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Monitoring Levels of Fine Sediment Within Tributaries to Flathead Lake, and Impacts of Fine Sediment on Bull Trout Recruitment[1]

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Abstract.--Streambed samples from known bull trout spawning areas in four tributaries to the North Fork of the Flathead River, Montana demonstrated that spawning areas in one of the tributaries (Coal Creek) contained significantly higher percentages of fine sediment than the other three tributaries. Bull trout embryo survival and subsequent fry emergence success was highly correlated (r^2=0.87) to the percentage of material less than 6.4 mm within the streambed of Coal Creek. A significant correlation (r^2=0.40, $p<0.001$) was found between substrate score and densities of juvenile bull trout (fish longer than 75 mm) in 26 Swan River tributary reaches. Increase in estimated sediment loads attributed to road development (expressed as percentage over natural) was significantly correlated ($p<0.001$) with three different expressions of substrate composition (substrate score, percentage of material less than 6.4 mm, and percentage of material less than 2.0 mm) for 46 Swan River tributary reaches.

INTRODUCTION

A trophy bull trout (Salvelinus confluentus) fishery supported entirely by wild production is popular in the upper Flathead River Basin in Montana and British Columbia. Anglers annually catch adult bull trout up to 9 kg (800 mm) with many exceeding 5 kg. These adfluvial adults mature at five or six years of age (400-500 mm) and migrate as far as 230 km upstream from Flathead Lake to spawn in upper basin tributaries (Shepard et al. 1984). Young bull trout rear from one to four years in their natal tributaries before emigrating downriver to Flathead Lake. Upon reaching Flathead Lake, growth rates increase as the piscivorous bull trout find abundant prey (Leathe and Graham 1982).

The Montana Department of Fish, Wildlife and Parks (MDFWP) closed four bull trout spawning tributaries to fishing and set a 457 mm minimum size limit for bull trout in 1951. In 1978, the Environmental Protection Agency funded the MDFWP to conduct baseline fishery investigations in the Flathead Basin because of the potential for development of an open pit coal mine in the upper Flathead Basin in British Columbia, increasing oil and gas exploration throughout the basin, and rapid population growth and land development in the area. The information collected during this five year study (1978 to 1982) identified important bull trout spawning and rearing habitat in headwater tributaries, documented the life history of the native bull trout, estimated annual harvest and catch statistics, estimated the value of water-based recreation, and recommended a monitoring program to gauge the impacts of development on the fishery (Shepard and Graham 1983a; Shepard et al. 1984).

This study found that bull trout consistently selected specific areas for spawning. Of 185 stream reaches surveyed covering 750 km, bull trout redds were located in only 48 reaches covering 215 km (28%). The fact that bull trout spawning occurs in limited areas suggests that degradation of these spawning grounds could have a significant impact on bull trout populations. A segment of the monitoring program involved sampling streambed composition in high density bull trout spawning areas. This streambed monitoring indicated an excessive amount of fine sediment was present in the streambed of several important bull trout spawning areas. We were concerned about the effect fine sediment might have on bull trout embryo survival and rearing capacity. Several researchers have documented

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the impacts of fine sediment on the spawning success of salmonids (Cardone and Kelley 1961, Cooper 1965, Koski 1966, Gibbons and Salo 1973, Phillips et al. 1975, Hausle and Coble 1976, Iwamoto et al. 1978) and on rearing capacity (Bjornn et al. 1977, Reiser and Bjornn 1979, Adams and Beschta 1980, Crouse et al. 1981).

Two additional studies were initiated in the Flathead Basin which allowed us to explore these relationships for bull trout. The USDA Forest Service, Flathead National Forest, contracted with the Montana Cooperative Fisheries Research Unit to determine the effects of forest development on spawning and rearing habitat in Coal Creek, a tributary to the North Fork of the Flathead River, and the Bonneville Power Administration contracted with MDFWP and the U.S. Forest Service to determine the potential cumulative impacts of several proposed micro-hydroelectric projects on the fishery in the Swan Lake drainage (which ultimately drains into Flathead Lake). This report documents our efforts to quantify levels of fine sediment within bull trout spawning and rearing areas, estimate impacts of fine sediment on bull trout embryo survival and juvenile rearing capacity, and predict impacts of land development on bull trout recruitment through a sediment response model.

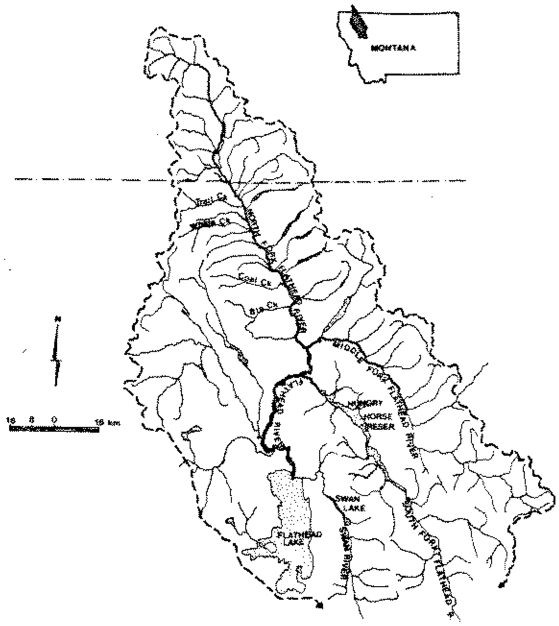

Figure 1.--Map of the upper Flathead River Basin, Montana.

