Suspended Sediment, Turbidity, and Organic Debris in a Belt Series Watershed of Western Montana

Bruce Konrad Muir Anderson

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SUSPENDED SEDIMENT, TURBIDITY, AND ORGANIC DEBRIS
IN A BELT SERIES WATERSHED OF WESTERN MONTANA

Bruce Konrad Muir Anderson
B.A. Biology, University of California, Santa Cruz 1983

Presented in partial fulfillment of the requirements for the degree of

Master of Science in Forestry

University of Montana

1985

Approved by:

Chairperson, Board of Examiners

Dean, Graduate School

11-12-85

Date
The purpose of this study was to 1) document changes in suspended sediment and turbidity associated with road construction and logging on Belt series metasediments, and 2) measure the magnitude of organic debris loading, and evaluate the significance of debris as an agent of stream equilibrium.

Forest management activities in a 2nd order drainage increased suspended sediment yields 7.7 fold in the first year following road construction, and 2 fold following logging in the second year. Severely limited sediment supplies resulted in poor correlations between suspended sediment and discharge. Sediment transport was strongly hysteretic, with highest concentrations of sediment occurring on the rising limbs of the snowmelt hydrograph as well as on individual peaks. Sediment-turbidity relationships were strongly discharge dependent, reflecting the changing composition of suspended load with stream power and sediment supplies.

Organic debris loads within the active channel were inversely proportional to stream order. All channels tended to concentrate debris; channels contained 1.8 to 5 times as much debris per unit area as the adjacent bank. The percentage of organic debris within the active channel which was involved in storage of sediments increased with stream order. Additionally, channel obstructions shifted from debris (< 10 cm) to logs as stream order increased. Organic obstructions stored from .009 to .021 m$^3$ of sediment /m$^2$ of active channel, and dissipated from 21% to 37% of the stream energy.
Facts are simple and facts are straight
Facts are lazy and facts are late
Facts all come with points of view
Facts don't do what I want them to

-talking heads
ACKNOWLEDGEMENTS

It's a scene from 20,000 Leagues Under the Sea. Big waves, darkness, tentacles everywhere. A master's degree has a way of ensnaring a lot of innocent people. I am grateful to those who unwittingly volunteered their time and energy to this project. In particular, special thanks go to Champion Timberlands for providing the squid, and to the taxpayers of Montana for providing the University. Also deserving are Liz Easterling, Lynda Saul, and Emily Chesick for patient measurements of organic debris exceeding 10 cm in diameter, and mapping of longitudinal profiles while knee-deep amid assertive Froude numbers. Mark Sembach was the driving force behind data collection throughout 1985. One wet quarter in Oregon was made worthwhile by Bob Beschta and Hank Froehlich during my stay as a visiting graduate student. And Bob Symes provided meticulous daily weather records. The extra-special thanks go to my committee members Don Potts, Tom Nimlos, Bill Woessner, and Hans Zuuring. Don, especially, contributed to my intellectual development here at the University. His sense of humor is nothing, if not extraordinary. Finally, thanks go to my mother and father. Without their active participation, this researcher would never have been possible.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Preface</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>List of Illustrations</td>
<td>vii</td>
</tr>
<tr>
<td>Organization</td>
<td>viii</td>
</tr>
<tr>
<td>Chapter I - Suspended Sediment and Turbidity Following Road Construction and Logging</td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Objectives</td>
<td>2</td>
</tr>
<tr>
<td>Study Area</td>
<td>3</td>
</tr>
<tr>
<td>Methods</td>
<td>3</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td></td>
</tr>
<tr>
<td>Suspended Sediment</td>
<td>7</td>
</tr>
<tr>
<td>Turbidity</td>
<td>17</td>
</tr>
<tr>
<td>Summary</td>
<td>21</td>
</tr>
<tr>
<td>Literature Cited</td>
<td>22</td>
</tr>
<tr>
<td>Chapter II- Organic Debris Loading, Sediment Storage, and Potential Energy Dissipation</td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>24</td>
</tr>
<tr>
<td>Objectives</td>
<td>27</td>
</tr>
<tr>
<td>Study Area</td>
<td>27</td>
</tr>
</tbody>
</table>
Methods ................................................. 28

Results and Discussion

Longitudinal Profiles .................................... 30
Debris loads ............................................ 35
Sediment storage ....................................... 37
Potential Energy Dissipation (Loss of Head) .......... 38
Summary .................................................. 40

Literature Cited ........................................ 41
LIST OF TABLES

1. Pre- and postdisturbance annual sediment yields .................. 7
2. Debris loads in 1st, 2nd, and 3rd order channel .................. 36
3. Sediment storage by channel obstructions .......................... 37
4. Head loss arising from channel obstructions ....................... 39

LIST OF FIGURES

1. Chapter I study area, Johnson Gulch .................................. 4
2. Sediment rating curves for the lower station ....................... 10
3. Sediment rating curves for the top station ......................... 10
4. Sediment, discharge, and turbidity, lower station 1985 .......... 14
5. Sediment, discharge, and turbidity, top station 1985 ............ 14
6. Sediment, discharge, and turbidity, lower station 1984 .......... 16
7. Sediment, discharge, and turbidity, top station 1984 ............ 16
8. Suspended sediment - turbidity regression, lower station ...... 20
9. Suspended sediment - turbidity regressions, top station ...... 20
10. Chapter II study area, Johnson Gulch ............................... 29
11-18. Longitudinal profiles of study reaches A-H .............. 31-34
ORGANIZATION

