SUSPENDED, BED, AND DISSOLVED SEDIMENT LOADS IN THE SLEEPERS RIVER, VERMONT

ARS 41-188
JUNE 1972

SOIL AND WATER
CONSERVATION
RESEARCH DIVISION

AGRICULTURAL RESEARCH SERVICE • U.S. DEPARTMENT OF AGRICULTURE

ABSTRACT

Sediment and dissolved solids were studied in the headwaters of the Connecticut River Basin near St. Johnsbury, Vt. The basin studied receives 750 to 1,125 mm. of precipitation annually, and the temperature averages 4.5° C. The bedrock is principally calcareous schists, micaceous quartzite, and quartz mica schists. Soils are fine sandy loams and loams derived from glacial tills and bedrock. Land use is primarily mixed dairy farms and forests. Elevations range from 201 to 790 meters above sea level. The topography is hilly, and slopes of about 10 to 40 percent are common.

Intensive study during 1967 to 1969, as well as limited measurements during 1964 to 1966, provided the data. The yield of particulate material (50 to 69 metric tons/km.^{2} /yr.) was similar in magnitude to that of the dissolved substances (53 to 55). Most of the transported materials apparently originated in the stream banks. The *total* yield of about 113 m. tons/km.^{2} /yr. was equivalent to a denudation rate of about 4.0 cm./1,000 yrs.

About one-third of the transported particulate yield was bedload. More than 80 percent of the suspended sediment and bedload and about one-half of the dissolved material was moved during the spring snowmelt period. The storms monitored carried only a minor part of the annual yield. A rising stormflow carried more suspended sediment than a receding flow of equal volume. In the 0.5 to 110 km.^{2} —size basins studied, smaller streams carried more suspended material per given discharge than larger streams.

Specific electrical conductance (EC) was a good indicator of dissolved solids in the unpolluted watersheds, where EC in micromhos at 25° C. × 0.7 = dissolved solids in milligrams per liter. The dissolved-solids concentrations were highly dependent on rate of streamflow.

CONTENTS

Results:

Analysis of data:

ACKNOWLEDGMENTS

The authors appreciate the participation of M. G. Wolman, Professor of Geography, Johns Hopkins University, Baltimore, Md.; M. L. Johnson, Hydraulic Engineer, Sleepers River Watershed, Danville, Vt.; and E. T. Engman, Director, Northeast Watershed Research Center, University Park, Pa. in the early stages of planning the project and of the field work. M. G. Wolman and M. L. Johnson also provided data used in some of the trap efficiency calculations and information on movement of large cobbles.

The help of the staff of the Sleepers River Research Watershed in the field work, the laboratory analyses, the data reduction, and the preparation of this report is appreciated.

CONVERSION FACTORS

MULTIPLY	BY	TO OBTAIN
meters (m.)	3.281	feet (ft.)
cubic meters (m.^{3})	35.31	cubic feet (ft.^{3})
centimeters (cm.)	0.0328	ft.
millimeters (mm.)	0.03937	inches (in.)
kilometers (km.)	0.6214	miles (mi.)
km.^{2}	0.3861	mi.^{2}
km./km.^{2}	1.609	mi./mi.^{2}
m.^{3}/sec.	35.31	ft.^{3}/sec.
m.^{3} km.^{2}	91.46	ft.^{3}/mi.^{2}
m.^{3} km.^{2}	0.0021	acre-ft./mi.^{2}
m.^{3}/sec./km.^{2}	91.46	ft.^{3}/sec./mi.^{2}
liters (l.)	0.03531	cubic feet (ft.^{3})
hectares (ha.)	2.47	acres
metric tons (m. tons)	1.102	U.S. tons
m. tons/km.^{2}	2.857	U.S. tons/mi.^{2}
grams (g.)	0.002205	pounds (lb.)
kilograms (kg.)	2.2046	pounds (lb.)
TO OBTAIN	BY	DIVIDE

188, 31p.
June 1972

2007

SUSPENDED, BED, AND DISSOLVED SEDIMENT LOADS IN THE SLEEPERS RIVER, VERMONT

By
Samuel H. Kunkle and George H. Comer[1]

INTRODUCTION

In northern New England, practically no evaluations of solid or dissolved yields of sediment in natural streams have been made. No data are available showing the proportions of suspended, bed, and dissolved loads in streams of the region or giving values of annual yields common to the area. The lack of sediment information for the region led to this study. The values obtained provide some approximations of total annual yields, proportions of bedload, seasonal distributions of sediment movement, and dissolved-solids yields for catchments that are representative of much of the headwaters of the Connecticut River and Lake Champlain drainage basins.

DESCRIPTION OF THE RESEARCH AREA

Catchments of the Sleepers Rivers research watershed, near St. Johnsbury, Vt. were used in this study (fig. 1). The research watershed is a 111.1-km² basin. It is a tributary to the Passumpsic River within the Connecticut River drainage basin. Elevations in the Sleepers River watershed range from 201 to 790 meters above sea level.

The climate of the area is continental. Temperatures range from -40° C. to 36° C., with an average of 4.5° C. Precipitation, about one-third of which is snow, ranges from 750 mm. at 201 meters elevation to 1,125 mm. at 671 meters. Snow generally covers the ground from December until March or April.

The land is used primarily for forests and dairy farming (permanent hay and pasture). Less than 1 percent is cultivated. The forests are predominantly mixed maple, birch, beech, elm, white ''cedar'' (*Thuja occidentalis*), spruce, hemlock, and fir in stands of all ages. Very little logging is done. Dairying provides most of the income for the population of the watershed. A typical dairy has about 75 head of cattle on 100 hectares of land. The soils, land use, and slopes of the catchments are described in table 1.

Runoff from the catchments averages about 400 mm. per year. Peak flows normally occur in the spring snowmelt period, a time when more than one-half the annual volume of runoff is produced. The minimum annual flow normally occurs late in summer.

The lower part of the watershed is underlain by interbedded schists and limestone of the Waits River formation. The more resistant Gile Mountain formation of micaceous-quartzite and quartz mica schists forms the higher ridges of the watershed (*6, 10*)[2]. Surficial deposits are primarily glacial tills of less than 4½ meters in depth (*21*).

---

[1] Respectively, Research Hydrologist, New England Watershed Research Center, Northeast Branch, Soil and Water Conservation Research Division, Burlington, Vt.; and Hydraulic Engineer, U.S. Hydrograph Laboratory, SWCRD, Beltsville, Md.

[2] Italicized numbers are those of References on pages 30 and 31.

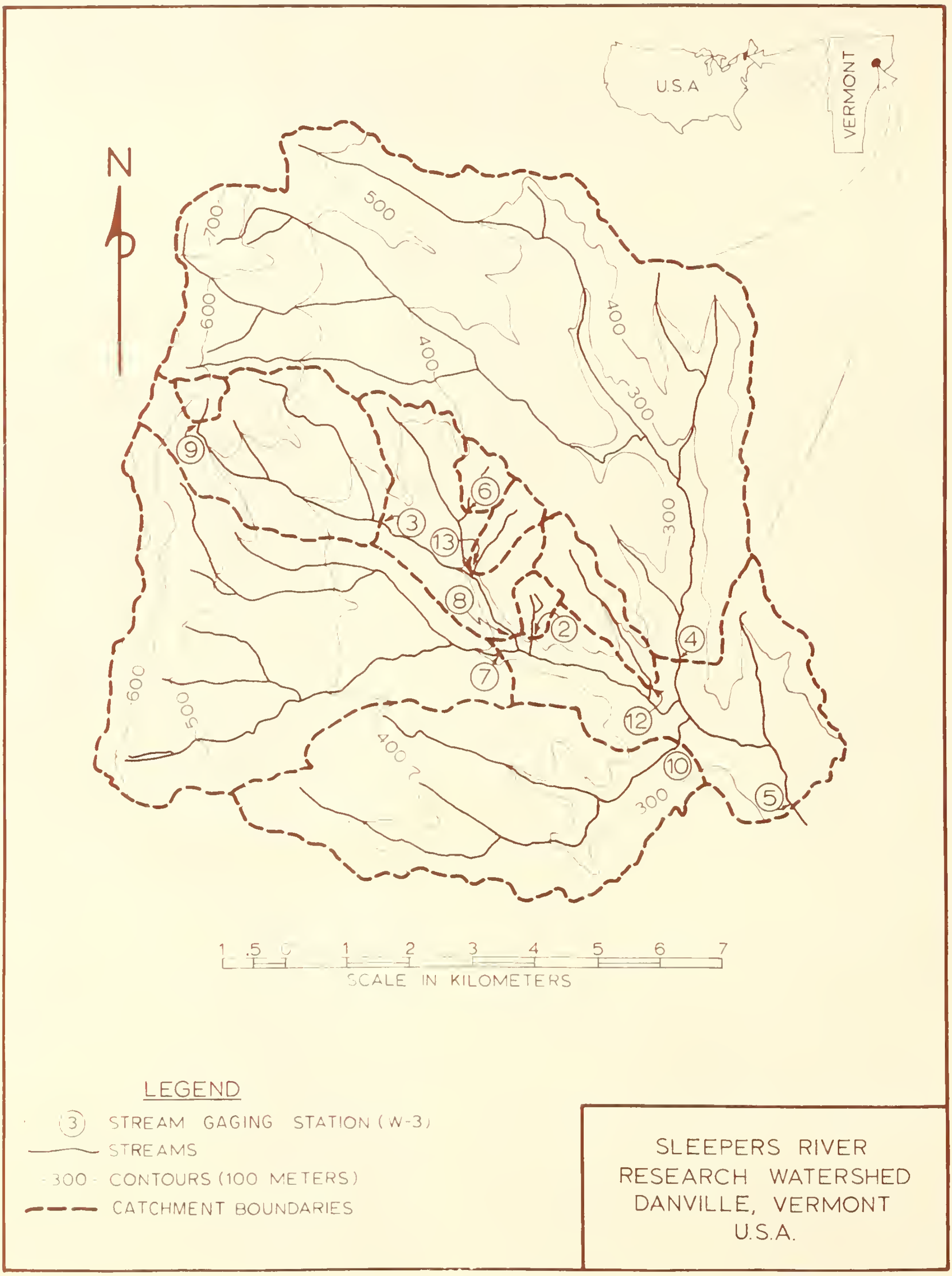


Figure 1.—Map of the Sleepers River research watershed, showing the catchments studied and location of stream-gaging stations where sampling was done.

Table 1.—*Soils, slopes, and land use of catchments in the Sleepers River watershed*

	Size		Soils			Slopes		Land use	
Catchment No.	Metric	U.S.	Name	Internal drainage	Part of area	Percent of slope	Part of area	Use	Part of area
	Km.²	*Mi.²*			*Pct.*		*Pct.*		*Pct.*
W-2	0.57	0.22	Colrain fine sandy loam	R	36	0 to 3	2	Forest	25
			Woodstock fine sandy loam	R	20	3 to 8	16	Cultivated	37
			Cabot silt loam	M	17	8 to 15	41	Pasture	38
			Buckland loam	M	12	15 to 25	35		
			Calais loam	M	10	25 and over	6		
			Peacham loam	VS	5				
W—4	43.5	16.8	Woodstock fine sandy loam	R	23	0 to 3	3	Forest	74
			Cabot silt loam	M	21	3 to 8	21	Cultivated	12
			Buckland loam	M	17	8 to 15	30	Pasture	12
			Colrain fine sandy loan	R	12	15 to 25	27	Idle	2
			Glover rocky loam	M	12	25 and over	19		
			Calais loam	M	8				
			Peacham loam	VS	8				
			Worthington loam	R	1				
			Saco silt loam	VS	1				
			Miscellaneous		2				
W—6	0.67	0.26	Woodstock fine sandy loam	R	39	0 to 3	4	Forest	23
			Cabot silt loam	M	18	3 to 8	36	Cultivated	23
			Buckland loam	M	14	8 to 15	31	Pasture	54
			Calais loam	M	10	15 to 25	22		
			Peacham loam	VS	10	25 and over	7		
			Colrain fine sandy loam	R	9				
W—7	21.8	8.42	Cabot silt loam	M	41	0 to 3	2	Cultivated	14
			Buckland loam	M	20	3 to 8	52	Forest	74
			Calais loam	M	17	8 to 15	23	Pasture	8
			Glover rocky loam	M	16	15 to 25	13	Idle	4
			Peacham loam	VS	3	25 and over	10		
			Woodstock fine sandy loam	VS	1				
			Colrain fine sandy loam	R	1				
			Miscellaneous		1				
W—9	0.47	0.18	Calais loam	M	43	0 to 8	1	Forest	100
			Glover rocky loam	M	37	8 to 15	8		
			Cabot silt loam	M	20	15 to 25	55		
						25 and over	37		
W—10	16.20	6.30	Cabot silt loam	M	28	0 to 3	4	Forest	64
			Colrain fine sandy loam	R	21	3 to 8	31	Cultivated	21
			Buckland loam	M	15	8 to 15	37	Pasture	15
			Calais loam	M	15	15 to 25	23	Idle	1
			Woodstock fine sandy loam	R	8	25 and over	5		
			Glover rocky loam	M	6				
			Peacham loam	VS	4				
			Limerick silt loam	S	1				
			Miscellaneous		2				
W—13	1.04	0.40	Woodstock fine sandy loam	R	45	0 to 3	1	Forest	31
			Cabot silt loam	M	32	3 to 8	43	Cultivated	40
			Buckland loam	M	11	8 to 15	27	Pasture	29
			Calais loam	M	5	15 to 25	20		
			Colrain fine sandy loam	R	5	25 and over	7		
			Peacham loam	VS	2				

[1] R = rapid, M = medium, S = slow, VS = very slow.

The soils have developed from weathering till and bedrock, Weathering of the thicker till has generally produced Cabot and Peachlam loams. The bedrock or thin till over bedrock has weathered into moderately-well-drained Buckland loam, well-drained Calais loam and Colrain fine sandy loan, and excessively-well-drained Glover loam and Woodstock fine sandy loam. The soils data are from unpublished Soil Conservation Service maps.

RESEARCH METHODS

Suspended sediment, bedload, and dissolved solids were measured. The objectives of the research were to obtain reasonable approximations of total annual yields, proportions of bedload, seasonal distributions of sediment transport, and dissolved-solids yields for the Sleepers River watershed, which is representative of headwaters of much of the Connecticut and Lake Champlain basins. During the 1964 to 69 period of study, land use in the watershed was essentially static.