STUDY AREA DESCRIPTION

Flathead Lake, the largest natural freshwater lake (based on surface area) west of the Mississippi River, drains a 18,353 km² area of northwest Montana and southeast British Columbia (fig. 1). The Flathead and Swan rivers are the only major tributaries to Flathead Lake and have drainage areas of 16,444 and 1,909 km², respectively. Five major tributaries join the Flathead River before it enters Flathead Lake from the north. These tributaries are the Stillwater River, Whitefish River, and the North, Middle and South forks of the Flathead River. The South Fork of the Flathead River was isolated from the rest of the system by Hungry Horse Dam in 1951. Our investigations were conducted primarily in tributaries to the North and Middle Forks of the Flathead River and tributaries to the Swan River.

The Lewis Overthrust Fault extends through most of the upper Flathead River Basin and is responsible for layers of Precambrian argillite, quartzite and carbonate rocks overlying younger sedimentary limestones, dolomites, shales and sandstones deposited during the more recent Paleozoic and Mesozoic eras. Consequently, the surface geology in the basin is dominated by those Precambrian rock types with sedimentary rock types occasionally found near the surface. Quaternary glacial deposits cover most of the valley bottoms. Water quality of tributaries in the basin is generally excellent and typical of unproductive mountain streams.

Gamefish species present in tributaries include westslope cutthroat trout (Salmo clarki lewisi), Yellowstone cutthroat trout (Salmo clarki bouvieri), bull trout (Salvelinus confluentus), brook trout (Salvelinus fontinalis), rainbow trout (Salmo gairdneri), and mountain whitefish (Prosopium williamsoni). Cutthroat and bull trout were the most abundant species found in tributaries to the Upper Flathead River, while these two species and brook trout dominated fish populations in tributaries to the Swan River. In the Flathead Lake/River system both cutthroat and bull trout follow an adfluvial life history pattern described by Behnke (1979). The adults mature in Flathead Lake, spawn in small headwater tributaries, their progeny rear in natal tributaries for one to four years, and then emigrate downstream to Flathead Lake (Shepard et al. 1984). While the majority of bull trout in the basin follow an adfluvial pattern, cutthroat trout may be either adfluvial, fluvial, or resident. Cutthroat trout populations in the Swan River drainage are comprised mostly of resident fish inhabiting high gradient headwater areas of tributary streams. Both westslope cutthroat and bull trout are native to the basin.

METHODS

Streambed Composition of Spawning Areas

Field Sampling

Sample sites were located in Big, Coal, Whale, and Trail creeks, tributaries to the North Fork of the Flathead River (fig 1). Sampling stations were established in areas where high densities of bull trout redds were observed during annual fall redd counts. Two or three permanent transects perpendicular to the streamflow were set up in each monitored spawning area. Four sites were sampled across each transect. Cored sites were generally at equal distances across the stream channel, but an effort was made to sample spawning bed material. Big and Whale creeks each had 12 core samples taken from one spawning area, while Coal and Trail creeks each had 20 core samples taken from two spawning areas. Sampling was done during the fall of 1981, 1982, and 1983 when streamflows were typically low.

A hollow core sampler similar to that described by McNeil and Ahnell (1964) was pushed into the streambed to a depth of 15 cm. Field observation in sampled natural redds verified that this was the depth of egg deposition since when eggs were encountered in core samples, they were found at the very bottom of the cored samples. At least 10 kg of streambed material was removed from each cored site. Shirazi and Seim (1979) believed that hollow core samples of 10 kg adequately represented overall streambed composition by site. We modified McNeil and Ahnell's (1964) procedure for sampling the very fine material that often remains suspended in the water because of logistical constraints encountered in sampling remote locations. Instead of retaining the turbid water within the corer with the sample, we subsampled the turbid water within the corer with an Imhoff settling cone. Imhoff cone water samples were allowed to settle for 20 to 25 minutes and the amount of fine sediment was recorded as milliliters of sediment per liter of water. Imhoff cone samples of stream water outside the corer produced undetectable amounts of fine sediment. Water depth in the corer was measured to the nearest centimeter allowing us to calculate intra-corer water volume.

Laboratory Analysis

Streambed samples were oven dried and shaken through a sieve series containing 76.2, 50.8, 16.0, 6.4, 2.0, and 0.063 mm mesh screens. We found that by excluding water from within the corer, oven drying time was reduced by as much as 12 hours. The material retained on each sieve and in the pan (material less than 0.063 mm) was weighed to the nearest gram. The estimated weight of the fine material sampled with the Imhoff cone was added to the weight of material less than 0.063 mm. To estimate the dry weight of sediment suspended in the water within the corer, we used the following estimator:

$$Wt_{sediment} = (Vol_{water})*(Vol_{sediment})*0.27$$

Where: $Wt_{sediment}$ = Dry weight of sediment suspended within corer.
Vol_{water} = Volume of water (in liters) within corer.
$Vol_{sediment}$ = Volume of sediment in the one liter Imhoff cone.
0.27 = Factor to convert wet volume of sediment to dry weight.