Quite simple really. This thesis is composed of two parts: Chapter I, which concerns itself with suspended sediment and turbidity following forest management activities; and Chapter II, which features the topics organic debris loading, sediment storage, and potential energy dissipation.
CHAPTER I

SUSPENDED SEDIMENT AND TURBIDITY

INTRODUCTION

Timber harvest and road construction in mountainous terrain are frequently cited as major contributors to increased suspended sediment concentrations and turbidity in stream systems. Elevated suspended sediment concentrations and turbidity levels have potentially detrimental effects on fisheries and aquatic invertebrates (Stowell et al. 1983), as well as causing losses in downstream water quality, reservoir storage, and recreational values. Forest management planning requires knowledge of natural and management-induced rates of sediment production for the assurance of continued high quality water supplies. Additionally, most states have water quality standards addressing changes in stream turbidity, assumed to be related to suspended load. Knowledge of the temporal variability of turbidity-suspended sediment relationships is requisite to enforcement of these standards.

Suspended sediment production and turbidity following forest
management activities are well documented for small watersheds in Coastal Oregon (Beschta 1978, 1980, 1983; Paustian and Beschta 1979, Milhous and Klingeman 1978), and central Idaho (King 1979, Megahan 1975). Unfortunately, little data exist assessing the impact of management activities in watersheds located on Precambrian metasediments of the northern Rockies. Belt series metasediments are extensive, underlying 13.2 million acres (47%) of the USFS Northern region forests (Snyder 1976). Sediment studies have generally focused on highly erodible soils, or on unstable terrain where mass soil movement is the dominant mechanism of sediment delivery to stream channels. On the hard metasediments of the Northern Rockies, mass failure is infrequent. Soils tend to be stable, requiring the least stringent road construction standards to minimize erosion (Packer 1967). A sediment yield model developed for the northern Rockies (Cline et al. 1981) employs erodibility coefficients which predict low suspended sediment yields from hard sediments, however, little field verification has been available to evaluate actual rates of sediment production.

The objectives of this study were to investigate the relationships between suspended sediment concentration, turbidity, and discharge, and to evaluate changes in sediment yield associated with logging and road construction in a basin underlain by Belt series metasediments.
THE STUDY AREA

Johnson Gulch is a third order basin on the southern edge of the Jocko Mountains which joins the Blackfoot River 20 km north east of Missoula, Montana. The watershed drains 23 km², and is underlain predominantly by four Missoula group formations of the Precambrian Belt series. Soils have developed on colluvium and tend to be shallow with a high cobble fraction. Slopes are steep, ranging from 15-70%, and averaging 45%. The basin is forested with Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and ponderosa pine (*Pinus ponderosa*). Substantial areas of talus and open grassy slopes are present on the drier southerly aspects, and 35% of the basin is sparsely vegetated (< 25% cover). Annual precipitation at the mouth of the basin is 680 mm, 30% of which falls as snow. Annual runoff is 450mm at the mouth, but only 130 mm in an instrumented mid elevation sub-basin within the watershed. First order channel gradients average 31%, second order channels average 16%, and active channel widths range from 1 to 1.8 meters. Additional documentation of site characteristics may be found in Scott (1983).

METHODS

In 1982, prior to any disturbance, two H-flumes were installed in a second order sub-basin within the watershed (Figure 1). The upper
Figure 1. Johnson Gulch
station is a 280 l/s capacity H-flume in a first order channel draining 0.68 km², and the lower station is a 560 l/s capacity H-flume in a second order channel draining 1.37 km². Discharge was monitored continuously with Stevens recorders, and total suspended sediment was determined from 1 liter depth integrated water samples taken at each station. Sampling was roughly stratified according to discharge; daily samples were taken during snowmelt peak flows, and sampling was reduced to three times weekly during low flows. Turbidity was measured immediately upon return to the laboratory with a Hach Model 16800 turbidimeter in nephelometric turbidity units (NTU's). Suspended sediment was measured using standard filtration and gravimetric procedures (APHA 1975). Finely divided organics were not separated consequently, sediment figures include both organic and inorganic components.

The lower and upper stations are in series along the same channel, and form a "nested pair". All logging and road construction occurred below the upper station; the upper station acts as a control, monitoring undisturbed conditions, and the lower station integrates the impacts of management activities upstream. Baseline data were collected in 1982 prior to any disturbance. In the late summer of 1983, 2.5 kms of side-cast road which cross the channel three times were constructed above the lower station. In late 1984, 20% of the sub-basin was selectively harvested with feller-bunchers, tractors, and rubber-tired skidders. Twenty to forty meter buffer strips were left adjacent the stream.
Statistical comparison of suspended sediment concentrations, discharge, and turbidity during the pre and post-treatment periods was accomplished using Model II, Bartlett's 3-group linear regressions (Sokal and Rohlf 1981) of logarithmically transformed data.