Suspended-Sediment Methods

At irregular intervals during the 1964 to 69 period, more than 200 samples of suspended sediment were collected. A DH-48 "depth-integrating" stream sampler was used. Nearly all of the samples were taken during storm runoff or spring snowmelt periods, since streams in the watershed transport negligible quantities of sediment at other times. During the observation time there were no exceptionally large runoff events (greater than a 10-year return period), and no activities of man that significantly altered the catchments or channels.

Samples were analyzed by filtration, drying, and weighing to the nearest ten-thousandth gram. Estimates for annual yields (based on 1967-68) are reported for the three largest catchments sampled, 43.5, 21.8, and 16.3 km^2. Data from four other catchments also are discussed. The annual yields for 1968 were computed from sediment-transport curves derived from the 1964 to 68 period, using stream-discharge records, where sediment concentration × discharge equaled delivery rate for a segment of time. Turbidity measurements where made for many of the suspended sediment samples (*14*).

Bedload Methods

Bedload yields for the 1968 spring-runoff period were determined from seven weir ponds by surveying the cleaned ponds in the fall of 1967 and resurveying early in the summer of 1968. The three largest weir ponds also were surveyed in the autumn of 1968, after a 45-mm. storm (about a 2-year event). Spring yield of bedload on the 43.5- and 16.3- km.^{2} watersheds were determined for 1969 as well. Samples of bed material taken from the seven ponds were used to determine the particle size and specific gravity of the trapped material.

Of course not only part of the moving bedload is trapped by debris basins, such as the weir ponds used in the study, while some of the load continues to move downstream. Estimates of bedload are only as good as trap-efficiency determinations for the weir ponds, because bedload values are based on these pond surveys. There is, unfortunately, no simple proven method to determine the percent of sediment caught by a weir pond. Calculations of trap efficiency of a weir pond vary greatly, depending on the method used.

The method of Brune (*3*) estimated the weir ponds' trap efficiencies at almost zero, while the procedure of Fair and Geyer (*9*) yielded results as high as 80 percent for the same weir ponds. The method of Fair and Geyer is intended for use in settling basins, where the velocity through the pond is quite small. Similarly, Brune's technique is based on flow retention time. Efficiencies also were calculated by Brown's method (*2*) as well as that of Hazen (*9*) for comparison.

Wolman, working with the Sleepers River weirs in 1966, developed a field technique for approximating trap efficiency of the weir ponds. By this method, particle-size distributions from sediment deposits downstream from the weir and in the weir pond itself can be used as an index of trap efficiency. He reasoned that if a given size of material was more predominant in the weir pond than in the channel deposits below the weir, the weir was retaining more of that particular size. Based on

Wolman's technique, trap efficiencies were calculated by:

$$TE = \Sigma RS$$

where: TE = trap efficiency in percent.

R = decimal fraction of the material in the size range that is trapped. $R = 1.0$ if $r > 1.0$; $R = 0.5$ if $r = 1.0$; $R = 0$ if $r = 0.0$.

$$r = \frac{\text{percent of material trapped in weir pond}}{\text{percent of material in deposits downstream of weir}}$$

S = percent of the material trapped in the weir pond that is in the size range considered.

The computed trap efficiencies ranged from 41 to 70 percent for the individual weirs. These values were used to adjust the field survey results, as shown in the table 4 data.

Dissolved-Solids Methods

Samples of water were collected 34 times from February until November of 1968 at each of 11 separate stream sites. These were analyzed for specific conductivity by use of a Beckman Model RC-16B2 meter and pipette cell. The cell was calibrated before each use. About half of the samples were analyzed for Ca, Mg, K, and Na on an atomic absorption spectrophotometer. A few complete inorganic analyses also were made. As used in this report, dissolved-solids values are estimates of "total dissolved solids" based on specific electrical conductance (EC) measurements. Comparisons of EC with chemical analyses of stream samples showed EC in micromhos per cm. at 25° C., multiplied by 0.7, to be a reasonable approximation of total dissolved-solids concentrations in milligrams per liter (mg./l.). Evaporation to dryness of membrane-filtered samples that had been tested for conductivity also showed 0.7 to be a reasonable constant. The value is within the 0.55 to 0.70 range suggested by the American Public Health Association (*1*) and close to the 0.64 presented by Camp (*4*) and used in Agriculture Handbook 60 (*23*). Total milliequivalents per liter of cations also closely followed the graph of cation me./l. vs EC in micromhos/cm. at 25° C. shown by Richards (*23*).

Annual yields of total dissolved solids for the individual sites were computed from stream-discharge data (m.^{3}/sec.) and dissolved-solids analyses (mg./l.) by developing a rating curve for dissolved-solids delivery. The year's hydrograph plus the rating curve was then used to summarize the annual yield.

RESULTS

Suspended-Sediment Data

Suspended-sediment samples collected during the 1964 to 69 period on the three largest catchments (43.5, 21.8, and 16.3km.^{2}) were used to draw the sediment-transport curves. The concentrations ranged from 16 to 1,790 mg./l.[3] As might be expected, the individual stream sites exhibit different transport curves, while points from a single site follow essentially the same curve from year to year. Transport curves for the three largest catchments are shown in figure 2. To calculate annual yields, a transport curve for each site was used to draw a "sediment hydrograph", which was then planimetered for the volume under the curve. The annual-yield values are based on the one-year period for which bed-load yields were determined (autumn 1967 to autumn 1968).

The spring-snowmelt period in March produced by far the largest part of the annual yield of suspended sediment, as shown in table 2.

More than 900 tons of sediment, for example, moved out of the 43.5-km.^{2} catchment (W-4) in three consecutive days in March, 1968—almost half the annual yield for the catchment. About 80 percent of the annual yield of suspended sediment from the study catchments was associated with the snowmelt period.

Storms of average size were apparently minor contributors of suspended sediment compared to the spring-snowmelt period. The largest storm—45 mm. on September 11 and 12, 1968, (return period of about 2 years)—transported only a minor part of the

---

[3] Note that, in the range discussed, p.p.m. = mg./l. – g./m^3. for all practical purposes.

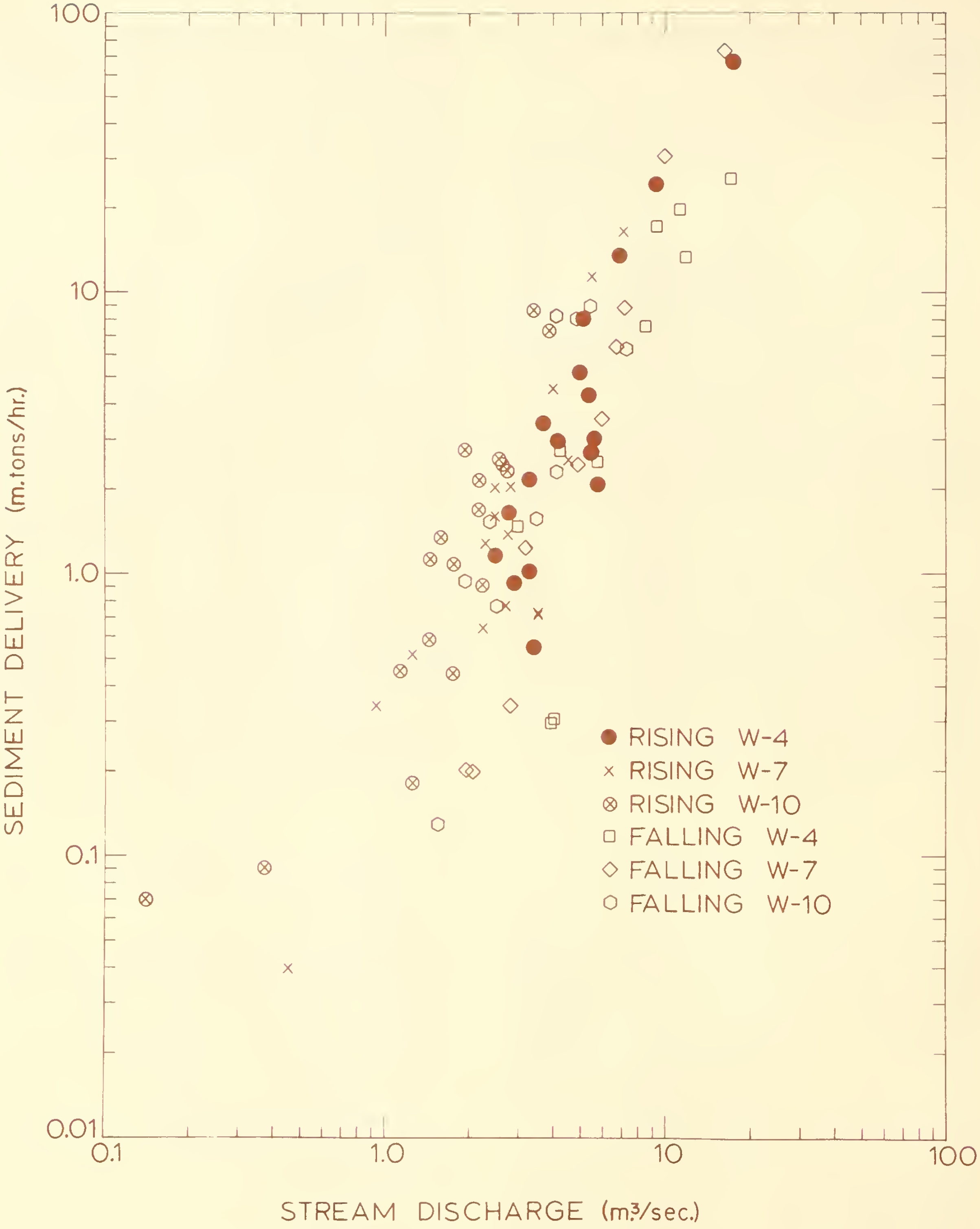


Figure 2.—Sediment transport curves for catchments W-4, W-7, and W-10.

Table 2.—Stream-discharge rates, suspended-sediment concentrations, and total load of suspended sediment by dates for three catchments[1]

Date	Catchment W—4			Catchment W—7			Catchment W—10		
	Stream discharge	Suspended sediment concentration	Suspended—sediment load	Stream discharge	Suspended—sediment concentration	Suspended—sediment load	Stream discharge	Suspended—sediment concentration	Suspended—sediment load
	Q(m.³/sec.)	*P.p.m.*	*M. tons*	*Q(m.³/sec.)*	*P.p.m.*	*M. tons*	*Q(m.³/sec.)*	*P.p.m.*	*M. tons*
1967:									
11—3	0.76	55	3.62	0.65	27	1.54	- -	- -	- -
11—4	.65	61	3.44	.53	33	1.54	0.28	37	0.90
11—5	.76	63	4.17	- -	- -	- -	.33	15	.45
11—6	.48	11	.45	- -	- -	- -	- -	- -	- -
11—23	.62	51	2.72	.87	30	2.26	.33	59	1.72
11—24	.93	67	5.44	.90	5	.36	.53	12	.54
11—25	.53	55	2.54	- -	- -	- -	- -	- -	- -
12—12	2.32	255	51.25	1.69	143	20.95	1.47	378	48.08
12—13	2.88	128	32.02	1.84	19	2.99	2.40	118	24.49
12—14	1.10	68	6.53	- -	- -	- -	1.38	51	6.16
12—15	.65	15	.81	- -	- -	- -	.42	7	.27
1968:									
3—17	.65	79	4.44	.50	41	1.81	.56	95	4.62
3—18	1.67	53	7.62	1.44	20	2.54	1.47	39	4.89
3—19	2.60	109	24.49	1.89	94	15.42	1.67	122	17.69
3—20	2.74	105	24.94	2.23	30	5.71	1.86	67	10.79
3—21	2.46	94	20.04	2.12	31	5.62	1.75	126	19.05
3—22	7.47	492	317.70	4.10	209	73.93	3.31	385	110.04
3—23	7.41	636	407.42	3.20	150	41.54	2.71	412	96.70
3—24	7.64	338	223.26	3.28	86	24.49	2.52	164	35.65
3—25	2.37	99	20.41	1.16	32	3.17	1.18	63	6.44
3—26	2.20	91	17.32	.99	31	2.63	1.10	75	7.16
3—27	2.57	117	26.12	1.33	24	2.72	1.44	160	19.95
3—28	2.74	130	30.84	1.61	31	4.35	1.55	77	10.34
3—29	3.37	140	40.82	2.23	92	17.69	1.81	130	20.41
3—30	3.62	130	40.73	2.52	38	8.34	1.84	106	16.78
3—31	3.34	140	40.37	2.23	58	11.15	1.67	104	14.96
4—1	4.61	174	64.40	3.62	101	31.57	2.26	190	37.10
4—2	2.80	85	20.59	1.64	28	3.99	1.33	71	8.16
4—3	2.57	102	22.68	1.41	35	4.26	1.18	70	7.16
4—4	2.86	103	25.49	1.75	34	5.17	1.35	93	10.88
4—5	4.64	190	76.20	3.00	80	20.68	1.67	94	13.60
4—6	2.60	94	21.13	1.41	25	3.08	1.01	23	1.99
4—7	2.23	95	18.41	1.16	16	1.63	- -	- -	- -
4—8	2.26	78	15.33	1.27	22	2.44	- -	- -	- -
4—9	2.52	62	13.51	1.50	10	1.27	- -	- -	- -
4—10	2.23	67	12.88	1.18	8	.81	- -	- -	- -
4—11	1.89	80	13.06	- -	- -	- -	- -	- -	- -
4—12	1.78	87	13.42	- -	- -	- -	- -	- -	- -
4—13	1.89	75	12.33	- -	- -	- -	- -	- -	- -
4—14	1.86	73	11.70	- -	- -	- -	- -	- -	- -
4—15	2.03	111	19.59	1.04	58	5.26	.82	111	7.89
4—16	2.12	91	16.69	1.18	22	2.26	1.04	48	4.35
4—17	1.38	67	8.07	.65	8	.45	- -	- -	- -
4—18	1.21	47	4.98	- -	- -	- -	- -	- -	- -
4—19	1.07	24	2.26	- -	- -	- -	- -	- -	- -

See footnote at end of table.

