Great Lakes Coastal Geology

Sediment Contributions of Western New York Streams to Lake Erie

Herbert Thomas Buxton,
Robert K. Fahnestock and
Parker E. Calkin

New York Sea Grant Institute

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Herbert Thomas Buxton

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Robert K. Fahnestock

Department of Geology
State University College, Fredonia, New York

Parker E. Calkin
Department of Geological Sciences
State University of New York at Buffalo

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply metric (SI)[1] units	By	To obtain inch-pound units
cubic meters per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
square kilometers (km^2)	0.3861	square miles (mi^2)
kilometers (km)	0.6214	miles (mi)
meters (m)	3.281	feet (ft)
megagram (Mg) (or metric ton)	1.102	tons, short (tn)

Multiply inch-pound units	By	To obtain metric (SI)[1] units
cubic feet per second (ft^3/s)	.0283	cubic meters per second (m^3/s)
square miles (mi^2)	2.590	square kilometers (km^2)
miles (mi)	1.609	kilometers (km)
feet (ft)	0.3048	meters (m)
tons, short (tn)	0.9072	megagram (Mg) (or metric ton)

[1]International system of units

ABSTRACT

The disappearance of large areas of recreational beaches and the rapid undercutting of roads and structures along wave-cut shorelines have necessitated a study of the sediment balance along Lake Erie's western New York coast. This report describes our attempt to quantify and understand fluvial contribution from small drainage basins to Lake Erie's sediment budget and particularly to the coastal portion. We categorized 29 watersheds encompassing our field area with most of Lake Erie's western New York drainage into five groups according to significant geomorphic parameters. One representative was chosen from each group. Detailed investigation of both coarse and fine sediment yields on the representative basins allowed us to extrapolate the sediment yield of the entire group. The estimated total sediment yield of the 1,435 km^2 (554 mi^2) field area was approximately 1.02 million Mg (1.12 million tn) for 1975, with approximately 100,000 Mg (110,000 tn) coarse fraction. This stream total is about three times that of 0.32 million Mg (0.36 million tn) subaerially eroded from Lake Erie's western New York coast per year. However, the coarse (bedload) fraction of the streams is roughly one-half of the annual amount of sand and gravel contributed to the littoral zone by bluff erosion.

Relative sediment production of the individual basins was dependent upon the availability of sediment in the form of thick moraine deposits and thick sequences of glacial drift over buried valleys. Sediment yields increased significantly during periods of high flows and although summer suspended sediment contributions were higher, exceeding high flows during winter contributed higher sediment yields. We found that nine days of high flow during the winter of 1975 contributed 73 percent of the annual sediment yield of Canadaway Creek.

Influxes of coarse fluvial sediment to the lake also occur during high flows. Sand and gravel stored in bars along the stream channel out in the settling pond-like estuaries at the mouth can then be transported to the lake in spite of high lake levels and obstructing littoral sediments.

INTRODUCTION

The Problem and the Procedures

The disappearance of large areas of Lake Erie's recreational beaches and the relentless undercutting of roads and structures along wave-cut bluffs are constant reminders that beach sediment is in short supply along the western New York Erie coast. Geier and Calkin (in press) have estimated that approximately 323,000 Mg (356,000 tn)* per year are eroded from Lake Erie's western New York shore, of which up to 226,000 Mg (249,000 tn) may be sand and gravel suitable for nourishment of the beach environment. In this study we have attempted to isolate and to demonstrate important contributions of western New York streams to the littoral as well as to the deep water portions of Lake Erie's sediment budget. In addition, we have assessed the relative sediment contribution of streams of different geomorphic character in the area although our primary concern is the small drainage basins.