Annual suspended sediment yield for the upper and lower stations was calculated by applying measured sediment concentrations to continuous discharge records. Annual yields are expressed in mass/ unit channel length as well as in the traditional mass/ unit area. In the absence of overland flow or extensive mass wasting, the majority of sediment in undisturbed forested basins is derived from channel erosion, and soil creep entering the stream network along the perimeter of the channel. Sediment is not derived from widespread areas of the basin, as might be anticipated where overland flow processes are dominant. Consequently, sediment production in forested basins should be more closely related to channel length than basin area. Indeed, main channel length was an important predictor of sediment yield in 36 basins in southern Alberta (McPherson 1975), and Marston (1978) concluded that annual sediment yield is more closely related to channel length than basin area for 15 Oregon watersheds. Mass/ unit channel length provides a better basis for comparison of sediment yield between watersheds with differing drainage densities, and it acknowledges the functional relationship between sediment yield and channel length.
RESULTS AND DISCUSSION

Suspended Sediment

Comparison of annual yields indicates a 7.7 fold increase in suspended sediment yield at the lower station in the first year following road construction, and 2 fold increase in the second year (Table 1). Although the second year figure integrates possible effects of timber harvest, it is highly unlikely that cutting or skidding operations contributed directly to sediment production. Soil disturbance was negligible, and no overland flow or sediment delivery was observed from the 10-20% slopes in the logged area.

Table I.Annual Suspended Sediment Yield.

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<td>Kg/km²</td>
<td>56</td>
<td>102</td>
<td>83</td>
<td>177</td>
<td>1365</td>
<td>356</td>
</tr>
<tr>
<td>Kg/km channel</td>
<td>32</td>
<td>58</td>
<td>47</td>
<td>93</td>
<td>713</td>
<td>186</td>
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</table>
Channel disturbance and direct additions of soil during road construction account for most of the increased sediment yield, plus some surface erosion of fill slopes immediately adjacent to culverts. Suspended sediment yield appears to be decaying rapidly towards pretreatment levels in the second year, however, this may be largely a consequence of low water yields during 1985. Water yields during the pretreatment and first-year posttreatment periods were essentially equivalent; water yield in the second year was 50% of the previous years. If scaled up to equivalent water yield, the increase in suspended sediment yield for 1985 would be 4 fold. Implicit in this comparison is a linear relationship between sediment yield and water yield; admittedly the true relationship is likely to be exponential.

In a comparable study, Beschta (1978) reported a three fold increase in annual suspended sediment yield from Deer Creek of central Oregon in the first year following road construction, and minimal increases in the second year following logging activities. The elevated suspended sediment yield was attributed primarily to road construction. Sediment yield increases in Johnson Gulch are significantly larger than those reported for Deer Creek. Additionally, the elevated yields appear to be of longer duration. The pretreatment sediment yield of Johnson Gulch was very low relative to pretreatment levels at Deer Creek (.097 t/km versus 19.9 t/km, or .18 t/km² vs. 97
t/km²), thus, many-fold increases over naturally occurring levels were easily achieved. Although percent increases were large, the actual erosion and delivery of sediment from roads in Johnson Gulch was undoubtedly less than that observed in Deer Creek. Changes in sediment yield expressed as "increases over natural" may be deceptive if used as a means of comparing relative impacts of forest management activities between drainages.

The equation commonly employed to model sediment concentration as a function of discharge, originally developed by Campbell and Bauder (1940), is of the form \( Y = aX^b \), where \( Y \) is the concentration of suspended sediment, \( X \) is discharge, and \( a \) and \( b \) are coefficients determined from the intercept and slope of the log-log plot.

The suspended sediment rating curves for pre and post disturbance conditions are shown in Figures 2 and 3. Suspended sediment concentrations at the upper station ranged from 0.01 to 5.6 mg/l, and averaged 0.9 mg/l during the three year study (\( n=133 \)). Although the upper station experienced no disturbance, the suspended sediment concentrations were weakly but significantly correlated to discharge during two of the three years (\( r^2 = .02, .08, .14; P = .64, .024, .023 \) for pre, 1st, and 2nd years, respectively). Individual regressions were not significantly different at the 95% confidence level. Pre-disturbance suspended sediment concentrations at the lower station range from 0.5 to 3.4 mg/l, averaging 1.5 mg/l (\( n=50 \)). Prior to disturbance, no correlation existed between suspended sediment concentration and discharge (\( r^2 = .003, P = .68 \)). Following road
Figure 2. Pre and Post Disturbance Sediment Rating Curves for the Lower Station.

Figure 3. Pre and Post Disturbance Sediment Rating Curves for the Top Station.
construction, suspended sediment concentration ranged from 0.46 to 69 mg/l, averaging 6.7 mg/l (n=63), and in the second year ranged from 1.6 to 43.4 mg/l, averaging 6.4 mg/l (n=36). Higher suspended sediment concentrations are correlated with higher discharges ($r^2 = .35, P < .0001$) in the first year, but are poorly correlated in the second ($r^2 = .05, P = .085$). The sediment rating curve has shifted to a regime of higher sediment concentrations for a given discharge in the first year following road construction, with the slopes and intercepts being significantly different at the 95% confidence level ($P = .0001$). The 2nd year post-disturbance rating curve was not statistically different from the pre-disturbance curve at the 95% confidence level ($P = .11$).

