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SOUTHERN FOREST EXPERIMENT STATION

sediment

in a michigan trout stream

its source, movement & some effects on fish habitat

EDWARD A. HANSEN

NORTH CENTRAL FOREST EXPERIMENT STATION
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

North Central Forest Experiment Station
D. B. King, Director
Forest Service - U.S. Department of Agriculture
Folwell Avenue
St. Paul, Minnesota 55101

(Maintained in cooperation with the University of Minnesota)

The author is a Hydrologist for the Station. His project is headquartered at Cadillac, Michigan.

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SEDIMENT IN A MICHIGAN TROUT STREAM

Its Source, Movement, and Some Effects on Fish Habitat

Edward A. Hansen

A large area of the Lake States is covered by a deep mantle of sandy glacial drift. Streams in this area generally have lower sediment concentrations than other areas of the United States. Even so, stream sediments are slowly filling harbors and reservoirs and possibly damaging fish habitat.

Much stream improvement work, including bank stabilization, has been done to reduce the already low sediment concentration in these streams and, in turn, improve the fish habitat. However, there is very little quantitative information on the sediment regime of streams in the Lake States, or the effects of bank erosion on sediment load (Striffler 1964). Also, the few studies on the effect of stream improvement programs on fish populations have not investigated the impact of sediment reduction on the aquatic environment (Tarzwell 1937, Shetter *et al.* 1949, Hale 1969, Hunt 1969).

This paper gives the results of a study designed to determine the sediment sources, the size and quantity of bank sediments, the timing of delivery, and the method of transport. The change in sediment load and streambed composition, and some possible effects of streambank stabilization are also presented for a section of stream with many eroding banks.

THE STUDY AREA

The study was made from 1967 through 1969 on the Pine River, tributary of the Manistee, in the northwestern part of Michigan's Lower Peninsula (fig. 1). The Pine River is a relatively high gradient pool and riffle stream with a long section of eroding banks. The river drains a 265-square mile watershed above Stronach Dam. The 640-acre-foot capacity reservoir at Stronach Dam was completely filled with sediment in 40 years (1912-1953) and power generation was terminated shortly thereafter. The Michigan Department of Natural Resources built fish habitat improvement devices and stabilized most of the eroding banks in the upper part of the watershed in the mid-1950's. However, no work was done in the lower part of the watershed which includes the study area.

The study section, which includes 204 eroding banks, is 26 miles in length measured along the meandering stream; the straight line distance is about half as much. The mean stream width is 55 feet and mean depth is 2.2 feet, with pools 4 to 8 feet in depth. Mean stream gradient is 0.00175, or about 9 feet per mile.

Stream discharge increases 80 percent as it passes through the study section. Only 14 percent of this increase comes from the three major tributaries; most of the remainder originates from springs, seeps, and ground water inflow through the streambed.

The discharge at a relatively long-term U.S. Geological Survey gaging station situated 5 miles upstream from Stronach Dam has averaged 282 c.f.s. during the 17 years of record. The minimum discharge was 161 c.f.s., and the two largest peaks were 1,430 c.f.s. and 2,440 c.f.s. The mean discharge 5 miles downstream at Stronach Dam is about 30 percent greater. However, peak discharges are about the same due to the storage capacity of a broad flood plain above Stronach Dam and a lack of surface runoff between the two stations.

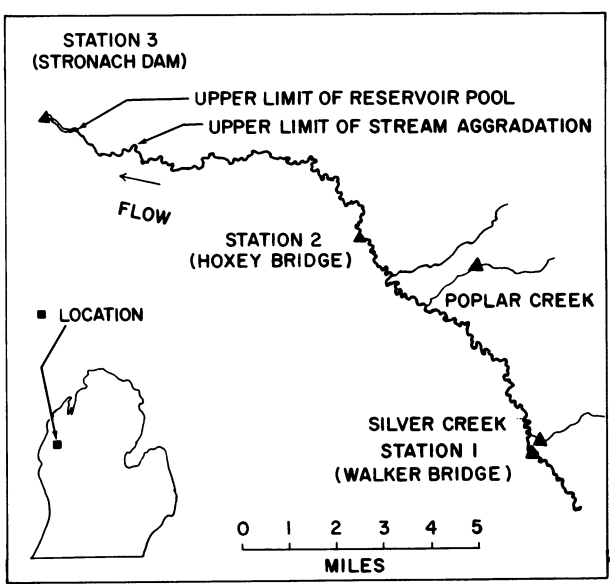

Figure 1. — *Pine River study area.*

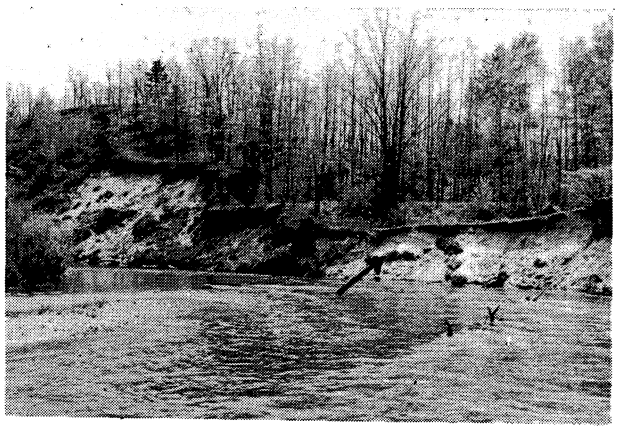

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Figure 2. — *River terraces 11, 17, and 40 feet above the present water surface. Arrow shows location of photo in figure 3.*

The Pine is a geologically youthful stream — entrenched about 100 feet into sandy glacial outwash and moraines. Large inclusions of consolidated clays occur that are highly resistant to erosion. However, because the ground surface of the entire area is covered with sand, the presence and extent of the clay masses can only be inferred by their exposure in eroding streambanks and by the occurrence of swamps on the uplands. The stream has gradually eroded away the loose sand, consolidating the small amounts of gravel and leaving the more resistant clay masses exposed. The clay acts as a control for many, if not most, of the rapids on the river. These clay controls often have a thin veneer of cobbles and boulders which may add to their durability.

Evidence of past meandering is present in river terraces at levels high above the stream (fig. 2). Eroding banks that intersect the old elevated stream channels often expose bands of stream-laid gravels (fig. 3). These deposits, like the present streambed gravels, are rarely more than 12 to 18 inches thick. Underneath the gravel is the glacially deposited sand or sometimes a clay inclusion.

As the Pine meanders across the valley, it moves laterally off its gravel pavement. However, at the same time it erodes into the old terraces with their alluvial gravel deposits. Thus, it is likely that the amounts of gravel gained and lost to the stream channel by lateral erosion are nearly equal.

METHODS

Definitions

Bedload. — sediment that moves in essentially continuous contact with the streambed by rolling, sliding, or saltation.

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Figure 3. — *Ancient gravel streambed deposits now exposed by streambank erosion. Gravel lies on top of uncohesive sand glacial drift, a situation common with many present-day streambed gravel areas.*

Bedload discharge. — the quantity of bedload passing a given stream cross section in a unit time.

Bed material. — sediment composing the bed of the stream.

Suspended sediment. — sediment that is moved in suspension in water and is maintained in suspension by the upward components of the stream turbulence, or by colloidal suspension.