To determine the wet volume to dry weight conversion factor for fine material sampled by the Imhoff cone, we collected 11 water samples from within the corer at the time Imhoff cone samples were taken. These water samples were filtered through a 0.45 micron filter and oven dried. Dry weight of the fine sediment retained on the filter revealed that wet volume could be converted to dry weight by using a conversion factor of 0.27 (range: 0.23 to 0.33) (Shepard and Graham 1982). Streambed compositions were reported as percentage of each size class by weight.

A Kruskal-Wallis one-way analysis of variance by ranks test (Daniel 1978) was conducted to determine if significant differences existed between creeks by year for percentages of fine material less than 6.4 mm and less than 2.0 mm. If a significant difference was found, Mann-Whitney tests (Daniel 1978) were run on each pair of creeks by year.

Streambed Composition and Bull Trout Embryo Survival

In early September, 1983 eight artificial redds were constructed in a bull trout spawning area in Coal Creek. Each artificial redd had a tailspill area approximately 2.0 m long when completed, similar to the size of a natural redd (Shepard et al. 1984). A streambed sample was removed from each tailspill area, using methods described above, prior to planting fertilized eggs.

Adult bull trout were captured and spawned on 12 September, 1983. The ripe fish were anesthetized and eggs were taken dry, fertilized, and allowed to water harden. One hundred fertilized eggs and some natural stream gravels were placed in each of 32 fiberglass screen bags. Half the bags were stapled shut and planted approximately 15.0 cm deep in the four downstream redds. These closed bags were used to monitor embryo survival and development. The other 16 bags were left open at the top, allowing fry to emerge, and placed in the four upstream redds. Care was taken to ensure that each open egg bag remained upright during the planting procedure. Cylinders of wire screen were placed around each open egg bag to prevent lateral emigration of emerging fry.

Gravel was placed over each artificial redd after egg bags were planted and the tailspills were covered with 12.7 mm mesh screening to prevent natural spawning activity from disturbing artificial redds. This screening was removed after natural spawning was completed.

Survival and Development

On 24 October, 1983; 13 January, 1984; 20 February, 1984; and 6 March, 1984 egg bags were removed from the four downstream redds. Live and dead embryos from each bag were enumerated and preserved. Once embryos reached the alevin stage, 40 alevins were measured at each sampling period. A thermograph recorded water temperatures throughout the incubation period.

Fry Emergence

In late February 1984, emergence traps (Phillips and Koski 1969, Fraley and Graham 1982) were placed over all open egg bags. These traps were placed on the wire screen cylinders to ensure all emerged fry were captured. Emergent fry were enumerated and a subsample of up to 50 fry were measured and preserved. Three egg bags were excavated on 23 April, seven were excavated on 18 May, four were excavated on 28 May, and the remaining two were excavated on 18 June. All live and dead embryos remaining in the egg bags were enumerated and recorded by life-stage (ie. dead eggs, dead alevins, live alevins). Streambed samples were again taken with the corer.

Temperature units required for each stage of development were estimated using daily mean temperatures from thermograph records. The relationship between fry emergence and percentage of streambed material less than 6.4 mm was evaluated using a regression computer program (Lund 1983).

Juvenile Rearing Versus Streambed Composition

Relationships between juvenile bull trout rearing capacity and streambed composition were examined as part of the Swan River drainage study. Aerial pre-surveys were conducted for all streams in the Swan River drainage during the summer and fall of 1982 to delineate stream reach boundaries. Reaches were defined as continuous stream sections having "a repetitious sequence of physical processes and habitat types" (Chamberlin 1981). Changes in channel gradient and stream habitat uniformity were the two predominant factors defining reach boundaries.

Streambed Composition

Physical stream habitat surveys were conducted by crews of two technicians on a one or two kilometer section of each reach. Representative survey sections were located during aerial surveys. Fifteen randomly selected channel cross sections were sampled in each survey section as described by Shepard and Graham (1983b). Ocular streambed composition estimates were made for a minimum of five equally spaced cells across each transect. Within each cell we recorded the dominant and subdominant particle size classes and ranked the extent to which the dominant particles were embedded in sand and silt (table 1). The ranks for each of these three substrate characteristics within each cell were added together to produce a modified version of substrate score (Crouse et al. 1981).

A combined frequency distribution for dominant and subdominant particle size groups was used to determine the streambed composition (in percent) within each reach. Reach substrate scores were calculated by averaging the substrate scores for all cells examined in the reach. Generally, substrate composition estimates were made for 80 to 120 cells within each reach.

Juvenile Fish Population Estimates

Fish population estimates were made in 100 to 150 m long sections within each habitat survey section. Electrofishing sections were isolated by blocking their downstream boundary by 12.2 mm mesh nylon netting or hardware cloth. Upstream movement was prevented by a natural velocity barrier or a block net.

Table 1.--Substrate characteristics and associated ranks for calculating substrate score (modified from Crouse et al. 1981).