Although the mean weekly, monthly, and annual sediment concentrations and sediment yields were all consistently higher following logging and road construction, none of these differences were statistically significant ($\alpha = .05$) as a consequence of highly variable sediment concentrations.

Variation around sediment rating curves commonly spans one or two orders of magnitude, both in small watersheds (Beschta 1978) and large rivers (Leopold and Maddock 1953). High variability was characteristic of this study as well, and appears to be typical of sediment rating curves developed for small watersheds in this region. Snyder (1976) developed rating curves for seven watersheds in Idaho and western Montana as part of an effort to characterize regional water quality characteristics. Sediment concentration was uncorrelated to discharge in several basins and strongly correlated in others, with the
coefficients of determination averaging 0.30. Rating curves developed for ten sub-basins of the Horse Creek watershed in Idaho were statistically significant ($K = .01$), and $r^2$ values ranged from 0.20 to 0.49 (King 1978). Application of simple bivariate rating curves such as these to calculate sediment yields is likely to result in substantial error (Walling 1977), and poor correlations hamper statistical analysis aimed at detecting altered sedimentation rates.

Considerable variations in suspended sediment concentration at a given discharge may arise from numerous interrelated factors, including temperature effects (Lane et al. 1949), desynchronization of kinematic flood peaks and sediment peaks (Heidel 1956), seasonal effects (Walling 1977), and probably most importantly, changes in sediment supply.

If sediment supply is not limiting, increasing stream power, and expansion of channel length and cross sectional area (sediment source area) associated with increasing discharge usually result in higher suspended sediment concentrations at elevated flows. Given ample sediment supplies, the sediment-discharge relationship is adequately modeled by the simple power function. Transport capacity of stream systems nearly always exceeds supplies of suspended sediment, however, and depletion of sediment within the channel results in hysteretic relationships between suspended sediment concentrations and discharge. Supply effects have been noted on a seasonal time scale as well as within individual storm events. Seasonal hysteresis is characterized by a decline in suspended sediment concentration as the runoff season
progresses (VanSickle and Beschta 1983), and concentrations are generally higher on the rising limb of the seasonal hydrograph than on the falling limb and recession. Similarly, storm hydrographs usually carry the highest concentrations on the rising limb (Striffler 1963, Paustian and Beschta 1979). Stratification of data by factors such as limb and season often improves rating curves and predictions of sediment yield (Walling 1977, Loughran 1976).

Both seasonal decline and hysteresis during individual hydrograph peaks are evident for suspended sediment concentrations during the snowmelt hydrographs in 1984 and 1985. Hysteretic effects are especially pronounced in the 1985 lower station record (Figure 4). Suspended sediment concentrations are 5 to 10 times higher on the rising limb than on the falling limb during individual peaks occurring on Julian days 77, 93, and 101. Peak sediment concentrations precede discharge peaks by several days, and sediment concentrations during discharge peaks may actually return to near pre-peak levels. This desynchronization of discharge and sediment peaks weakens stratification of data by rising and falling limbs, unless observations at the crest are discarded. This is unfortunate, since sediment concentrations during peak discharges are often of the greatest interest. Nevertheless, multiple regression shows limb to be a significant predictor of sediment concentration (P = .038), explaining more of the variance than discharge (21% vs 5%). Striffler (1963) reported similar results for 20 sampling stations in northern Michigan's Tobacco River watershed, where limb explained 43% of the
Figure 4. Suspended Sediment, Turbidity, and Discharge, Lower Station 1985.

Figure 5. Suspended Sediment, Turbidity, and Discharge, Top Station 1985.
variance in sediment concentration vs. 1% for discharge.

The phenomenon of seasonal decline is also apparent in Figure 4; sediment concentration on Julian day 101 is half that of day 93, although discharge on day 101 is twice that of day 93. The peak of 25 liters/second on day 93 was apparently of sufficient magnitude and duration to flush much of the readily available sediment from the channel. Sediment is rapidly transported from the watershed during spring snowmelt. For both stations, 65 to 75% of the suspended load is transported during April, and most of this is actually transported within several days during the rising limb of the maximum flow.

The top station experienced a sequence of discharge peaks similar to those at the lower station in 1985, however, sediment transport was quite different (Figure 5). Hysteresis is present during the major peak of Julian day 103, but is less consistent otherwise. Seasonal decline appears to be absent. In particular, sediment concentrations during days 115-125 are anomalously high, and probably represent new additions of sediment to the channel from collapse of undercut banks. Presumably the undisturbed top station has more severe supply limitations than the lower station, yet the anticipated hysteretic effects are less pronounced. This may reflect the overriding importance of stochastic processes such as bank caving in determining sediment loads for extremely supply limited systems.

Data for 1984 are probably more representative of complex conditions typically encountered during spring snowmelt (Figure 6 & 7). The hydrographs are multi-peaked as a result of numerous rain and
Figure 6. Suspended Sediment, Turbidity, and Discharge, Lower Station 1984.