The field work was undertaken through the 1975 calendar year and encompassed a study area of approximately 2,200 km^2 (850 mi^2) covering a significant portion of western New York's drainage to the Erie basin (Figure 1). Twenty-nine river basins, each draining into Lake Erie, compose this study area. They range from about 5 km^2 (2 mi^2) to the 1,435 km^2 (554 mi2) basin of Cattaraugus Creek, stretching 72 km (45 mi) east of Lake Erie. The area extends from Twentymile Creek at the Pennsylvania border northeastward to Pike Creek near Hamburg, NY (Figure 1). Therefore it does not cover basins of the half dozen streams reaching Lake Erie between Pike Creek and the Niagara River, including the large basins of Eighteenmile Creek and Buffalo Creek. Because of their size and location with respect to Buffalo, the latter two have been part of earlier studies (Archer and LaSala 1968). Furthermore, the large coarse sediment load of Buffalo Creek does not contribute to beach nourishment; rather it forms an obstruction at Buffalo that must be removed by man (Archer and LaSala 1968).

We divided the 29 basins in the field area into five groups based on geomorphic parameters which we felt would best reflect their sediment production characteristics. We chose one representative basin from each of the five categories for a more detailed investigation of sediment yield. We then used an estimate of annual sediment for each representative basin to extrapolate the expected sediment yield of the entire field area. The representative basins were sampled during most runoff events in 1975 and we attempted to monitor both suspended (fine) and bedload (coarse) transport.

We determined the annual sediment yield to help answer these important questions:

What characteristic drainage basin contributes the most sediment and at what times and locations does it enter the coastal environment?

*Mg = megagrams or metric tons; tn = short tons.