Table 2.—Stream-discharge rates, suspended-sediment concentrations, and total load of suspended sediment by dates for three catchments[1] —Continued

Date	Catchment W—4			Catchment W—7			Catchment W—10		
	Stream discharge	Suspended sediment concentration	Suspended—sediment load	Stream discharge	Suspended—sediment concentration	Suspended—sediment load	Stream discharge	Suspended—sediment concentration	Suspended—sediment load
	Q(m.^{3}/ sec.)	*P.p.m.*	*M. tons*	*Q(m.^{3}/ sec.)*	*P.p.m.*	*M. tons*	*Q(m.^{3}/ sec.)*	*P.p.m.*	*M. tons*
1968 (Con.):									
4—24	1.81	216	33.83	.90	233	18.23	.79	309	21.13
4—25	6.20	358	91.87	3.87	213	71.39	2.54	213	46.81
4—26	1.92	75	12.51	- -	- -	- -	.93	53	4.26
4—27	2.06	97	17.23	1.10	29	2.81	1.07	73	6.80
4—28	1.67	82	11.79	- -	- -	- -	.84	19	1.36
4—29	1.27	62	6.80	- -	- -	- -	- -	- -	- -
4—30	1.13	28	2.72	- -	- -	- -	- -	- -	- -
5—17	2.01	91	15.87	1.04	49	4.44	1.01	77	6.80
5—18	1.16	59	5.89	.76	8	.54	.62	42	2.26
5—19	2.03	100	17.59	1.35	39	4.62	1.24	103	11.06
5—20	3.03	170	44.54	2.12	76	13.97	1.52	151	19.95
5—21	1.78	82	12.70	1.16	13	1.36	1.13	37	3.62
5—22	1.27	83	9.16	- -	- -	- -	- -	- -	- -
5—23	1.04	34	3.08	- -	- -	- -	- -	- -	- -
5—30	.56	9	.45	- -	- -	- -	- -	- -	- -
5—31	.93	67	5.44	- -	- -	- -	.48	22	1.90
6—1	.70	62	3.71	- -	- -	- -	- -	- -	- -
6—9	.79	62	4.26	.25	29	.63	.39	70	2.44
6—10	1.81	104	16.05	1.35	44	5.17	1.41	117	14.24
6—11	.73	14	.90	- -	- -	- -	- -	- -	- -
6—13	- -	- -	- -	- -	- -	- -	.73	58	3.62
6—14	- -	- -	- -	- -	- -	- -	.48	54	2.17
6—15	.50	40	1.81	.25	12	.27	.22	32	.63
6—16	.76	41	2.63	- -	- -	- -	.36	9	.27
6—19	.50	35	1.54	- -	- -	- -	.36	49	1.54
6—20	.76	30	1.90	.56	17	.81	.65	29	1.63
6—24	.53	44	2.08	.33	19	.54	.39	54	1.81
6—25	.79	46	3.17	.62	3	.18	.62	35	1.81
6—29	.70	42	2.54	.48	31	1.27	.42	18	.63
6—30	1.21	72	7.62	1.01	31	2.72	.79	84	5.71
7—1	.84	50	3.71	.93	8	.63	.82	45	3.17
7—10	1.30	89	10.06	.53	29	1.36	.53	69	3.17
7—11	.59	81	4.26	- -	- -	- -	- -	- -	- -
8—20	.33	47	1.36	.08	243	1.90	- -	- -	- -
8—21	.50	27	1.17	.19	60	1.08	.28	56	1.36
9—11	1.04	115	10.34	.42	100	3.62	.84	123	9.16
9—12	.76	34	2.17	.42	38	1.36	- -	- -	- -
10—7	.31	72	1.90	- -	- -	- -	- -	- -	- -
10—8	- -	- -	- -	.28	81	1.90	- -	- -	- -
10—20	.36	34	1.08	- -	- -	- -	- -	- -	- -
Total yield (m. tons)			2258			477			748
Total yield (m. tons/km.^{2})			51.9			21.9			50.6

---

[1] Derived from hydrographs and from rating curves shown in figure 2.

annual suspended-sediment yield (table 2). A resume of storms for catchment W-2 (centrally-located) is given in table 3. All storms together accounted for less than 20 percent of the annual yield (table 2).

Total annual suspended-sediment yields for the study year 1967-68 ranged from 22 to 52 m. tons/km.^{2} (table 2). The lowest value of 22 m. tons/km.^{2} annual yield was from the quartzite, presumably less erodible, catchment W-7. The less resistant limestone and schist catchments yielded 50 to 52 m. tons/km.^{2} suspended yield for the 1967 to 1968 year. Days when sediment delivery was negligible (based on stream discharge and the transport curve) are not listed in table 2. The average daily concentrations were derived from daily yields, and yields were determined from each site's sediment transport curve and hydrograph. The sum of all days in the one-year period equals the annual yield.

The sediment-transport curves of figure 2 also demonstrated a loop similar to those observed by Dragoun and Miller (*8*) and others, where a rising flow at a site carries more sediment than a receding flow of the same rate. Peak sediment concentrations also were observed to precede peak stream discharge at a

Table 3.—Precipitation on catchment W-2 for 12 months Nov. 1, 1967 to Oct. 31, 1968

Day of month	Precipitation											
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
	Mm.	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*
1	2	- - -[1]	- - -	1	2	6	- - -	- - -	1	3	2	- - -
2	3	10	- - -	3	- - -	- - -	- - -	1	- - -	1	1	- - -
3	8	- - -	- - -	7	- - -	- - -	- - -	3	- - -	- - -	- - -	4
4	- - -	- - -	- - -	- - -	- - -	4	5	- - -	- - -	- - -	- - -	7
5	- - -	- - -	- - -	- - -	- - -	3	- - -	- - -	- - -	- - -	- - -	2
6	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	8	- - -	8	- - -
7	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	1	- - -	16
8	- - -	6	- - -	- - -	- - -	1	- - -	- - -	- - -	1	- - -	- - -
9	- - -	- - -	- - -	- - -	- - -	1	4	20	9	5	- - -	- - -
10	- - -	- - -	- - -	1	- - -	1	1	15	11	1	- - -	2
11	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	40	- - -
12	3	32	- - -	1	7	- - -	2	3	- - -	- - -	5	- - -
13	2	- - -	- - -	- - -	7	- - -	- - -	6	- - -	- - -	- - -	- - -
14	- - -	- - -	- - -	1	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
15	5	- - -	2	3	- - -	11	- - -	10	- - -	- - -	- - -	- - -
16	- - -	- - -	- - -	- - -	- - -	1	2	- - -	- - -	- - -	- - -	- - -
17	3	- - -	- - -	1	21	30	30	2	13	12	- - -	- - -
18	4	1	- - -	- - -	2	11	11	- - -	- - -	- - -	- - -	- - -
19	2	2	1	- - -	- - -	- - -	3	11	10	- - -	- - -	13
20	1	- - -	- - -	1	- - -	- - -	19	1	- - -	19	- - -	- - -
21	- - -	1	2	- - -	3	- - -	1	- - -	- - -	1	- - -	- - -
22	- - -	- - -	- - -	1	13	- - -	9	2	- - -	- - -	- - -	- - -
23	12	- - -	4	- - -	23	- - -	- - -	- - -	- - -	- - -	- - -	- - -
24	- - -	- - -	- - -	- - -	1	- - -	- - -	9	1	4	- - -	- - -
25	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	1	13	8	6
26	2	2	- - -	- - -	- - -	- - -	- - -	3	- - -	- - -	- - -	1
27	- - -	- - -	- - -	- - -	- - -	8	- - -	- - -	1	- - -	1	- - -
28	2	8	2	- - -	- - -	- - -	- - -	6	19	- - -	1	13
29	1	19	3	2	- - -	- - -	5	13	- - -	- - -	- - -	- - -
30	- - -	- - -	5	- - -	- - -	- - -	6	7	- - -	- - -	- - -	- - -
31	- - -	2	- - -	- - -	- - -	- - -	4	- - -	- - -	- - -	- - -	- - -
Monthly totals	50	83	19	22	79	77	102	112	74	61	66	64

[1] Negligible or nonexistent.

site during storm events, and demonstrated by representative data of figure 3.

Data collected at seven catchments over a period of 5 years are shown in figure 4. The catchments range in size from 0.57 to 111.2 km.[2] The curves indicate the relationship of stream discharge to sediment concentration for the range of catchment sizes. As shown in the curves, there is a tendency for streams in smaller watersheds to carry a larger load of suspended sediment for a given rate of flow. This tendency is best illustrated by figure 5. The figure shows for example, that a stream draining 20 km.[2] can transport 600 milligrams of suspended sediment per liter with about 10 m.[3] /sec. flow, whereas a larger, 100 km.[2], catchment's stream at the *same* discharge could transport only about 300 mg./1., or half as much.

Bedload Data

Suspended sediment and bedload normally are considered separately, although there is no real line of demarcation. For purposes of this study, bedload is considered to be the sediment moving along the bed and in saltation up to the lowest point sampled by the DH-48 suspended-sediment sampler (6.4 cm.).

Part of the moving bedload is trapped by debris basins, such as the weir ponds of the study. As explained earlier, trap-efficiency estimates were made, using stream and pond particle-size distribution and other information. Any attempt to separate suspended sediment and bedload, as well as attempts to estimate trap efficiencies, are at best assumptions made to simplify a process that is in fact complex.

The bed material found in the ponds was generally sand and gravel, with only a small percentage less than 0.1 mm. in diameter (fig. 6). Wolman and Johnson (unpublished data) also observed movement of larger cobbles and boulders, by tagging rocks in stream channels of the same catchments[4].

Bedload yields for the winter to spring (1967-68) and summer to autumn (1968) period are presented in table 4. The annual yields of bedload for seven catchments based on the one-year period ranged from 10.8 to 122.0 m. tons/km.[2] with a median of 26.0 m. tons/km.[2] An average of 87 percent of the annual yield occurred during the spring-runoff period (table 4). Storms presumably moved less than 13 percent of the annual load. Most of this 13 percent in 1968 was apparently the result of a 45-mm. rainfall on September 11 and 12, 1968. Smaller storms of less than 20 mm. also occurred, but these events probably did not produce stream discharges with tractive forces adequate to move the larger bedload material.

As a check on the yield determinations for the 1967-68 period of bedload study, two of the largest ponds were cleaned in the autumn of 1968, surveyed, then resurveyed after the 1969 spring runoff. The values of yield for spring 1968 were within 1.5 m. tons/km.[2] of the spring 1968 determinations for the 43.5-km.[2] catchment (W-4) and within 0.1 m. tons/km.[2] for the 16.2-km.[2] drainage (W-10). Runoff volumes during the two spring periods were also similar. Peak runoff from both W-10 and W-4 was about 5 percent higher in 1969 than in 1968, according to weir records.

A plot of bedload yields from the catchments for the year of measurements shows that yields per square kilometer were greater for the smaller catchments (fig. 7). In other words, bedload yields for the year studied were inversely related to catchment size. The average annual runoff per unit area is not related to catchment size in the Sleepers River watershed, however, slopes and drainage densities are inversely related to drainage size (table 5). This relationship of bedload yield to drainage area also is considered in the Discussion section.

Schulits and Hill (*24*) made a thorough study of bedload prediction formulas. They recommended the Schoklitsch, the Straub, and Meyer-Peter Müller formulas for use. As noted by Vanoni and others (*27*), "Values of sediment discharge calculated by formulas are to be considered as estimates only, since the errors involved may be 100 percent or more." Only the field-measured values of bedload are considered in this report.

---

[4] Cobbles up to 4.5 kg. in weight have been observed to move several meters during spring runoff.

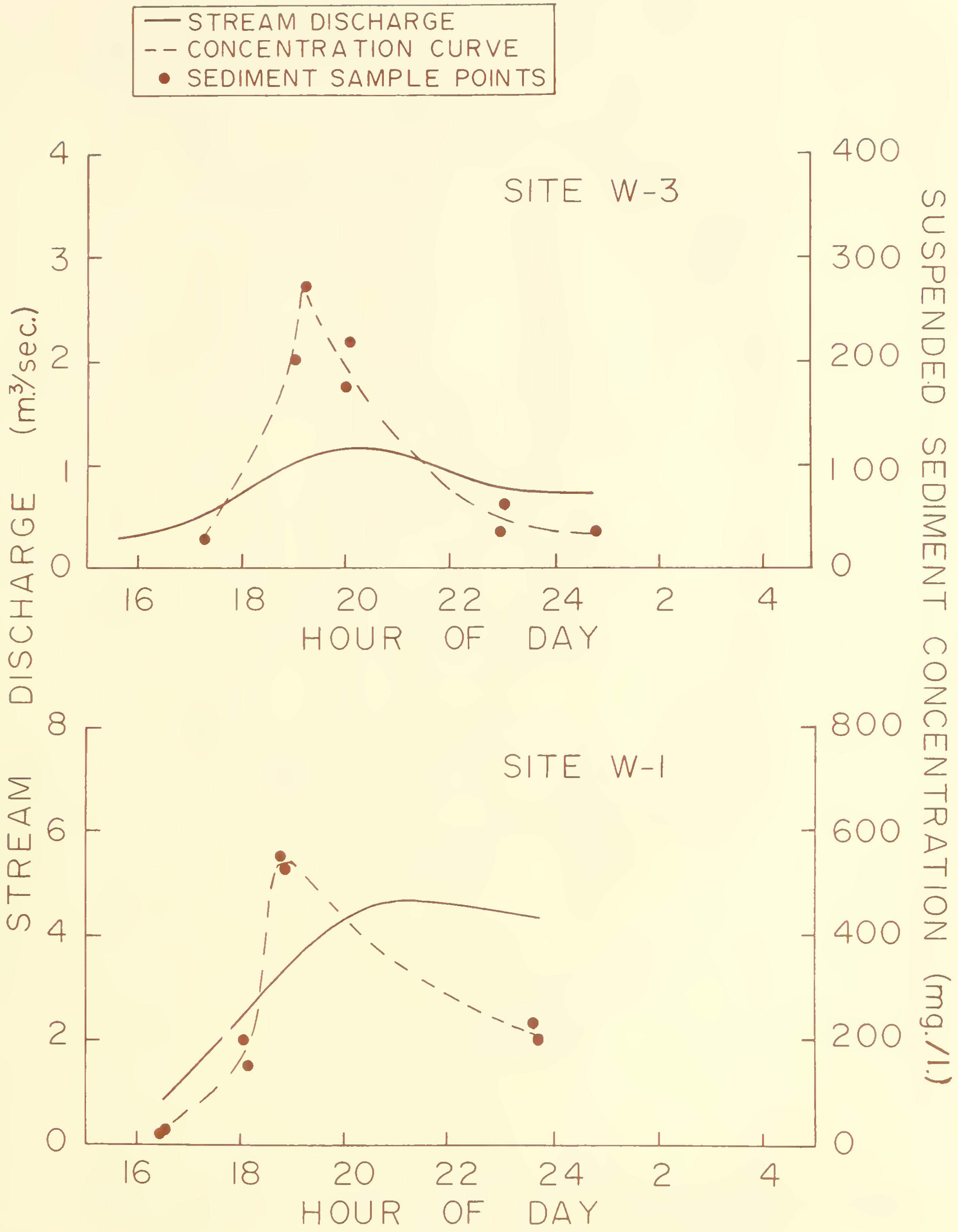


Figure 3.—Sediment concentrations compared to streamflow for one of the storms sampled during 1964 to 1969, showing how sediment peak preceded runoff peak.

