Abstract

Cumulative watershed effects (CWEs) result from the overlapping effects of management activities in time or space. The routing and downstream accumulation of sediment from forest management activities is of particular concern because it directly affects key aquatic resources, and these sedimentary CWEs are often the most severe constraints on forest management activities. The prediction and detection of sedimentary CWEs is particularly difficult because of the complex interactions among temporal scale, spatial scale, and measurement uncertainty. The goal of this project was to evaluate the extent to which sedimentary CWEs are dependent on the spatial scale of the analysis. In reality, the effects of spatial scale cannot be separated from the temporal scale or measurement uncertainty. Thus this report evaluates each of these factors as a guide to developing more effective monitoring programs, improving the predictability of sedimentary CWEs, and identifying avenues for future research.

Temporal scale considerations range from the short-term variability of sediment transport rates to the variability in annual sediment loads within a single basin. Short-term fluctuations in bedload transport rates commonly extend over one order of magnitude, and high-intensity sequential samples had an average coefficient of variation of 79% for near constant flow, and 95% when samples were taken during a high flow event. An analysis of existing data indicated that 13-95% of the variation in sediment transport rates could be explained by discharge.

At the interannual scale, the coefficient of variation for annual sediment loads is typically at least 70-100%. There was a weak tendency for the interannual variability to increase with increasing annual sediment yields, but there was no indication that interannual variability decreased with increasing basin size. The distribution of annual sediment yields tended to be lognormal, although basins with lower annual sediment yields were often normally distributed. Given this variability, almost a decade of measurements are needed to determine the annual sediment yield to within 100% of the true value at the 95% confidence level.

The effects of spatial scale range from the variability in sediment loads within a cross-section, to the variation in the amount of sediment transport along a downstream gradient, and the interbasin variability in annual sediment loads. Temporal and spatial scales are not easily separated, and a knowledge of both spatial and temporal variability is necessary to efficiently allocate sampling effort. The short-term and small-scale variability problems tend to be more severe for bedload transport than suspended sediment.

Spatial scale issues are particularly important in terms of the downstream delivery of sediment and the reliability of interbasin comparisons. Sediment delivery ratios are not appropriate for routing different-sized particles through a sequence of varying stream types. An analysis of tracer data suggested that mean annual transport distances increase with gradient in braided or aggrading streams, but decline with gradient in steep, hydraulically-rough streams. Although there are a series of problems with extrapolating from tracer studies, typical annual transport distances are estimated to be approximately 10, 2, and 0.1 km for suspended sediment, sand, and coarse particles, respectively. These rates indicate that there will often be a substantial lag in the occurrence of a sedimentary CWE, and the timing and location of a sedimentary CWE is highly dependent on key factors such as the particle size of the sediment being introduced, the sequence of stream types, and the sedimentary state of the streams through which the sediment must pass.

A series of interbasin comparisons indicated considerable variability in the strength of the correlation in annual sediment yields between adjacent undisturbed basins. Of particular concern was the observation that a slight shift in the years of comparison could greatly alter the strength and slope of the relationship between basins. This instability also extended to the relationship between various flow parameters (e.g., annual water yield) and annual sediment yields on a given basin.

The uncertainty in detecting sedimentary CWEs is further compounded by the problems of accurately measuring sediment transport rates over a range of temporal scales. Since any sampler disturbs the flow lines in the stream, there is an inherent bias in the data and this varies as a function of particle size. Since we typically sample much less than one percent of the possible samples in time and space, sediment yield estimates require considerable extrapolation. Both summation and rating curve techniques are subject to bias, and a change in the calculation or bias-adjustment procedure can alter the estimated sediment yields by more than a factor of two. Unfortunately, sediment transport equations are even less accurate, and calculated sediment transport rates extremely sensitive to which equation is used and the value of the key input parameters.