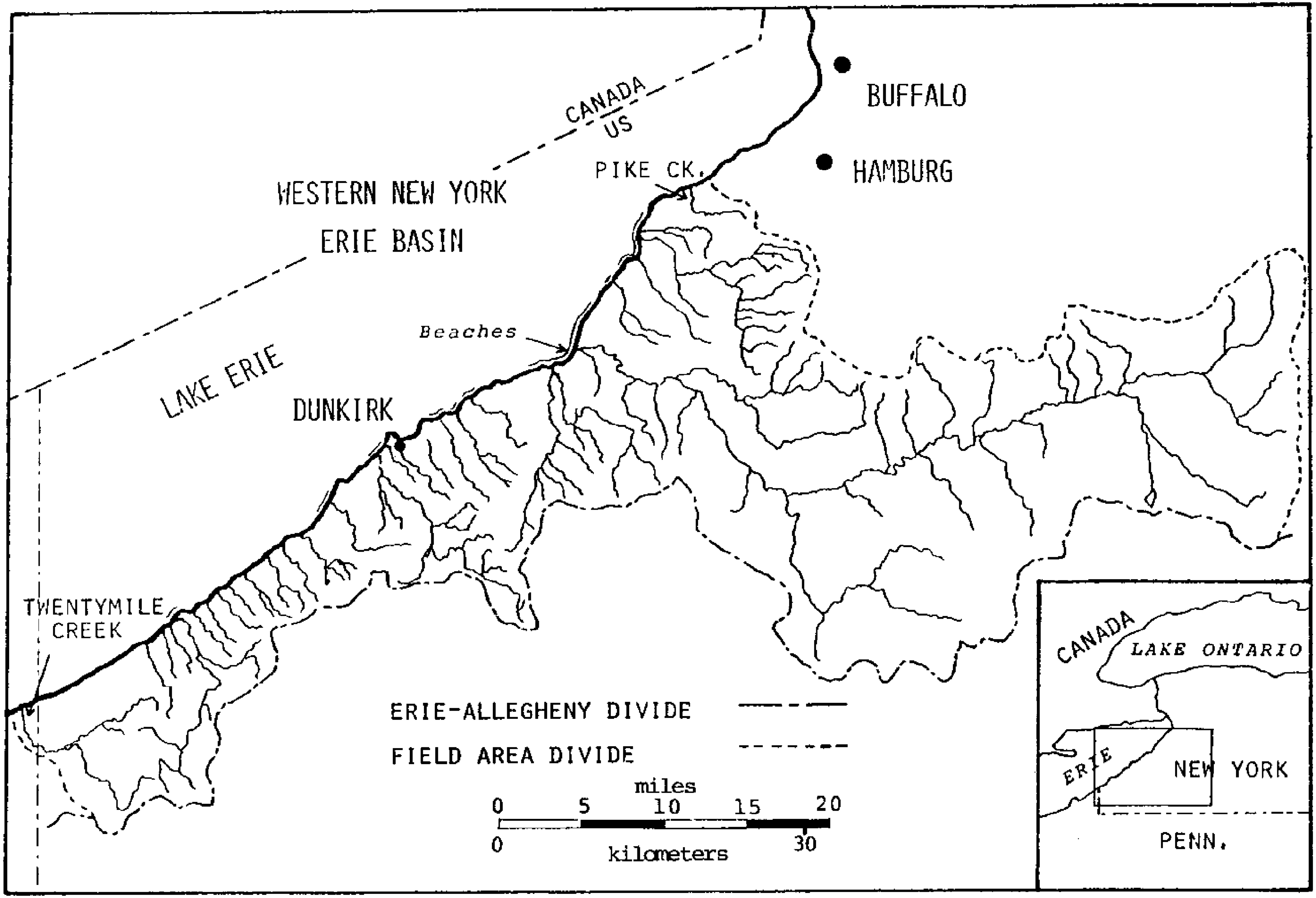


FIGURE 1 Location of the Study Area in Western New York

What is the total sediment contribution of the area to Lake Erie's coastal sediment budget?

What fraction of the total contribution is suitable as nourishment to local beaches and what fraction contributes to fine sediment pollution in the lake?

What effect do the transport of sediment in streams and the interaction of fluvial and littoral sediment movement have on fish spawning activities and local pollution problems in the creeks?

Physiographic and Geologic Setting

Extensive erosion of soft shale has afforded significant relief in the study area (Figure 2). From northwest to southeast the topography is characterized, respectively, by nearly flat lake plain to 13 km (8 mi) in width, the steep face of the escarpment, and, finally, the Allegheny section of the Appalachian Plateaus. At its steepest, the escarpment rises 230 m in 1.5 km (800 ft/mi). The nearly flat concordant surfaces of the stream-dissected Allegheny Plateau to the southeast are interrupted by hummocky morainal deposits and smooth drumlinized erosional surfaces (Muller 1963).

The 80 km (50 mi) of coast in the study area includes several long stretches of beaches (Figure 1) between bedrock and till bluffs. The bedrock bluffs dominate in the southwest, the beaches in the northeastern portions of the study area.

The area is underlaid by Upper Devonian fissile shales and interbedded and more resistant siltstones belonging to the West Falls, Canadaway, and Conewango groups (Buehler and Tesmer 1963; Tesmer 1963, 1975). These rocks dip gently southward 4 to 10 m/km (20 to 50 ft/mi) with very gentle anticlines (folds with their convex sides up) and synclines (folds with their concave sides up). They crop out along the lake bluffs in steep faces of the escarpment, and along stream channels. The resistance of the bedrock determines whether the channel it controls is wide and shallow or narrow and deep. Harder units often produce wide, shallow streams; softer bedrock yields deep, narrow ones.

Glaciation has been a major factor in shaping the present surface of western New York. The effects include scour of preglacial bedrock topography, and deposition of large amounts of drift with rearrangement of drainage patterns and divides (Muller 1963, 1975, 1977).

The glacial deposits in the field area are of Late Wisconsin age (Muller 1977) (Figures 3 and 4). They include drift of the earliest and maximum Kent Moraine glaciation radiocarbon about 20,000 yr B.P. (before present) through that associated with the Hamburg Moraine formed during the Port Huron Stadial about 13,000 yr B.P. (Calkin and McAndrews 1980).