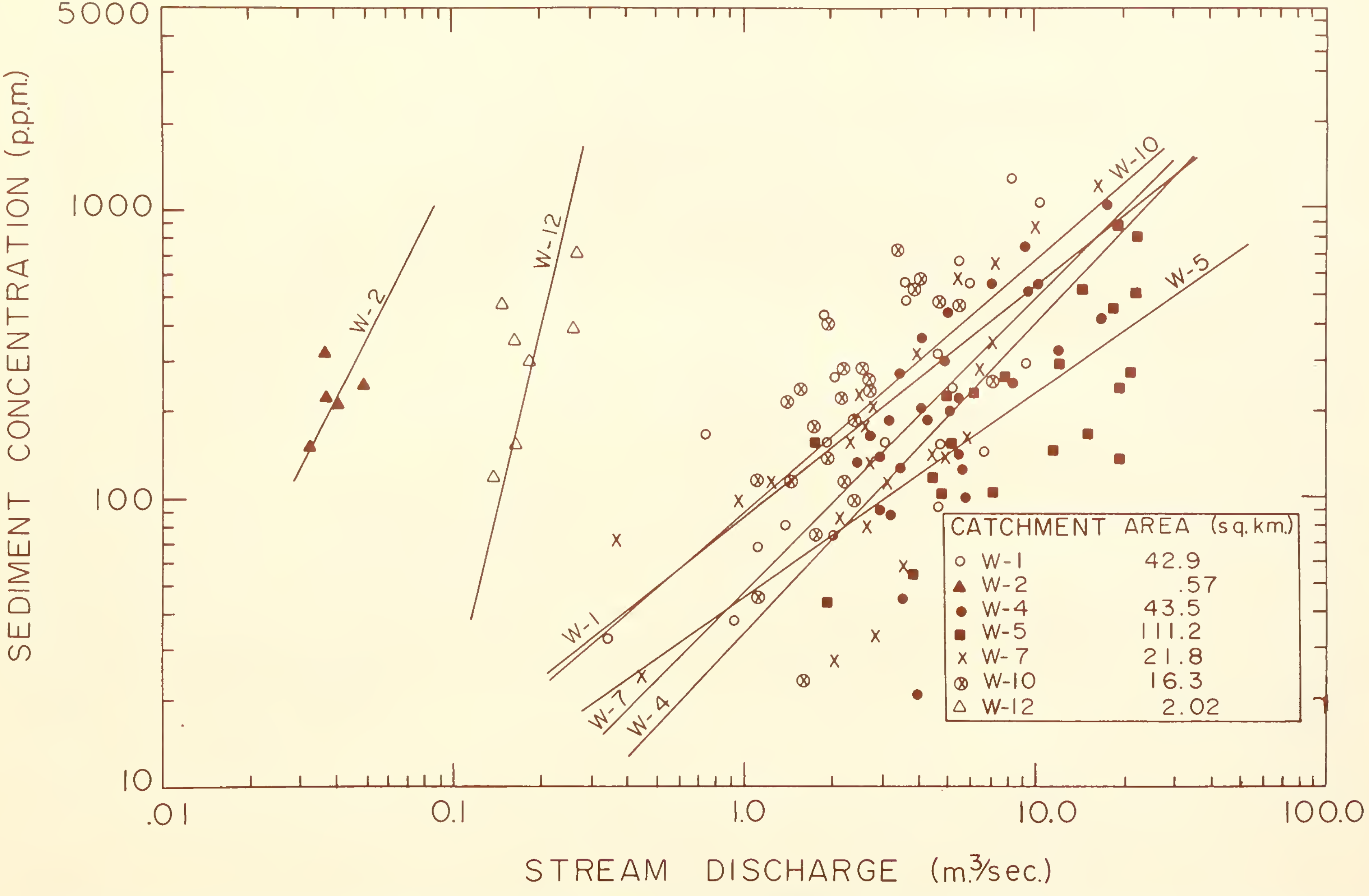


Figure 4.—Suspended-sediment concentrations vs. stream-discharge rate for seven catchments in the Sleepers River watershed from 1964 through 1969.

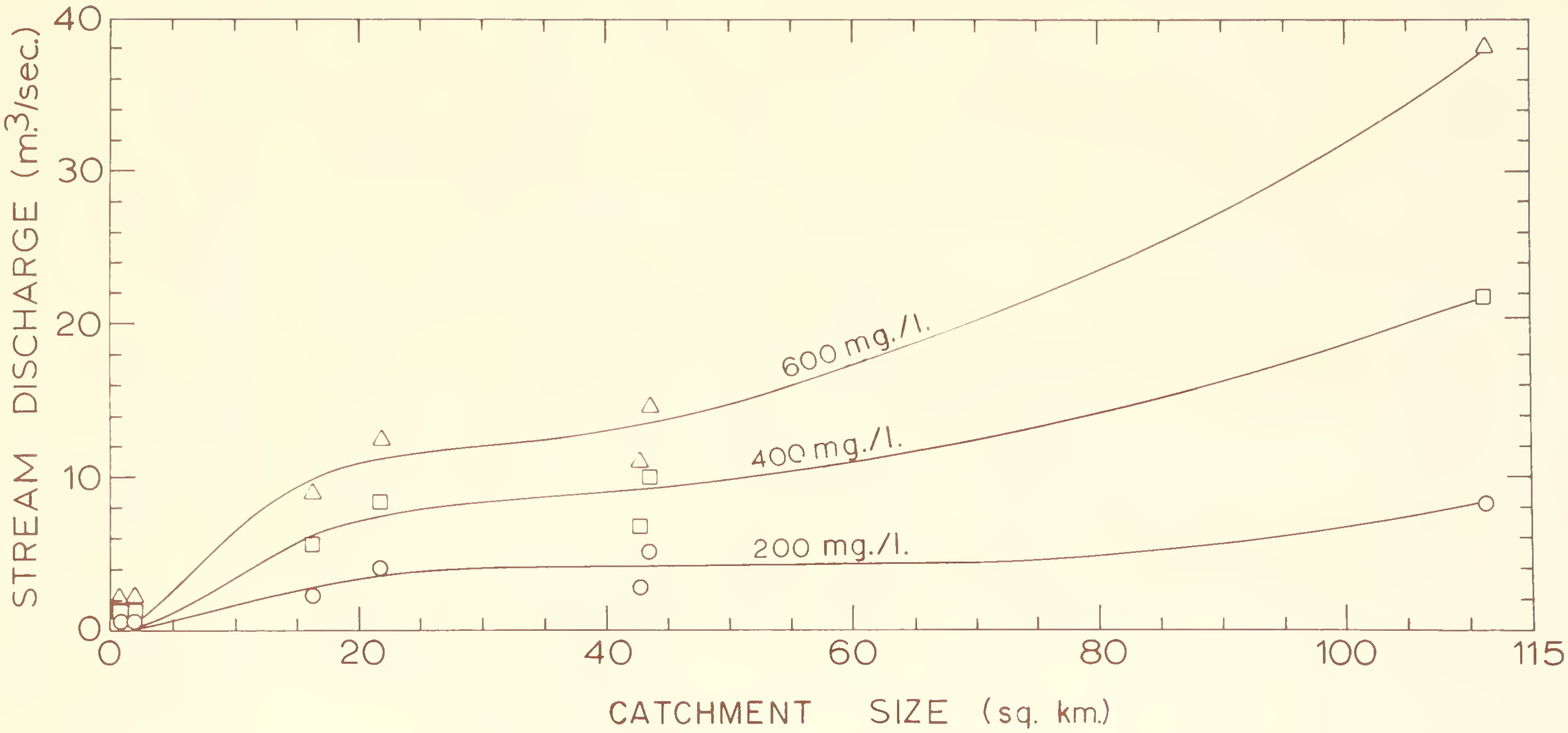
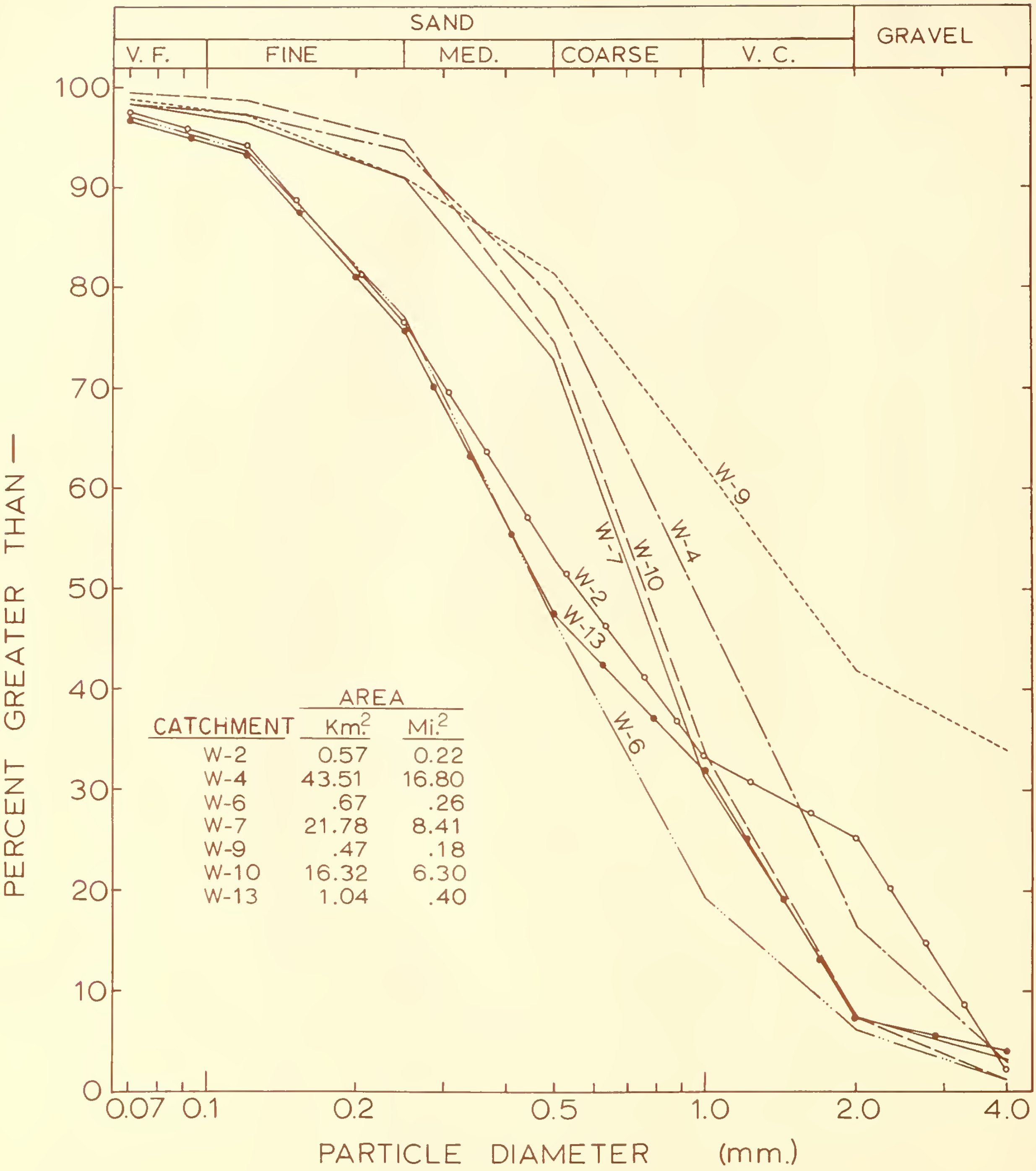


Figure 5.—Stream discharge rates needed to carry 200, 400, and 600 mg./1. suspended sediment for catchments ranging in size from 0.57 to 111.2 km². Points were selected from the curves in figure 4.



CATCHMENT	AREA Km.^{2}	AREA Mi.^{2}
W-2	0.57	0.22
W-4	43.51	16.80
W-6	.67	.26
W-7	21.78	8.41
W-9	.47	.18
W-10	16.32	6.30
W-13	1.04	.40

Figure 6.—Particle-size distributions of material trapped in weir ponds.