Figure 7. Suspended Sediment, Turbidity, and Discharge, Top Station 1984.
rain-on-snow events, and although hysteretic effects are evident for both stations, the sediment–discharge relationship is unclear. Multiple regression for data of the lower station improves the fit of the rating curve from 0.35 to 0.61 by incorporating the variable \( \frac{dQ}{dt} \), and an interaction term, the product of \( \frac{dQ}{dt} \) and a dummy variable for limb. The predictive value of such an equation developed from limited data is suspect, but it serves to illustrate that sediment concentrations may be an intricate function of hydrograph characteristics.

Sediment concentration is poorly modeled as a simple power function of discharge, and models for supply limited systems need to incorporate a variable which accounts for the history of antecedent conditions. VanSickle and Beschta (1983) have included a supply function which simulates depletion and replenishment of discrete sediment compartments, and future refinement of this approach promises to improve predictions of sediment concentration in supply limited situations.

Turbidity

Turbidity has long been considered an index of suspended solids (Bull and Darby 1928, Grassy 1943), and its expedient measurement has prompted state regulatory agencies throughout the Northwest to adopt standards which define acceptable/unacceptable sediment loads in terms of turbidity units (NTU's). Turbidity, however, is not a measurement
of suspended sediment concentration. Turbidity is due to complex interactions of solution color, particle size and shape, refractive index, solute concentration, and dissolved air, and any measurement of turbidity is an integration of the optical properties of all these factors. Thus, turbidity may or may not reflect actual sediment loads. Where inorganic sediment is the dominant factor, turbidity may be a useful predictor of sediment concentration. Correlations between suspended sediment and turbidity in natural stream systems have ranged from excellent to poor (Kunkle and Comer 1971, Costa 1977, Larson et al. 1978, Settergren et al. 1980, Stednick 1980, Beschta 1980). Larson et al. (1978) found differences in regressions from adjacent watersheds, indicating the need for development of site specific predictive equations. Additionally, the ratio of sediment concentration (mg/l) to turbidity (NTU), or coefficient of fineness, has been shown to be a function of discharge (Grassy 1943), and is subject to hysteretic effects during storms (Beschta 1980). Nevertheless, turbidity records may prove superior to sediment rating curves for calculating sediment yield where sediment production may be weakly related to discharge (Truhlar 1976).

Turbidity records for 1984 and 1985 (Figures 4-7) show that turbidity, like suspended sediment, is subject to hysteresis and seasonal decline. Low discharges occurring before the peak flow are typically very turbid relative to equivalent discharges following the peak. Measurements of turbidity before and after filtration showed colloidal particles finer than 0.45u were responsible for 50-70% of
the total turbidity during 1984.

Regression analysis of the suspended sediment/turbidity relationship generally follows the form $Y = aX^b$, where $X$ is turbidity, $Y$ is suspended sediment, and $a$ and $b$ are coefficients from the intercept and slope of the log log plot. Individual regressions of sediment on turbidity (Figures 8 & 9) are statistically significant at the 95% confidence level for both stations, and none of these are statistically different from one another ($\alpha=0.05$). Coefficients of determination are low, especially for the undisturbed top station which had characteristically low sediment concentrations and turbidities. Poor correlations probably reflect random measurement error, as well as the increasing importance of factors such as dissolved air in determining turbidity.

The sediment turbidity relationship at the lower station was discharge dependent, with the coefficient of fineness being directly proportional to discharge. For 1984 data, multiple regression showed discharge explained 41% of the variation in the coefficient of fineness, and a dummy variable for pre/post peak explained an additional 7%. The dependence of the sediment/turbidity relationship on these factors is understandable in terms of stream power and supply phenomena. Since turbidity caused by inorganic sediment is most strongly dependent on the fine fractions (Holstrom and Hawkins 1980), it follows that turbidity will be correlated to sediment concentration to the degree that the fine fractions are related to the total sediment load. At low flows, fines predominate and turbidity is high.
Figure 8. Suspended Sediment - Turbidity Regressions for the Lower Station.

Figure 9. Suspended Sediment - Turbidity Regressions for the Top Station.
relative to the suspended load. As discharge (surrogate for stream power) increases, larger particles less responsible for turbidity are recruited from the channel, and the suspended load becomes large relative to the turbidity. Exhaustion of fine colloidal particles at elevated discharges also contribute to the increasing coefficient of fineness. Despite the discharge dependency of the sediment/turbidity relationship, correlations were higher than those of the sediment rating curves, and unlike the rating curves, all turbidity regressions were statistically significant. Turbidity is thus indicated as a better parameter than discharge for prediction of sediment concentration in this supply limited system.