The Kent End Moraine occurs just south of the field area and gives way northward to associated groundmoraine within the area. This is in turn

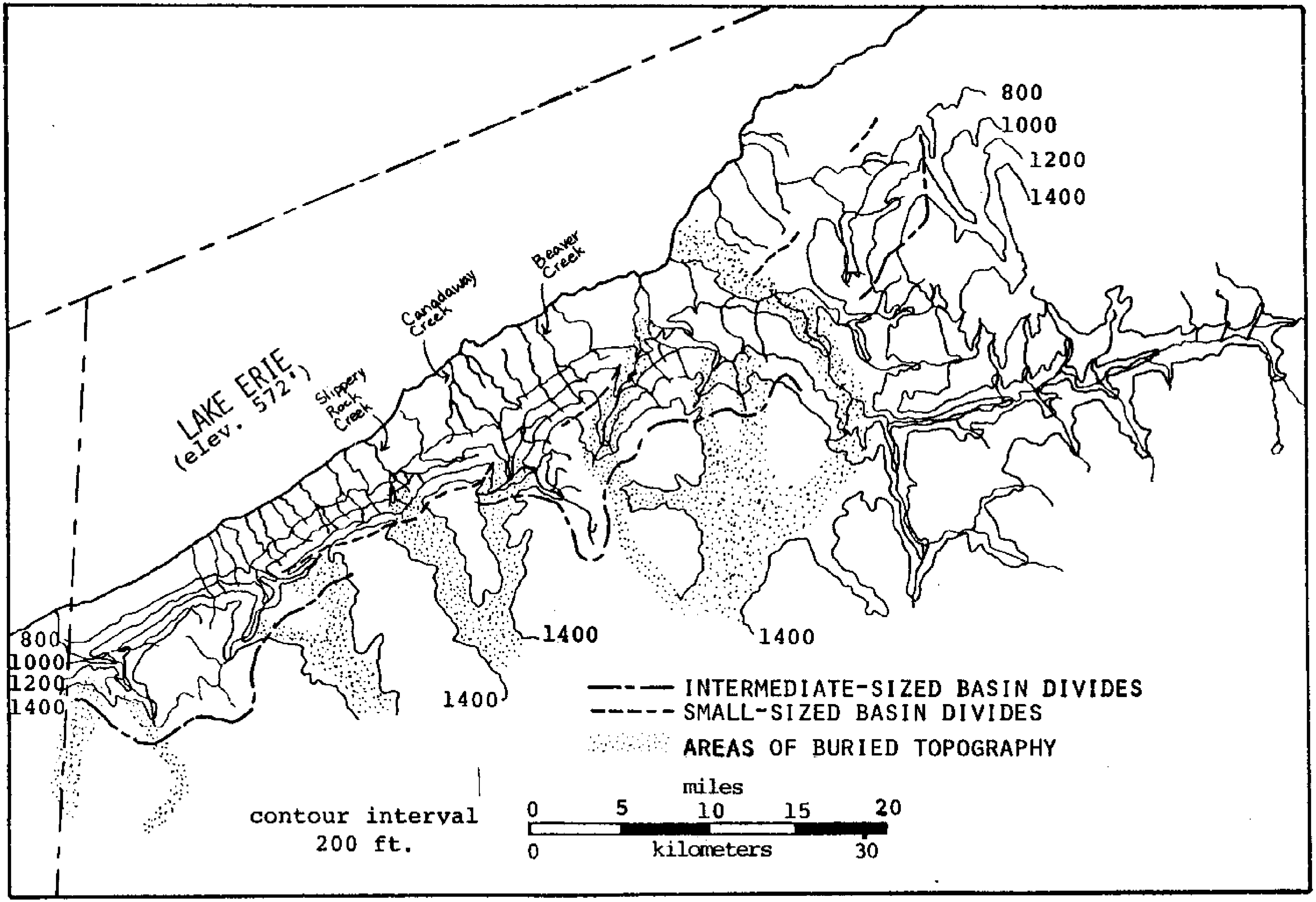


FIGURE 2 Surface and Topography of the Western New York Field Area (modified from Fahnestock and Metzger 1972; Muller 1963; Muller and Fahnestock 1974)