Rank	Characteristic
	Particle size class (range)
1	Silt and/or detritus
2	Sand (<2.0 mm)
3	Small gravel (2.0-6.4 mm)
4	Large gravel (6.5-64.0 mm)
5	Cobble (64.1-256.0 mm)
6	Boulder and bedrock (>256.0 mm)
	Embeddedness[a/]
1	Completely embedded (or nearly so)
2	3/4 embedded
3	1/2 embedded
4	1/4 embedded
5	Unembedded

a/ Extent to which dominant sized particles are buried in sand and silt (see Bjornn et al. 1977 for an illustration).

Electrofishing was done using a gas powered backpack electrofishing unit in smaller streams and bank electrofishing gear on large (streamflow higher than 0.6 cms) accessible streams. Population estimates were calculated for fish 75 mm and larger using primarily the two-sample removal method, or occasionally using three-sample or mark-recapture techniques (Seber 1973). A more detailed description of estimation techniques can be found in Leathe and Graham (1983). Juvenile bull trout density (number of fish longer than 75 mm per 100 m^2 of stream surface area) was regressed against substrate score (Lund 1983).

Estimation of Sediment Loads to Swan River Tributaries

Annual sediment loads were estimated for 78 stream reaches in the Swan River drainage using erosion coefficients developed by soil scientists and hydrologists of the Flathead National Forest. These sediment delivery coefficients were based on a landtype classification system which accounts for variability in vegetation, soil characteristics, and physical slope functions. Both natural and man-induced erosion was simulated. Roads and timber harvest were the sources of man-induced erosion. Road sediment coefficients were based on ground exposed in road surface, cut slope, fill slope, and drainage ditches. Logging-related sediment was estimated by considering skid trail requirements for various size clearcuts. Recovery of disturbed sites was accounted for in the analysis by decreasing sediment coefficients as age of disturbance increased. Sediment produced in areas upstream from the reach of interest was routed to the reach using delivery ratios based on drainage area (Cline et al. 1981).

Road building and timber harvest histories were assembled into a chronological database for the study area. Records were available for all transportation system roads. Clearcut logging was the only type of timber harvest assumed to produce significant amounts of additional sediment. Clearcut information was available for the previous six years. A computer program was developed to calculate annual sediment loads by reach. The program applied appropriate sediment coefficients for land within each drainage and summed both natural and man-induced sediment loads delivered to each stream reach.

Using a multiple regression program (Lund 1983), relationships between sediment loads and existing substrate conditions were examined. Forty-six individual reaches were included in the analysis. Stream channel characters such as channel gradient, number of pools, and debris frequency were also tested as determinant variables in the prediction equation. Three expressions of streambed composition were entered as dependent variables: percentage of fine material less than 2.0 mm, percentage of fine material less than 6.4 mm, and substrate score.

RESULTS

Streambed Composition of Spawning Areas

The streambed monitoring program for tributaries to the North Fork of the Flathead River identified significant differences in percentages of material less than 2.0 mm between creeks all three years, and significant differences in percentages of material less than 6.4 mm between creeks in 1982 and 1983 (table 2). Spawning areas in Coal Creek had significantly higher percentages of fine material than the other three creeks during all years (table 3). Material less than 6.4 mm consistently comprised 34-39% of Coal Creek's spawning areas, while material less than 2.0 mm made up 16-18%. Spawning areas in the other three creeks contains 25-33% less than 6.4 mm and 8-13% less than 2.0 mm. Within creeks, no significance between year differences were found except for material less than 6.4 mm in Whale Creek between 1981 and 1982 ($p<0.025$).

Table 2.—Mean and median percentages of streambed material less than 2.0 mm and less than 6.4 mm in bull trout spawning areas of Big, Coal, Whale and Trail creeks during 1981 through 1983 with results of Kruskal-Wallis one-way analysis of variance by ranks tests between creeks.

	Percent material <6.4 mm				Percent material <2.0 mm			
	Big	Coal	Whale	Trail	Big	Coal	Whale	Trail
1981								
n[a]	11	20	13	20	11	20	13	20
Mean	26	34	25	26	8	16	8	11
Median	25	34	27	25	9	16	6	11
Ranks[b]	314.5	879.5	323.5	562.5	229.5	923.5	281	646
H[c]			5.7 n.s.				19.5 **	
1982								
n	10	20	11	19	10	20	11	19
Mean	28	38	32	23	9	18	12	10
Median	31	39	31	22	10	17	11	10
Ranks	246.5	904.5	344	335	211.5	885	303	430.5
H			25.7 **				19.4 **	
1983								
n	12	20	12	12	12	20	12	12
Mean	28	37	33	28	11	18	13	13
Median	28	39	32	27	11	18	12	13
Ranks	211	779.5	369	236.5	223.5	789.5	286	297
H			17.3 **				15.1 **	

a/ Sample size (n) is the number of cores.
b/ Ranks is the sum of ranks for each creek.
c/ "H" is the test statistic for the Kruskal-Wallis one-way analysis of variance by ranks and is distributed approximately as a chi-square with k-1 degrees of freedom. Levels of significance are: 99 percent (**), 95 percent (*), and not significant (n.s.).

Table 3.—Results of Mann-Whitney[a] tests for percentages of fine material less than 6.5 mm and less than 2.0 mm between Big, Coal, Whale, and Trail creeks by year (1981-1983).