Taken together, these factors suggest that we should not expect to detect less than a twofold change in sediment transport rates or sediment yields. Changes in measurement techniques, calculation procedures, or the period of comparison can create the appearance of a sedimentary CWE when none actually exists. The inherent spatial and temporal variability suggests that at least 5-10 years of both pre- and post-monitoring are likely to be necessary to reliably detect a sedimentary CWE. Since management decisions often cannot be delayed and longer-term monitoring projects cannot be implemented on all reaches of concern, alternative approaches are necessary. A geomorphic analysis of the current sedimentary state of the stream network is an essential first step towards any CWE analysis or monitoring effort. Modified sediment delivery ratios can be developed by considering, at a minimum, the sizes of the particles being introduced, as well as the sequence and condition of stream types. This basin-specific understanding is essential for determining the appropriate temporal and spatial scales for analysis and monitoring. A universal sedimentary CWE model is simply not realistic given the diversity and complexity of sediment production, transport, and delivery processes.

Part D: Conclusions and Recommendations

1. The issue of spatial scale in sedimentary cumulative watershed effects

Cumulative watershed effects (CWEs) arise from the overlapping effects of management activities in time or in space. Although CWEs can be expressed in terms of runoff, nutrients, temperature, or other parameters important for aquatic ecosystems, we focussed on sediment because this is critical to several designated uses and often the limiting constraint on forest management activities. The basic precept behind this project was that the detectability of a sedimentary CWE is controlled by the variability across a range of temporal scales, measurement uncertainty, the storage and dilution of the constituents of concern, and the magnitude and duration of the changes induced by management activities.

Both temporal and spatial scales affect the occurrence and detectability of CWEs (Bunte and MacDonald 1995). For example, the short-term temporal variability controls the uncertainty associated with a given measurement, while the interannual variability in annual sediment loads governs the magnitude of change that can be detected within a given time period. Similarly, spatial scale issues range from the variability in sediment transport across a stream cross-section to the basin-scale decline in sediment delivery with increasing area and the variability in annual sediment loads between adjacent basins. The principal focus of this report has been on the extent to which potential increases in sediment load from forest management activities can be transported downstream, our ability to detect these changes, and the extent to which these cumulative effects are scale dependent.

This issue of spatial scaling is intuitively obvious for the extreme cases, but has only recently been explicitly addressed in state and federal documents to guide cumulative effects analyses. Both the USFS and the State of Washington procedures (Ecosystem Analysis at the Watershed Scale, 1995; Washington Forest Practices Board, 1992) suggest that the appropriate spatial scale for watershed analysis is 20-200 square miles (50-500 square kilometers), and this range was derived at least in part from the hydrologic considerations set out in Harr (1989). However, it is not necessarily true that this scale is most appropriate for sedimentary cumulative effects.

Of particular concern is the fact that sediment is not transported downstream with the water unless we assume perfect suspension. In contrast to discharge, management-induced inputs of sediment are much more subject to storage in or adjacent to the channel. Scale considerations for sedimentary cumulative effects are also complicated because changes in flow can increase the amount of sediment, sediment is much more difficult to measure than discharge, and the downstream transport of sediment is dependent on numerous factors such as the particle size of the introduced sediment, stream gradient, degree of confinement, bed characteristics, available storage, and the magnitude, duration, and frequency of high flows. The likelihood of cumulative sedimentary effects will also be highly dependent on the current condition and budgetary state of the stream, and thus the effect of management activities cannot be considered in isolation from the natural processes and long-term geomorphic context in the basin of interest.

The mechanistic approach that can be applied to hydrologic cumulative effects is also of limited applicability for sedimentary cumulative effects because the timing of sediment inputs are often much more persistent and complex with regard to time. Again the particle size of the introduced sediment will combine with the pattern of discharge, the stream channel characteristics, and the overall sedimentary state of the basin to create a relatively unique and somewhat unpredictable downstream response. Thus certain aspects of the scale problem can be generalized, but the relevant spatial scale for analyzing cumulative watershed effects is a unique function of the basin under consideration, the issues of primary concern, and the extent to which a particular effect needs to be documented rather than presumed. It should be obvious, for example, that the construction of roads and forest harvest on several small watershed in the upper reaches of the Mississippi Valley will not be detectable in Minneapolis much less in New Orleans or St. Louis, but that some--presumably quite small--proportion of the introduced sand will eventually be transmitted downstream and contribute to the building of the Mississippi delta in the same way as every other natural and anthropogenic sediment source.