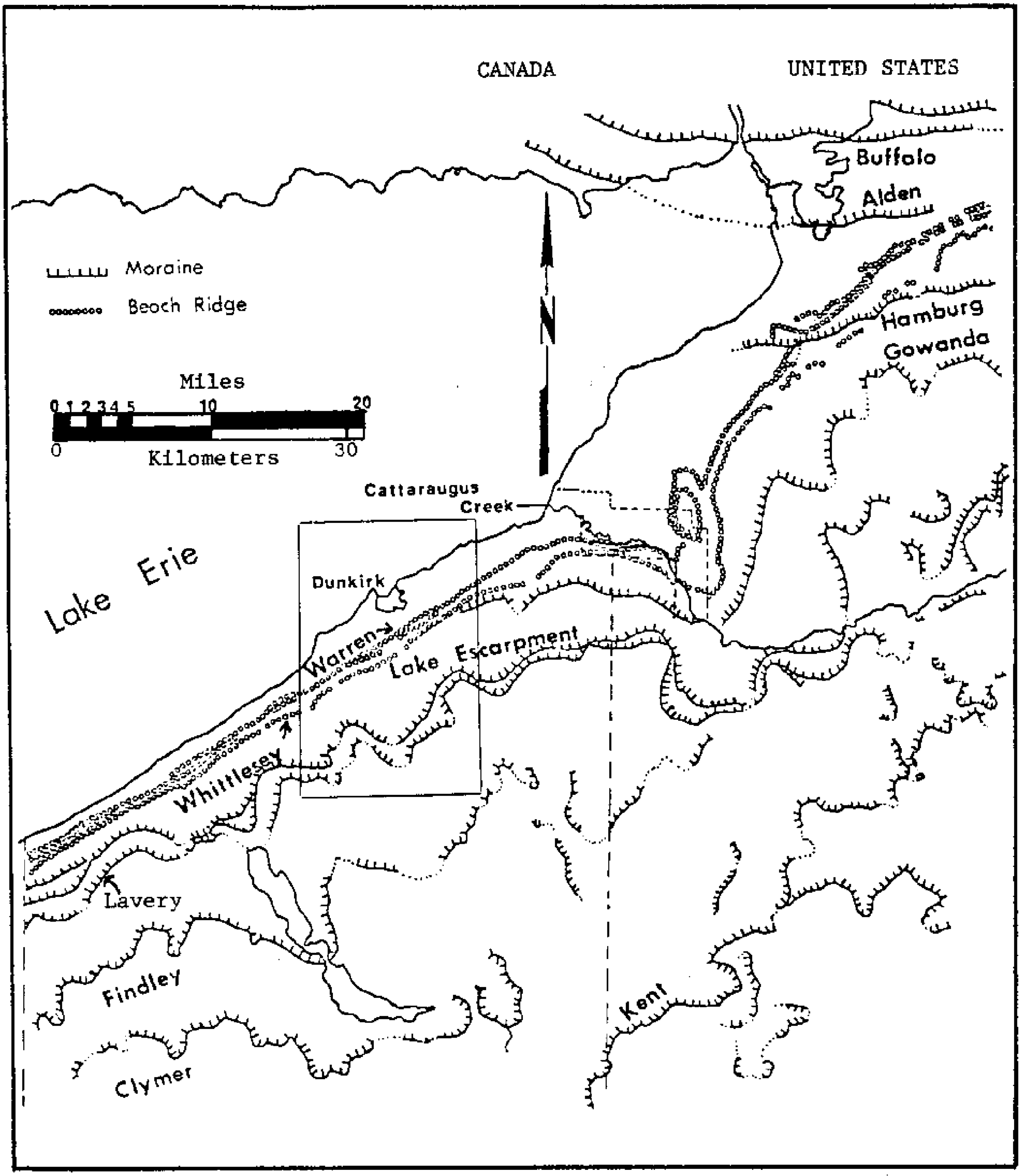


FIGURE 3 Glacial Map of Western New York Field Area Showing Moraines and High Level Beaches of Glacial Lakes Whittlesey and Warren (area around Dunkirk is shown in greater detail in Figure 4) (modified from Muller 1963, 1975, 1977)