	Percent material <6.4 mm			Percent material <2.0 mm		
	1981[b]	1982	1983	1981	1982	1983
Coal versus						
Big	—	**	**	**	**	**
Whale	—	*	n.s.	**	*	**
Trail	—	**	**	**	**	**
Big versus						
Whale	—	n.s.	*	n.s.	n.s.	n.s.
Trail	—	n.s.	n.s.	*	n.s.	n.s.
Whale versus						
Trail	—	*	n.s.	*	n.s.	n.s.

a/ Levels of significance are: 99 percent (**), 95 percent (*), and not significant (n.s.).
b/ Two-way comparisons were not done for material less than 6.4 mm in 1981 because the Kruskal-Wallis test showed no significant difference between creeks.

Relationship Between Streambed Composition and Bull Trout Embryo Survival

Streambed Composition in Artificial Redds

The streambed in eight artificial redds in Coal Creek prior to planting egg bags contained an average of 42%, by weight, of material smaller than 6.4 mm (range: 36-50%) and 19% material smaller than 2.0 mm (range 15-23%). The core samples taken from artificial redds were found to contain higher percentages of fine materials than core samples taken from the surrounding undisturbed streambed. These higher percentages of fines in the artificial redds may reflect a trapping of fine sediments during construction of the redds.

Survival and Development of Trout Embryos

Two sealed egg bags were removed on 6 March, 1984. Eye-up and hatching were estimated to occur after 35 and 113 days, respectively, or after accumulating 200 and 350 temperature units, respectively. Length of alevins averaged 19.3 mm (n = 40) on 13 January, 23.6 mm (n = 40) on 20 February, and 26.6 mm (n = 20) on 6 March. Average survival observed in sealed egg bags was 71% to the eyed stage and 60-64% to hatch. Subsequent calculations for emergence success assumed 71% of the eggs in each open egg bag were viable.

Emergence of Bull Trout Fry

Fry emerged from 23 April through 28 May. Fry emergence was first observed and the majority of fry emerged (83%) in a four-day period from 23

April to 27 April during and following a preliminary spring peak flow. Approximately 634 temperature units had accumulated during the 223 day incubation period. During the first day of emergence sampling (following the preliminary peak event), 315 fry were captured, averaging 27.2 mm (n = 50). More than half of these emerged fry were dead, indicating emergence had probably occurred during the previous three days of high flows. Overall emergence success from artificial redds in Coal Creek was 53%. Embryo survival and subsequent fry emergence success was highly correlated ($r^2 = 0.87$) to percentage of fine material less than 6.4 mm within the streambed (fig. 2). Ninety dead alevins were found in excavated egg bags indicating entombment and/or crushing may have occurred.

Juvenile Rearing Versus Streambed Composition

Relationships between juvenile bull trout density and streambed characteristics were determined using information collected during 1982 and 1983 in 26 stream reaches in tributaries to the Swan River. These reaches were selected because they were accessible to migratory bull trout. Juvenile bull trout densities (fish 75 mm and longer) in these reaches ranged between three and 270 fish per 300 m of stream length and from 0.1 to 12.4 fish per 100 m^2 of wetted stream surface. Percentage of fine material (less than 6.4 mm) ranged from 4-89% and substrate scores ranged from four to 15.

Significant statistical relationships were observed between the logarithm of juvenile bull trout densities (fish per 100 m^2 of wetted stream surface) and both the percentage of streambed material less than 6.4 mm and substrate score. The correlation between juvenile bull trout density and substrate score ($r^2 = 0.40$, $p < 0.001$; fig. 3) was more significant than was the relationship between juvenile bull trout density and the percentage of material less than 6.4 mm in the streambed ($r^2 = 0.33$, $p = 0.002$).

Estimation of Sediment Loads to Swan River Tributaries

Natural sediment loads estimated for Swan River tributaries in 1983 were roughly proportional to drainage basin size and varied from 173 to 8,810 tons per year. Road construction and maintenance accounted for the majority of man-induced sediment loads to streams. In 1983, roads produced 0.2 to 303 tons of sediment in the 46 study reaches, representing from 0-79% over natural sediment loads. Logging-related sediment varied from 0.9 to 160 tons per year representing 0-5% over natural sediment loads.

Increase in sediment loads due to road development (expressed as a percentage over natural after Stowell et al. 1984) was correlated ($p<0.01$) with three different expressions of substrate composition (substrate score, percentage of streambed material less than 6.4 mm, and percentage of streambed material less than 2.0 mm). Stream gradient was inversely related to streambed composition ($p<0.001$). No other stream variables tested were significantly related to streambed condition nor was the association between sediment yield and clearcutting a significant variable in any of the regression.

The highest coefficient of determination ($R^2 = 0.56$) was obtained by regressing percentage increase in sediment over natural due to roads and a logarithmic transformation of stream gradient

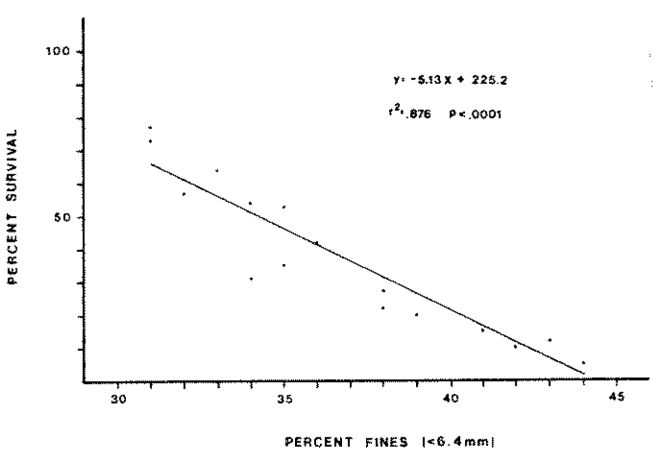

Figure 2.--Relationship between percentage of fines (material less than 6.4 mm) within the streambed and percentage survival of bull trout embryos through emergence in Coal Creek, a North Fork Flathead River tributary, during 1984.