2. Detectability of CWEs

From a forest management perspective, the question is whether a specific set of activities can lead to a detectable change in sediment transport rates, stream channel condition, or the designated beneficial uses. From a regulatory perspective, the absence of explicit standards for many variables, such as the bed material particle size or stream channel condition, leads to the difficult problem of translating some physical measurement of the channel into an adverse effect on one or more designated beneficial uses. While these issues are beyond the scope of this report, they ultimately affect the extent to which one should attempt to detect a sedimentary cumulative effect, where one might look for such effects, and what changes are of principal concern. Again there will be different levels of concern associated with the input of sediment into particular water bodies, such as Lake Tahoe or Crater Lake, as compared to a small steep stream that may empty directly into the Pacific Ocean.

3. Measurement uncertainty

If one accepts that we wish to detect either a measurable increase in the sediment load or the effects thereof, then one first has to address the issue of measurement uncertainty. The first chapter of this report documented the large temporal fluctuations in sediment transport rates at several scales. Short-term fluctuations in bedload transport rates (e.g., on the order of seconds to a few hours) at a relatively constant discharge typically extend over one order of magnitude. These short-term fluctuations are associated with a variety of physical processes, including the passage of bedforms, local turbulence, selective transport, the interaction of particles on the bed of the stream, and sudden events such as bank collapse or the movement of a piece of large woody debris. The net result is that these fluctuations are largely unpredictable, and one either has to capture this variability through intensive sampling or accept the fact that a single sample has a very high degree of uncertainty with regard to its representativeness of the mean transport rate. These short-term fluctuations in sediment transport rates are generally several times greater for bedload transport than for suspended sediment.

Measurement of bedload transport in both flumes and streams suggest that high-intensity, sequential sampling tends to produce a lognormal distribution. Typical coefficients of variation during periods of constant discharge are 55-100%. This means that 12-40 samples are required to be 95% certain that the estimated mean is within a factor of two of the true mean.

Fluctuations in sediment transport rates will also occur over the time scale at which changes in discharge are apparent. Unfortunately discharge is not necessarily a good predictor of sediment transport rates, as our review of intensively sampled high flows indicated that discharge accounted for 13-85% of the observed variability in bedload transport rates. This variability in discharge-sediment transport relationships is due to a variety of physical processes such as sediment exhaustion, changing inputs of sediment from tributaries, and sudden events such as the break-up of the armor layer, bank erosion, or the movement of large woody debris. A clockwise hysteresis loop between a storm hydrograph and sediment transport rates cannot be assumed, and thus the separation of a sediment rating curve into rising and falling limbs may not significantly improve the predictability of either bedload or suspended sediment transport rates. Other studies have shown that there may also be a seasonal dependence in sediment supply and sediment transport rates as a result of different types of storm events, the resulting variations in runoff processes, and seasonal variations in erodibility and erosion processes.

For any given flow sediment transport rates can be expected to vary by 1-2 orders of magnitude. Typical coefficients of variation for sediment transport rates during high flows for a single event are around 90-110%, and these increase to around 150% for high flows over a single snowmelt high flow. The relatively small increases in the coefficient of variation over changing discharges again suggest that smaller changes in discharge (e.g., a factor of two) are not well correlated with changes in sediment transport rates. Thus the sampling of sediment transport rates is constantly subject to the trade-off between costly and intensive sampling to better characterize the mean, or less intensive measurements with a correspondingly higher degree of uncertainty. The limited data also suggest that an increasing grain size is associated with a higher variability in bedload transport rates.