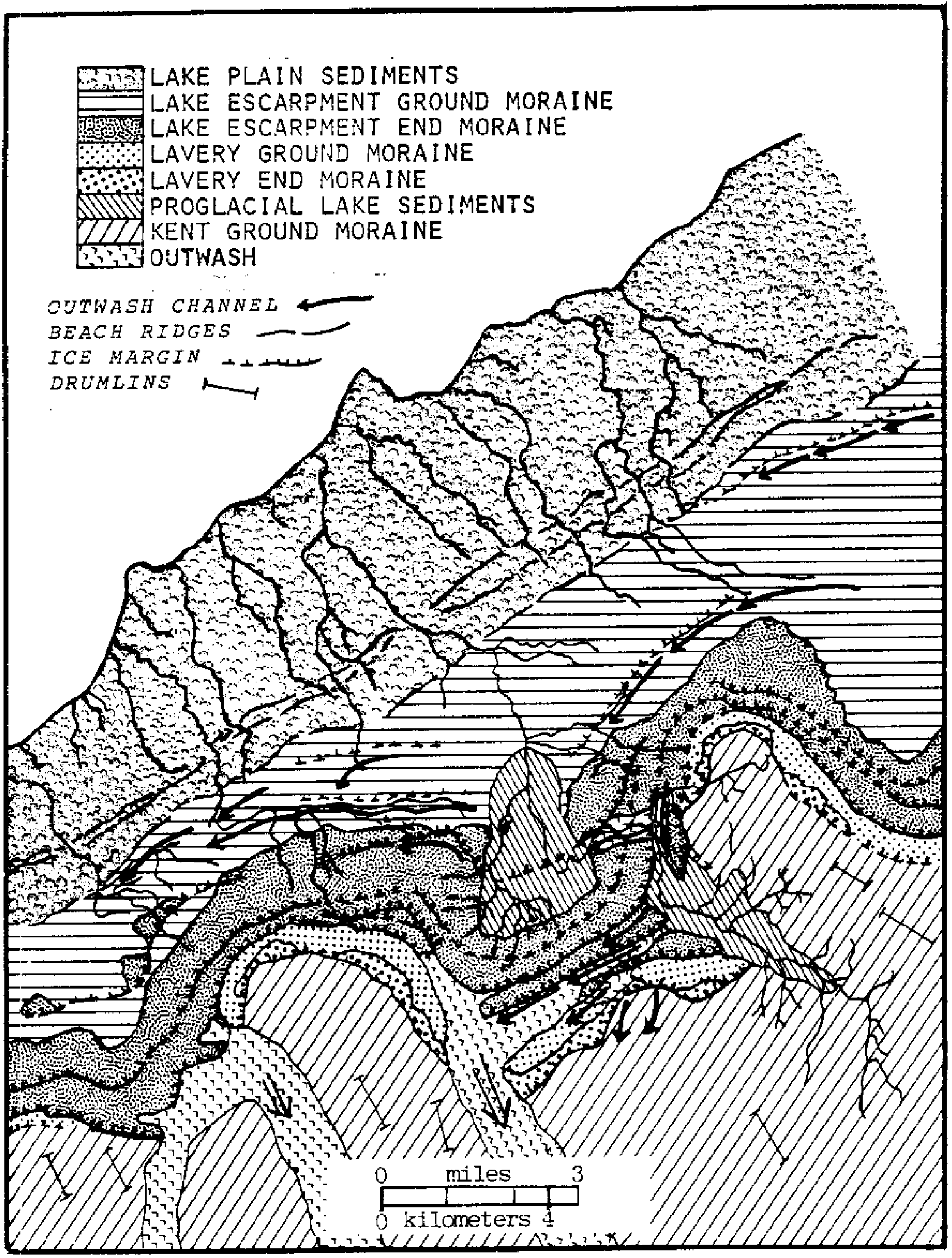


FIGURE 4 A Magnified Portion of the Glacial Map of Western New York (Figure 3) Showing Details of the Effects of Glaciation in the Vicinity of Canadaway, Beaver, and Slippery Rock Creeks (modified from Muller 1963)

