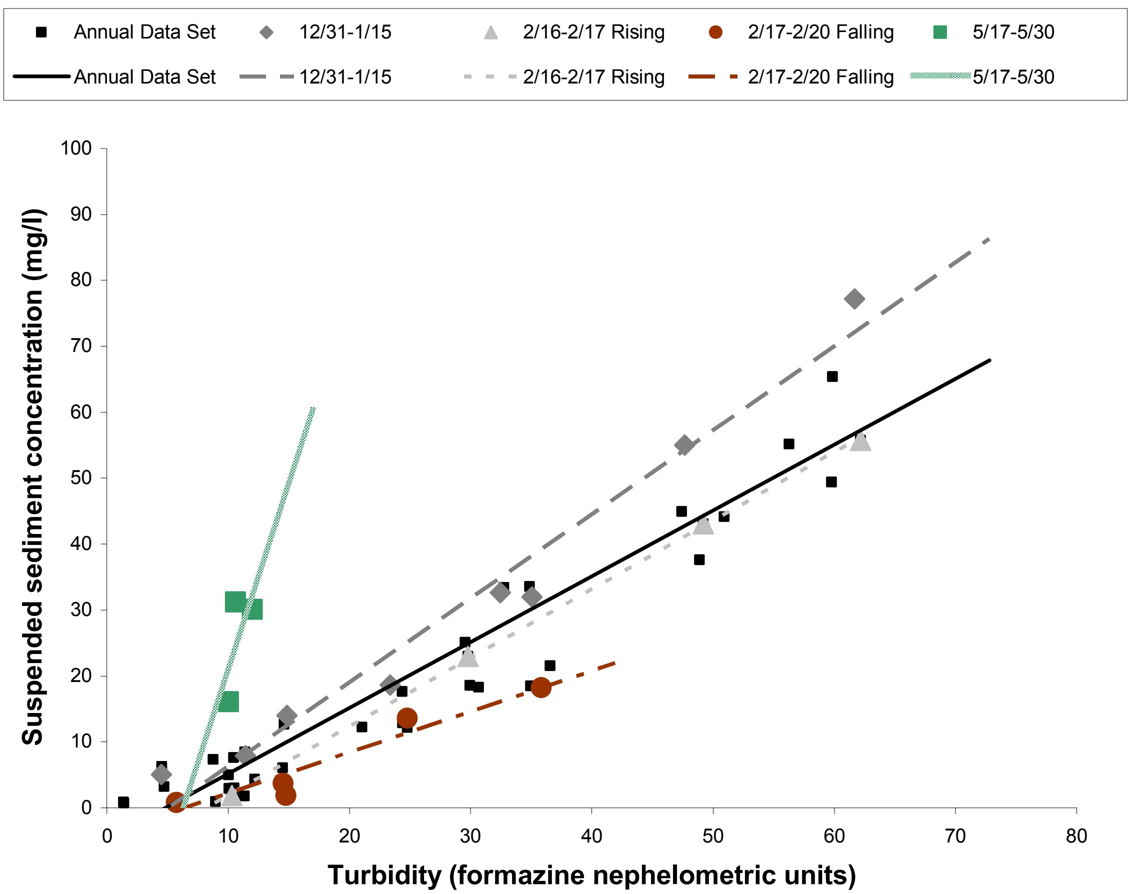

Figure 19. Suspended sediment concentration – turbidity relationship for annual data set and for selected storm events at Little South Fork Elk River.

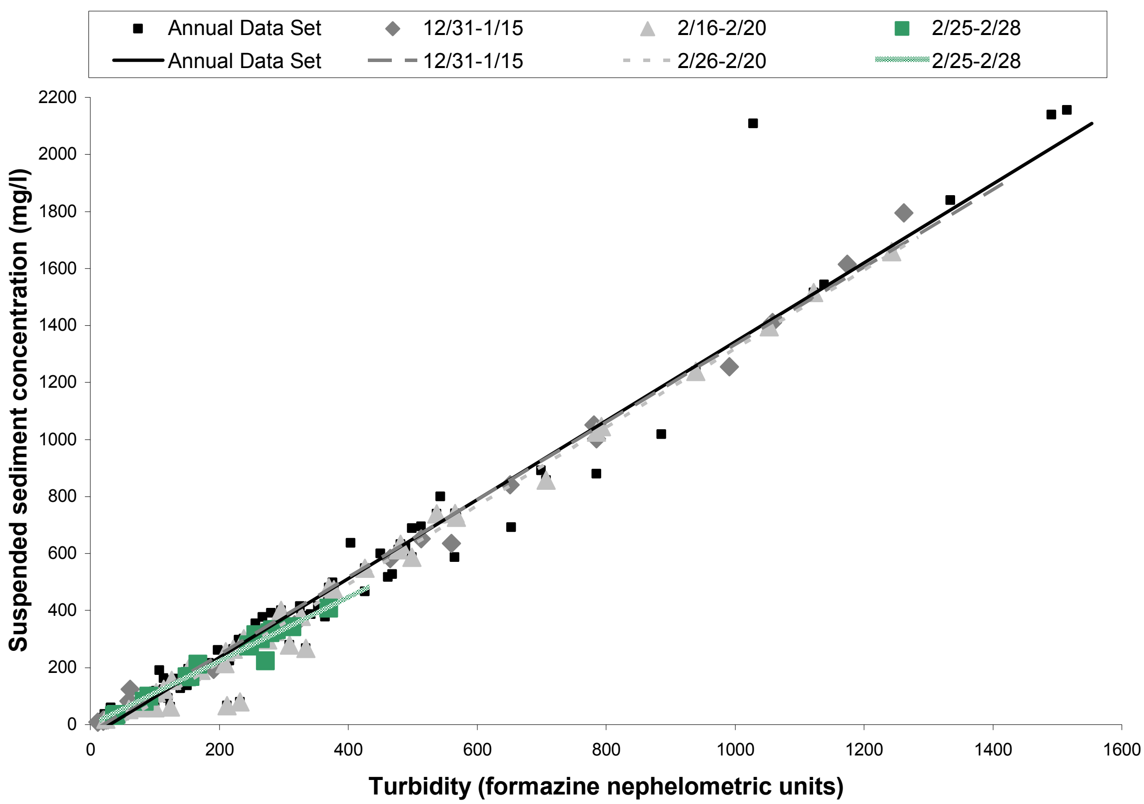

Figure 20. Suspended sediment concentration – turbidity relationship for annual data set and for selected storm events at South Brach North Fork Elk River.

the total annual load. There was, however, insufficient data for the fourth largest storm of the year to make an individual storm load prediction. This omission may have had some, but unlikely a large influence on that figure.

Particle Size Distribution

All physical sediment samples were divided into two size classes. Particles larger than 0.0635 mm are classified as sands and particles between 0.0635 mm and 0.001 mm (the pore size of the smallest filter used) are classified as fines (silts and clays). Loess models were used to compute the total suspended sediment load that moved as fines and as sands in each watershed. The total yield of both fines and sands was highest at South Branch North Fork Elk River and lowest at Little South Fork Elk River (Table 5). The percentage of the total suspended sediment load that moved as fines was similar for the two managed watersheds; 90 percent at South Branch North Fork Elk River and 87 percent at Corrigan Creek. The percentage of the total load that moved as fines was only 75 percent at Little South Fork Elk River. Figures 21, 22, and 23 show the percentage of sand observed in each sediment sample as a function of discharge at the three sampling locations. All three sites showed greater variability and higher sand fractions at lower discharges. Little South Fork Elk River had the greatest variability and the highest sand fractions throughout the range of discharges.

Every third consecutive sediment sample whose field turbidity was greater than 200 FNU was also first passed through four additional sieves; 1000, 500, 250, and 125 μm. There were 29 sediment samples that were passed through the four additional sieves

Table 5. Estimates of suspended sediment load composition and statistics for loess plots of fines and sands versus turbidity.

	Fines (0.0635 mm - 0.001 mm)			Sands (>0.0635mm)		
	Corrigan Creek	Little South Fork Elk River	South Branch North Fork Elk River	Corrigan Creek	Little South Fork Elk River	South Branch North Fork Elk River
Plot type	Loess	Loess	Loess	Loess	Loess	Loess
Family	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian
Degree	1	1	1	1	1	1
Span	0.67	0.67	0.67	0.67	0.67	0.67
Number of Observations	168	59	213	168	59	213
Residual Standard Error	36.36	4.21	61.36	12.99	3.95	17.97
Linear Extrapolation Above (mg/L)	724.00	62.16	1515.00	724.00	62.16	1515.00
Linear Extrapolation Below (mg/L)	2.59	1.37	12.00	2.59	1.37	12.00
Total Load in Size Class (tons)	191.5	15.2	538.7	29.7	5.1	62.7
Total Yield in Size Class (tons/km^2)	47.7	4.9	109.5	7.4	1.6	12.8
Percentage of Total Suspended Sediment Load in Size Class	87	75	90	13	25	10