The measurement of sediment transport rates is also complicated by the corresponding and interacting spatial variability. Over the short-term one has to account for the variation in sediment transport rates across the cross-section and, in the case of suspended sediment, in the vertical dimension. Generalizations about the magnitude and distribution of cross-sectional variability are difficult, and different authors suggest quite different allocations of bedload sampling effort to account for the short-term temporal variability vis-a-vis the spatial variability across the cross-section. Is it better to have 10 replicate samples at just four cross-section locations or just two replicate samples at 20 locations? One can optimize sampling effort to minimize the uncertainty in the total estimated bedload transport rate, but this requires a knowledge of both the short-term temporal variability and the variability across the cross-section. Our literature review and analyses suggest the short-term variability is so severe in single-thread channels that it is probably better to repetitively sample fewer locations than to sample more locations with a lower intensity. It should be noted that this generalization is more likely to be true for coarse-bedded mountain streams than low-gradient, fine-bedded streams with a high width-depth ratio. Again the cross-sectional variability is greatly reduced for suspended sediment, but the variation with depth must be accounted for by depth-integrated sampling if one wishes to estimate actual sediment loads.

At a slightly larger spatial scale, there may be some variation in measured sediment transport rates according to the location of the sampling cross-section relative to the local bedforms. Sediment transport rates will differ between pools and riffles, and this difference can be expected to change with changing discharge. On the reach scale, sediment transport rates will vary if the upstream reaches are either aggrading or degrading. This means the selection of a sampling location requires a basic understanding of the existing sedimentary state of the stream with regard to the material to be sampled (bedload or suspended load), the particle size of the incoming sediment, and the transport capacity of the intervening stream reaches.

Another critical component of measurement uncertainty is simply the intensity and the accuracy of the sampling techniques. We defined sampling intensity as the proportion of the channel sampled times the proportion of time that sampling actually took place over the period of interest. One hour per week of actual sampling time with a 7.5-cm Helley-Smith in a 5-m wide stream equates to a sampling intensity of 0.036%, or a little more than one-three thousandth of the samples that would be taken by continuous sampling across the entire cross-section over a one-week period. The point is that most typical field sampling regimes require very high levels of extrapolation to estimate total sediment loads. This extrapolation is further hindered by the fact that high flows rarely occur at times that are conducive to sampling. Peak daily runoff in snowmelt-dominated basins typically occurs in the evening or at night, depending on the size of the basin. The timing of mean daily transport rates is both unpredictable and inconsistent, and this again indicates that a relatively intensive sampling regime is necessary to accurately estimate sediment transport rates for a specific period of time (e.g., daily) or a specific discharge.

The accuracy of an individual sample is typically defined by the sampling efficiency. A sampling efficiency of one means that the sampler captured exactly the same mass of sediment that would have passed through the sampling location had the sampler not been there. In reality, the definition of sampling efficiency should be strengthened by specifying that the sample should also have a similar grain-size distribution, as different-sized particles have different likelihoods for being sampled. This is important because different particle sizes have varying implications for channel morphology and aquatic life.

Since all samplers disturb the flow lines, an efficiency of 100% is not possible. Sampling efficiency will vary with the velocity profile in front of the sampler, the particle sizes being sampled, and the characteristics of the sample reservoir or net. The choice of samplers, sampling duration, and sampling location is a compromise between competing objectives. Pressure-difference samplers, such as a Helley-Smith bedload sampler, tend to oversample smaller (<8 mm) particles and undersample larger (>11 mm) particles. Use of a larger (e.g., 15 x 15 cm) bedload sampler will generally increase the oversampling of smaller particles to better capture the larger particles, but the mechanics of using a larger sampler at high flows means that the measured sediment loads may not be very accurate. The use of any bedload sampler under high flow conditions is very difficult, as it is almost impossible to control the exact placement of the sampler. The problems of scooping, stirring, and misalignment are particularly difficult for bedload samplers in coarse-bottomed streams. Several studies have developed calibration factors for specific particle sizes under specific conditions, but there is not a comprehensive set of calibrations that might be used to correct data from a variety of stream types and flow conditions by sampler and particle size. The placement and use of log or concrete sills is recommended for more accurate bedload sampling in streams.

The limitations of measuring suspended sediment are not quite as severe as measuring bedload, but standard techniques result in an unsampled zone immediate above the bottom of the stream where concentrations are expected to be at a maximum. Pump samplers only sample one point in space, and the hydraulics of pumping distort the flow lines and therefore produce an unrepresentative sample with regard to particle size and possibly also concentration.