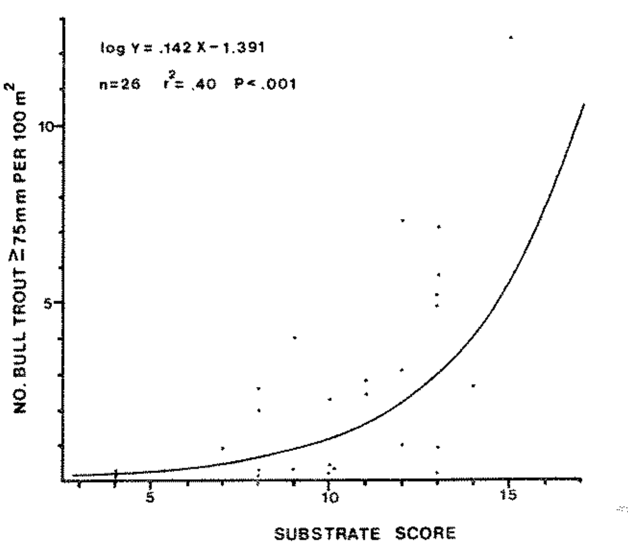

Figure 3.--Relationship between juvenile bull trout density (fish ≥75 mm per 100 m^2 of stream surface area) and streambed substrate score for 26 stream reaches in the Swan River drainage, Montana.

against substrate score (fig. 4). The regression coefficient for sediment produced from road development was associated with decreased substrate scores. Decreasing scores are associated with increasing levels of fine sediment (illustrated by a strong inverse linear regression: $r^2 = 0.91$) and increased embeddedness.

DISCUSSION

Streambed Composition versus Bull Trout Spawning Success and Rearing Capcity

Streambed sampling allowed us to document the relative condition of bull trout spawning areas in four Flathead River tributaries (Trail, Whale, Coal and Big creeks). Based on these samples and using estimated fry emergence success computed by Tappel and Bjornn (1983) for chinook salmon, we estimated bull trout fry emergence success would be between 40% and 60% in Coal Creek (Shepard and Graham 1983b). Actual bull trout emergence success in Coal Creek averaged 53%.

Based on the results from artificial redds in Coal Creek, survival of bull trout embryos through emergence appeared to be unaffected when the percentage of material less than 6.4 mm comprised up to 30% of the streambed. However, at levels of fine sediment above 30%, embryo survival through emergence dropped off sharply. When the streambed contained nearly 40% fine material, survival to emergence fell below 20%. Bull trout embryos incubated in Coal Creek appeared to be more tolerant of fine sediment than cutthroat trout (unpublished data, Idaho Cooperative Fisheries Research Unit, University of Idaho, Moscow, Idaho), steelhead trout (Tappel and Bjornn 1983), and brook trout (Hausle and Coble 1976), although bull trout embryo survival appeared to be similar to survival reported for chinook salmon embryos (Tappel and Bjornn 1983).

Densities of juvenile bull trout declined sharply when substrate scores fell below 12 (or when the streambed contained more than 30% material less than 6.4 mm). Bjornn et al. (1977) found that when embeddedness levels increased, summer and winter rearing capacity generally decreased for juvenile steelhead trout and chinook salmon. Crouse et al. (1981) found that increased sedimentation suppressed production of juvenile coho salmon.

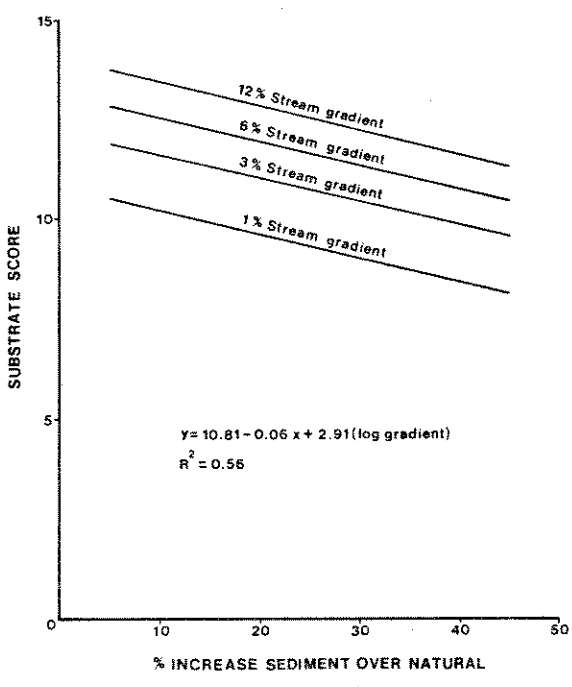

Figure 4.--Predicted response of streambed substrate score in streams of various gradients to changes in sediment loading rates (expressed as percent increase above natural levels) attributed to the construction and maintenance of roads in tributary drainages of the Swan River, Montana.