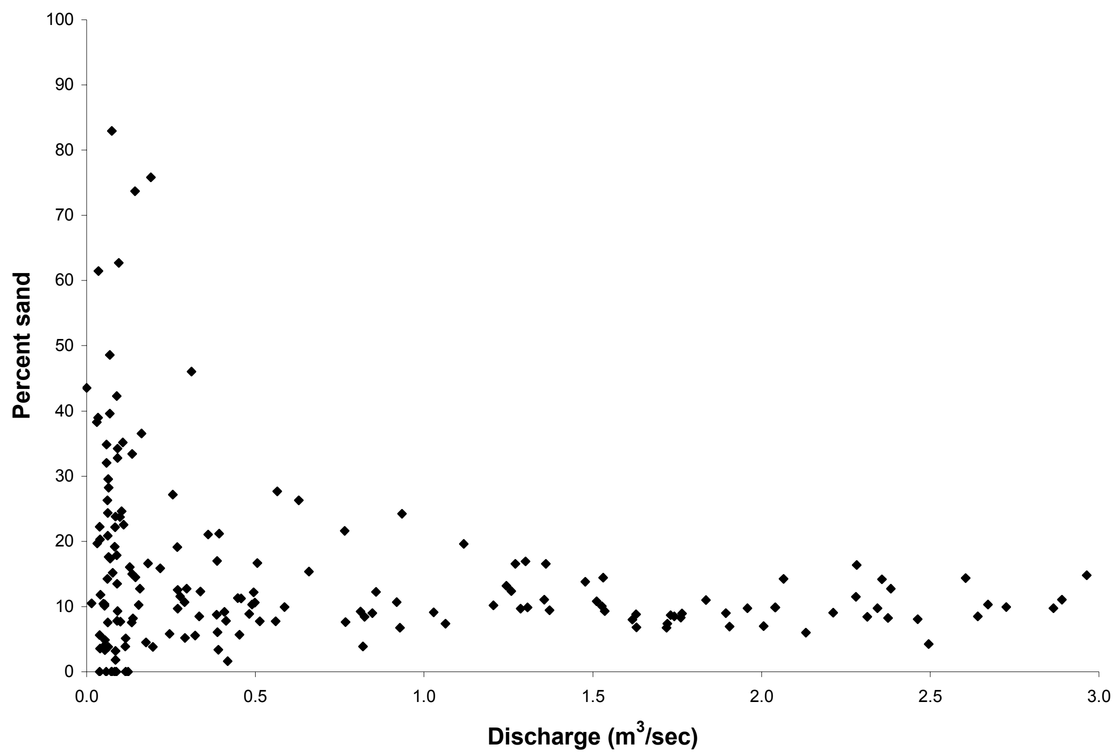

Figure 21. Percent sands as a function of discharge at Corrigan Creek.

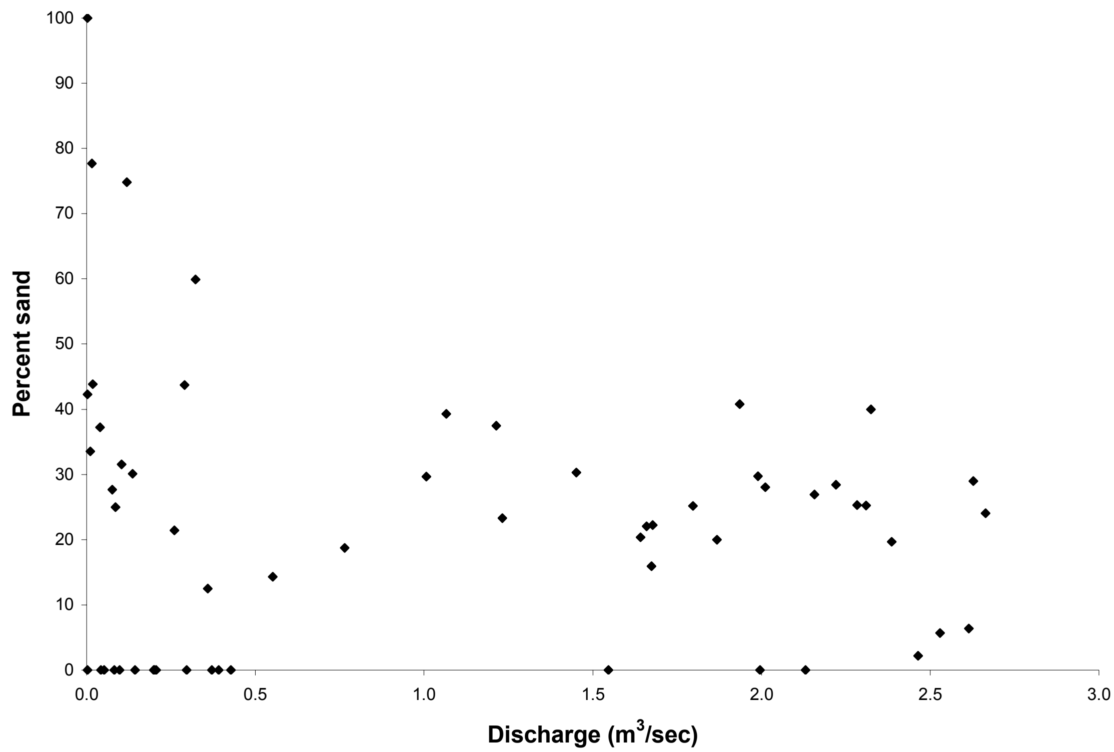

Figure 22. Percent sands as a function of discharge at Little South Fork Elk River.

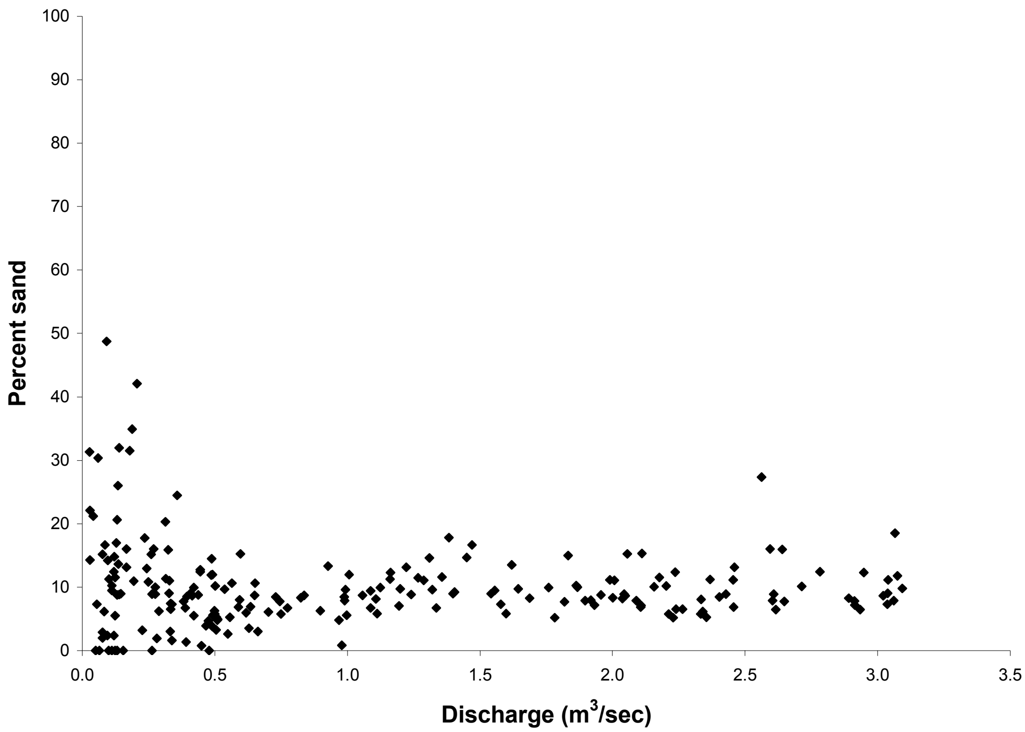

Figure 23. Percent sands as a function of discharge at South Branch North Fork Elk River.

(25 from South Branch North Fork and 4 from Corrigan Creek). Analysis of the sieve data showed no appreciable trends when plotted against time, sample suspended sediment concentration, and discharge. There was an inadequate number of samples at Corrigan Creek and Little South Fork Elk River to allow for comparison between sites.

Timing of Sediment Movement

There were 17 storm events observed during water year 2004, representing 33 percent of the study period. Hydrographs (stream discharge against time) were very similar for all three sites (Figure 24). The onset of storm events and the timing of storm peaks were nearly simultaneous at all three sites, though there were subtle differences in peak discharges and low flow magnitude. For clarity in presentation, a composite discharge was generated by averaging each of the 10 minute discharges at the three sites (Figure 25).