The net result is that all sediment samples are really an index of sediment transport, and we can only crudely estimate the likely errors. In practical terms, this means that a change in measurement techniques can have a substantial effect on the estimate sediment load, and a "cumulative watershed effect" could be created by simply shifting from a 7.5- to a 15-cm Helley-Smith, or from depth-integrating to point sampler. Sediment ponds may be the most practical means to obtain an accurate estimate of sediment transport rates, but these raise questions of cost, stream channel disturbance, and what to do with the captured sediment.

4. Determination of annual sediment loads

A final component of measurement uncertainty is the integration and extrapolation from individual measurements to estimates of total loads over time. Sediment rating curves (using discharge to predict sediment transport rates) are a common approach, but measured sediment transport rates typically range over two orders of magnitude for a given discharge. The use of a log-log scale for sediment rating curves often leads to a substantial underestimate of sediment transport rates because interpolation between log values produces a geometric mean, while interpolation between antilogged values yields the more accurate and higher arithmetic mean. Incorporating a bias correction factor for a sediment rating curve based on weekly samples will usually increase the estimated annual sediment load by several times.

The reliability of a sediment rating curve is highly dependent on the extent to which sediment transport is directly related to hydraulic factors. Thus sediment rating curves tend to be most effective for bedload transport in sand-bedded streams, and are less appropriate in situations where the entrainment of particles is not readily predictable and sediment transport rates are highly dependent on sediment inputs from outside the immediate channel. Sediment rating curves are generally improved by incorporating a wider range of data, averaging over longer time periods, and increasing the sample size.

Sediment rating curves and estimated sediment yields are particularly sensitive to the number and value of high flow samples. Increasing the number of high flow samples will typically result in more consistent sediment rating curves, higher coefficients of determination, higher estimates of sediment loads, and estimated sediment loads that are closer to the true value.

Meade et al. (1990) estimated an average error of about 50% for annual sediment loads derived from suspended sediment rating curves. Sediment rating curves for bedload transport will typically explain around 50% of the variation in bedload transport rates, but one should also expect that in smaller basins the coefficient of determination (r^2) may well be less than 25%. A number of studies have also indicated that sediment rating curves can exhibit considerable seasonal and interannual variation. A change in the sediment rating curve is often, but not necessarily, associated with a change in sediment supply. Changes in sediment rating curves must be explicitly considered in any effort to detect sedimentary CWEs, and this implies a continuing and moderately-intensive sampling regime.

Summation procedures are an alternative to sediment rating curves, and these estimate total sediment loads by multiplying each sediment transport measurement by the time represented by that measurement, and summing these values for the desired time period. Summation procedures are most effective if sediment transport data are available every 1-2 days, and in such cases the summation procedure may provide a more accurate estimate of total sediment loads than a rating curve. Ketcheson (1986) found that using the summation procedure for samples taken every other day had similar errors to the more common rating curve technique; in both cases the estimates were within 50% of the true value in 75% of the years.

On the other hand, the use of a summation procedure for weekly samples can underestimate annual sediment loads by a factor of two or more. The process by which data are averaged and then summed can also greatly affect the estimated annual sediment load (Walling and

Webb 1981; 1988; Walling et al. 1992). With regard to scale, one would expect the summation procedure to be more accurate in larger basins where the changes in discharge are more gradual, but we could not find any explicit consideration of this factor in the literature. A separate analysis of this issue, using data sets from basins of varying size in different geomorphic regions, would be of interest.

5. Interannual and interbasin variability in sediment loads

The final scale of temporal and spatial variability considered in this report is the interannual and interbasin variation in annual sediment loads. A high degree of interannual variability would suggest that long measurement periods would be needed to detect all but the largest changes in annual sediment loads, while a high interbasin variability would call into question the validity of comparisons between disturbed and undisturbed basins (e.g., a paired catchment approach). An analysis of 37 data sets with 11-35 years of data indicated that the typical coefficient of variation for annual sediment loads was 70-130%, while the range was from 38 to 467%. The variability in annual sediment loads for undisturbed watersheds tended to be slightly larger for basins in the Pacific Northwest than for basins in Colorado or the northeastern U.S. There was a weak trend towards increasing variability with increasing sediment loads ($r^2=0.24$), but there appears to be no significant relationship between basin size and the relative variability of annual sediment yields. This means that despite the tendency for sediment yields to diminish in the downstream direction, we cannot expect a downstream reduction in interannual variability as originally hypothesized.