Suspended sediment discharge (or load). — the quantity of suspended sediment passing a given stream cross section in a unit time.

Total sediment discharge (or load). — the quantity of total sediment (suspended sediment plus bedload) passing a given stream cross section in a unit time.

Unsampled zone. — the distance between the streambed and the lowest point in the vertical profile of a stream at which suspended sediment can be sampled with a U.S. series sediment sampler; usually about 0.3 foot.

Study Design

Three sediment sampling stations were located on the main channel of the Pine River and will hereafter be referred to as Stations 1, 2, and 3 (fig. 1). These stations were in operation for a 3-year period. Station 1, the uppermost station, was located at Walker Bridge several miles below the last stream improvement work done by the Michigan Department of Natural Resources. Station 3, the lowermost station, was 26 miles downstream at Stronach Dam. Station 2 was located at Hoxey Bridge, midway between Stations 1 and 3. Two other sampling stations

were on Poplar and Silver Creeks, tributaries of the Pine between Stations 1 and 2. These tributary sampling sites were in continuous operation only during the last year of the study, although intermittent sampling was done prior to that.

Total sediment load was meaured at Station 1, above which there was relatively little sediment contribution, and again at Station 3, 26 miles downstream. The data collected on Poplar and Silver Creeks, two of the three main tributaries, permitted an approximation of the total tributary sediment contribution. Observation of the three road crossings on the main stream between Stations 1 and 3 indicated that their contribution could be safely assumed as zero. Overland flow to the main channel almost never occurred. Therefore, most of the measured sediment increase between Stations 1 and 3 would be attributable to bank erosion or tributary input. Since tributary input was being measured, the bank contribution could be estimated by the difference.

Even though Stronach reservoir above Station 3 is filled with sediment, deposition will theoretically continue until the stream gradient through the reservoir approaches that of the original channel; or in the case of a pool and riffle stream, deposition will continue until the increased slope is great enough to transport the available sediment load. Changes in stream morphology indicate that deposition has occurred up to 2.8 miles upstream from the dam and 1.8 miles upstream from the original reservoir limit (fig. 1). Significant deposition would reduce the measured sediment load at the dam, which would result in an underestimate of both the total sediment load and the eroding bank contribution. Consequently, five permanent profiles were established across the valley to detect any appreciable current flood plain building. These profiles were surveyed annually.

Sediment Sampling Techniques

Sediment samples were collected weekly at each sediment sampling station, except during floods when up to three samples a day were collected. Hand operated DH-48 and DH-59 sediment samplers utilizing a 1-pint sample container were used. Samples were collected by the "equal transit rate" technique, which consists of sampling at several equally spaced points across the stream (Inter-Agency Committee on Water Resources 1963). At each point the sampler is traversed at a constant rate throughout the complete vertical profile of flow. The number of sampling points per station ranged from five to 17, depending upon stream width and discharge.

Because the samplers could not operate closer than 0.3 foot from the streambed, wooden sills were constructed to force all bedload off the streambed as it passed over the sill. The sills were made of 2-inch lumber placed on edge so that they protruded about 3 inches above the original bed of the stream and extended completely across the streambed perpendicular to the flow. A sill was not required at Station 3 where the sampling was done over the metal control gates at the dam, which effectively eliminated any unsampled zone. The sediment samples were collected by lowering the sampler down through the vertical profile of flow until the sampler intake touched the sill or metal control gate, and then raising it back to the surface (fig. 4). A metal guide was used for positioning the sampler when high turbidity obscured the sill or gate.

Since the samplers collect sediments adequately only up through the sand size range (2.0 mm.), a "screen" sampler was devised to sample the gravel size sediment. This is a 44 by 305 mm. rectangular open box with a 1 mm. mesh screen sack attached to the downstream end to trap the sediments. The

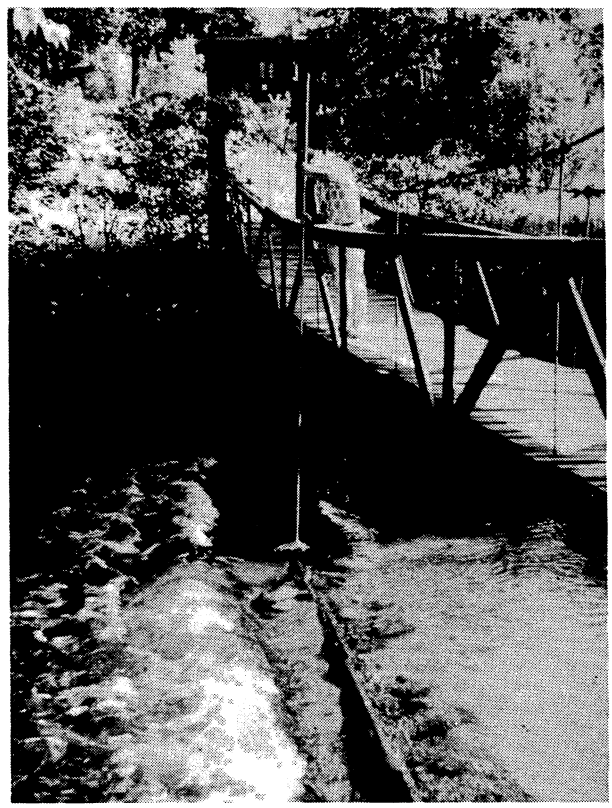

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Figure 4. — *Sampling the sediment load at a wooden sill.*

Table 1. — *Eroding streambanks by size, percent of waterline eroded, and texture (In number of banks)*

Soil class	Small banks (100-200 sq. ft. soil exposed)				Medium banks (201-2,000 sq. ft. soil exposed)				Large banks (>2,000 sq. ft. soil exposed)			
	Percent of waterline eroded:				Percent of waterline eroded:				Percent of waterline eroded			
	1-10	11-30:	31-70:	71-100:	1-10	11-30:	31-70:	71-100:	1-10	11-30:	31-70:	71-100
90+ percent sand[1/]	2	7	3	13	11	11	2	10	2	2	2	5
90+ percent clay	3	4	2	8	4	2	7	3	4	0	2	12
10+ percent sand and 10+ percent clay	0	1	2	4	3	3	1	4	5	1	5	18
5+ percent gravel and sand or clay	0	3	5	6	1	2	7	8	1	0	2	1

[1/] Percent of exposed bank face covered by given soil class.

metal sides are flared 10° to compensate for head loss. The sampler was hooked on to the sill at different points for a constant timed interval.

Several checks indicated that the data collected with the instruments and techniques outlined above adequately represented the total sediment load (Hansen 1970).

All sediment samples were analyzed for total sediment concentration and for the percent of material greater than 0.062 mm. (sand size and larger). In addition, a particle size distribution of material greater than 0.062 mm. was made on selected DH-48 and DH-59 samples and on all of the "screen" samples.[1]

Channel Survey

Stream cross sections were mapped at 1/3-mile intervals along the upper 23 miles of stream channel to determine the relationship between changes in sediment load and stream channel characteristics. Stream width, depth, and gradient measurements were made at all of the 70 cross sections. Stream bottom composition was mapped by size classes, and the material was probed to a maximum depth of 18 inches to determine the thickness of deposits. Bed material samples were collected in sand-bed areas at the same 70 locations to determine: (1) The size relationship between bed material and total load in those areas having an erodible bed, (2) the minimum particle size present and hence the minimum size moved as bedload in sand-bed areas, and (3) whether large changes in water discharge, sediment discharge, and gradient along the stream had any effect on the particle-size distribution in sand-bed areas. Bed material samples were also collected from six coho salmon (*Oncorhynchus kisutch* (Walbaun)) spawning beds located in gravel areas. The samples were collected on November 24, 1967, shortly after spawning, and 3 months later on February 25 before egg hatching.