Sediment movement occurred primarily in several large fluxes corresponding to several large rainstorms (Figure 25). The 8 largest sediment movement events transported roughly 90 percent of the load for the entire year in 16 percent of the study period at all three stations (Figure 26). The two largest events alone moved over 50 percent of the total load at all three sites in just 9 percent of the study period. There was very little sediment movement observed outside of the defined storm events; only 2-5 percent of the total load moved during the inter-storm period. Figure 27 is a plot of the percentage of the flow frequency, flow volume, and sediment flux occurring at discharges

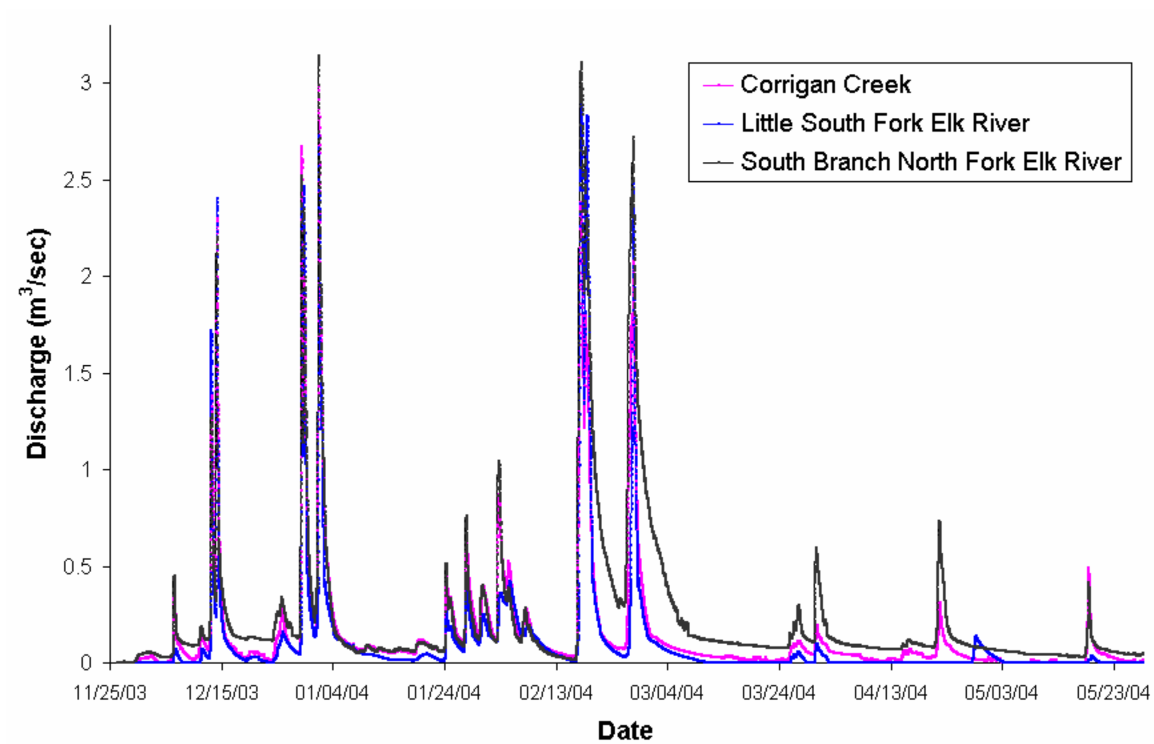

Figure 24. Hydrograph for Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River.

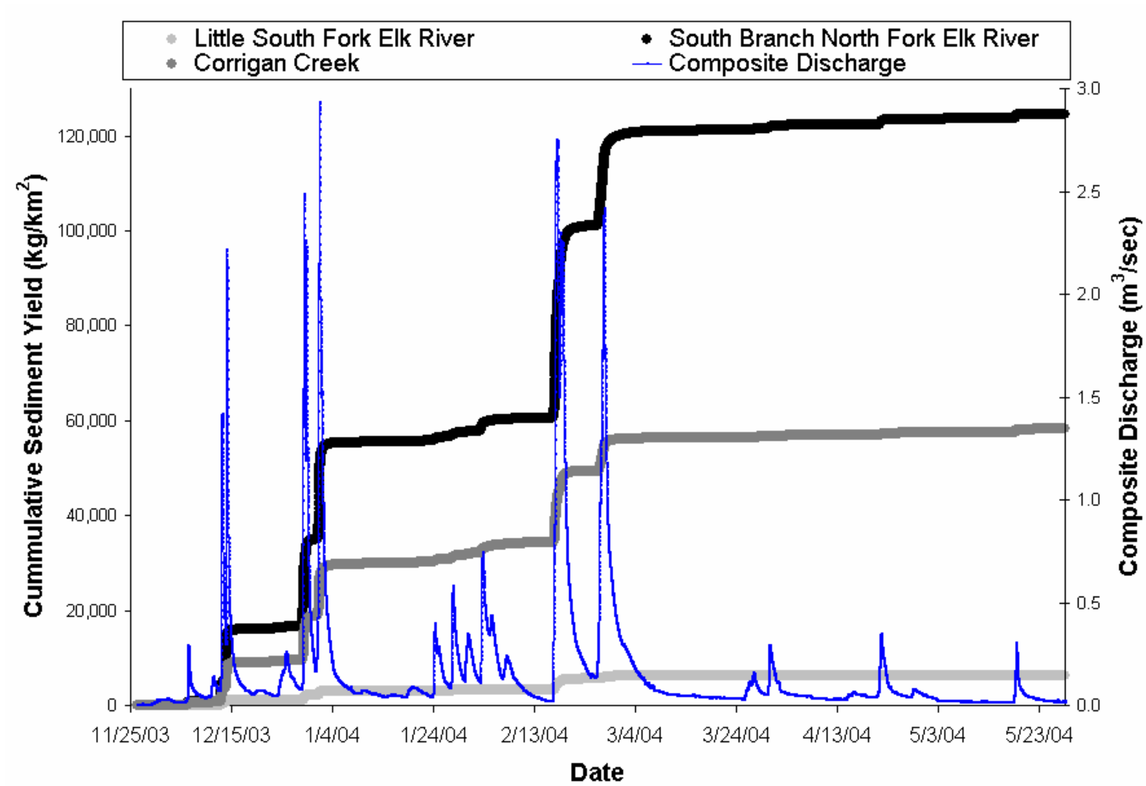

Figure 25. Sediment yield accumulation and composite discharge generated by averaging the discharges at Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River.

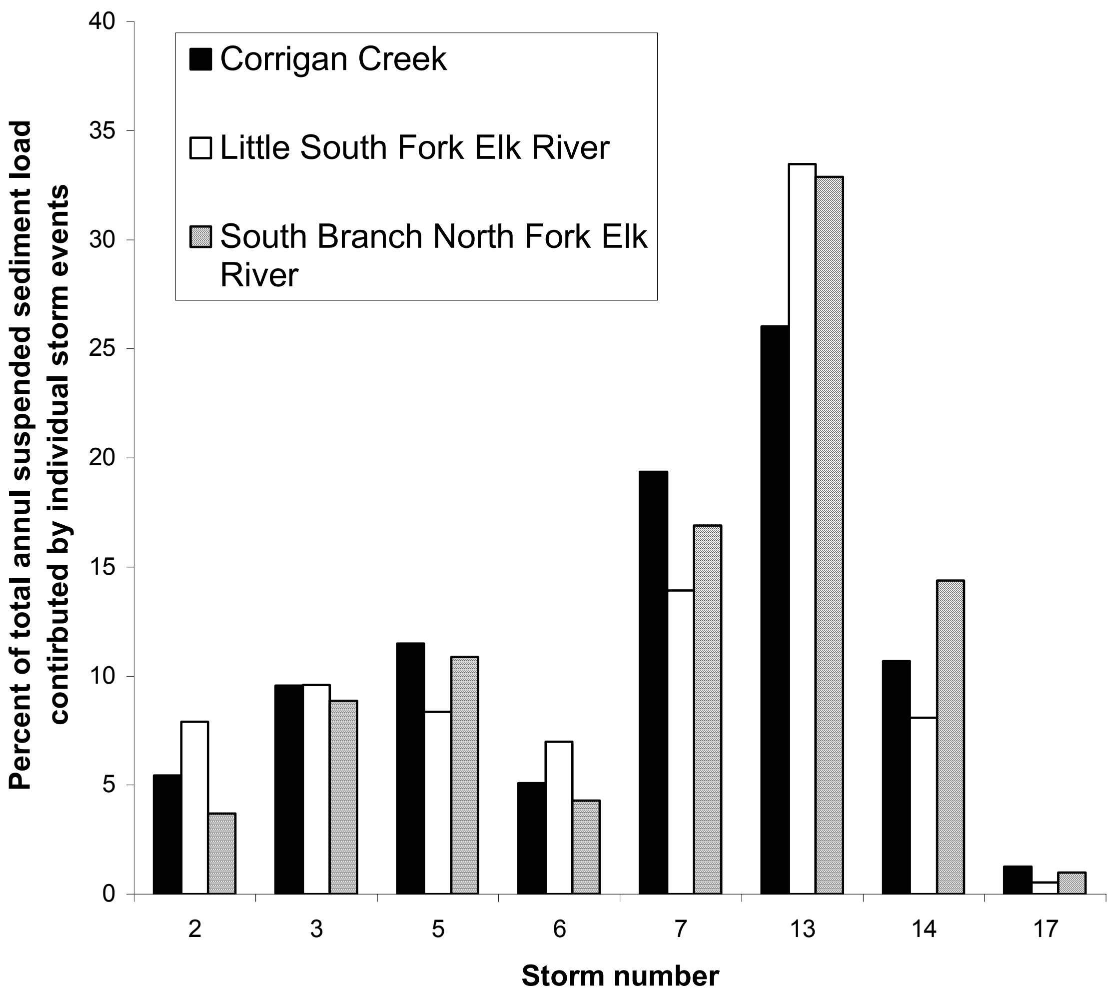

Figure 26. Percent of total annual suspended sediment load contributed by individual storm events.