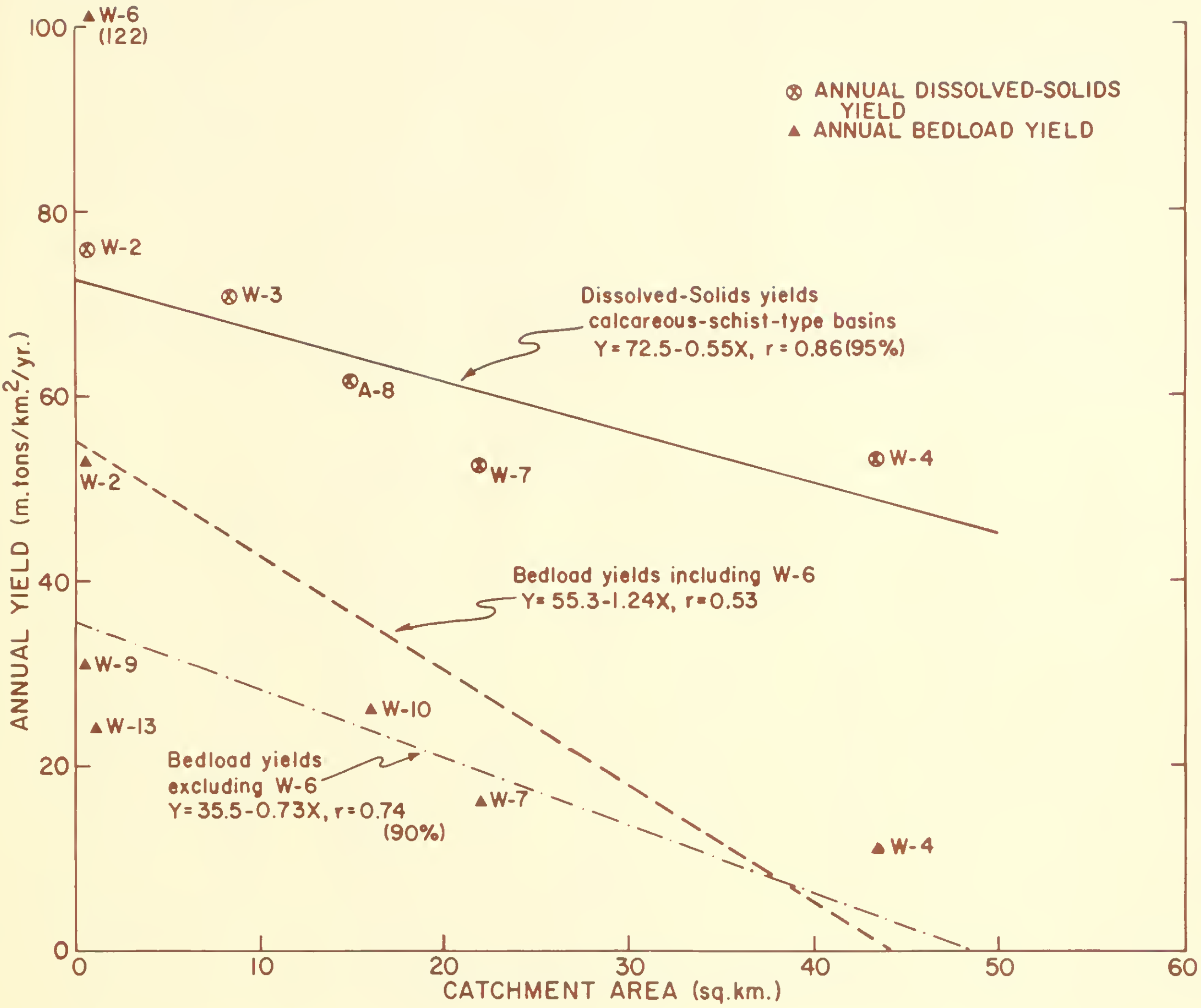


Figure 7.—Relationships between annual yields of bedloads and dissolved-solids loads and catchment size for catchments in the Sleepers River watershed.

Table 4.—Bedload yields from seven catchments in the Sleepers River watershed, Vt.

Catchment	Area	Measured yield[1]			Measured yield			Estimated trap efficiency	Estimated total bedload[2]	
		Winter-spring	Summer-autumn	Annual	Winter-spring	Summer-autumn	Annual			
	Km.^{2}	*M. tons*	*M. tons*	*M. tons*	*M. tons/km.^{2}*	*M. tons/km.^{2}*	*M. tons/km.^{2}*		*M. tons/km.^{2}*	*M.^{3}/km.^{2}*
W—9 . . .	0.47	5.2	- -	[3] 5.9	11.1	- -	[3] 12.68	41	30.93	19.3
W—2 . . .	0.57	18.0	- -	[3] 20.6	31.5	- -	[3] 35.97	68	52.82	32.9
W—6 . . .	0.67	50.5	- -	[3] 57.7	74.8	- -	[3] 85.41	70	122.01	76.1
W-13 . . .	1.04	15.3	- -	[3] 17.5	14.7	- -	[3] 16.79	70	23.99	15.0
W—10 . .	16.0	240.0	25.0	265.0	14.6	1.54	16.14	62	26.03	16.2
W—7 . . .	21.80	174.5	38.6	213.1	8.0	1.75	9.75	63	15.47	9.7
W—4 . . .	43.50	237.5	20.7	258.2	5.5	0.56	6.06	56	10.82	6.7

[1] Sediment weight was estimated to be 1,603 kg./m.^{3} (100 lb./ft.^{3}), which, according to weir-pond samples, would be a reasonable figure. [2] Estimated total bedload is "corrected" for the trap efficiency of the weirs. [3] Values obtained by multiplying winter-spring yield by 1.14, which is the average ratio of annual to winter-spring yields from W—4, W—7, and W—10 where summer-autumn measurements were made.

Table 5.—Selected geomorphic parameters of the study catchments.

Catchment	Area	RO[1] of area	Length of streams	Drainage density	Stream	Stream frequency	Relief ratio	Stream slope
	Km.^{2}	*Mm.*	*Km.*	*Km./km.^{2}*	*No.*	*No./km.^{2}*	*M./m.*	*M./m.*
W—2[2]	0.57	339	2.59	4.54	6	10.53	0.078	0.054
W—3	8.37	543	29.53	3.53	52	6.21	.092	.055
W—4	43.5	436	163.34	3.75	285	6.55	.049	.034
W—6	.67	N/A	3.17	4.73	7	10.45	.075	.026
W—7	21.8	464	78.21	3.59	100	4.59	.069	.044
W—8[3]	15.6	441	55.20	3.54	96	6.15	.065	.045
W—9[4]	.47	578	2.51	5.34	6	12.77	.272	.085
W—10	16.20	467	70.17	4.33	137	8.46	.041	.021
W—13[4]	1.04	345	3.83	3.68	8	7.69	.080	.048
W—5	111.0	460	- -	- -	- -	- -	- -	- -

[1] RO = mean annual runoff = average for the 1964 to 1968 period, in millimeters depth on a respective catchment. Data came from hydrograph analyses. [2] 1968 runoff data missing. [3] Geomorphic data for T—8 and A-8 are essentially the same as those shown for W—8. [4] 1964 runoff data missing.

Dissolved-Solids Data

As detailed in the Research Methods section, annual yields of dissolved solids were calculated from conductivity measurements and discharge records from the stream sites. Six of 12 study sites were considered "natural" or "unpolluted" (see descriptions in table 6). These six sites were used for comparison of annual dissolved-solids yields for natural streams of various sizes.

Annual yields of dissolved solids ranged from 37 to 76 m. tons per square kilometer for natural streams draining the calcareous-schist rock type, as shown in table 6. The median yield was 61.4. Yields in polluted streams ran higher. The lowest yield (37.2 m. tons/km.^{2}/yr.) was for an all-forested drainage of micaceous-quartzite and quartz-mica-schist rock types—a catchment draining 0.47 km.^{2} along the upper ridge of the research watershed.

Table 6.—Annual yields of dissolved solids in runoff from 11 catchments, based on chemical analyses and stream-discharge measurements

Catchment				Dissolved solids in runoff		
Number	Area	Description	Classification[2]	Total amount	Coliform bacteria[1] (Mean/median)	Mean Cl^-
	Km.^{2}			*M. tons/km.*^{2}*/yr.*	*Colonies/100 ml. water*	*P.p.m.*
W—3	8.37	"*Natural stream*" emerging from forest lands.	N	70.6	100/9	5.9
A—8	15.0	Downstream another kilometer, still *unpolluted.*	N	61.4	358/75	- - -
T—8	15.3	100 meters downstream from A—8, below a house and *barn pollution* source.	- - -	63.7	3,818/1,100	- - -
W—8	15.6	500 meters downstream from T—8, below a village dumping *raw sewage.* Includes catchments above.	- - -	66.7	5,251/2,200	- - -
W—7	21.8	A large, *unpolluted stream* draining forests and fields.	N	52.4	420/200	- - -
M—12	2.02	A small stream *drastically polluted by cattle* in stream, barn drainage.	- - -	281.4	3,548/1,250	- - -
W—2	0.57	A small, reasonably *clean stream.*	N	75.9	652/230	- - -
T—1	42.9	A mixture of all the above streams, that is, W—8, W—7, M—12, and W—2.	- - -	52.9	2,520/1,600	7.0
W—10	16.3	A larger stream, found to receive large inputs of *highway salt.*	- - -	90.1	759/460	19.7
W—4	43.5	A larger, essentially *unpolluted* drainage.	N	53.1	1,454/1,000	4.9
T—5	111.2	The *composite* of all the above, that is, T—1, W—10, and W—4, plus possibly some added house, barn, and highway pollution.	- - -	91.8	1,444/880	9.2
W—9	0.47	"*Natural stream*" draining forest only.	N	37.2	NA[3]	- - -

[1] Based on samples throughout the year. Bacteria values are in colonies per 100 ml. of water. [2] N = those streams considered reasonably "natural", that is, basically unpolluted by farms, sewage, or highway salt, as shown by bacteria and chloride values. [3] Not available.

Chemical analyses indicated that the principal constituent in the natural streams was calcium bicarbonate (table 7), derived from leaching of carbonates in the calcareous schists of the area[5]. Numerous cation analyses during 1966 to 1970 likewise demonstrated a predominance of calcium ions (*13*).

The annual dissolved-solids yields were slightly higher per unit area and also higher per stream length for the smaller, headwater catchments drainage the same rock type. Within the range sampled, the natural streams draining the calcareous-schist rock type demonstrated an inverse relationship between annual yield (on a unit area basis) and catchment size (fig. 7).

A comparison of yield to stream lengths likewise show the inverse relationship of figure 8. The curves of figures 7 and 8 imply that the headwater catchments or steeper, first-order streams yielded more dissolved substances per unit area or per stream length than did the larger catchments downstream.

Specific electrical conductance was highly dependent on rate of streamflow as shown in figure 9. In the discharge from watershed W-4, electrical conductance may be predicted from stream discharge by:

$$EC = 184\ Q^{-0.161}$$

where EC = specific conductance in micromhos per cm. at 25° C. and Q = $m.^3$ sec. These data appear in figure 9A. The correlation coefficient is 0.945 for 33 pairs. Other sites demonstrated the same nonlinear relationship.

As shown in figure 9 the dissolved solids daily yield is a direct function of streamflow. The daily yield (or delivery rate or transport rate) is the product of milligrams per liter concentration and cubic meters per second stream discharge records.

The strong relationship between dissolved-solids concentrations and deliveries was also expressed in the seasonal patterns. As shown in figure 10, the spring-snowmelt season carried about one-half the annual dissolved-solids yield for the catchments (again using natural catchment W-4 as an example). During the spring melt, *concentrations* were low, but *yields* were high (fig. 10). The seasonal pattern of figure 10 was typical for all 12 of the sites studied.

Chloride analyses showed concentrations were twice as great at site W-10 as at other sites throughout the year (table 6). The site is below where the stream closely follows along about 4 kilometers of a heavily-salted highway. The coliform bacteria counts were low, indicating no fecal contamination at W-10. The highway salting effect is reported in detail in another report (*13*).

The relationship of dissolved-solids yields to domestic or farm pollution was distinct, hence the use by the authors of only "natural" sites for certain analyses. As the stream passed sites A-8, T-8, and W-8, for example, (table 6) the added pollution showed up in both the bacterial and dissolved-solids concentrations. Note that the three sites are very close together, so that stream discharge was essentially, the same. Site M-12, where cattle were wading and defecating in the small stream, show high electrical-conductance values.

ANALYSIS OF DATA

Load Comparisons

Table 8 presents a summary of dissolved, suspended, and bed loads in the streams studied and comparisons where two or more of the three types of data were available. Catchments W-4 and W-7 also are averaged, because they are the only "unpolluted" streams where all three types of load were computed. The m. tons/$km.^2$ annual values are given, and the same data also appear by percentages.

The dissolved-solids yield was 53 to 55 m. tons/$km.^2$ for the year, and the solid-load yield (bed plus suspended) was 50 to 69. In other words, the yield of dissolved material was approximately equivalent to the yield of particulate material.

Between 26 and 40 percent of the Sleepers River solids (particulate) yield for the year was bedload. Such separation of suspended and bedload is approximate, as are estimates of trap efficiency, but it is reasonable to conclude that about one-third of the Sleepers River solids yield was bedload.

---

[5] Newell, Wayne L. Saprolite development in the Sleepers River watershed, Danville, Vermont. M. A. Thesis, Dartmouth College. 71 pp. 1966.

Table 7.—One set of chemical analyses[1] of discharge water from nine catchments in the Sleepers River watershed

Catchment	Dissolved solids in discharge water									Discharge water	
	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	SiO_2	pH[2]	[3] EC
	Mg./l	*Mg./l*	*Mg./l*	*Mg./l*	*Mg./l*	*Mg./l*	*Mg./l*	*Mg./l*	*Mg./l*		*μ mhos/ cm.*
W—1	45.0	1.55	3.0	4.0	127	1	23	3.5	6.1	8.4	243
W—3	38.0	1.15	2.5	3.0	100	0	19	2.5	5.5	8.2	193
W—4	47.5	1.55	2.5	4.1	139	1	22	2.0	3.4	8.3	253
W—5	48.0	1.60	3.5	4.2	140	1	18	5.5	3.2	8.3	271
W—8	42.0	1.40	2.6	3.5	121	0	12	3.0	5.2	8.2	232
W—9	30.0	1.15	2.0	1.9	79	0	28	1.0	3.6	7.6	156
W—10	60.0	2.00	9.0	5.2	170	1	12	[4] 26	3.7	8.4	378
W—16	45.0	1.30	3.2	2.6	129	0	28	3.5	2.1	8.1	247
W—17	30.0	1.10	2.0	2.2	84	0	12	1.5	1.3	8.1	165

[1] Analyses by F. R. Hall, Department of Soil and Water Science, and John Plumer, Engineering Experiment Station, at the University of New Hampshire. [2] At 25° C. [3] Electrical conductance in micromhos per cm. at 25° C. [4] The effect of road salt is obvious on this watershed.

Table 8.—Annual yields of dissolved, suspended, and bedloads of sediment in five catchments in the Sleepers River watershed, Vt.