Annual sediment yields tended to be normally distributed in basins with a low coefficient of variation (CV), while basins with higher CVs tended to have a lognormal distribution of annual sediment yields. Although there is a wide range of variability, approximately a decade of monitoring is needed to estimate average annual sediment yields to within 50% of their true value at the 95% confidence level, while 3-7 years may suffice to estimate the annual sediment load to within a factor of two. Given a typical CV of approximately 100%, approximately 15 years of pre- and post-disturbance monitoring would be required to detect a twofold change in annual sediment yields at a 95% confidence level. We also found a wide variability in the strengths of the relationship between various flow parameters (e.g., maximum annual flows, annual water yield, or duration of a given flow) and annual sediment yields.

The various data sets also showed a relatively high interbasin variability, even within a single experimental forest. In some cases the measured sediment loads on one undisturbed basin explained less than 10% of the variability in annual sediment loads on an adjacent, theoretically paired, undisturbed basin. Depending on the hydrological and sedimentological conditions of the basin, the interbasin predictability may be better or worse for wetter periods as compared to drier periods. In many cases the strength of the relationship, as indicated by the r^2 value, can change quite dramatically with a shift in the time period being compared, or even with the addition or exclusion of a single year. At the Fraser Experimental Forest, for example, the r^2 between two undisturbed catchments (East St. Louis and Lexen Creeks) dropped from 0.65 to 0.12 if the seven-year period of comparison was extended by one year. The implication is that the relationship between paired basins can change quite dramatically depending on the time period selected for calibration. Thus a relative decrease in sediment from a paired basin should not automatically be attributed to the initiation of additional management activities, nor should a decrease be automatically attributed to restoration activities or natural recovery.

A comparison of sediment yields from managed and unmanaged basins indicates that forest management activities have increased mean annual sediment yields by 7-200%, but this does not necessarily mean that there is a concomitant increase in the variability of the annual sediment loads in managed basins. In many cases the range in annual sediment yields in undisturbed basins was comparable to the range of annual sediment yields following forest management activities. Several other studies have also noted a lack of significant change in the mean or variability of annual sediment loads following the initiation of forest management activities.

The detectability of a change in annual sediment loads may be further hampered by the timing and duration of the increase in sediment loads due to management. Some data sets from smaller basins show a several-year lag between management activities and an apparent increase in sediment yields, while in other cases there was a sudden increase and then a relatively rapid decline in annual sediment yields as the catchment "recovered". The timing and duration of an increase in sediment yields is highly dependent on the source of the sediment, the delivery of this sediment to the stream channel, and the delivery of this sediment to the monitoring location. For example, a change in sediment yields due to a decrease in root strength and an increase in mass movements might not be expressed for more than a decade, whereas much of the fine sediment from roads or bank erosion would be generated in the year of construction and might be rapidly routed into and through the stream channel. Similarly, a slug of sediment that is introduced in one reach may take years or decades to reach the monitoring location. Thus the observed change in the mean and variability of annual sediment yields will be highly dependent on the timing of the sediment being generated and the routing of the sediment through the stream system. Both temporal and spatial scales come into play because the change in the mean and variability will be an interacting function of the monitoring location and the length of the post-disturbance period chosen for analysis.

6. Downstream travel velocity

The amount and rate of downstream sediment transport is critical to the prediction and efficient detection of sedimentary CWEs. In a given basin sedimentary CWEs could appear in different locations and at different times depending on the particle sizes being evaluated. Sediment delivery ratios (SDRs) are usually assigned solely as a function of basin area. Thus the implicit assumption in applying SDRs is that there is a general homogeneity in terms of geomorphic processes and climatic conditions within the basin. SDRs have been derived primarily from agricultural areas and for smaller particle sizes, and the application of such SDRs to topographically diverse and geomorphically complex basins is highly questionable. The reality is that SDRs have been shown to vary widely within a basin, between seasons, among years, and especially among basins. At present there is a large gap between the oversimplified approach of delivery ratios and more complex physically-based models, and there may be some potential to develop more specific SDRs for certain combinations of sediment sources, sediment sizes, and stream types.