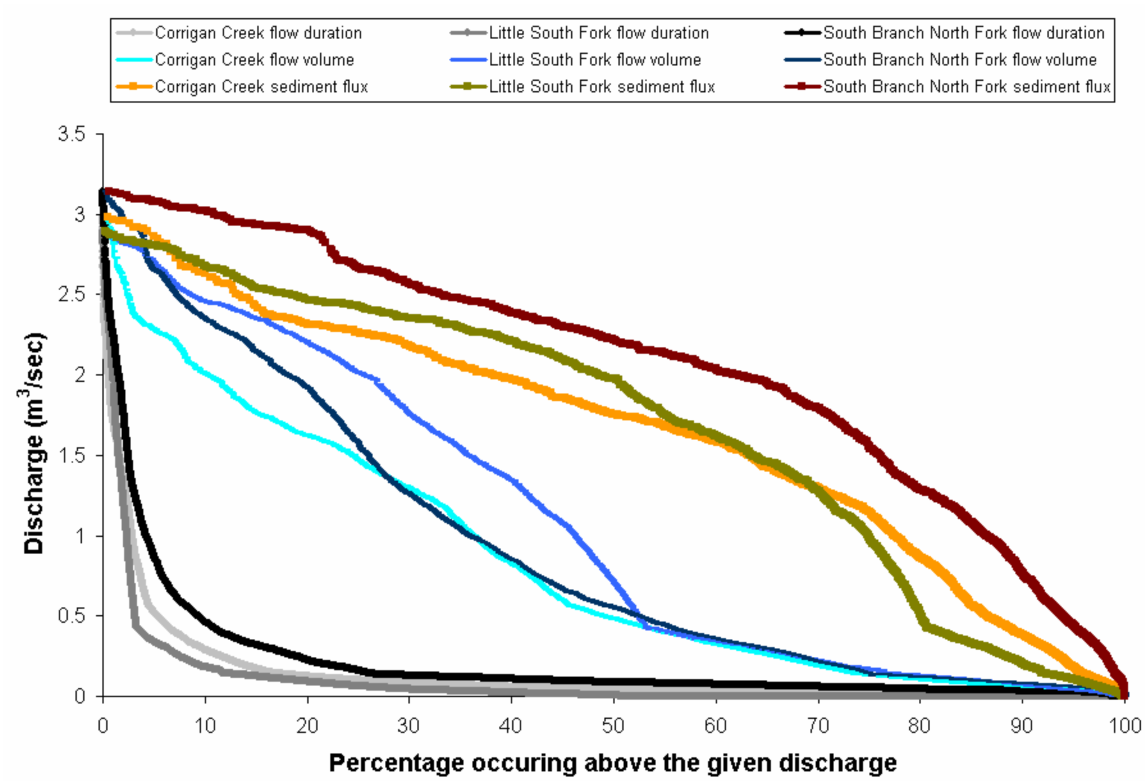

Figure 27. Flow and sediment regimes at Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River.

greater than the level indicated at all three sites. At South Branch North Fork Elk River for example, discharges greater than 1.5 m^3/sec occurred less than 5 percent of the time, but accounted for approximately 30 percent of the flow volume and 80 percent of the sediment flux.

Elevated Sediment Duration

In addition to the total suspended sediment load, the duration of elevated suspended sediment concentrations in a stream is important from a biological and a water quality perspective. Figure 28 shows the total (non-continuous) hours that thresholds of suspended sediment concentration were exceeded at each of the three Elk River sampling locations, based on the annual loess regressions (Figures 12, 13, 14).

Newcombe (1991), Newcombe and MacDonald (1994), and Newcombe and Jensen (1996) synthesized numerous studies on the physiological response of fish to increased suspended sediment concentration. They proposed a severity (SEV) of ill effects index that describes the response of fish to different doses [concentration (mg/L) × duration of exposure (hours)] of sediment. They created a SEV scale of 0-14 based on the regression of exposure duration and sediment concentration in the numerous studies that they examined. This allowed creation of multiple functions based on taxonomy, life stage, and life history. The SEV scale is provided in Table 6.

Figures 29, 30, and 31 show the continuous number of hours that particular suspended sediment concentration thresholds were met or exceeded at each of the three sediment sampling sites in Elk River based on the annual loess regressions (Figures 12,

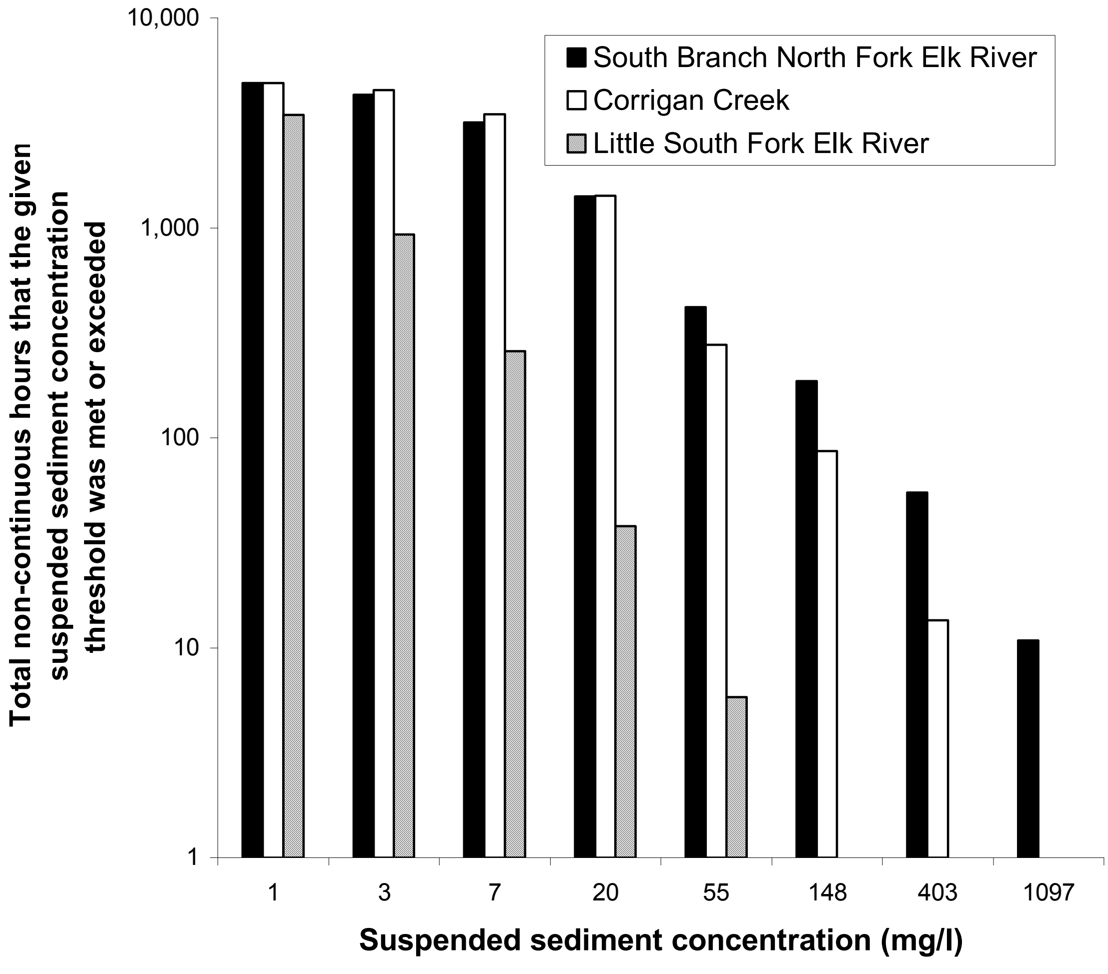

Figure 28. Total non-continuous hours that suspended sediment concentration thresholds were met or exceeded.

Table 6. Scale of the severity (SEV) of ill effects associated with excess suspended sediment. Reproduced from Newcombe and Jensen (1996).

SEV	Description of effect
	Nil effect
0	No behavioral effects
	Behavioral effects
1	Alarm reaction
2	Abandonment of cover
3	Avoidance response
	Sublethal effects
4	Short-term reduction in feeding rates; short-term reduction in feeding success
5	Minor physiological stress; increase in rate of coughing; increased respiration rate
6	Moderate physiological stress
7	Moderate habitat degradation; impaired homing
8	Indications of major physiological stress; long-term reduction in feeding rate; long term reduction in feeding success; poor condition
	Lethal and paralethal effects
9	Reduced growth rate; delayed hatching; reduced fish density
10	0-20% mortality; increased predation; moderate to severe habitat degradation
11	>20-40% mortality
12	>40-60% mortality
13	>60-80% mortality
14	>80-100% mortality

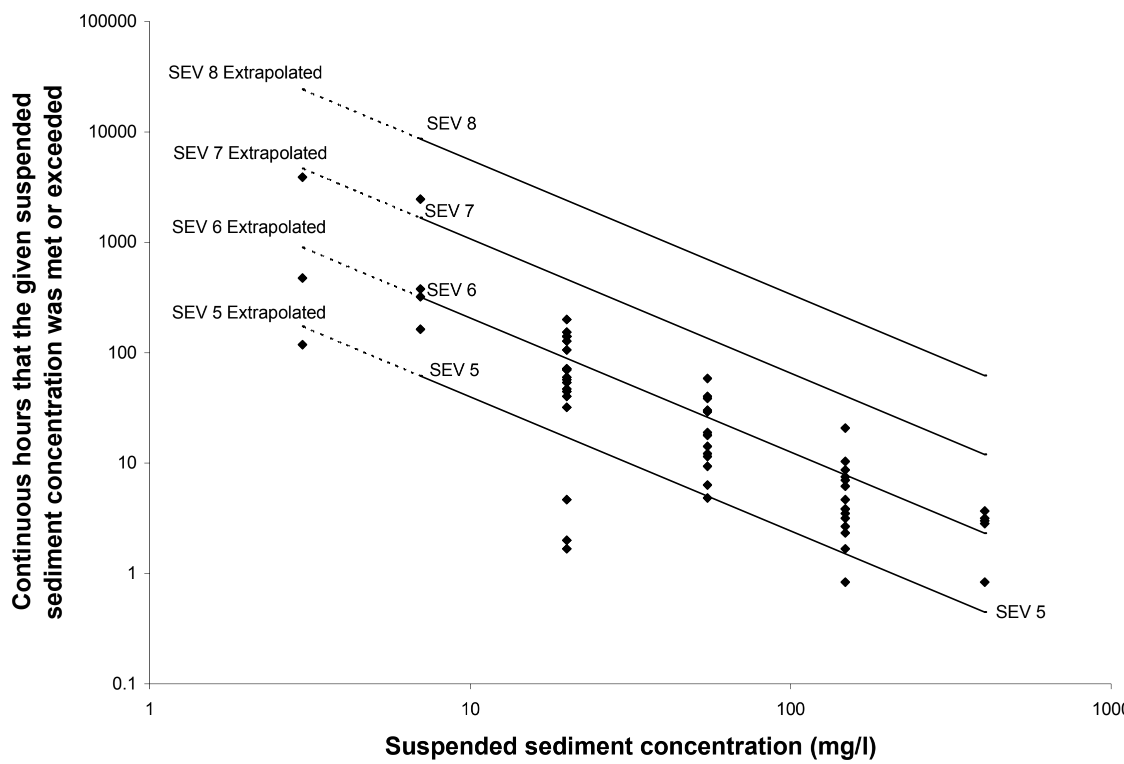

Figure 29. Continuous hours that a given suspended sediment concentration was met or exceeded at Corrigan Creek accompanied by Newcombe and Jensen model 1 severity of ill effects index (SEV) values for juvenile and adult salmonids.