SUMMARY

Forest management activities in a 2nd order drainage increased suspended sediment yields 7.7 fold in the first year following road construction, and 2 fold following logging in the second year. Severely limited sediment supplies resulted in poor correlations between suspended sediment and discharge. Sediment transport was strongly hysteretic, with highest concentrations of sediment occurring on the rising limbs of snowmelt hydrographs as well as on individual peaks. Sediment-turbidity relationships were discharge dependent, reflecting the changing composition of suspended load with stream power and sediment supplies. Higher discharges were associated with an increasing ratio of suspended sediment to turbidity.
LITERATURE CITED


CHAPTER II

ORGANIC DEBRIS LOADS, SEDIMENT STORAGE, AND HEAD LOSS

INTRODUCTION

Woody organic debris is an integral part of forested watersheds. Especially in low order channels, organic debris plays an important role in stream channel morphology, stability, and sediment transport. Organic debris is central to the development of stepped bed profiles widely reported for small, high gradient streams (Likens and Bilby 1982, Heede 1981). Stepped bed profiles are characterized by an alternating sequence of relatively long, low gradient pools or stored sediments, and short, steep falls which frequently terminate in scour pools. In addition to organic debris, bedrock exposures, transverse rock bars, and immobile boulders may all contribute to falls and cascades.

Organic debris lodging within the active channel causes redistribution of sediments through local scour and deposition. Three independent fluvial variables, channel width, depth, and slope, all
tend to increase in variability as organic debris is incorporated into bed architecture. Pools created by organic obstructions generally increase channel width and depth (Keller and Tally 1979, Keller and Swanson 1979), and as pools fill with sediments, channel gradients decrease. Organic debris either controlled or influenced 50% to 90% of the pools in 3rd and 4th order streams in Redwood ecosystems (Keller and Tally 1979), and Bilby (1984) reported debris formed 70% to 86% of the pools in 4th order channels in Washington. Organic obstructions are important as storage sites for sediment. Megahan (1982) reported an average of 15 times the annual sediment yield was stored by organic debris in 1st, 2nd, and 3rd order channels in central Idaho. Marston (1982) reported storage provided by logs totaled 123% of the estimated annual yield from 3rd, 4th and 5th order basins in the Oregon Coast Range. The diversity of flow conditions and storage elements inherent in stepped bed profiles limit the application of traditional sediment transport equations. Small fluctuations in storage easily account for high variability observed in annual sediment yield from small watersheds, and may drastically change interpretations of erosional conditions based on sediment yield data alone (Janda 1978). Kelsey (1980) demonstrated that storage in channels may delay and subdue the peak of downstream sediment delivery from hillslope sources. Presumably, buffering effects are proportional to the magnitude of sediment storage capacity.

The distribution of potential energy in stream systems is considered to be diagnostic of equilibrium conditions (Yang 1971), and
provides another approach to evaluate the contribution of organic debris to stream equilibrium. Fully developed log steps reduce the energy grade line of the water surface, and dissipation of potential energy is concentrated at the channel obstruction. Sediment is invariably trapped to some extent at obstructions which dissipate potential energy, thus, head losses at obstructions may be employed as an index of relative sediment storage and buffering capacities.

Theoretically, potential energy dissipation may influence the development of the long profile at the macroscale (Langbein and Leopold 1964, Leopold and Langbein 1962), however, in a study based on Yang's (1971) "law of average stream fall", Marston (1982) concluded that log steps and rock falls were insufficient to overcome the influence of lithologic controls on stream relief.

Instream organic debris also contribute to kinetic energy losses by increasing channel roughness and diverting streamflow. Although increased turbulence and flow deflection can accelerate localized scour (Beschta 1983a, Mosley 1981), the dissipation of kinetic energy by instream debris necessarily results in a lower total energy available to transport sediments. Thus, an overall reduction in bedload transport rates may be realized through a given reach (Beschta 1983a). Energy dissipation, whether kinetic or potential, represents energy lost for transportation of sediment.

Clearly, woody debris plays an active part in establishing conditions of stream equilibrium. Forest management activities have the potential to greatly modify debris loads in riparian areas. Prudent
forest management requires knowledge of naturally occurring debris loads, and an understanding of the sediment storage associated with debris. In effect, management of riparian vegetation and organic debris constitutes management of channel characteristics and behavior.

The objectives of this study were to measure the extent of debris loading in first, second and third order channels of Johnson Gulch, and to determine the potential energy losses and sediment storage associated with in-channel organic obstructions.

THE STUDY AREA

Johnson Gulch is a third order basin on the southern edge of the Jocko Mountains joining the Blackfoot River 20 km north east of Missoula, Montana. The 23 km2 watershed is underlain by hard Precambrian metasediments. Soils have developed on colluvium and tend to be shallow with a high cobble fraction. Slopes are steep, ranging from 15-70%, and averaging 45%. The basin is forested with Douglas-fir (Pseudotsuga menziesii), western larch (Larix occidentalis), and ponderosa pine (Pinus ponderosa). The watershed is relatively undisturbed, although some of the gentle lower slopes were logged in the 1920's with horses. Basal area ranges from 10 to 29 m2/ha. Substantial areas of talus and open grassy slopes are present on the drier southerly aspects, and 35% of the basin is sparsely vegetated (< 25 % cover). Annual precipitation at the mouth of the basin is 680 mm,
30% of which falls as snow. Annual runoff averages 450mm at the mouth, but 130 mm in a second order sub-basin within the watershed. First order channel gradients average 31%, second order channels average 16%, and active channel widths range from 1 to 1.8 meters. The third order channel has an average gradient of 10% and is 3.75 meters wide.