Conceptually we know that the downstream transport of sediment is largely a function of the size of the introduced sediment, the mode of transport (i.e., bedload or suspended load) the energy available (which itself is primarily a function of discharge, slope, depth, and velocity), the amount of available sediment, and stream type. The problem is that our physically-based models can't accurately predict sediment transport rates unless they have been explicitly calibrated to the situation of interest, and they require more data and effort than most land management agencies are prepared to invest. Modifying sediment delivery ratios according to some of the key factors controlling sediment transport may provide an intermediate level of analysis that would be both practical and more realistic in terms of predicting sedimentary CWEs. We might expect, for example, that specific grain-size distributions can be associated with particular erosional processes. A simple mapping of stream types or even stream gradients can be used to indicate the likely rate of travel and accumulation. By also considering the existing sedimentary state of the stream network (i.e., aggrading, degrading, or in quasi-equilibrium), a relatively simple model could be developed to predict downstream sedimentary CWEs.

For suspended sediment we can't assume that the delivery ratio will simply be 1.0. Deposition will occur, particularly in lower-velocity areas such as overbank flows, side channels and backwater eddies. Fine sediment may also infiltrate into the streambed if there are sufficiently large interparticle pore spaces and the bed material is not in motion. Although the deposition of fine sediment will not be solely a function of basin area, SDRs may be a useful first step towards predicting the downstream transport of suspended sediment. Results from a simple watershed-scale model suggest that, depending on the detection limit an increase in suspended sediment loads may be more detectable when this is superimposed on "dirty water" than clean water.

The section reviewed and analyzed the travel rates of different-sized particles in various stream types. Approximately forty individual studies were identified that had traced the downstream movement of particles over time. These studies indicate that the downstream dispersal of tracer particles generally follows a Poisson process, and the resulting spatial distribution is described by either a gamma or a negative exponential distribution. These patterns are consistent with the precept set forth in the first chapter on sediment transport processes, namely that individual particles are mostly at rest with only occasional periods of movement. Mean transport rates are not necessarily a valid indicator of sediment transport or an appropriate means to predict sedimentary CWEs, as a few particles may travel a great distance while the vast majority of particles travel only a short distance. Transport distance was found to be partly a function of particle shape, with disk-shaped particles traveling only about one-third as far as ellipsoids, spheres, or rod-shaped particles of the same mass and density.

One would also expect transport distance to increase with decreasing particle size, but this was not always the case. The equal mobility concept suggests that when the entire bed is in motion, bedload particles should move at approximately the same rate regardless of size, and this was observed in some of the tracer studies. On the other hand, if sediment transport is selective, the smaller particles should be more easily entrained and exhibit a correspondingly greater travel distance per unit time. Overall, the smaller grain sizes did tend to have a greater travel distance per unit time than the larger particles, although the relative difference varied according to stream type, the type of flow event(s), and the grain sizes being compared.

Our analysis also indicated that the hydraulic roughness of the stream bed is an important control on the rate of downstream particle movement. In streams with a wide distribution of particle sizes, the smaller particles may be trapped or hidden by the larger particles. Bedload particles generally seem to be transported further in hydraulically-smooth streams as compared to steep step-pool or cascade channels, despite the greater amounts of energy being dissipated in the latter. There is also an interaction between gradient and hydraulic roughness, as the data indicate that travel distances generally increase with increasing gradient in braided and aggrading streams, but decreased with gradient in streams that were characterized as hydraulically rough. This latter result is somewhat surprising, as it suggests that the average annual travel distance for bedload may be smaller in steep headwater streams than in some of the lower-gradient, higher-order "response" reaches. If these results are confirmed by future tracer studies, the implication is that sedimentary CWEs might occur higher in the basin and be more persistent than commonly believed. On the other hand, this decrease in travel distance with gradient in hydraulically rough streams probably does not apply to the finer particle sizes. The problem is that there are very few data on travel rates for small particles in steep mountain streams.