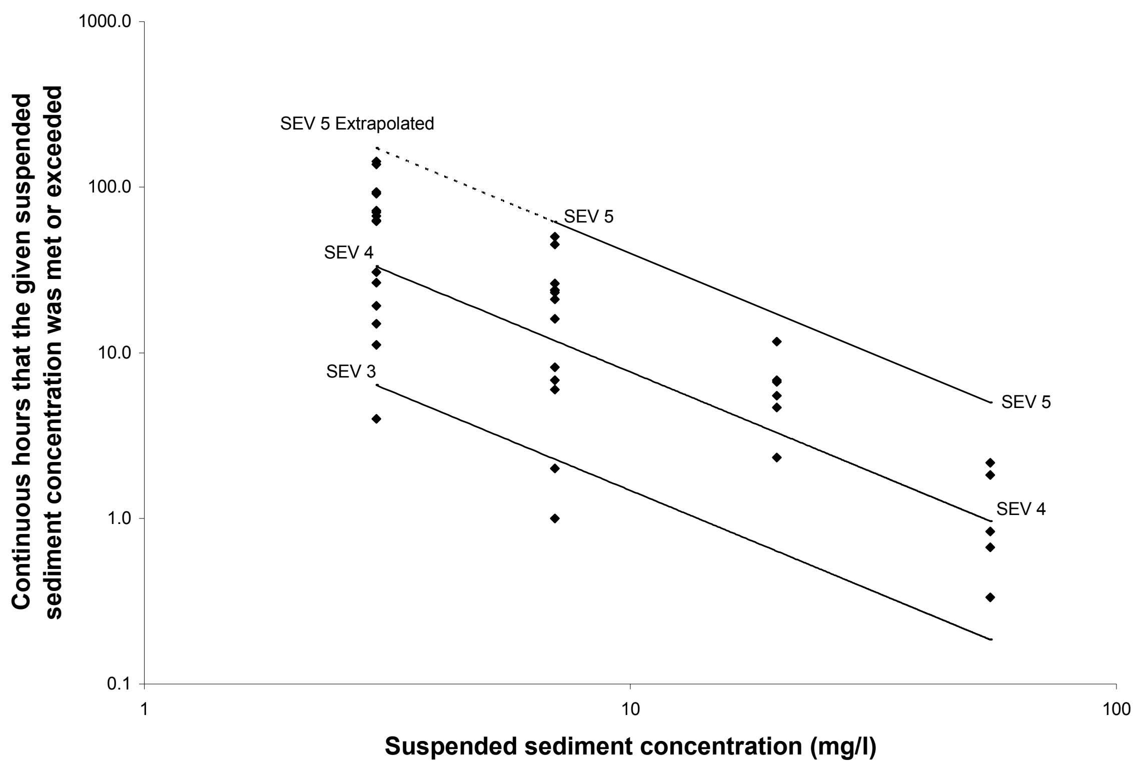

Figure 30. Continuous hours that a given suspended sediment concentration was met or exceeded at Little South Fork Elk River accompanied by Newcombe and Jensen model 1 severity of ill effects index (SEV) values for juvenile and adult salmonids.

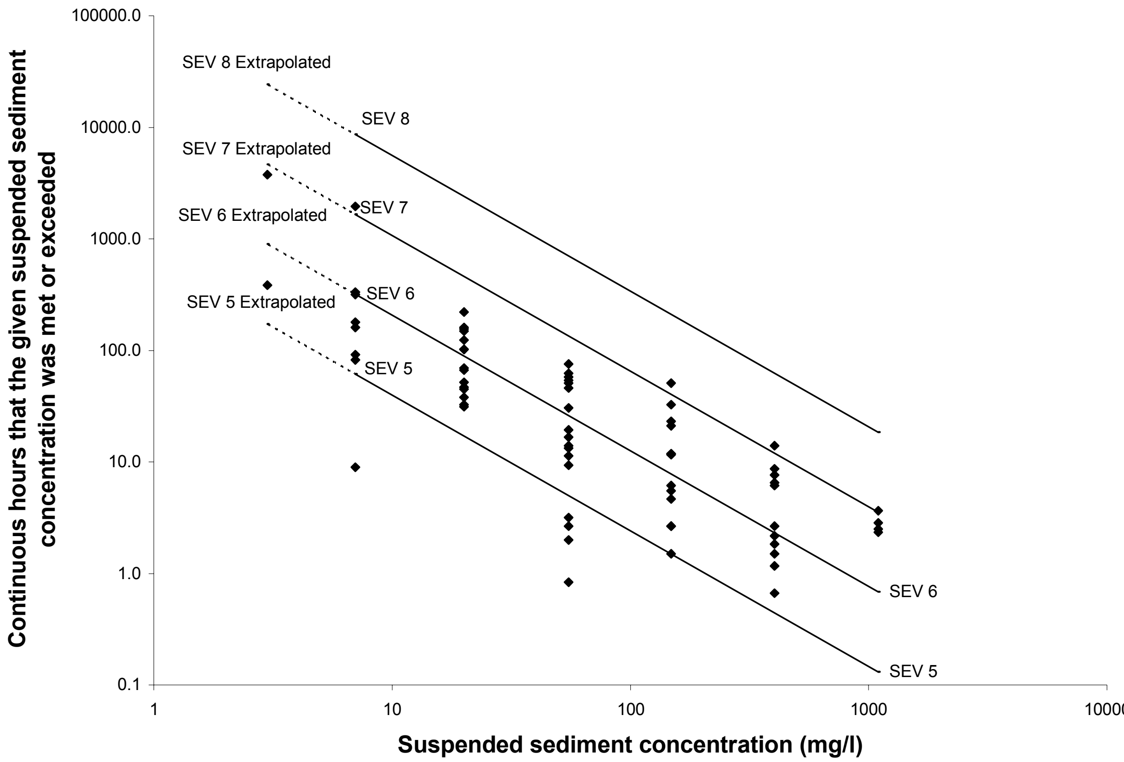

Figure 31. Continuous hours that a given suspended sediment concentration was met or exceeded at South Branch North Fork Elk River accompanied by Newcombe and Jensen model 1 severity of ill effects index (SEV) values for juvenile and adult salmonids.

13, 14). Each point on the plot shows the number of hours that a threshold was met or exceeded during a single occurrence (from when a concentration threshold was exceeded until the concentration fell below the threshold). The SEV values from Newcombe and Jensen (1996) model 1 are included on these figures. Model 1 describes the severity of ill effects experienced by juvenile and adult salmonids in 171 studies or experimental units that were summarized. The sediment thresholds on these plots are the same ones that were used by Newcombe and Jensen (1996). They were chosen because of biological significance and to facilitate logarithmic analysis.

Figures 32, 33, and 34 show the continuous number of hours that particular suspended sediment concentration thresholds were met or exceeded at each of the three sites in relation to the SEV values from Newcombe and Jensen (1996) model 4. Model 4 describes the severity of ill effects experienced by eggs and larvae of salmonids and non-salmonids in 43 studies or experimental units.