Catchment Number	Catchment Size	Suspended solids		Bedload		Bedload + suspended solids		Dissolved solids		Total sediment load	
	Km.^{2}	*M. tons/ km.*^{2}	*Pct.*	*M. tons/ km.*^{2}	*Pct.*	*M. tons/ km.*^{2}	*Pct.*	*M. tons/ km.*^{2}	*Pct.*	*M. tons/ km.*^{2}	*Pct.*
W—4	4.35	51.9	---	10.8	---	62.7	---	53.1	---	115.8	---
W—7	21.8	21.9	---	15.5	---	37.4	---	52.4	---	89.9	---
W—10	16.3	50.6	---	26.0	---	76.6	---	[1] 90.1	---	166.7	---
W—9	.47	---	---	30.9	---	---	---	37.2	---	---	---
W—2	.57	---	---	52.9	---	---	---	75.9	---	---	---
Mean of W—4 and W—7:	32.7										
Amount	---	36.9	---	13.2	---	50.1	---	52.8	---	102.9	---
Percent of total sediment:	---	---	35.9	---	12.8	---	48.7	---	51.3	---	100.0
Percent of total solids: . . .	---	---	73.7	---	26.3	---	100.0	---	---	---	---
Mean of all sites:	16.5										
Amount	---	41.5	---	27.2	---	68.7	---	[2] 54.7	---	123.4	---
Percent of total sediment	---	---	33.6	---	22.1	---	55.7	---	44.3	---	100.0
Percent of total solids	---	---	60.4	---	39.6	---	100.0	---	---	---	---

[1] This figure exaggerated by salt contamination from highway. [2] Dissolved-solids value for W—10 excluded because of salt contamination.

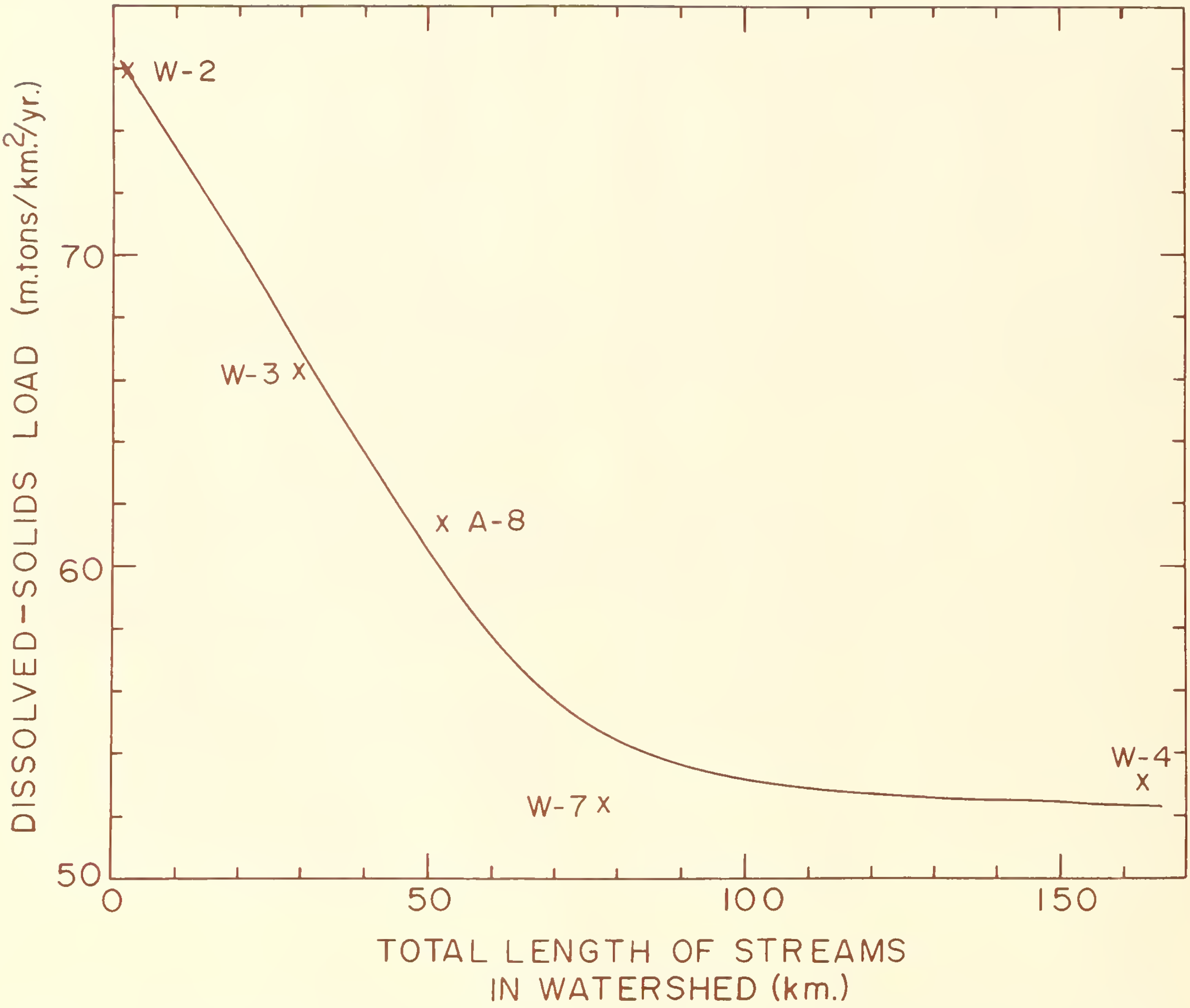


Figure 8.—Annual yield of dissolved solids compared to total length of stream in the five "unpolluted" catchments. Each point is based on 29 to 33 samples for the year.

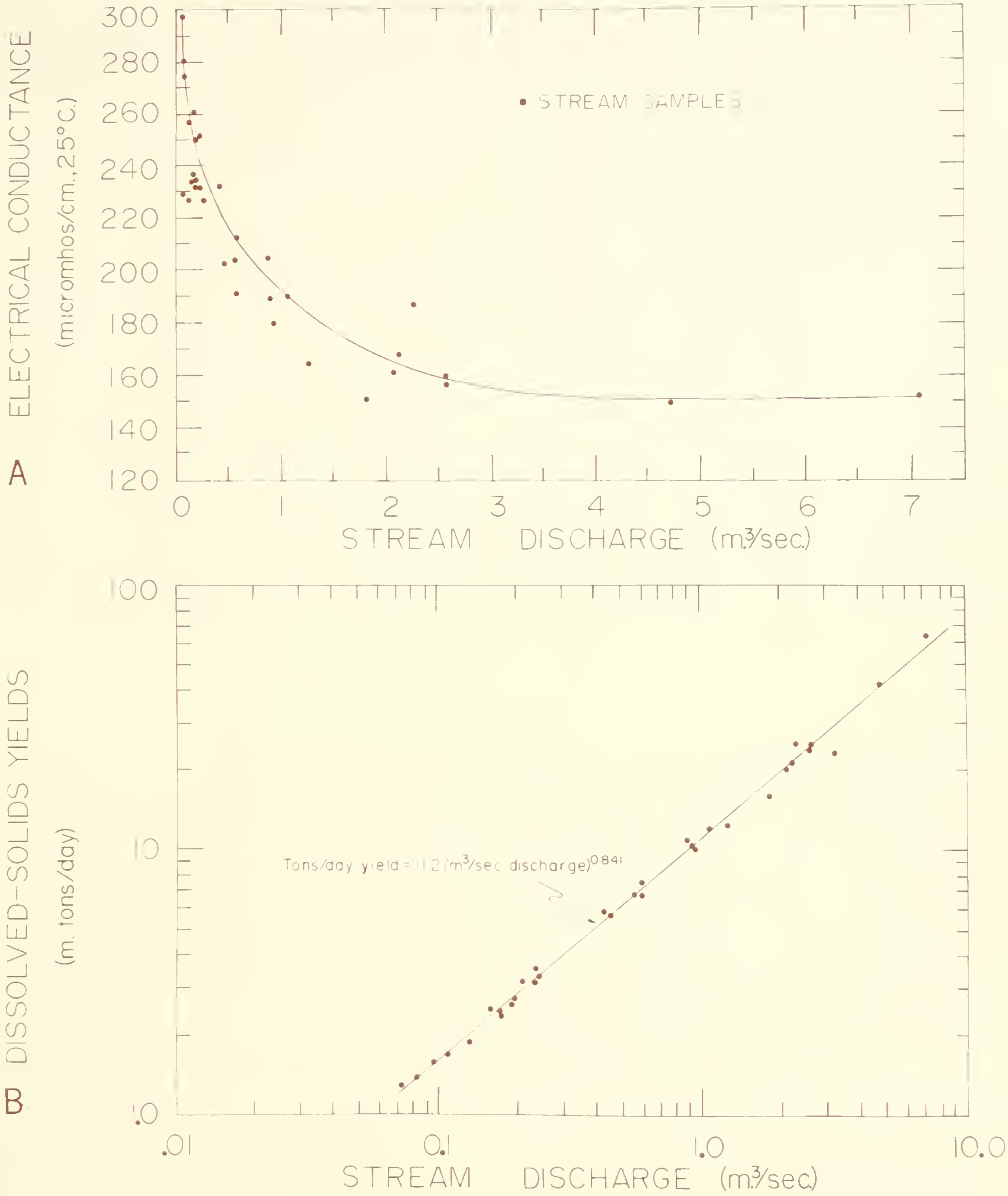


Figure 9.—A.—Comparison of electrical conductance to stream discharge for 33 samples throughout the year on watershed W-4. B.—The same points produce a dissolved-solids yield curve as shown.

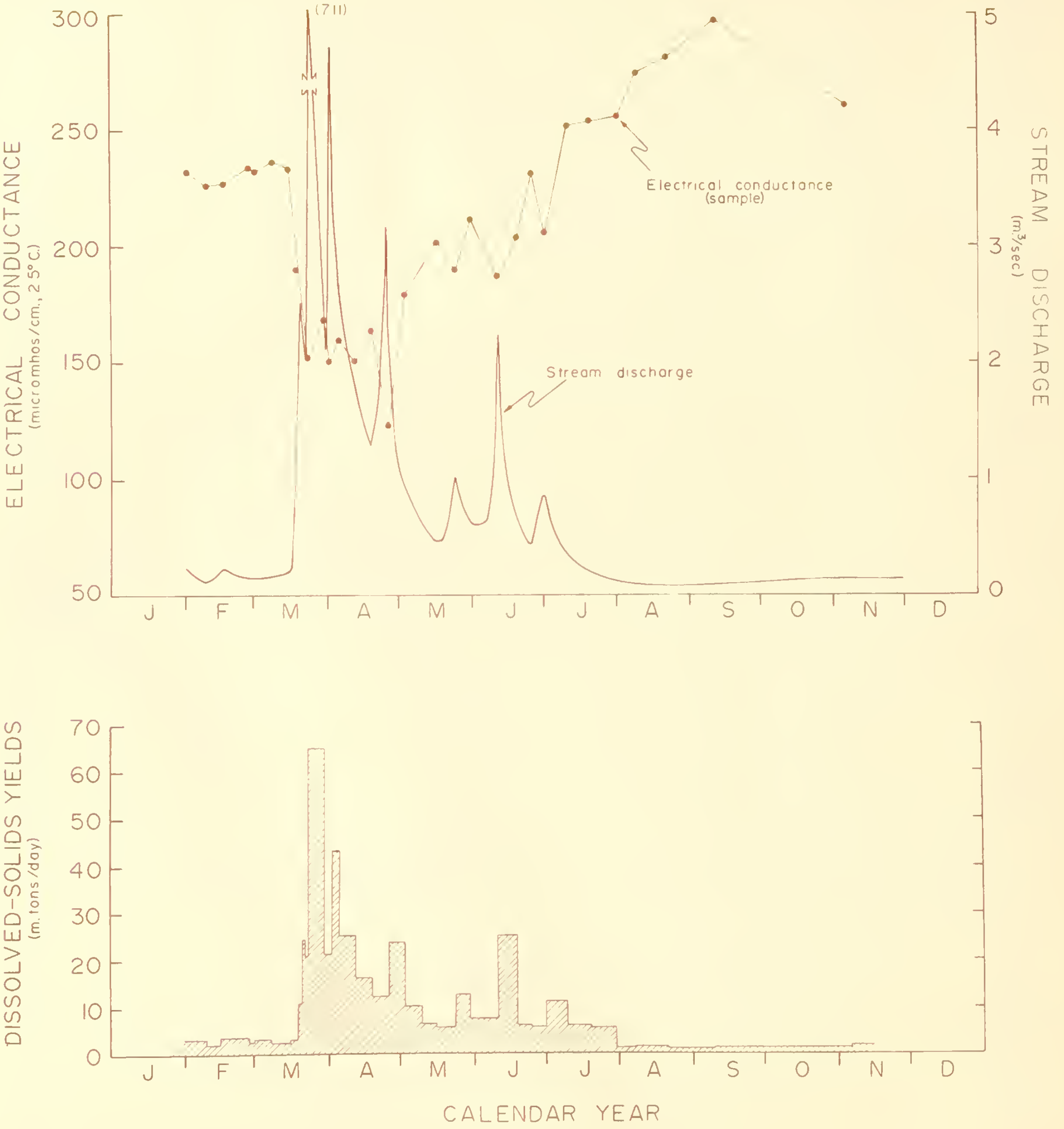


Figure 10.—Annual trend of dissolved-solids yields, as estimated from electrical conductance at site W-4—a larger watershed of mixed forests and fields.

The bulk of all three types of yields was carried by the spring runoff. About 80 percent of the suspended load, more than 80 percent of the bedload, and more than half of the dissolved load moved during the spring runoff in the year of study. By comparison, storms carried minor parts of all three types of load.

Sediment Sources

In the Sleepers River watershed, there is no indication that the sediment originated as sheet or rill erosion. Virtually no such erosion was observed. The land use is predominantly forest or grassland farming, with less than one percent in cultivation. Most of the farmed fields are on gentle slopes, separated from the steams by wooded buffer strips. Soil Conservation Service soils maps of soils, slopes, and erosion classes for the watershed show more than 99 percent of the land to be in the "little or no erosion" class. The overland stormflow necessary for sheet erosion appears to be rare in the Sleepers River watershed, except in wet "seeps", where the groundwater is near the surface[6]. The vegetative cover and root mats in such seepy areas protect them from erosion.

The stream banks and beds are no doubt the principal sources of sediment in the catchments. Undercut and slumping banks are common sights along the streams, particularly in the spring. Observations by Wolman and Johnson (unpublished station data) also indicated that the stream banks and bed are the key sources of sediment. They observed marked cobbles weighing from 0.1 to 4.5 kg. to move in the streams, some of the cobbles moving several meters during the year.