Streambank Survey

The 204 eroding banks were tentatively stratified into classes that were believed to be related to erosion rates. These classes were based on area of exposed soil (bank size), soil texture, and evidence of recent waterline erosion; i.e., devoid of vegetation (table 1). A 24-percent sample was randomly selected from each class or, when few banks were present, a group of closely related classes. Thus, 48 banks were selected for annual surveys to determine the volume of erosion.

Permanent bench marks placed along the top of the surveyed banks were used as reference points from which to measure the recession rate of the bank crest. Also, they were used to establish points along the crest so that profiles could be surveyed down the bank face at 10-foot intervals. The volume of eroded material was obtained graphically by plotting the annual profiles and measuring the cross-sectional area between them. The eroded area multiplied by the width of the bank gave the volume eroded from that section. The volumes eroded from all sections were then summed to obtain the total erosion for the bank. The volume of material eroded from the unsurveyed banks was estimated from these data.

Soil samples were collected by textural class from each bank for particle-size analysis.

RESULTS

Flood Frequency

The interpretation of data must be done within the limitations imposed by the storm events and the resultant hydrologic conditions that were encountered. Therefore, a brief comparison was made between the study period and the previous 14 years of record on

[1] *Most of the basic sediment load data used in this paper are published (USDI Geological Survey 1967, 1968, 1969).*

the Pine River. The three factors selected for comparison, because of their importance and the availability of records, were the maximum annual flood peak, the frequency of summer floods, and the mean annual water discharge.

The annual peak discharges in 1967 and 1969 were fourth and fifth highest out of the 17 years of record for the Pine River. Also, four of the nine summer floods over 650 c.f.s. occurred during the same 2 years, with three unusually large summer floods occurring in 1969. Twenty-five percent of all flood peaks greater than 650 c.f.s. (regardless of season) during the 17 years of record occurred in 1967 and 1969. Also, the two largest total annual stream discharges were experienced in 1967 and 1969. In contrast, 1968 was average or below average in its stream discharge characteristics.

It was concluded that mean sediment discharge, which is closely related to stream discharge, was probably greater during the 3-year study than during the previous 14 years of record. There was no good basis for speculating whether eroding streambanks contributed proportionately more or less sediment during the 3-year study.

Sediment Budget

MAIN CHANNEL SEDIMENT LOAD

The annual stream sediment load averaged 9,000 tons[2] at Station 1 compared with 50,000 tons at Station 3 (table 2). The relatively consistent increase between these two stations ranged from a low of 490 percent in 1969 to a high of 700 percent in 1970 and averaged 560 percent for the 4-year period.[3] The sediment load increase along the channel was quite consistent on a monthly basis also (fig. 5).

Sediment concentration and consequently sediment load increased with stream discharge. Sediment concentration ranged generally between 0 and 400 mg./liter at Station 1 (depending upon stream discharge) and during low flows was typically less than 50 mg./liter. Downstream at Station 3, concentrations averaged three times greater, with a maximum of around 800 mg./liter.

Table 2. — *Annual sediment discharge (In tons)*

Water year	Sampling station				
	Station 1	Station 2	Station 3	Silver Creek	Poplar Creek
1967	13,000	--	70,000	--	--
1968	6,600	17,000	39,000	--	--
1969	9,900	24,000	48,000	550	770
1970	6,300	17,000	44,000	280	680
Average	9,000		50,000		

TRIBUTARY SEDIMENT LOAD

Sediment measurements on the larger two of the three major tributaries entering between Stations 1 and 3 showed a combined sediment discharge of 1,320 tons in water year 1969 and 960 tons in 1970 (table 2). This represents 3.4 and 2.2 percent of the sediment discharge *increase* from Stations 1 to 3 for the two years respectively.

Allowing for the third tributary, and several smaller ones, it seems probable that the total tributary sediment contribution would be less than 10 percent of the sediment increase between Stations 1 and 3, and possibly as little as 5 percent. Sediment contributed directly to the main stream from the few road crossings and other man-induced causes is negligible. Therefore, about 90 percent of the sediment increase from Stations 1 to 3 comes from other sources — with streambank and channel erosion the most probable contributors.

FLOOD PLAIN SEDIMENTATION

Five profiles were surveyed across the valley on the reservoir fill and on the adjacent upstream valley fill in order to check for permanent sediment deposition on the flood plains. The present rate of flood plain sedimentation had no significant effect on the sediment budget during the 3-year period.[4]

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[2] *Conversion of units from tons to cubic yards and vice versa were made with the assumptions, based on extensive field data, that 70 percent (by weight) of the sediment load and of the eroding bank material was sand and 30 percent was silt and clay (see fig. 8), and the specific gravity of undisturbed eroding bank sediments was 1.49 for sand and 2.15 for the silt-clay fraction. The resulting conversion factor was 1 cubic yard = 1.39 tons. This conversion permitted convenient comparisons between tonages of sediment load and cubic yards of eroding bank sediments.*

[3] *Data obtained during water year 1970 after completion of the formal study are included in these values and in table 2.*

[4] *Considering sampling variation, 0.014 foot deposition would have been the minimum detectable change at a 95-percent confidence level. Such an increase, if assumed to have occurred over the 500-foot average width of the flood plain along the 2 miles of stream channel influenced by the dam, would have been the equivalent of 2,600 cubic yards (3,600 tons) of sediment, or only 2 percent of the 3-year total sediment discharge of 157,000 tons at Station 3. The actual measured change was —0.006 foot. It was concluded that the present reservoir filling rate and flood plain building had no significant effect on the sediment budget.*