Newcombe and Jensen (1996) developed functions to describe SEV throughout a matrix of suspended sediment concentrations and time ranging from 1 mg/L to 162,755 mg/L and from 1 hour to 30 months. Some points in this matrix (especially at low sediment concentrations and extended durations) were not supported by actual physiological studies, but rather extrapolated from other points within the matrix that were supported by experimentation. Figures 29-34 contain dashed lines in areas where the functions have been extrapolated past the range of experimental data and solid lines

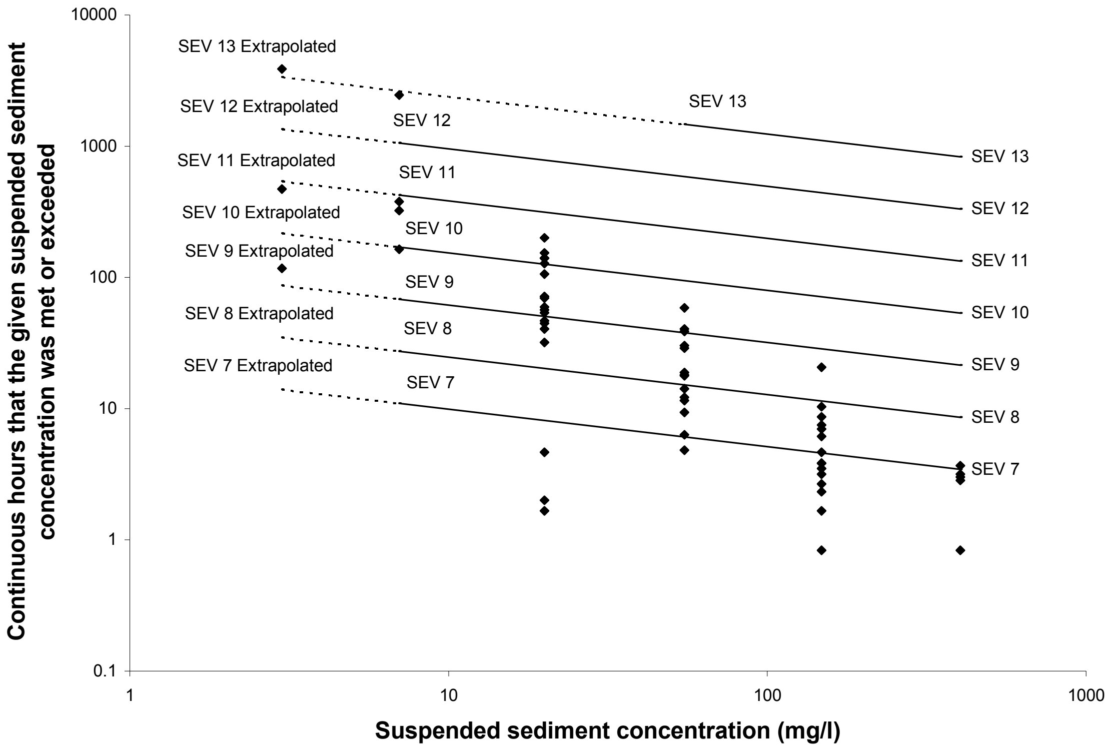

Figure 32. Continuous hours that a given suspended sediment concentration was met or exceeded at Corrigan Creek accompanied by Newcombe and Jensen model 4 severity of ill effects index (SEV) values for eggs and larvae of salmonids and non-salmonids.

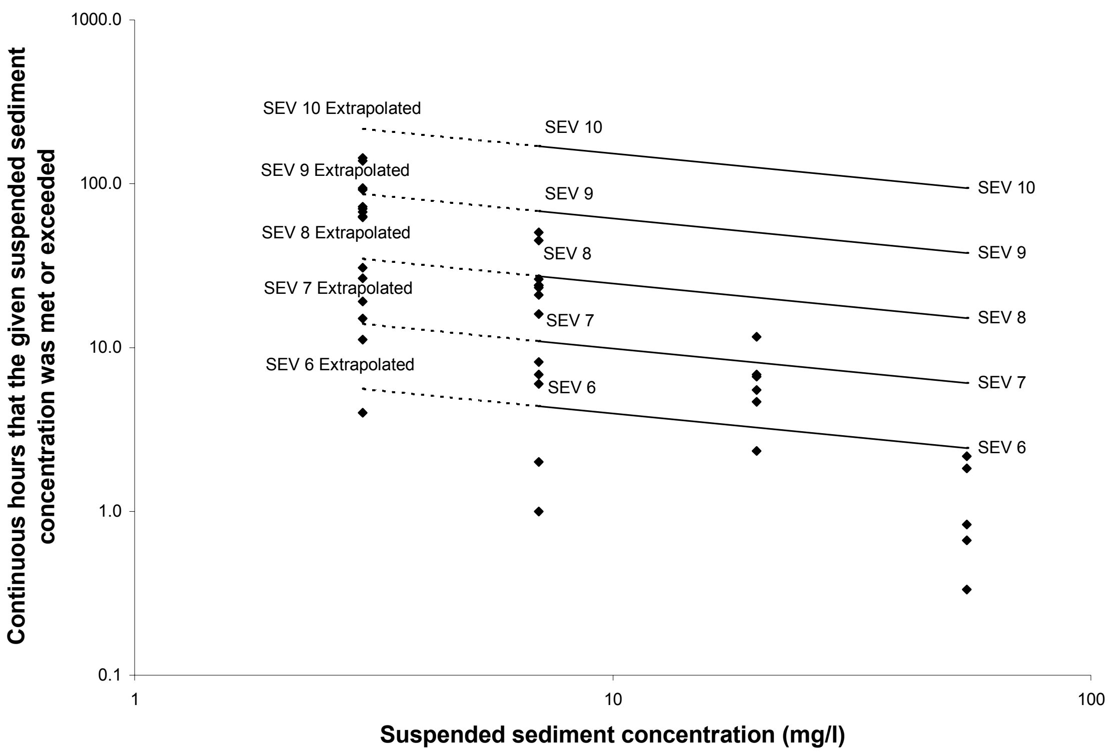

Figure 33. Continuous hours that a given suspended sediment concentration was met or exceeded at Little South Fork Elk River accompanied by Newcombe and Jensen model 4 severity of ill effects index (SEV) values for eggs and larvae of salmonids and non-salmonids.

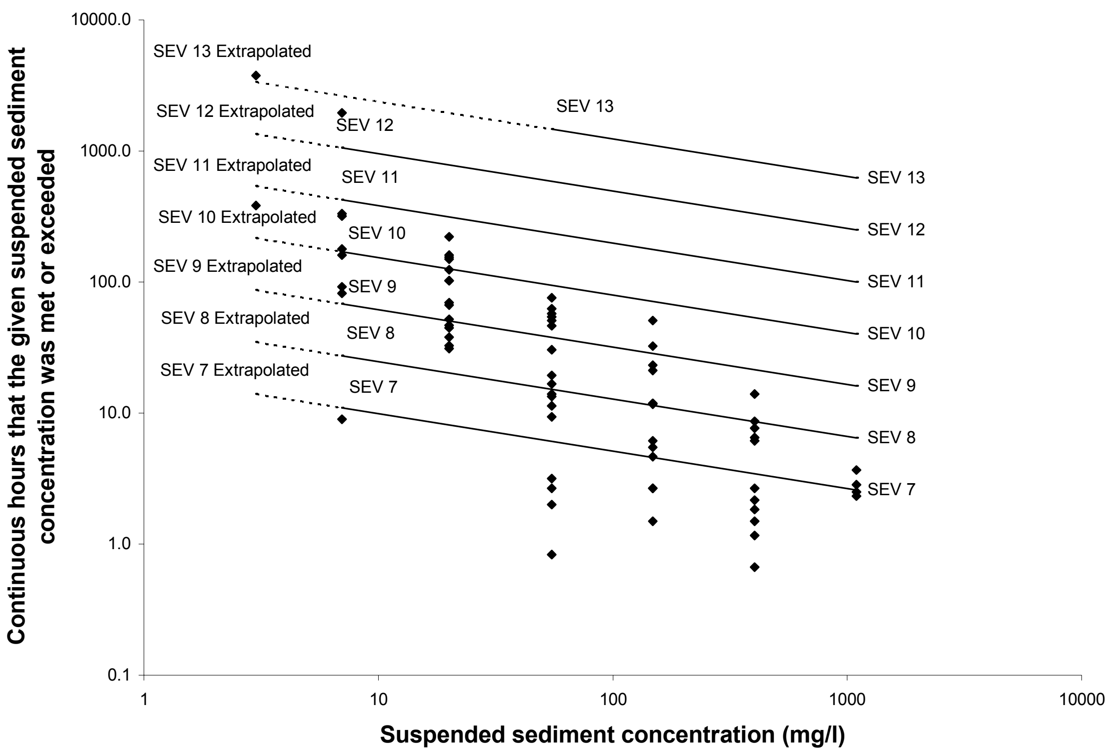

Figure 34. Continuous hours that a given suspended sediment concentration was met or exceeded at South Branch North Fork Elk River accompanied by Newcombe and Jensen model 4 severity of ill effects index (SEV) values for eggs and larvae of salmonids and non-salmonids.

where relationships are based on experimental data. Extrapolated data was not considered when evaluating SEV exceedance in this study.

The suspended sediment doses at South Branch North Fork Elk River and Corrigan Creek exceeded a severity of ill effects index of 6 (moderate physiological stress) and 7 (moderate habitat degradation and impaired homing) for juvenile and adult salmonids (model 1). SEV exceeded 4 (reduced feeding rate and success), but did not exceed 5 (minor physiological stress) at Little South Fork with respect to juvenile and adult salmonids. Egg and larval stages are more sensitive to prolonged exposure to sediment even at relatively low concentrations (Stober 1981). SEV exceeded 12 (>40-60% mortality) at both South Branch North Fork and Corrigan Creek while SEV 8 (indications of major physiological stress, long-term reduction in feeding rate and feeding success) was the highest level exceeded at Little South Fork with respect to egg and larval stages (model 4).

DISCUSSION

Annual versus Individual Storm Regression

When estimating sediment load, using a best fit relationship of the suspended sediment concentration to turbidity for the entire year can produce considerably different results than using one or several unique relationships for each individual storm event. The ability of suspended sediment - turbidity relationship to change for individual storm events (Peart and Walling 1982, Bogen 1992, Lewis 2002) gives strength to the argument that individual storm regression, especially of the largest storm events, is the most accurate way to estimate sediment load. Methods based on annual regression lack the precision inherent in creating unique relationships for individual storm events and even discrete portions of the hydrograph. Use of annual regression ignores the potential shifting of the relationship of suspended sediment concentration to turbidity, or to other continuously measured parameters such as stage, over the course of a season. This could ultimately lead to significant errors in sediment load estimates if such shifts occur.