METHODS

Fifty to one hundred meter reaches were surveyed along first, second, and third order channels within Johnson Gulch (Figure 10). Channel longitudinal profiles were measured with a stream gradient gage, modified from a design by Walkotten and Bryant (1980). The diameter and length of organic debris exceeding 10 cm in diameter was measured to determine the volume of debris both within (and above) the active channel and within 5 meters of the bank. Wood volumes were converted to mass assuming 400 kg/m³.

The volume of sediment stored behind channel obstructions was determined geometrically from measurements of active channel width, length of deposit, and elevation loss over the obstruction. Volumes were converted to mass assuming 1800 kg/m³ for water deposited sediments (Gottschalk 1964). Channel obstructions composed of material less than 10cm in diameter were classified as "debris", and obstructions greater than 10cm were classified as "logs".

Measurements of potential energy dissipation due to organic debris
Figure 10. Johnson Gulch
were made when streamflow was approximately 25% of the peak discharge. Water elevation loss over channel obstructions was considered to be "head loss" if more than 50% of the streamflow was directed over the obstruction, and if water not flowing over the obstruction was diverted over rocks well anchored by the debris. This eliminated some debris which stored sediments but was only lodged partially within the channel, and all debris which merely deflected flow.

RESULTS AND DISCUSSION

Longitudinal Profiles

The longitudinal profiles of eight study reaches (Figures 11-18) illustrate the stepped profiles characteristic of forested watersheds. First order (1o) channels averaged 15.4 organic obstructions per 100 meters, 22% of which were logs, 88% debris. Second order (2o) channels averaged 14 organic obstructions per 100 meters, 39% of which were logs, 61% of which were debris. Third order (3o) channels averaged only 3.7 organic obstructions per 100 meters. 80% of these were logs, 20% debris. The proportion of logs to debris obstructions, and total number of obstructions were inversely proportional to stream order. The greater width and discharge of the third order channel limited the formation of debris obstructions and lowered the total numbers. The
Figure 11. Longitudinal Profile for Reach A.

Figure 12. Longitudinal Profile for Reach B.
Figure 13. Longitudinal Profile for Reach C.

Figure 14. Longitudinal Profile for Reach D.
Figure 15. Longitudinal Profile for Reach E.

Figure 16. Longitudinal Profile for Reach F.
Figure 17. Longitudinal Profile Reach G.

Figure 18. Longitudinal Profile for Reach H.
formation of obstructions made of smaller debris appeared to be dependent on the presence of rocks which protruded from the streambed. In first, second, and third order streams of central Idaho, Megahan (1982) reported averages of 8.4 to 14 organic obstructions per 100m. Although Megahan did not observe increasing numbers of obstructions with channel gradient, this trend has been reported elsewhere in the literature (Heede 1972, 1981; Likens and Bilby 1982). Bilby and Likens (1980) reported 33.5 organic obstructions per 100m for 1st order channel, 13.7 obstructions/100m for 2nd order channel, and 2.5 obstructions/100m in third order channel in New England. Basal area in the adjacent forest averaged 24m²/ha, which is somewhat higher than the present study. Undoubtedly the frequency of organic obstructions is in part a function of the forest biomass.

Debris Loads

Debris loads within 5 meters of the banks were 6.4 kg/m² for 1o channels, 2.1 kg/m² for 2o channels, and 4.1 kg/m² for 3o channels (Table 2). These values are in close agreement with +3 fuel loads of 2 to 7.6 kg/m² reported for similar stands in an adjacent watershed (Fischer 1981). Channels tended to concentrate logs and woody debris. Debris loads within the active channel were 2.4 times higher than the adjacent bank for 1o channels, 5 times higher in 2o channels, and 1.8 times higher in 3o channels. This finding is consistent with observations of others (Froehlich, pers. comm.). Debris loads within
the active channel were inversely proportional to stream order. 1o channel averaged 15.2 kg/m2, 2o channel averaged 10 kg/m2, and 3o channel averaged 7.2 kg/m2. This trend has been reported by Bilby and Likens (1980) and Keller and Swanson (1979). With increasing stream order, greater channel widths, depths, stream competence, and decreasing hillslope steepness all tend to contribute to lower in-channel debris loading.

<table>
<thead>
<tr>
<th>ORDER</th>
<th>W/IN ACTIVE CHANNEL</th>
<th>STORING SEDIMENT</th>
<th>W/IN 5m OF BANK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m3/m2 (kg/m2)</td>
<td>m3/m2 (kg/m2)</td>
<td>m3/m2 (kg/m2)</td>
</tr>
<tr>
<td>1</td>
<td>.038 (15.2)</td>
<td>.004 (1.60)</td>
<td>.016 (6.4)</td>
</tr>
<tr>
<td>2</td>
<td>.025 (10.0)</td>
<td>.006 (2.4)</td>
<td>.005 (2.0)</td>
</tr>
<tr>
<td>3</td>
<td>.018 (7.2)</td>
<td>.006 (2.4)</td>
<td>.010 (4.0)</td>
</tr>
</tbody>
</table>

The amount of debris within the active channel involved in sediment storage was somewhat less in 1o channels (1.6 kg/m2) than in 2o and 3o channels (2.4 kg/m2). The percentage of organic debris within the active channel involved in storing sediment was directly
proportional to stream order: 12% of the debris within 1o channel stored sediment, versus 22% and 32% for 2o and 3o channels. The increasing involvement of debris within the active channel as a site for sediment storage reflects the increasing ease with which the larger organic materials may be incorporated into the bed as stream order increases.