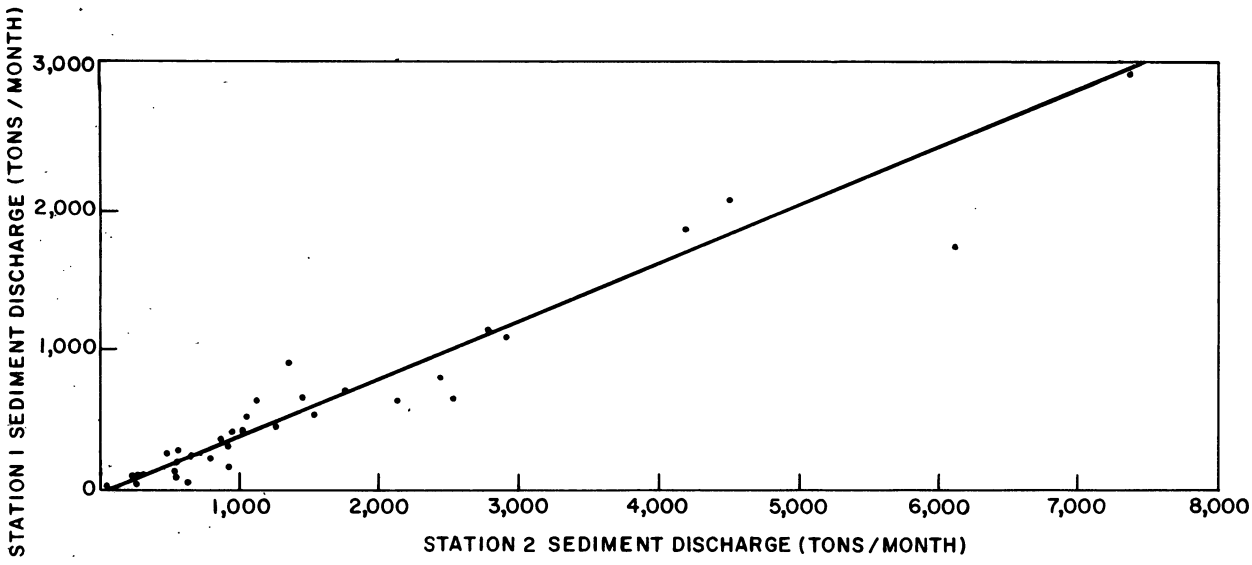

Figure 5.—*Monthly sediment discharge at Station 1 plotted against that for Station 2.*

STREAMBANK SEDIMENT CONTRIBUTION

Streambank surveys indicated that 70,000 tons of material eroded from all the banks during the 3-year study. This accounted for 55 percent of the sediment load increase in the study section of stream.

The quantity of eroding bank sediments ranged from a high of 50,000 tons in 1967 to no measurable erosion in 1968 (table 3). The volume of eroding bank sediments was related generally to the total mean annual discharge and the magnitude of the flood peak.

Table 3. — *Annual eroding bank contribution (In tons)*

Water: year	Total sediment load	Sediment load increase in study section	Eroding bank contribution
1967	70,000	57,000	50,000
1968	39,000	32,000	1/0
1969	48,000	38,000	20,000
Total	157,000	127,000	70,000

1/Only a partial survey was made in 1968. Therefore, the zero estimate may have a considerable error. Any erosion that might have occurred is included in the 1969 data.

The method of selection and survey of the banks probably underestimated the volume of erosion. It was first assumed that only eroding streambanks with raw, unvegetated faces contributed sediment. However, vegetated portions of streambanks were apparently also undergoing moderate sheet and rill erosion, and yet were maintaining at least a semblance of plant cover with pioneer herbaceous species. Since only a small number of the vegetated streambanks were included in the survey, the volume of material eroded from that source was underestimated.

Another source of measurement error was due to subsidence of the entire bank together with the surveyed control points. This resulted in an underestimate of the volume of eroded material. Also, several new points of erosion started during the summer of the third year. These banks were not surveyed, resulting in a further, though slight, underestimate of bank erosion.

TOTAL SEDIMENT BUDGET

As stated previously, about 55 percent of the sediment load *increase* was attributable to measured bank erosion. An additional small amount, estimated to be less than 10 percent, came from tributaries. The remaining 35 percent was believed to have come primarily from slow and unobtrusive but widespread sheet erosion, and in some cases gradual subsidence and slumping of long sections of the bank.

The total sediment budget for the three years is shown in figure 6. Also shown are the individual annual sediment budgets, which give an indication

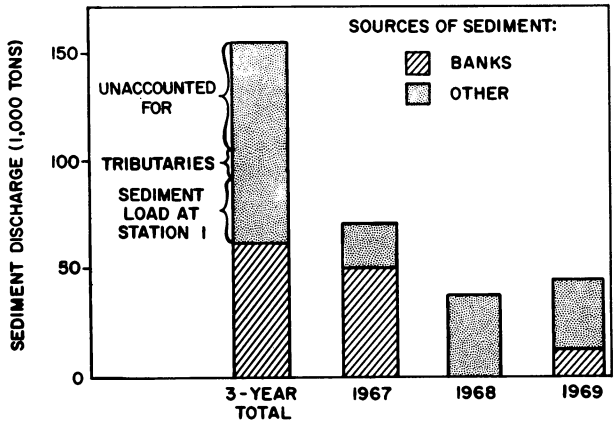

Figure 6. — *Pine River sediment budget at Station 3.*

of the year-to-year variation in bank erosion and sediment discharge rates.

Sediment Size

TOTAL LOAD SEDIMENT SIZE

Seventy to seventy-five percent of the Pine River sediment load was sand size (0.062 to 2.0 mm.). Stream discharge rate had no effect on the proportion of the sediment in sand size (fig. 7). Apparently, even at the lowest discharges, the stream can move some sand-size material.

The particle-size distribution of the total sediment load was essentially unchanged as it moved down the section of stream channel from Station 1 to Station 3, despite the large increase in both stream discharge and sediment load (fig. 8).

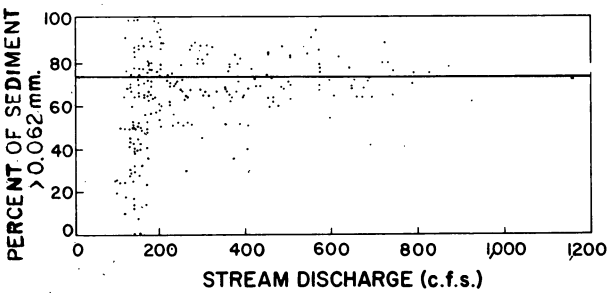

Figure 7. — *Variation of sand (0.062 to 2.0 mm.) content of sediment load with stream discharge at Station 1.(The large variation in the proportion of sand at discharges less than 200 c.f.s. was due to concentrations less than 20 mg./liter, where a fluctuation of a few sand grains could result in a large percentage change.)*

ERODING BANK SEDIMENT SIZE

The particle-size distribution of eroding bank sediments, except for the coarse material greater than 1.0 mm., was almost the same as the sediment already in transport in the stream at Station 1 (fig. 8). Since the eroding banks are a major sediment source and since the bank sediments have a similar size distribution to that already in transport at Station 1, the little change noted in the size of sediments discharged downstream at Station 3 would be expected.

There were, however, more coarse particles in the eroding bank sediments than were moving in the stream. This gravel-size material, primarily larger than 4 mm., constitutes about 5 percent of the eroding bank sediments (fig. 8). Much of the gravel is from old stream deposits in river terraces. The small amount of gravel measured in transport, even at high stream discharges, indicates that most of the eroded streambank gravels are again being redeposited on the streambed.

BED-MATERIAL SIZE

Except for small areas of silt deposits, sand streambed areas constitute the sole area where significant interchange between streambed sediments and the sediments in transport is possible. Bed-material samples from sand-bed areas indicated that about 88 percent was between 0.125 to 0.5 mm. in size (fig. 8). This is the same size group that constitutes 60 percent of both the eroding bank sediments and the sediment in transport. Less than 2 percent of the bed material in the sand-bed areas was finer than 0.125 mm. Since sand-bed areas were in the sections of the stream with minimum gradient, the smallest particles that move as bedload would be traveling there. In more turbulent sections of the stream, more sands would be in suspension and the minimum bedload particle size would likely be greater than 0.125 mm. Therefore, the smallest particle commonly moved as bedload on the Pine River was 0.125 mm.

There was no significant change in the sand bed material size distribution along the channel from the mean distribution shown in figure 8. Evidently there was little sorting of sand sizes, even in those high gradient sections where sand comprised a minor portion of the streambed.