Figure 19 is a plot of the suspended sediment concentration against turbidity at Little South Fork Elk River for water year 2004. This plot contains the entire annual data set as well as highlighting selected storm events. It is clear that the suspended sediment – turbidity relationship changed over the course of the year, though the progression was not a consistent one. Use of annual regression of this relationship for storm 7 (12/31/03-1/15/04) predicts a lower suspended sediment concentration for a given turbidity than storm-wise linear regression resulting in a 14 percent lower estimate of the storm load than storm-wise regression (Table 4). Annual regression of storm 13 (2/16 – 2/20/04) predicts a higher suspended sediment concentration for a given turbidity resulting in a 45 percent higher estimate of the storm load than storm-wise linear regression. A 45 percent difference in storm load estimates for this storm is important because storm 13 was the largest storm of the season and contributed one third of the total sediment load at Little South Fork Elk River (Figure 26). The sediment load estimated by annual regression for this event is outside the 95 percent confidence interval calculated by storm-wise linear regression (Table 4). This storm also exhibits considerable hysteresis: The suspended sediment – turbidity relationship shifts between the rising and falling limbs of the hydrograph (Knighton 1998). Use of annual regression for storm 17 (5/17-5/30/04) predicts a much lower suspended sediment concentration for a given turbidity than storm-wise regression, resulting in a 74 percent lower storm load estimate than storm-wise regression. This shows that the trend does not consistently increase or decrease at this station throughout the year.

The same plot of the same storms on Corrigan Creek (Figure 18) shows that the patterns observed at Little South Fork were not consistent at all of the sampling locations. One notable difference is that storm 7 (12/31/03 -1/15/04) showed no appreciable hysteresis at Little South Fork, but showed considerable hysteresis at Corrigan Creek. In addition, the suspended sediment concentration values for a given turbidity were lower on the rising limb of the hydrograph than on the falling limb of the hydrograph which is the opposite of the pattern observed during other storms exhibiting hysteresis in this study. Annual regression for storm 13 (2/16 – 2/20/04), the largest storm of the year at Corrigan Creek, estimated a sediment load that was 15 percent lower than that predicted by storm-wise regression. The sediment load estimated by annual regression for this event is outside the 95 percent confidence interval calculated by storm-wise linear regression (Table 4). Annual regression for storm 17 (5/17 – 5/30/04) predicted a higher storm load than the storm-wise regression. This is in direct contrast to the same storm at Little South Fork where storm-wise regression predicted a much higher load than annual regression for that event.

A similar plot at South Branch North Fork (Figure 20) shows no appreciable hysteresis or deviation from the annual regression for linear plots of the aforementioned storm events. There was no data available for storm 17 (5/17 – 5/30/04), so storm 14 (2/25 – 2/28/04) was plotted instead. At South Branch North Fork there was only one storm event (storm 2, 12/10 – 12/31/03) for which the storm load as predicted by annual regression was outside the 95 percent confidence interval calculated by storm-wise regression. Of the eight storms analyzed, there were three such storms at Corrigan Creek and four at Little South Fork (Table 4).

A potential explanation for the relative lack of agreement between individual storm load estimates based on annual regression and storm-wise regression at Corrigan Creek and Little South Fork Elk River is that the type and size of sediment being transported at these sites experiences greater change over time. The sediment sources that are activated by storms can vary with time and runoff intensity. Different sediment sources can vary greatly in the type of material that they contribute and the timing of delivery to the stream system (Knighton 1998). Plots of percent sand in sediment samples against discharge (Figures 21, 22, 23) have larger ranges and greater variability at Little South Fork Elk River and Corrigan Creek than at South Branch North Fork Elk River. Particle size variations can cause turbidity to vary by a factor of four for the same concentration of suspended solids with larger particles tending to have higher turbidity values for a given suspended sediment concentration (Gippel 1995).

The organic component of the suspended sediment load may also have influenced observed differences in the suspended sediment – turbidity relationship. The organic fraction of the sediment load tends to be higher at lower sediment concentrations (Madej 2005) and organic particles tend to have turbidity values two to three times higher than mineral particles for a given mass (Gippel 1995). Since suspended sediment concentrations were much higher at South Branch North Fork, the suspended sediment – turbidity relationship is less likely to be affected by potential variability associated with the presence of organic sediments. Madej (2005) also observed that the organic portion of the suspended sediment load may be larger in stream systems that have lesser degrees of management. This would help to explain the increasing variability in the suspended sediment – turbidity relationship with a decreasing degree of management that was observed in this study. The organic component of the suspended sediment load was not differentiated in this study. Measurement of the organic content of a subset of the sediment samples analyzed would provide valuable information that may explain observed trends, and is strongly recommended for future sampling protocols.

Individual storm regression helps capture the variability in load composition at the three sites and has the potential to generate more accurate sediment load estimates. The use of storm-wise regressions would also be expected to improve the reliability of the severity of ill effects model evaluations.

Sediment Load Composition

Every sediment sample was divided into two size classes; sands (>0.0635mm) and fines (0.0635mm – 0.001mm). This allowed for separate calculations of a sand load and of a fine load, each based on the same number of observations that were used to calculate the total suspended sediment load (Table 5). The percent of the total load contributed by fine material was similar for the two managed watersheds; 90 percent at South Branch North Fork and 87 percent at Corrigan Creek. Only 75 percent of the total load at Little South Fork was comprised of fine material. These results are consistent with other studies that found higher percent fines present in stream channels associated with an increased extent of logging and roads (Cederholm and Reid 1987, Adams and Beschta 1980) and with increased sediment inputs from timber management (Platts et al. 1989).

The percentage of sand in sediment samples was higher at lower stream discharges (a negative correlation) and showed greater variability at lower discharges at all three sampling locations (Figures 21, 22, 23). Little South Fork Elk River had the greatest variability and the highest sand fractions throughout the range of discharges. Rubin and Topping (2001) concluded that a negative correlation between percent sand and discharge is an indication that sediment transport is regulated mainly by the grain-size of the stream bed sediment; a supply limited system. A positive correlation between percent sand and discharge is associated with a flow regulated system. These findings suggest that Little South Fork Elk River is the most limited by sediment supply and that South Branch North Fork Elk River is the least limited by sediment supply of the three stream systems.

Despite having the lowest percentage of the total sediment load move as sand, South Branch North Fork had the highest total sand yield while Little South Fork had the lowest sand yield (Table 5). The total sand yield from a watershed is important because sands are the component of the suspended sediment load that is most likely to settle out of suspension and contribute to the bed material and to morphological response of the stream channel (Knighton 1998). It is useful to ascertain what component of the suspended sediment load does not settle out of suspension (the wash load) and, in the case of Elk River, is ultimately washed out to the ocean. These are typically very fine particles that have very low settling velocities (Knighton 1998). Surveys of the bed material composition of the low gradient reaches of Elk River would provide information about the size distribution of particles that settle out of suspension. This information could then be used to determine what particle size classes observed at the sampling stations have the greatest potential to affect stream morphology.

Sediment and Flow Regime

Most of the sediment load and flow volume at all three sites were transported during short periods of substantially elevated discharges and most of the time flows were low relative to maximum discharge (Figure 26). This is typical of the sediment and flow regimes of many small, forested watersheds (Rice et al. 1979). Total stream discharge per unit area was highest at South Branch North Fork Elk River and lowest at Little South Fork Elk River (Table 2). This is consistent with studies that have documented increased stream discharge following timber harvest (Bosch and Hewlett 1982, Harr 1980). These effects may be caused by decreases in evapotranspiration, infiltration, and interception leading to increased surface flow and water yield following timber harvest and road construction and tend to decrease as time after management increases (Brooks et al. 1987). The onset of storm events and the timing of peak discharges were nearly simultaneous for all three sites (Figure 24). This suggests that there is little spatial and temporal variability in rainfall in the vicinity of the sampled watersheds and that flow routing in the three watersheds has not been drastically altered by management activities.

Elevated Sediment Duration

Estimates of exceedance times at low suspended sediment concentrations (below 10 mg/l) are not as reliable as estimates at higher concentrations because field measurement errors due to minor fouling, nearby objects (e.g. water surface and channel bed), ambient sunlight, scratched optics, and calibration errors all become more important at low turbidities relative to sampling errors (Personal Communication, J. Lewis 2005.

Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata, CA 95521). The SEV model is based on experimental physiological observations and does not provide direct evidence of adverse effects experienced by aquatic species in the three study streams. It is, however, a useful tool in examining how fish may be affected by varying sediment regimes in natural systems.

The SEV models suggest that adult and juvenile salmonids experienced similar degrees of ill effects due to prolonged exposure to relatively low concentrations of suspended sediment compared to shorter durations of exposure to elevated levels of suspended sediment at the Elk River sites during water year 2004 (Figures 29, 30, 31). Egg and larval stages, however, may have experienced higher degrees of ill effects as a result of prolonged exposure to relatively low suspended sediment concentrations in all three streams (Figures 32, 33, 34).

These trends are dependent on the timing, frequency, and magnitude of storm events and their interaction with available sediment sources. Additional data at these sites will provide more specific information about the dynamics of the sediment regime and the potential adverse effects to aquatic species. This, in turn, will allow resource managers to more effectively develop strategies for fisheries restoration and enhancement.