In the immediate channel area of small brooks, perhaps two to four meters on either side of the stream, some "piping" erosion has been observed. As channels shift location, it appears that small tunnels remain behind. These passageways are particularly subject to "piping" erosion during storm-runoff and spring-melt periods.

DISCUSSION

The range of annual suspended-sediment yields of from 22 to 52 m. tons/km.^{2} in the Sleepers River watershed is comparable to or slightly higher than data found in southern New England by the U.S. Geological Survey on the Merrimack River at Lowell, Mass. (a 12,004-km.^{2} drainage) and on the Scantic River at Broad Brook, Conn. (225 km.^{2}) These are apparently the closest available sediment data (*25*, *26*.) The total suspended yields for the two rivers for 1967 was about 31 m. tons/km.^{2} for the Scantic and 10 m. tons/km.^{2} for the Merrimack. Concentrations ran higher in the Sleepers River streams during spring runoff (and possibly during storms) than in the larger Merrimack and Scantic Rivers. However, the two larger streams maintain higher sediment concentrations during periods of lower flow, indicating that the smaller Sleepers River streams are more "flashy" sediment carriers.

Storms of modest return periods on the Sleepers River catchments did not appear to be important transporters of suspended sediment, compared to the very effective spring-snowmelt period. The long duration of the snowmelt period, when flow remains very high for many days, makes it unlikely that a storm—except perhaps one of the catastrophic size—would appreciably compete with the spring-melt period in terms of sediment transport. Such observations are not in concensus with findings in other geographic locations, particularly areas where the spring runoff is less consequential. Certain streams have been found to transport 90 percent of a year's sediment load during a single storm, according to Leopold, Wolman, and Miller (*17*). They note that "In many snow-fed streams maximum discharge occurs during the period of snowmelt; however, the maximum sediment load per unit time is frequently transported during times of thunderstorm summer rainfall." The importance of modest-size storms was studied by Piest (*22*), who found that "storms with a return period of less than 1 year were the cause of 34 to 92

---

[6] Dunne, T. Runoff production in a humid area. Ph.D. disseration, Johns Hopkins University. 1969.

percent of total suspended sediment yield" in 72 small watersheds in 17 States. Storms in the Sleepers River probably convey less than 20 percent of the annual suspended-sediment yield.

A comparison of data for a number of U.S. Geological Survey sampling stations along the Appalachian chain indicates that in the Sleepers River the proportion of suspended sediment carried in the spring is much larger than is the case at sites further south in the same range. The stations further south in the Appalachians generally carry only 30 to 50 percent of the annual sediment yield during the spring runoff, as compared to about 80 percent on the Sleepers River. In the Sleepers River, where snow constitutes about one-third of the annual precipitation, a higher percentage of the annual flow occurs in the spring than is the case in most areas. Ice may be yet another reason why springtime yields of suspended sediment are high in the Sleepers River. The authors, after observing a number of melt periods in Vermont, believe ice chunks act as gouging or planing tools, tearing at the streambanks. In contrast to our observations, Parsons[7] believes that ice along streambanks in New York State acts as a buffer, protecting banks against potentially destructive flows in the channels. Such "buffering" is not apparent in the Sleepers River.

As noted in figures 4 and 5, the smaller streams were capable of carrying a higher concentration of suspended sediment per given discharge. Presumably the amount of eroding bank area per volume of flow was greater for the smaller streams than for the flatter, larger streams. It is not possible (with the data available) to say there is more suspended-sediment yield (m. tons/km.^{2}) for smaller catchments, but the greater sediment load carried by a smaller stream for a given amount of discharge does suggest that smaller headwater streambanks may yield more suspended sediment per stream reach than downstream stretches.

As shown in table 4, the 1968 bedload yields for seven catchments ranged from 10.8 to 122.0 m. tons/km.^{2}, with a median of 26.0 m. tons/km.^{2}. Much of the material was coarse, sandy, and gravelly. Wolman and Brush (*28*) note that stream velocity is of key importance in initiating particle motion on stream beds. Velocities up to 2.5 meters per second have been measured in streams of the Sleepers River watershed. The relationship of velocity of the depth-slope product is used in the Wolman-Brush study to describe the initiation of particle movement; for example, given a certain velocity and depth-slope product, how large a particle can the stream transport? Channel-geometry data for two Sleepers River catchments (the largest and smallest, W-4 and W-9) were fitted to the Wolman-Brush curves to evaluate bedload-movement potential for the streams. Discharge-velocity comparisons and flow-duration curves for the two streams were used to determine what percent of the time particles of a certain size could be moving. The stream draining 0.47 km.^{2} (W-9) could theoretically move gravel of 3.2-mm. size only for a few hours during spring runoff. A sand grain of 1.7 mm. could be moved about two percent of the year, and sand of only 0.67-mm. diameter could be transported as much as 25 percent of the time, according to the curves. The larger stream (43.5 km.^{2} at W-4), although less steep than the small stream, is much more capable of moving larger material. The 0.67-mm. sand may be moved 60 percent of the time, while gravel up to 15.5 mm. in diameter may be transported two percent of the time (note in table 5, geomorphic descriptors for the catchments).

In summary, the Wolman-Brush curves, if applied to Sleepers River data, indicate that the larger sizes of bed material primarily would be moved during the extended high discharges of spring snowmelt. This is consistent with field observations from the catchments (table 4), which indicate that more than 80 percent of the annual yield of bedload was conveyed in the springtime. The curves and calculations also indicate that larger streams on the Sleepers River are theoretically capable of transporting larger diameter particles. It should be noted that the average annual runoff per unit area is not related to catchment size (table 5). Stream slopes and drainage densities are inversely related to drainage size (table 5). The same runoff per unit area in the small drainages presumably would put a given discharge into contact with more area of erodible streambank

---

[7] Parsons, D.A. Streambank erosion processes and control. Joint Agricultural Research Service-Soil Conservation Service Workshop, Oxford, Miss., Sept. 16-18, 1959.

than would be the case downstream, where larger, wider stream channels exist.

Measured yields of bedload for the Sleepers River were comparable to values observed in the Frazier Forest in the Rocky Mountains of Colorado (*16*). At both the Sleepers River and Frazier Forest, peak flows normally occur during snowmelt season. Soils, climate, and topography are similar in many ways.

Transport curves of dissolved solids for 11 catchments on the Sleepers River are assembled in figure 11, where the curves are compared with those of 17 large river basins (using data from Leopold, Wolman, and Miller, (*17*). Positioning of the curve for a particular catchment does not necessarily indicate the annual yield, since the transport curves may be similar for two streams that are quite different in size, hence quite different in total yield.

As shown in figure 10, daily and seasonal variation in dissolved-solids yields were very distinct, because of a strong dependence of dissolved-solids concentrations on stream discharge (fig. 9). For this reason, Sleepers River annual yields were based on a number of samples (29 to 34) at each site, collected throughout the year, using continuous stream-discharge records in conjunction with the specific-conductance analyses. Miller (*19*) analyzed single samples from a number of streams in the Sangre de Cristo Mountains, in a study of dissolved-solids concentrations. He assumed "average concentrations of dissolved solids reported for waters derived from each rock will be considered as mean annual values; and . . . concentrations at any given station changes very slightly with variation in discharge." Such assumptions clearly are not applicable to the Sleepers River.

Climate and geology are the broad, long-term independent variables determining "denudation rates" or rates of lowering of the land (*20*). Langbein and Schumm (*15*) have assembled data for denudation of basins in the U.S.A., in relation to "effective precipitation".[8] Their gaging-station data (table 9) include dissolved and suspended loads. Comparable denudation rates from the Sleepers Rivers are 3.4 cm./1,000 yr. (for stations where dissolved-solids and suspended loads are available). As used in this paper, the "denudation per 1,000 years" is strictly a convenient term for comparison, with no 1,000-year prediction or extrapolation implied. Taking all types of yield (dissolved, bed, and suspended), the Sleepers River denudation rate, according to the data, would theoretically be 102.9 m. tons/km.^{2} /yr., or 4.0 cm./1,000 yr.

The 4.0 cm./1,000 yr. denudation rate for the Sleepers River is probably a conservative estimte, since the data used are from a period during which no extreme events occurred. The rate is nonetheless higher than the 2.7 world-wide denudation rate referred to by Leopold, Wolman, and Miller (*17*) or the 3.3 rate for the U.S.A. given by Dole and Stabler (7), but still falls far short of Corbel's (5) estimate of 50 cm./1,000 yr. for mountainous regions. Judson (*11*) notes that "the rate (of lowering) varies between about 2 cm. per 1,000 yr. on slopes of 5 degrees and 20 cm. on slopes of 30 degrees." Regional values of denudation within the U.S.A. (total load), implied from sediment-yield measurements, are 4 to 5 cm./1,000 yr. for the Atlantic States, according to Judson and Ritter (*12*).

The dissolved-solids proportion of the Sleepers River load was high, compared to most areas of the country, as evidenced by superimposing Sleepers River values on a dissolved- versus solid-yield curve for the U.S.A. (fig. 12) by Judson and Ritter (*12*). According to data from a number of watersheds throughout the U.S.A. (*17*), the dissolved load may constitute as much as 64 percent of the total load in certain areas. On the Sleepers River, dissolved-solids loads made up about one-half the total load. Data obtained by Langbein and Dawdy (*17*) imply that the proportion of the total load that is dissolved depends on "effective precipitation" of the area. In areas of low precipitation, suspended loads are greater than dissolved loads, while in areas like the Sleepers River, with 750 to 1,000 mm. runoff per year, suspended and dissolved yields are much more similar in magnitude. The Sleepers River data appear to fit their pattern.

From 26 to 42 percent of the Sleepers River solid yields for the study year was bedload. These percentages may in reality be an underestimation. The near-filling of the weir ponds that occurred during spring runoff could very

---

[8] "Effective precipitation" as used in their context is the precipitation required to produce an amount of runoff based on a reference temperature of 50° F.

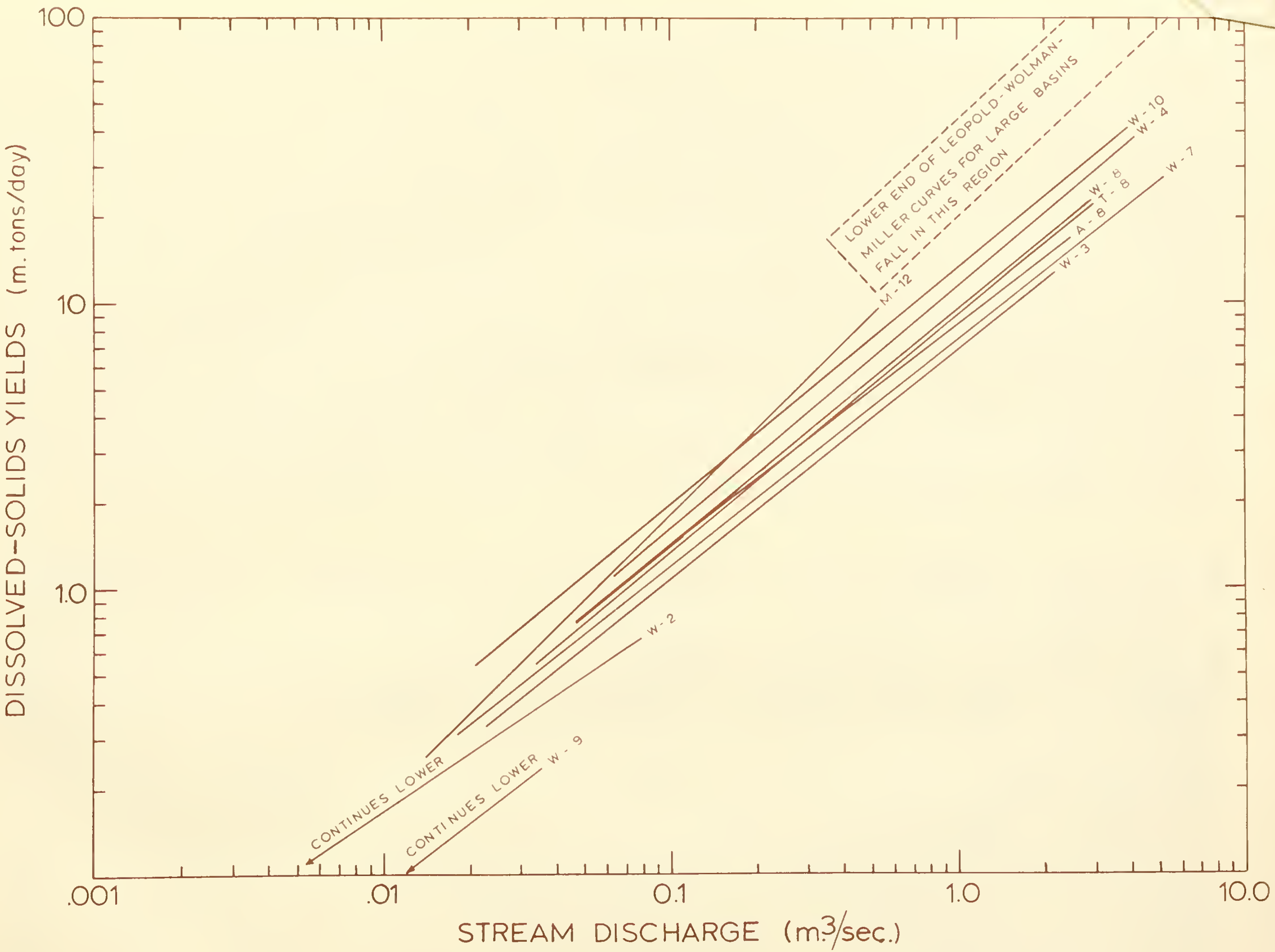


Figure 11.—Rating curves for amount of dissolved solids by stream-discharge rate for 10 Sleepers River catchments in 1968.