DEPOSITS ON FISH SPAWNING BEDS

From 23 to 36 percent by weight of all the spawning-bed material was less than 8.0 mm. The size distribution of sediment finer than 8.0 mm. deposited between the November and February sampling dates is plotted in figure 8. Proportionately more of the coarse sands from eroding banks and bed-material sediments were deposited on the spawning beds, probably as a result of the higher velocity and greater turbulence associated with the gravel streambed areas used for spawning. Almost no deposited sediment was finer than 0.125 mm., and 58 percent of the deposited material was between 0.125 and 1.0 mm. This latter size group also constitutes 55 percent of the eroding bank sediments and is in the size group that has been shown to be associated with large reductions in spawning-bed gravel permeability (Cooper 1965, Terhune 1958).

The eroding bank sediments were of the same size as the bulk of the sediments deposited on spawning beds. Therefore, there is a possibility that reduction of the stream sediment load through streambank stabilization would result in an improved spawning environment.

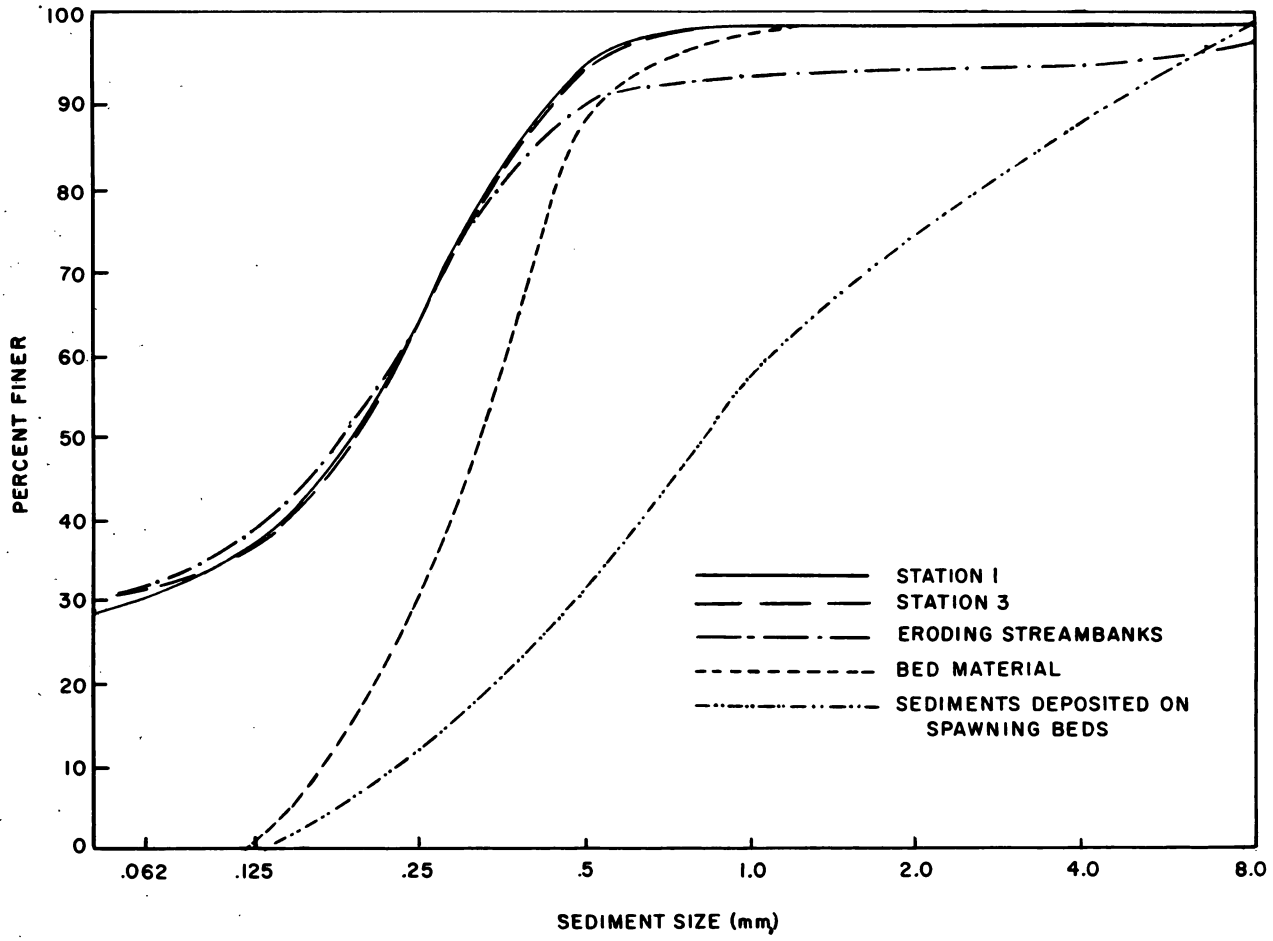

Figure 8. — *Particle-size distribution of sediment at its source, in transport, and in areas of deposition.*

STREAMBED COMPOSITION

Areas of erodible sand constituted 22 percent of the total streambed area of which more than half (12 percent) was covering gravel. Areas of essentially nonerodible material were: boulder 7 percent, cobble 17 percent, gravel 32 percent, and residual clay 12 percent. Silt deposits were present on 10 percent of the area, primarily in narrow bands along the stream's edges.

The major classes of sediment on the streambed were closely related to the water surface slope, which increased gradually toward the lower end of the study section. As slope increased, the percentage of the streambed covered by cobbles and boulders increased and the percentage covered by sand and gravel decreased (fig. 9). Silt areas increased downstream except in the last 6 miles with the steepest gradient, where the area of silt decreased. The proportion of the streambed occupied by exposed, consolidated clay remained about the same along the stream.

Streambank Erosion

STREAMBANK EROSION RELATIONS

The volume of sediment eroded from individual streambanks ranged from 0 to a total of 2,400 cubic yards for the 3-year study period. A partial breakdown of the volumes of eroded sediments from the 48 surveyed streambanks is as follows:

Three-year total of eroded sediments Cubic yards	*Number of banks*
0	6
0-100	21
100-1,000	19
$\geq$ 1,000	2

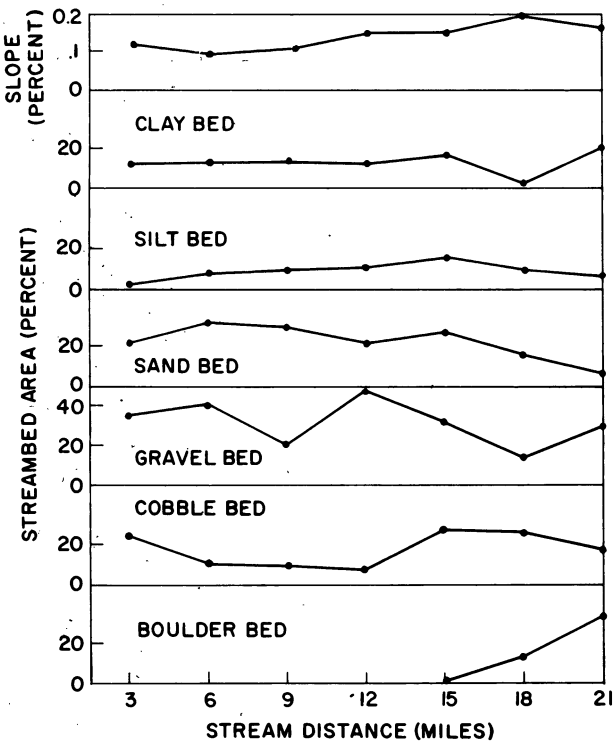

Figure 9. — *Relation of water surface slope to percent of various bed types along 23 miles of stream channel. Each point is the mean of 10 cross sections equally spaced along 3 miles of stream.*

The 50,000 cubic yards (70,000 tons, table 3) of eroding bank sediments came from 16,300 linear feet of eroding waterline. The maximum lateral recession of any streambank was 13 feet during the 3-year period, although 1 to 5 feet was most typical.