Sediment Yield

The locations of the sampling stations in this study were selected such that the watersheds above the sampling locations were of similar physiography (for details refer to “Study Site”). Despite their physical similarities, the three watersheds produced very different sediment yields. South Branch North Fork transported 20 times as much material per unit area as Little South Fork did and Corrigan Creek transported 10 times as much material as Little South Fork. Sediment production can increase 2 to 50 times after timber harvest and road building occur, but typically recovers to less than 5 times above background after 5 years and to less than twice background after 10 years (Reid 1993, Lewis 1998, Keppeler et al. 2003). If we interpret the sediment yield from the Little South Fork to represent an approximate background level for the given physiographic conditions, then continuation of the observed trends for several years would suggest that there is a delay in the recovery of the other two watersheds from their respective disturbances.

One possible explanation for a delay in recovery is that sediment sources activated by disturbance during management activities continue to contribute sediment to these systems. Sediment sources that have the potential to contribute sediment to these stream systems include mass wasting (landslides and debris flows), stream bank erosion, channel erosion, stream crossing failures, and surface erosion (mostly in the form of runoff from roads and areas compacted by management activities).

Roads have the potential to contribute large amounts of sediment to streams. Roads can contribute 50-80% of sediment that enters streams (Hagans et al. 1986) and the amount of sediment delivered to streams from forests with roads can be 300 times greater than the amount of sediment delivered from undisturbed forests (Morrison 1975).

A common technique used to appreciate the potential for sediment contribution from road systems is to measure the density of roads in a watershed within 200 feet of a stream. Roads in these locations have the greatest potential to contribute sediment to the stream system (Watershed Professionals Network 1999). Figure 35 shows mapped road and stream locations in the three watersheds (Hart - Crowser 2004). An analysis of the watersheds upstream of the sediment sampling sites shows that South Branch North Fork has the highest density of roads per unit area with 4.00 km/km^2. Corrigan Creek has 3.40 km/km^2 and Little South Fork has 0.75 km/km^2 of roads. Corrigan Creek, however, has the highest density of roads within 200 feet of a stream with 1.34 km/km^2. South Branch North Fork has a density of 0.99 km/km^2, and Little South Fork has 0.22 km/km^2 of roads within 200 feet of a stream.

Another useful tool in evaluating the potential for sediment contribution in a watershed is to look at the amount of area in a watershed with a high potential for landslides. SHALSTAB is a program that evaluates the risk for shallow, infinite-slope type landslides based on factors including slope angle, drainage area, and convergence of water (Dietrich et al. 1995). SHALSTAB modeling suggests that Corrigan Creek has the highest potential for these types of landslides; 32 percent of the area within the watershed of the sampling station is classified as unstable. In the South Branch North Fork and Little South Fork watersheds, 22 percent and 13 percent of the areas respectively, were classified as unstable.

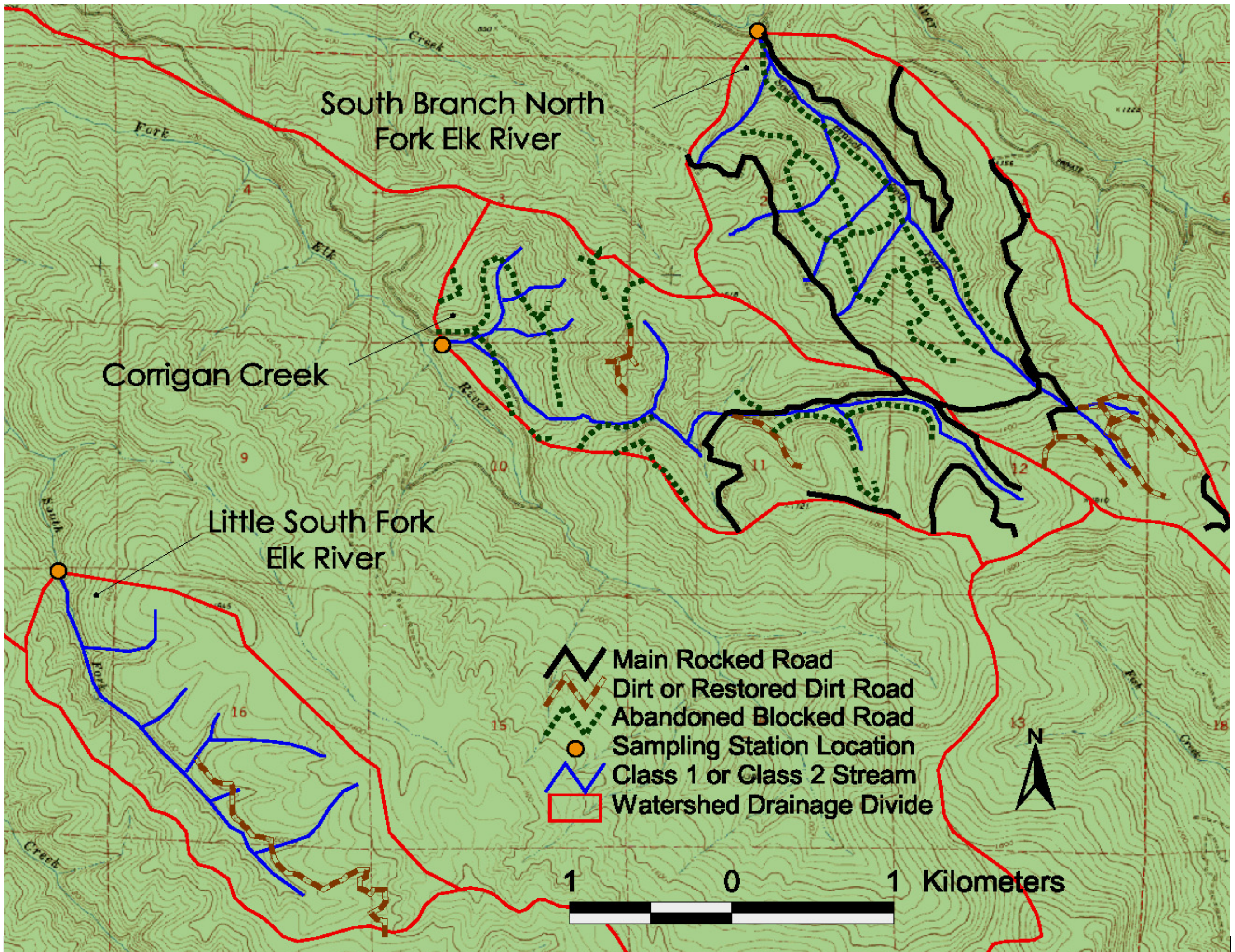

Figure 35. Mapped road locations in the Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River watersheds.

Trends in the SHALSTAB predictions rank the watersheds consistently with a mapping of actual shallow landslides conducted by Pacific Watershed Associates (Hart - Crowser 2004). Their landslide map shows 32 landslides in the Corrigan Creek watershed, of which 23 were classified as delivering sediment to the stream system. The South Branch North Fork watershed contains 12 mapped landslides with 7 delivering sediment to streams, and Little South Fork has 6 mapped landslides with 5 delivering sediment to streams.

The potential for shallow landslide activity, the actual number of shallow landslides contributing sediment to the stream system, and the amount of roads near streams all suggest that Corrigan Creek should have the highest sediment yield of the three sampled watersheds. The fact that the sediment yield at South Branch North Fork was double that at Corrigan Creek suggests that other sediment generating mechanisms are more important in determining sediment yield in these systems than roads near streams or shallow landslides.

Stream crossings can contain large amounts of stored material in locations that are directly connected stream channels. A single stream crossing can contain hundreds of cubic yards of sediment. Poorly designed, undersized, or unmaintained stream crossings are prone to failure during large runoff events potentially resulting in direct delivery of large volumes of sediment to streams (Weaver and Hagans 1994). Analysis of the available road maps (Hart – Crowser 2004) shows that the South Branch North Fork Elk River watershed has 16 stream crossings whereas the Corrigan Creek watershed has only

8 stream crossings. Little South Fork Elk River had 3 stream crossings, but these were decommissioned and all associated fill material was removed in 2003 eliminating the potential for large-scale, future sediment inputs from these areas.

Information about the size and condition of the shallow landslides, stream crossings, and roads near streams was unavailable and not examined. This information could provide insight into how these factors contribute to the observed sediment yields. Other sediment generating sources such as deep seated landslides, channel erosion, stream bank erosion, and surface runoff from compacted areas other than roads could also be contributing substantial amounts of sediment and should be evaluated. A field inventory of the size and contribution of actual sediment sources is the most effective way to gain an understanding of what sources are contributing large amounts of sediment to the stream system. With such information, one can more effectively create a strategy for mitigating sediment inputs and restoring watershed processes.

CONCLUSION

This study has shown that sediment yields from watersheds of similar size and physiography can vary widely. Management of these watersheds likely plays a large role in influencing these yields. Even after more than a decade since the most recent management activities, annual sediment yields varied by as much as a factor of 20.

Sediment yield data for the three streams from water year 2004 establishes points of reference against which recovery from management and response to future management activities can be evaluated. Though the sample period was average in terms of total rainfall, several years of additional data will be needed to observe how the sediment flux in these watersheds responds to annual climatic variations. Large annual variations in sediment yield for individual stream systems have been documented (Van Sickle 1981) and show the need for gathering multiple years of data in order to represent accurate long term averages.

Ultimately, it will be important to compare the sediment flux in these watersheds with other watersheds of varying size, physiography, and land-use history. Such an analysis would help to clarify how these factors interact to influence the dynamics of sediment storage and movement. This will provide land managers with an important understanding of watershed processes that is needed to make well informed policy and management decisions.

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