Land Use and Stream Sediment

The significant relationship between road development and stream substrate score found for tributaries to the Swan River is in agreement with previous studies that suggested roads were the major source of sediment produced during timber harvest activities (Megahan and Kidd 1972, Gibbons and Salo 1973, Anderson et al. 1976). Mass soil movements caused by changes in soil hydrology and loss of root cohesion after timber harvest reported to occur in other regions (Swanston 1970 and 1971, DeGraff 1979) have not been documented in the Flathead River Basin.

In spite of the multitude of hydrologic variables affecting sediment dynamics of mountain streams, increased sediment loads attributed to road development accounted for a significant portion ($p<0.001$) of the variation in streambed composition. Stream channel gradient was also an important variable which must be included in any analysis (fig. 3). It is worth noting that annual sediment loads expressed as a percent increase over natural levels provided the best regression fit, suggesting that streams in the study area are supply-limited in their undisturbed state (Megahan 1979).

Limitations of Sampling

We can document the streambed composition in spawning areas, but we presently have no quantitative data describing the source of fine sediments found in these spawning areas. The results from this streambed sampling program illustrated the ability of streambed monitoring in spawning areas to quantify changes in levels of fine sediments between creeks. We assume that long-term monitoring would detect changes in streambed composition over time.

The Coal Creek emergence success study was conducted in a relatively narrow range of streambed compositions (levels of material less than

6.4 mm ranged between 31% and 44%). To best quantify the relationship between fine sediment and bull trout spawning success, tests should be conducted in spawning gravels containing a wide range of fine sediment. The spawning area in Coal Creek where the field experiment was conducted has an unknown amount of groundwater entering the creek. This groundwater may have moderated the effect of fine sediment by flushing metabolic wastes away from the embryos and delivering oxygen to the embryos, although we did not measure the amount of dissolved oxygen carried by this groundwater.

The relationship between juvenile bull trout rearing capacity and substrate score developed in the Swan River drainage was based on the validity of ocular estimates of streambed condition and our assumption that observed densities of juvenile bull trout represented carrying capacity. Platts et al. (1983) found that some difficulty existed in accurately estimating particle sizes and embeddedness using ocular surveys. We have no way of verifying whether study streams were fully seeded with bull trout fry from natural reproduction. Regardless of these two problems, we obtained a significant correlation relating juvenile bull trout density to streambed condition. We recognize the fact that streambed condition was not the only physical habitat variable controlling juvenile bull trout densities, but it is a variable related to land-use practices.

The use of substrate score to describe streambed condition versus juvenile bull trout density resulted in a stronger correlation ($r^2 = 0.40$) than using percentage of material less than 6.4 mm or 2.0 mm (r^2's of 0.33 and 0.32, respectively). The advantage of using substrate score is that it can be obtained using ocular surveys, so it is a quick and inexpensive way to estimate streambed condition. The disadvantage is that it is not as easy to quantify as replicated streambed samples using a hollow core sampler.

Sediment Versus Bull Trout Recruitment

The functional response of juvenile bull trout densities to increasing levels of fine sediment could be caused by several factors. Studies have shown that during the summer juvenile bull trout hold positions close to the stream bottom and often seek cover within the substrate itself (Griffith 1979, Oliver 1979, Pratt 1984). Any loss of interstitial space or streambed complexity through the deposition of fine sediment would result in a loss of summer habitat. Winter habitat used by juvenile bull trout has not been identified, although studies of other salmonids have suggested deep pools (Lewis 1969, Chapman and Bjornn 1969, Bjornn et al. 1977) or streambeds composed of rubble and gravel (Everest 1969, Bustard and Narver 1975, Bjornn et al. 1977) provide important winter habitat. Deposition of sediment on the streambed reduces streambed complexity and pool volume and may lower winter carrying capacity (Bjornn et al. 1977). Food production in the form of aquatic invertebrates may also be reduced by sedimentation (Gibbons and Salo, 1973, Bjornn et al. 1977, Iwamoto et al. 1978).

The manner in which bull trout recruitment is affected by fine sediment can be evaluated by examining the relationship between the number of eggs deposited in a stream and the subsequent number of juvenile bull trout recruited to the lake population. This relationship can be described using a Beverton-Holt (Ricker 1975) stock-recruitment curve (fig. 5). Deposition of fine sediment lowers rearing capacity (shifting the upper limit of the curve from level A down to level B) because it reduces summer and winter habitat capacity and limits aquatic insect production. Deposition of fine sediment in spawning gravels decreases egg-to-fry survival which would limit juvenile bull trout recruitment only if egg deposition was at the asymptote of the curve (point C or F on fig. 5) or below. If the number of spawning adults returning to the stream deposited fewer eggs than were required to fully seed the stream, the effects of fine sediment on egg-to-fry survival would be more important than effects on juvenile rearing capacity (a reduction in number of recruited juvenile bull trout from point D to point E on the curve in fig. 5). If egg deposition was in excess of the number required to fully seed the stream (more than point C or point F on the curve in fig. 5) then the number of recruited juvenile bull trout would be controlled by the amount of rearing habitat available. If escapement of adults provided just enough eggs to fully seed the stream (point C or F on fig. 5) at levels of fine sediment which were not impacting egg-to-fry survival and additional fine sediment was deposited in the spawning areas, the only way to ensure that fry production remained adequate would be to reduce the harvest on adult spawners to allow more eggs to be deposited. The reduction of rearing habitat caused by sedimentation will ultimately reduce the potential number of recruited juveniles and additional egg deposition above the level required to fully seed the rearing