Efforts to determine "average" annual transport distance by particle size were hampered by several limitations of the compiled data sets. First, most tracer experiments were conducted over relatively short time periods. Extrapolation to average annual travel distances would require detailed information on the average number, magnitude, and duration of high flow events, but this information was generally not readily available. Such extrapolations would also implicitly assume that travel distances are highly correlated with discharge and that the observed travel velocities were representative. In reality, many studies had relatively low tracer recovery rates, and it is likely that most of the unrecovered particles were buried within the bed or other sediment storage locations. Particles still in an active transport phase were more likely to be recovered, and this bias in recovery would tend to increase the average estimated travel distance. Similarly, the placement of particles on the bed surface increases their likelihood of entrainment, and the few studies with more frequent measurements did suggest a decline in transport distance over time. Thus there is an inherent bias in the reported average transport distances, and a more accurate estimate of average annual transport distances would need to account for the proportions of particles in storage versus the proportion of particles on the surface of the stream bed and thus readily available for entrainment and downstream transport.

Although these limitations in the data could not be fully resolved, we nevertheless estimated the range and mean of annual travel distances (in kilometers per year) as follows:

Particle Size and Stream Type	Range	Mean
Suspended sediment in mountain streams	2 - 20	10
Sand as the predominant bedload	0.5 - 5	2
Pebbles and cobbles in mountain streams	0.02 - 0.5	0.1
Gravels in braided streams	0.02 - 5	

7. Detecting a sedimentary cumulative watershed effect

These rates of particle movement can be used as a first, crude estimate of the likely arrival of sediment waves originating from upstream source areas. This type of estimate can then help indicate where one might initiate a monitoring effort, and the time period that might be necessary to detect the initiation and passage of one or more sediment inputs. Clearly a much longer monitoring period will be needed for coarser particles and to document a return to pre-disturbance conditions or background levels with respect to sediment transport rates.

The extended lags in producing and delivering sediment to the monitoring location means that the true extent of the change in sediment loads can only be evaluated after all the directly and indirectly mobilized material has passed the monitoring location. Because this will usually require an extended period of monitoring, the results of such studies will be of more use in guiding future activities than for adjusting management on the basin being monitored.

Given the difficulties in making accurate measurements and the tremendous natural variability across a range of spatial and temporal scales, a more immediate feedback to adaptive management may be better provided by geomorphological field assessments. Such assessments may be criticized as subjective and highly dependent on the paradigm of the observer, but these objections can be largely overcome in controversial situations by relying on the consensus of several observers, each of whom is familiar with the landscape and geomorphic processes in the area. A variety of supporting data can also be utilized, and this might include quantitative assessments of key channel characteristics or, if available, plots of data collected to date (e.g., cumulative sediment yields or stream channel characteristics). these data, when combined with data from comparable basins, can then help determine how the stream has evolved to its present condition, and hence how it might be expected to respond in the future to a given set of sediment inputs.

If our short- and long-term objectives are to protect and enhance aquatic resources, then we clearly will have to rely on current assessments and relatively crude predictive tools. We acknowledge and have tried to point out the key issues with regard to measuring sedimentary CWEs, and that the complexity of stream-sediment issues poses severe challenges to the development of any rigorous, quantitative, and reliable predictive technique. Land management decisions can rarely wait until we have collected the necessary long-term data to define a trend or a change at the 90 or 95% confidence level. A universal sedimentary CWE model is simply not realistic given the diversity and complexity of sediment production and transport processes.

In effect we see two paths into the future. The first is continuing research to improve our understanding, and this must encompass shorter-term process studies and longer-term studies to better understand rates and variability. The other path is to conduct better quality, shorter-term assessments to provide immediate guidance to resource managers. In terms of aquatic resource management, both paths will lead to failure unless there is close interaction between each set of activities. We must also recognize the limitations of our efforts, as we will never have perfect, universal tools for prediction and analysis, and our imperfect short-term decisions will have longer-term implications for the health of our aquatic resources.