Eroding bank sediment contribution was much greater in the lower two-thirds of the study area (fig. 10). This was due to the higher banks and, possibly, to the greater stream discharge and gradient. Volume of eroding bank sediments increased in direct proportion to bank height. Even though high banks had more sediment entering the channel per foot of waterline, the banks did not recede more slowly. This indicates that the stream's sediment transport capability is in excess of the sediment supply to the stream. Sand sediments temporarily accumulated at the base of banks during dry weather were always removed during high flows. Slumped clay sediments sometimes remained at the base of banks for years. However, in this latter case, the durability of the slumped sediment was due to the erosion resistance of the cohesive sediments rather than the lack of transport capability of the stream.

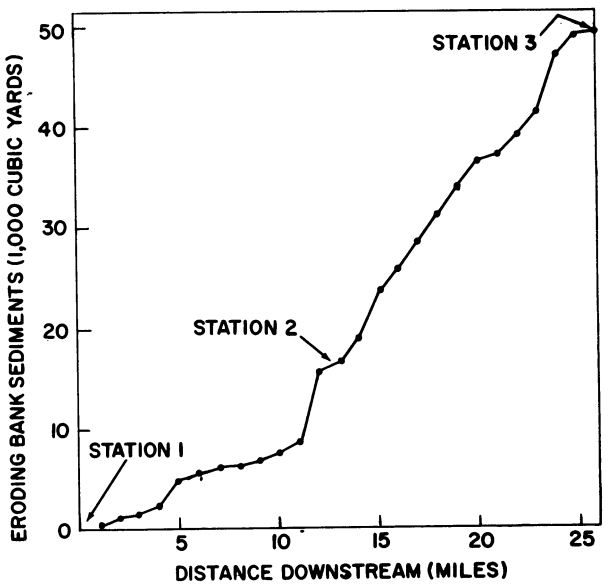

Figure 10. — *1966-69 cumulative sediment yield from eroding streambanks.*

Detailed eroding bank data would be useful in designing a stabilization program to: minimize cost, given a required level of sediment reduction; or, maximize sediment reduction, given a fixed input of funds. The following data from the Pine River illustrate some of the many relationships that can be developed for that stream using the streambank stratifications described earlier. Similar relations could be developed on other streams in the glacial drift region.

There is a large difference in the annual volume of sediment loss from streambanks of various sizes and erosion classes (fig. 11A). The greatest erosion rates were from the large banks in the "severe" and "moderate" erosion classes. There was no measurable sediment loss from banks in the "light" erosion class, regardless of bank size. The average length of eroding bank waterline also varied with bank size and erosion class (fig. 11B).

The data in figures 11A and 11B permit the calculation of the number of cubic yards of material eroded per linear foot of waterline for different types of eroding banks. This identifies the banks that would have the greatest volume of sediments stabilized per linear foot of bank treatment, or the highest "efficiency of stabilization." Stabilization of large banks in the "severe" and "moderate" erosion classes would produce the greatest efficiency (fig. 11C).

Large banks in the "severe" erosion class have by far the greatest total volume of sediment yields and

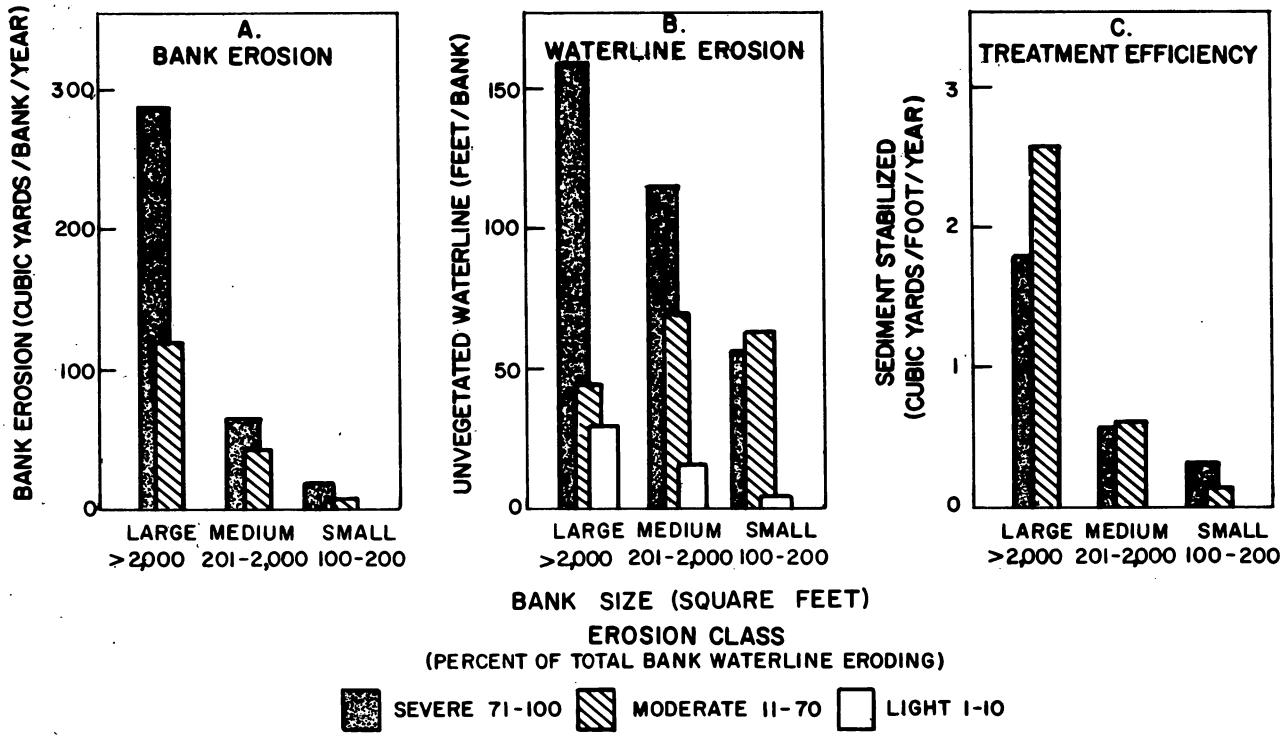

Figure 11. — *Variation of selected bank characteristics by erosion and size class.*

the greatest length of eroding waterline (figs. 12A and 12B). Stabilization of all the large banks in the "severe" and "moderate" erosion classes (the two strata with highest treatment efficiency shown in figure 11C) would result in a 74 percent reduction in eroding bank sediments from treatment of only 40 percent of the total eroding waterline. Banks in other strata could be treated to get further reduction in eroding bank sediments, but only with a reduced efficiency.