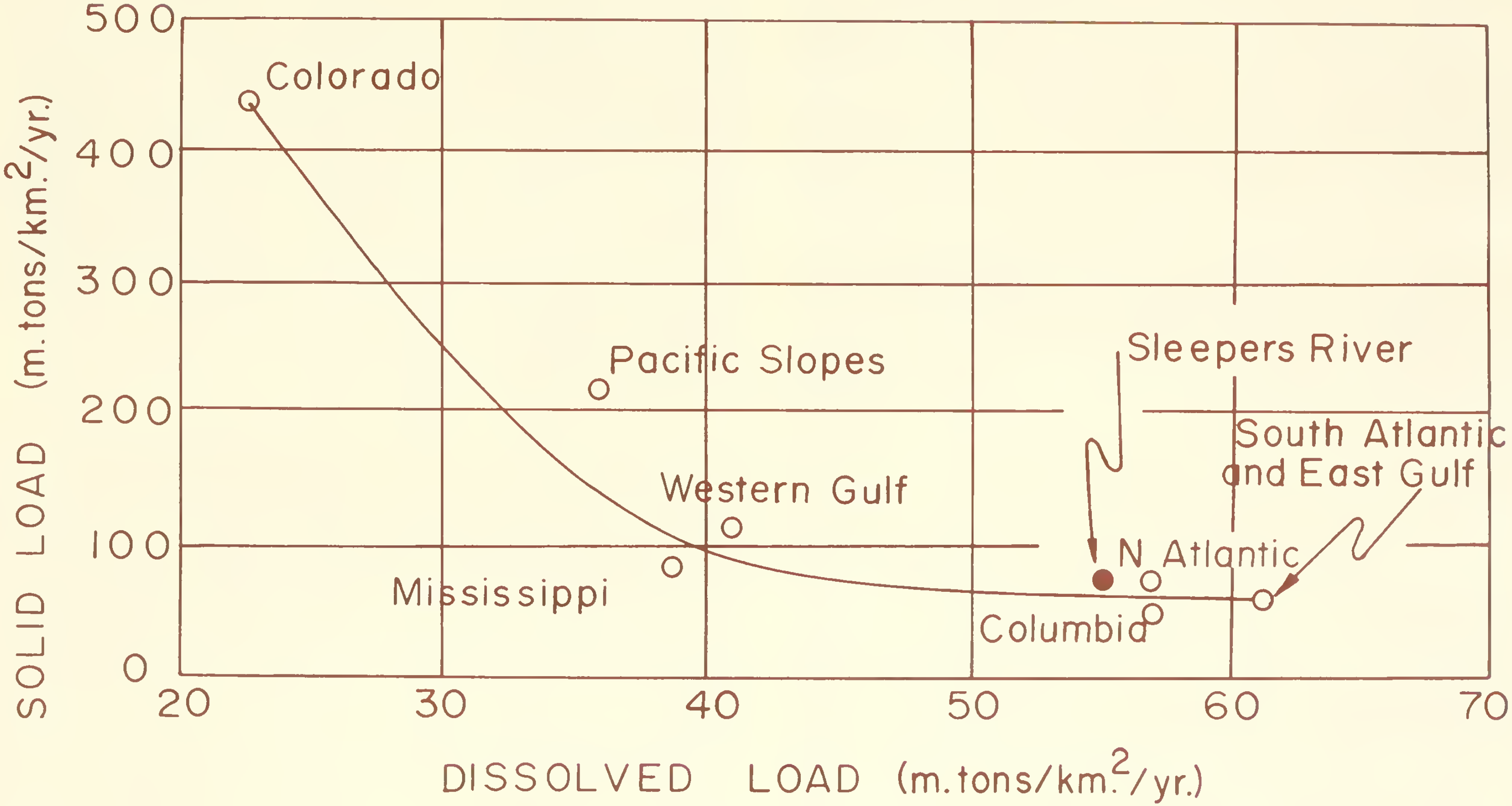


Figure 12.—Mean value of proportion of solid-sediment load to dissolved-sediment load in discharge of Sleepers River catchments superimposed on Judson and Ritter's curve (*12*) for this proportion in various watersheds in the United States.

Table 9.—Denudation rates of drainage basins in the United States[1]

Effective precipitation	Mean sediment yield	Mean denudation rate
Mm./yr.	*M. tons/km.²*	*Cm./1,000 yr.*
Gaging-station data:[2]		
250	235	8.8
250 to 375	273	10.4
375 to 500	193	7.3
500 to 750	193	7.3
[3] 750 to 1,000	140	[4] 5.2 (3.4)
1,000 to 1,500	77	3.0
Reservoir data:[5]		
200 to 230	490	18.6
255	413	15.5
280	525	19.8
355 to 635	396	14.9
635 to 760	501	18.9
760 to 965	277	10.4
[3] 965 to 1,015	196	7.3
1,015 to 1,395	165	6.4
1,395 to 2,540	[4] 154 (104)	[4] 5.8 (4.0)

[1] From Langbein-Schumm, 1958 (*15*). [2] Includes dissolved and suspended load. Drainage areas average about 3,900 km.² [3] Range of precipitation most like that on the Sleepers River watershed. [4] Average Sleepers River values in parentheses.

possibly mean that the trap-efficiency estimates determined and used were too high. In other words, more bed material may have gone over the weir than we could account for late in the spring, after some filling of the weir pond. Such over-estimation of trap efficiencies would have led to conservative or low calculations of bedload yields. In any event, it seems safe to say that one-third of the Sleepers River solid yields in a typical year is bedload material. This is still a high proportion by comparison to most areas of the country. Linsley, Kohler, and Paulhus (*18*) note, for example, "an arbitrary increase of ten to 20 percent (of the suspended-sediment values) is customarily included to allow for bedload."

SUMMARY

Sediment yields were studied in the Sleepers River watershed, northern Vermont, U.S.A. The watershed receives 750 to 1,125 mm. of precipitation annually, and the temperature averages 4.5° C. Land use is primarily forests and haylands, with very little cultivated land. The bedrock is principally calcareous schists, micaceous quartzite, and quartz mica schists. Soils are primarily find sandy loams and loams derived from weathering of glacial tills and bedrock.

Observation and measurement during 1964 through 1969 and intensive study during 1967 through 1969 are our basis for the conclusions listed here. These figures are believed to be reasonably representative of a typical year in the Connecticut River headwaters area studied.

A. Total Load and Comparisons.
   1. The yield of solid material (50 to 69 metric tons/km.²/yr.) was approximately equivalent to the yield of dissolved material (53 to 55 m. tons/km.²/yr.)
   2. Between 26 and 42 percent of the Sleepers River solid (particulate) yield for the study period was bedload.
   3. The bulk of all types of yield—suspended, bed, and dissolved—was carried in the spring runoff.

B. Suspended Sediment.

1. Concentrations of samples collected from streams during spring runoff and storms of 1964 to 1969 ranged from 16 to 1,790 milligrams per liter.
2. Almost half the 1968 yield occurred in three days in the March-snowmelt period. About 80 percent of the annual yield was associated with the snowmelt period.
3. Storms of average size (up to a 2-year return period) were minor contributors of suspended sediment in comparison to the snowmelt season.
4. Yields of suspended material ranged from 22 to 52 m. tons/km.^{2} annually.
5. A rising flow at a site carried more particulate matter than a receding flow of the same rate, that is, a "loop" was common to the transport curve.
6. A comparison of various sizes of catchments showed that the smaller streams carried more suspended-sediment load for a given rate of flow.

C. Bedload.

1. The bed material was usually sand and gravel with larger cobbles.
2. Annual yields for seven catchments ranged from 10.8 m. tons/km.^{2} to 122.0 m. tons/km.^{2}
3. An average of 87 percent of the annual bedload yield was associated with the spring runoff, according to 1968 and 1969 observations.
4. Storms of average size moved a very minor part of the annual load.
5. Annual yields per square kilometer were greater for the smaller headwater catchments, according to comparison of yields for catchments between 0.57 and 43.5 km.^{2} in size.

D. Dissolved Solids.

1. Specific conductance measurements (micromhos per cm. at 25° C.) could be used to estimate dissolved solids in the "unpolluted" Sleepers River streams, where conductance times about 0.7 equaled total dissolved solids. Calcium bicarbonate was the principal dissolved substance.
2. Annual yields of dissolved material were 37 to 76 m. tons/km.^{2} for the "unpolluted" catchments.
3. Within the range of sizes sampled for catchments draining the calcareous-schist rock type, dissolved-solids annual yield in m. tons/km.^{2} was inversely related to catchment size.
4. Specific electrical conductance was highly dependent on stream discharge. The largest catchment, for example, showed $EC = 184\,Q^{-0.161}$ where EC = specific electrical conductance in micromhos per cm. at 25° C. and Q = stream discharge in cubic meters per second. The EC to Q regression had a correlation coefficient of 0.945 for 33 pairs of observations throughout the year. Ten other catchments showed an equally good correlation between EC and Q.
5. The spring-runoff period carried about half the total yield, even though actual concentrations were low during the period.
6. Because of the strong dependence of specific conductance on discharge and the predictions of dissolved solids that could be made with specific conductance (in the Sleepers Rivers, a rating curve of dissolved-solids yields (concentration X discharge) versus discharge could be used to approximate instantaneous yields and yearly totals.
7. Highway salting polluted a 16.3-km^2 catchment's stream consistently through the year, as indicated by measurements of $C1^-$, specific conductance, and Na+.
8. Farm and domestic pollution, as well as cattle wading in a small stream, increased values of specific electrical conductance.
9. The "denudation rate" for the Sleepers River is 4.0 cm./1,000 years, based on approximation from the few years of study.

E. Source of Sediment.

1. The streambanks apparently supplied nearly all erosion and sediment.

REFERENCES

(1) American Public Health Association.
1965. Standards methods for the examination of water, sewage, and industrial wastes. Ed. 11, 626 pp. Amer. Public Health Assoc., New York.

(2) Brown, Carl B.
1950. Sedimentation in reservoirs. *In* Hunter Rouse (ed.), Engineering Hydraulics, pp. 825-834. John Wiley and Sons, Inc., New York.

(3) Brune, G. M.
1953. Trap efficiency of reservoirs. Trans. Amer. Geophys. Union 34 (3): 407-418.

(4) Camp, T. R.
1963. Water and its impurities. 355 pp. Reinhold Publ. Co.

(5) Corbel, J.
1959. Vitesse de l'erosion. Zeits. fur Geomorphologie 3:1-28.

(6) Dennis, John G.
1956. The geology of the Lyndonville area, Vermont. Vermont Development Commission Bull. 8: 98 pp. Montpelier, Vt.

(7) Dole, R. B., and Stabler, H.
1909. Denudation. U.S. Geol. Survey Water Supply Paper 234: 78-93.

(8) Dragoun, F. J., and Miller, C. R.
1966. Sediment characteristics of two small agricultural watersheds. Trans. ASAE 9 (1): 66-70.

(9) Fair, G. M., and Geyer, J. C.
1954. Water supply and waste water disposal. Ed. 6, pp. 584-598. John Wiley and Sons, Inc., New York.

(10) Hall, Leo M.
1959. The geology of the St. Johnsbury quadrangle, Vermont and New Hampshire. Vermont Development Commission Bull. 13: 105 pp. Montpelier, Vt.

(11) Judson, Sheldon.
1968. Erosion of the land or what's happening to our continents? Amer. Scientist 56 (4): 615-620.

(12) Judson, Sheldon, and Ritter, D.F.
1964. Rates of regional denudation in the United States. Jour. Geophys. Research 69: 3395-3401.

(13) Kunkle, S. H.
1971. Effects of road salt on a Vermont stream. Proc. SUNY Street Salting Urban Water Quality Workshop, Syracuse, N.Y., May 5-6, 1971. 25 pp.

(14) Kunkle, S. H., and Comer, G. H.
1971. Estimating suspended sediment concentrations in streams by turbidity measurements. Jour. Soil and Water Conservation 26 (1): 18-20.

(15) Langbein, W. B., and Schumm, S. A. Schumm, S. A.
1958. Yield of sediment in relation to mean annual precipitation Trans. Amer. Geophys. Union 39 (6): 1076-1084.

(16) Leaf, Charles F.
1966. Sediment yields from high mountain watersheds, central Colorado. U.S. Dept. Agr., U.S.F.S. Res. Paper RM-23: 15 pp. Fort Collins, Colo.

(17) Leopold, L. B., Wolman, M. G., and Miller, J. P.
1964. Fluvial processes in geomorphology. 522 pp. W. H. Freeman and Co., San Francisco.

(18) Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H.
1958. Hydrology for engineers. 340 pp. McGraw-Hill Book Co., Inc.

(19) Miller, J. P.
1961. Solutes in small streams draining single rock types, Sangre de Cristo Range, New Mexico. U.S. Dept. Inter., U.S. Geol. Survey Water Supply Paper 1535-F. 23 pp.

(20) Morisawa, Marie.
1968. Streams, their dynamics and morphology. 175 pp. McGraw-Hill Book Co., New York.

(21) Newell, Wayne L.
1970. Some factors influencing the grain of the topography along the Willoughby Arch in northeastern Vermont. Geografiska Annaler. 52 A (1970) - 2., pp. 103-112.

(22) Piest, R. G.
1963. The role of the large storm as a sediment contributor. *In* Proc.

Fed. Interagency Sedimentation Conf. U.S. Dept. Agr. Misc. Publ. 970: 98-108.

(23) Richards, L. A., ed.
1954. Diagnosis and improvement of saline and alkali soils. U.S. Dept. Agr. Agr. Handbook 60, 160 pp.

(24) Schulits, Sam, and Hill, R.D., Jr.
1968. Bedload formulas, parts A and B. Penn. State Univ., Dept. of Civil Engrg., Hydraulics Lab. Bul. 153 pp. University Park, Pa.

(25) United States Department of the Interior.
1968. Quality of surface waters in the United States, 1960. Parts 1 and 2. North Atlantic Slope Basins and South Atlantic Slope and Eastern Gulf of Mexico. U.S. Geol. Survey Water Supply Paper 1741. 417 pp.

(26) United States Department of the Interior.
1968. Water resources data for Massachusetts, New Hampshire, Rhode Island, Vermont, 1967. Part 1. Surface water records. Part 2. Water Quality Records. U.S. Dept. Inter., U.S. Geol. Survey, 305 pp. Boston.

(27) Vanoni, V. A., Brooks, N. A., and Kennedy, J. F.
1961. Lecture notes on sediment transportation and channel stability. Calif. Inst. Tech., W. M. Keck Lab. of Hydraulics and Water Resources Rpt. KH-R-1. Pasadena.

(28) Wolman, M. G., and Brush, L. M., Jr.
1961. Factors controlling the size and shape of stream channels in coarse noncohesive sands. U.S. Dept. Inter., U.S. Geol. Survey Prof. Paper 282G: 183-210.

U. S. DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE
BELTSVILLE, MARYLAND 20705