Sediment Storage

Organic obstructions were more important than transverse rock bars and obstructions as storage sites for sediment. Organic materials in 1o, 2o, and 3o channels stored, respectively, 63%, 82%, and 63% of the total obstruction related sediment (Table 3).

TABLE III. Sediment Storage.

<table>
<thead>
<tr>
<th>OBSTRUCTION</th>
<th>1ST (m³/m² channel (% total storage))</th>
<th>2ND</th>
<th>3RD</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOGS</td>
<td>0.0042 (29%)</td>
<td>0.0145 (56%)</td>
<td>0.011 (58%)</td>
</tr>
<tr>
<td>DEBRIS</td>
<td>0.0048 (33%)</td>
<td>0.0066 (26%)</td>
<td>0.001 (5%)</td>
</tr>
<tr>
<td>ROCK</td>
<td>0.0054 (38%)</td>
<td>0.0046 (18%)</td>
<td>0.0069 (37%)</td>
</tr>
<tr>
<td>ORGANIC</td>
<td>0.009 (63%)</td>
<td>0.0211 (82%)</td>
<td>0.012 (63%)</td>
</tr>
<tr>
<td>INORGANIC</td>
<td>0.0054 (38%)</td>
<td>0.0046 (18%)</td>
<td>0.0069 (37%)</td>
</tr>
</tbody>
</table>
Storage associated with organic obstructions amounted to 16.2 kg/m² in 1o channels, 37.8 kg/m² in 2o channels, and 21.6 kg/m² in 3o channels. Logs were increasingly important as storage sites with increasing stream order. In 1o channels, storage was about evenly distributed between debris (29%) and logs (33%). In 2o streams, storage shifted from debris (26%) to logs (56%). In 3o channels logs stored 11 times the amount stored by debris (56% vs. 5%). Debris obstructions remained intact in narrow channels with low peak flows, and were effective as sediment storage sites. The width and discharge of third order channels was sufficient to dislodge most accumulations of smaller debris, hence logs were the most important organic storage site.

Second order channels stored the greatest amounts of sediment per unit area. This probably arises because both logs and debris are effective storage sites. Although logs were effective storage sites for sediment in 1o channels, the steep v-notch topography and narrow, incised channels frequently prevented the large logs from orienting themselves so as to trap sediments.

Head Loss

Head losses associated with organic debris were 21% for 1o channels, 37% for 2o channels, and 21% for 3o channels (Table 4).
Head losses in lo channels were associated with debris (15%) rather than logs (6%). Logs were seldom oriented so that a drop in water surface elevation occurred. In 2o channels, both debris (20%) and logs (17%) contributed to head losses. Consequently, 2o channels had the highest overall head loss. In third order channels, logs (19%) were far more important than debris (1.3%).

Table IV. Head loss due to channel obstructions.

<table>
<thead>
<tr>
<th>OBSTRUCTION</th>
<th>HEAD LOSS (PERCENT %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STREAM ORDER</td>
<td>1ST</td>
</tr>
<tr>
<td>------------------</td>
<td>-----</td>
</tr>
<tr>
<td>LOGS</td>
<td>5.9</td>
</tr>
<tr>
<td>DEBRIS</td>
<td>14.8</td>
</tr>
<tr>
<td>ROCK</td>
<td>20.1</td>
</tr>
<tr>
<td>RIFFLE/POOL</td>
<td>59.2</td>
</tr>
<tr>
<td>ORGANIC</td>
<td>20.7</td>
</tr>
<tr>
<td>INORGANIC</td>
<td>79.3</td>
</tr>
</tbody>
</table>

These figures are lower than those reported by Keller and Swanson (1979) and Swanson et al (1976), who found, respectively, 30% to 80% and 32% to 52% energy dissipation by organic steps in the western Cascades. Others have reported figures for potential energy dissipation of 6% (Marston 1982), 4% (Dietrich 1975), 18% to 60%
Aside from true regional differences, discrepancies may arise due to failure of studies to adequately distinguish between potential and kinetic losses (Marston 1982), and measurement under different flow conditions. Marston's (1982) low figure of 4% for the Oregon Coast range may be a partially a function of discharge, which was "low" during stream surveys. The variability of energy dissipation with discharge remains undocumented.

**SUMMARY**

Organic debris loads within the active channel were inversely proportional to stream order. All channels tended to concentrate debris; channels contained 1.8 to 5 times as much debris per unit area as the adjacent bank. The percentage of organic debris within the active channel which was involved in storage of sediments increased with stream order. Additionally, channel obstructions shifted from debris (< 10 cm) to logs as stream order increased. Organic obstructions stored from .009 to .021 m³ of sediment / m² of active channel, and dissipated from 21% to 37% of the stream energy.
LITERATURE CITED