INDICATORS OF RAPID EROSION

Several additional factors, although subjective, may aid in identifying areas of rapid erosion when no other data are available.

Islands, bars, and fallen trees are all indicators of rapid erosion caused by a lateral shift in the stream course. As the stream cuts into a rapidly eroding bank, the stream becomes wider and shallower with gravel bars, islands, and a flood plain building up on the inside of the bend. These deposited sediments are rapidly vegetated with pioneer species such as willow and alder (fig. 13). Trees eroded from the bank lodge in the shallow water and catch additional debris. This debris sometimes helps stabilize the bank, but often it accelerates local scour.

Debris cones are an indication of past rapid stream erosion at the waterline and an oversteepening of the bank (fig. 14). Subsequent wind erosion of the bank face during dry periods and water erosion during short, high-intensity summer rainstorms contribute to the buildup of debris cones at the toe of the bank. The loose material is usually washed away during the next flood.

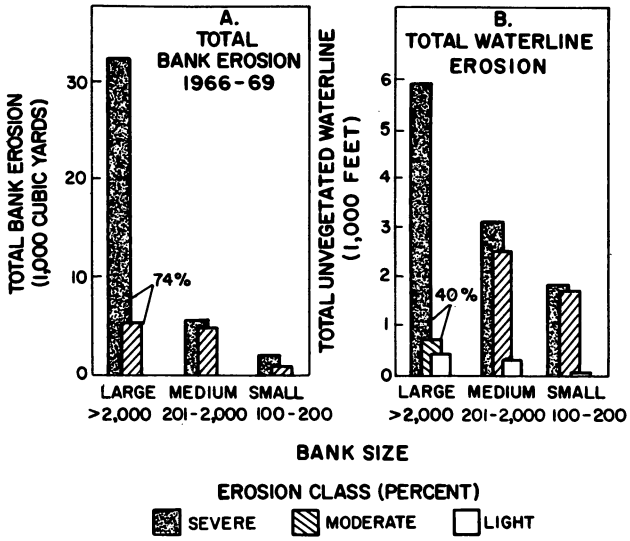

Figure 12. — *Total erosion of all banks by erosion and size class.*

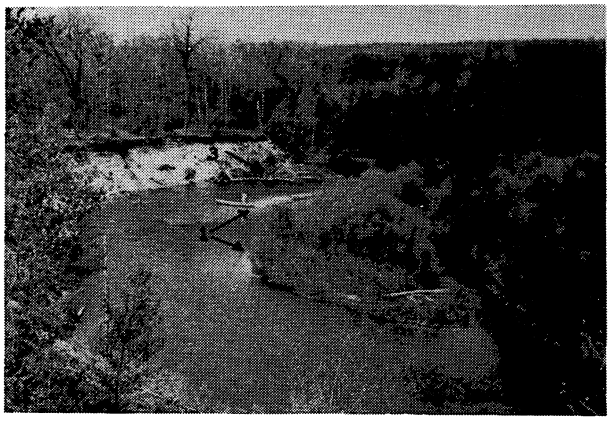

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Figure 13. — *A rapidly eroding bank associated with a lateral shift in the stream has resulted in the stream becoming wider and shallower. Features commonly associated with such a situation are: (1) islands, (2) pioneer vegetation, and (3) debris at the base of the bank.*

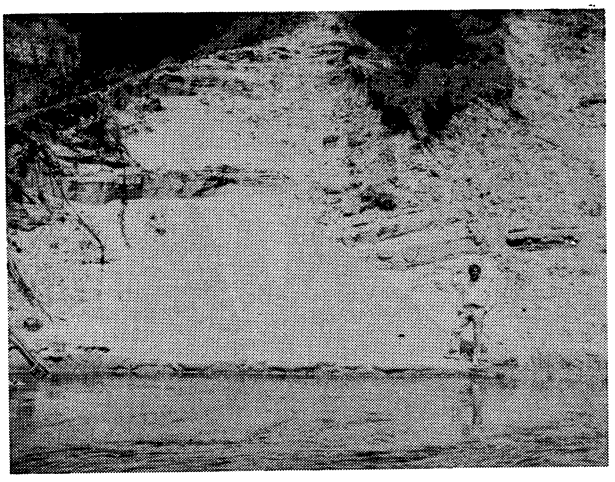

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Figure 14. — *Debris cones at the base of a mixed sand and clay bank. These cones were formed by wind erosion of sand bank faces steeper than the angle of repose.*

Clay banks sometimes sheer considerable distances (100+ feet) from the stream (fig. 15). The toe of such a slump narrows the stream with resultant higher stream velocities and greater erosive potential (fig. 16). The toe of the slump often contains submerged vegetation that originally grew above the water surface. The rate at which the slump erodes is greatly dependent upon the resistance of the clay, a factor for which there is no accurate measurement at present.

Banks containing wet clay areas with seeps or springs are prone to slumps and mud flows during wet seasons (fig. 17). Measurements indicated that such wet bank failures occurred at infrequent intervals, but the volume of material was large enough that wet banks had the highest erosion rates. In contrast, dry clay banks had the lowest erosion rates, and banks with sand or separate areas of both sand and clay were intermediate as shown below:

Number of banks	*Soil texture*	*Moisture status*	*Erosion rate Cubic yards/ bank/year*
7	Clay	Dry	27
17	Sand	Dry	57
15	Clay & sand	Dry	88
9	Clay & sand	Wet	207

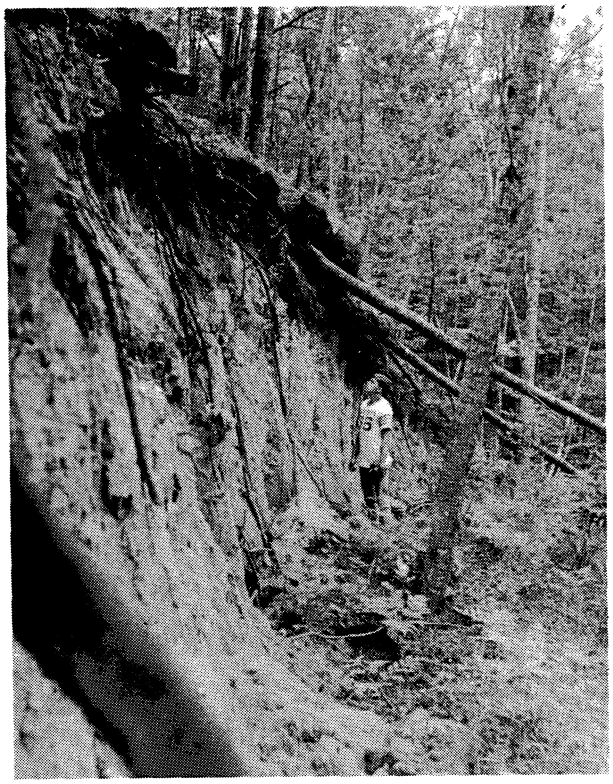

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Figure 15. — *A near-vertical shear zone in a clay bank. The shear is at a distance of 80 feet horizontally and 40 feet vertically from the stream, and occurred sometime during a 1-year period between visits. Such slumps may occur relatively quickly, perhaps in minutes or less.*