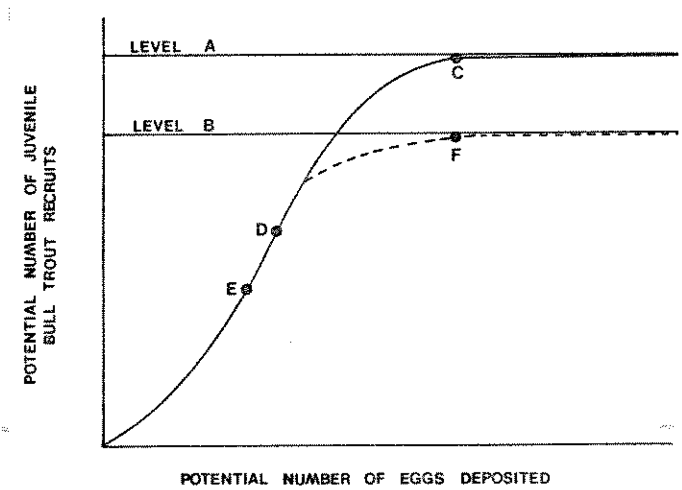

Figure 5.--Theoretical relationship between the number of bull trout eggs deposited and subsequent number of juvenile bull trout emigrating from a tributary stream. Adapted from Beverton-Holt (Ricker 1975).

habitat (point F on the curve) will not result in any additional juvenile bull trout recruited to the population. Land managers could possibly return the stream to its full potential for producing recruits through an intensive habitat enhancement program or by restricting land disturbing activities in a drainage allowing fine sediment to be flushed out of the streambed. Reducing recruitment of juvenile bull trout from a single tributary may not, by itself, represent a significant loss to an adfluvial lake population; however, the cumulative reduction of recruitment from a number of tributaries could result in a significant loss.

Management Implications

Increasing levels of fine sediment in bull trout spawning and rearing streams might significantly impact adfluvial bull trout populations by reducing the number of bull trout recruited from sediment-impacted streams. Land managers should be made aware of the consequences of increasing sedimentation rates in these sensitive drainages and consult fisheries professionals when land development activities are proposed. For their part, fisheries professionals should monitor streambed composition in important spawning and rearing tributaries and provide justification for any fisheries constraints placed on land management.

Sediment models, such as the one described above, can be used as a management tool for evaluating impacts of resource development on streambed composition. Coupled with predictive equations to estimate fry production and juvenile recruitment, this sediment model would allow land managers and fisheries biologists to develop management strategies which minimize or prevent unacceptable fisheries losses while maintaining the production of commodities. These strategies should include management practices described by the Western Division of the American Fisheries Society (1982). One suggestion not included in this report would be to construct roads over a long time period prior to any management activity, allowing land disturbed by road building to recover before other land disturbing activities commenced. Road systems should be built slowly, allowing each segment of the system three years to recover before the next portion of the road system is constructed. Incorporation of these practices would demand visionary land management planning, but would be well worth the effort.

The alternative to proper planning of land management activities is the loss of important habitat and the difficult decisions that must be faced to restore that habitat. Streams are dynamic systems that can, given the time, flush sediment from their streambed; however, to allow the hydraulic flushing of this sediment, no additional source of sediment can be added to the stream channel (Megahan et al. 1980). This can only be accomplished by instituting a moritorium on land activities for up to 20 years (ibid).

Recommendations

1. Streambed monitoring of known salmonid spawning areas should be included as part of any monitoring program established to evaluate the impact of land management activities on salmonid populations.

2. Regional intensive long-term watershed studies are needed to determine the sources of sediment from various land management activities (road building, various timber harvest prescriptions, grazing, etc.), delivery of that sediment to stream channels, and routing of that sediment through the stream channel including where that sediment is deposited and streamflows required to flush sediment out of stream gravels.

3. The relationship between streambed composition and bull trout embryo survival and fry emergence needs to be better defined over a wide range of streambed compositions. A laboratory study is presently underway at the Montana State Cooperative Fisheries Research Unit to develop predictive "survival bands" for bull trout incubation and emergence versus streambed composition similar to those developed by Tappel and Bjornn (1983).

4. The influence of groundwater on bull trout embryos needs to be better understood to fully evaluate the impacts of fine sediment on bull trout embryo survival because bull trout appear to spawn in areas influenced by groundwater (Graham et al. 1981).

5. How sediment impacts juvenile rearing capacity needs to be further investigated to determine what functional aspects of rearing habitat (summer rearing habitat, food production habitat, overwinter habitat, etc.) limits rearing capacity and what, if any, habitat improvement measures might mitigate sediment impacts.

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