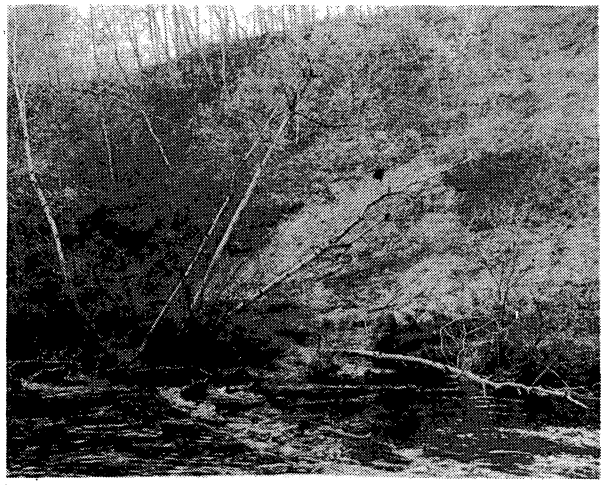

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Figure 16. — *Submerged vegetation is an indicator of obvious slumping as shown above, and of less obtrusive subsidence of large sections of streambank.*

Some of the apparent difference in erosion rates was due to an interaction between soil texture, the presence of springs, and bank size. As bank size increased, the probability increased that more than one major soil textural class would be exposed and also that the bank would intersect areas of ground water inflow to the stream. Therefore, banks containing mixed soil textures and classified as "wet" were to some extent the same large banks that produced more sediment. However, bank size explained only a small part of the above variation. Some of the remaining variation was no doubt due to the influence of soil texture and the moisture status on the erosion rate.

Eroding banks that are adjacent to recreational areas or at stream access points almost always have high erosion rates. Three such banks along the Pine River had an average sediment yield of 105 cubic yards/bank/year, higher than any of the erosion rates tabulated above for similar "dry" banks. Only the "wet" banks exceeded the banks receiving recreational usage in the severity of erosion rate.

DISCUSSION AND SUMMARY

The theory of sediment transport and the interactions between sediment load and the stream channel is incomplete. However, some apparent relationships and the trends in sediment dynamics following streambank stabilization can be mentioned.

F-520636

Figure 17. — *A mud flow on a wet clay bank.*

There was less sand on the streambed in the downstream section despite the 560-percent increase in sand sediment load. This is due to the greater energy gradient and more generally the high transport capacity of a pool and riffle stream. It implies that the capability of the stream to transport sands and finer material is in excess of the sediment supply. Consequently, an erosion reduction program designed to reduce total sediment load for the purpose of improving stream esthetics and fish habitat, or for reducing reservoir or harbor siltation rates, should result in a relatively rapid decrease in moving sediment and associated changes in streambed composition.

A hypothetical program stabilizing all of the identifiable eroding banks in the study section would reduce the total sediment load 45 percent at Station 3 (table 3), with a possibility of a wide error in either direction from the estimate. If the 53 eroding streambanks upstream from the study section were also stabilized, the total sediment load reduction would be 50 percent. In any event, a complete bank stabilization program would not result in complete elimination of the sediment load. The problem therefore becomes one of exploring possible effects of a partial reduction in sediment load on the stream channel.

Because the particle size distribution of streambank sediments was nearly the same as sediments already in transport, stabilization of all eroding banks would not produce much change on the particle size distribution of the sediment load. However, there is still some latitude in designing a program to change particle size. For example, a change in streambed composition and a maximum reduction in bedload could be attained by stabilizing only the banks with large

amounts of sand. This is possible because the minimum particle size present on the streambed and carried as bedload is between 0.125 and 0.25 mm. (fine sand). Since deposited silts and clays constitute only a small fraction of the streambed area and were not present in gravel, stabilization of such banks would have little effect on the stream bottom.

In contrast, if the objective were to lower turbidities during floods, banks containing clays and silts should be stabilized. However, since clays and silts constitute only 25 percent of the total sediment load, with concentrations rarely exceeding 100 mg./liter, the opportunities for producing dramatic changes in turbidities are limited. Also, stabilizing these banks would not noticeably affect low flow turbidities because there is almost a complete absence of movement of clays and silts during low flow.

A reduction in sediment load might result in the scouring of sand off buried gravels and also affect the amount of sand intermixed in gravel areas of the streambed. However, bedload movement in a pool and riffle stream is commonly concentrated in narrow bands parallel to the direction of flow and is not distributed over the entire width of the streambed (Love and Benedict 1948). Consequently, a reduction in sediment load in a pool and riffle stream might have its primary effects concentrated in the relatively small portion of the streambed experiencing moving bedload. The effects of this in terms of streambed composition changes and in cleaning sand from gravel areas with an already low bedload movement is not predictable.

These changes are all in the direction generally accepted as an improvement in fish habitat (Cordone and Kelley 1961). However, it has yet to be demonstrated that sediment changes of the above predicted magnitudes are large enough to have any measurable effect upon either fish or fish habitat.

The results of this study were highly dependent upon its duration and the prevailing climatic conditions. Results range from "verifiable relationships" which remained fairly constant throughout the course of the study, to "best estimates" of highly variable data which may be both climatically and time dependent, to "hypotheses" which attempt to formulate some order from the incomplete results. The main findings are summarized generally in that order.

1. Sediment load increased five to six times within a 26-mile-long section of the Pine River. Sediment concentration increased three times and stream discharge increased 1.8 times within the same section.

2. Seventy percent of the total sediment load was sand-size material (0.062 to 2.0 mm.).

3. Particle-size distribution of the sediment load did not change through the 26-mile reach even though there was a large increase in sediment load.

4. The mean particle-size distribution of eroding bank sediments (the major sediment source) was essentially the same as that of the sediment already in transport.

5. Fifty-eight percent of the material deposited on fish spawning beds was between 0.125 and 1.0 mm., the same size group that constituted 55 percent of the eroding bank sediments.

6. The minimum particle size present in any spawning gravels and in bed material samples was 0.125 mm.

7. Bank sediments greater than 1 to 2 mm. are not readily transported by the stream and probably aid in forming areas of stable bed.

8. Even though the sand sediment load increased five times along the channel reach, there was a decrease downstream in the proportion of the streambed covered with sand and an increase in cobbles and boulders. This was probably a result of the increased gradient.

9. Twelve percent of the streambed area was composed of gravels buried by sand. Therefore, this is the upper limit of any conversion of sand to gravel bottom type following a sediment load reduction.

10. During the 3-year study the eroding bank sediments contributed 55 percent of the total sediment load increase that occurred within the study section.

11. Most of the streambank sediment came from large banks in the most severe erosion class. A 74-percent reduction in eroding bank sediments could be achieved by stabilizing only 40 percent of the eroding waterline.

12. Tributaries and road crossings contributed less than 10 percent and possibly as little as 5 percent of the sediment load increase along the 26-mile channel reach.

13. It was hypothesized that the remaining 35-percent sediment contribution came from vegetated streambanks through sheet erosion and gradual bank subsidence.

14. The best estimate of the reduction of the Pine River sediment load following complete streambank stabilization along the 26-mile study section was 45 percent.

15. A complete streambank stabilization program would significantly reduce the sediment load but would not affect the particle-size distribution of the moving sediment.

16. It was hypothesized that a reduction in sediment load following bank stabilization would tend to increase the area of streambed covered with gravel, decrease the area of sand, and decrease the sand content in existing exposed gravels. However, the extent of such changes is not yet predictable.

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