characterized by a southeast to northwest streamlined topography interrupted by traces of hummocky drift representing the Findley and Clymer recessional moraines. The younger Lavery Moraine occurs through the southern part of the area as a continuous frontal ridge which stands out perpendicular to this streamlined drift surface. Lavery Till is overlain along the south side of the Cattaraugus Valley by Hiram Till with its associated Defiance Moraine (Muller 1975). Both the Lavery and Hiram tills are generally thin, and the latter in particular is rich in clay presumed to have been derived from proglacial lake deposits. These ice-marginal lakes developed in northward-draining buried valleys (Figure 2) during a short retreat following the Kent advance and are correlated with the Erie Interstadial (Muller 1975).

Behind the Lavery and Defiance moraines along the crest of the escarpment south of Gowanda and extending along the watershed north of Cattaraugus Creek are a series of prominent parallel gravelly ridges assigned to the massive Lake Escarpment Moraine System (Muller 1963). These ridges were formed during a period of balance between glacier flow and melting when the high relief helped maintain the ice position against the face of the escarpment. The topography displays a very hummocky appearance of kame knobs and kettle depressions with associated wedges of gravelly outwash in the valleys. Proglacial lake deposits occur where Lake Escarpment ice dammed small lakes against the escarpment (Figure 4). Farther north are the closely associated but less pronounced Gowanda Moraine and the hummocky Hamburg Moraine with associated drift sheets. Both of these moraines are barely perceptible on the lake plain where they have been reworked and winnowed by several proglacial lakes.

The lake plain is underlaid by bottom silts and clays as well as by sand and gravel beach and delta deposits related to a series of westward-draining proglacial Great Lake stages starting with glacial Great Lake Whittlesey. Formation of Lake Whittlesey is correlated with the Port Huron advance and locally with the formation of the Hamburg Moraine (Calkin and McAndrews 1980). Lake Whittlesey was succeeded by Lake Warrens I, II, and III and subsequently several shorter-lived lake stages before ice retreat allowed eastward drainage and the formation of Early Lake Erie and the Niagara River (Calkin 1970).

SEDIMENT AVAILABILITY

Several sources of sediment are available for transport by streams to Lake Erie from the thick sections of predominantly glacially deposited surface material. The various sources include:

- proglacial lake clays, silts, and gravel
- till
- outwash
- modern alluvium
- bedrock

The lake plain consists predominantly of a thin veneer of lake silt or clay locally over patches of till; their combined thickness seldom exceeds 3 to 4 m (9.8 to 13.1 ft). Similarly, deposits on the face of the escarpment are often less than a meter thick because of erosion by ice marginal streams. Once the postglacial streams have cut down through these deposits, they become incised in bedrock, limiting lateral migration. Therefore, neither the lake plain nor escarpment face appears to be a significant source of sediment. The bedrock itself provides sediment only slowly to the streams except periodically when weathered material is encountered.

Two groups of physiographic features may provide the largest sources of stream sediment. These are the morainal ridges at or near the escarpment crest, and the buried through-valley deposits farther east. The massive morainal ridges at the escarpment and farther south or east still reflect the geometry of the depositing ice margin. Thick sections of till and stratified drift are constantly exposed here to stream dissection and transport.

A striking geologic feature of the Allegheny section of the Appalachian plateaus in western New York is a series of broad, partly filled, flat-floored, preglacial stream valleys (sometimes called through-valleys). These all trend in a north-northwest direction (Figure 2). Near the surface, the valley fills seem to consist largely of outwash as well as some lake silts and clays or till, and vary in thickness up to 335 m (1100 ft) (Muller 1963, 1977). The streams presently occupying these valleys are underfit, and stream divides consist of low rises of glacial drift. The buried valley deposits are probably the largest source of sediment readily available to stream erosion in the field and a number of streams have their headwaters in the thick deposits of these valleys.

The discussion above suggests that those streams which reach headward across the lake plain and into thick deposits of the plateau will come in contact with considerably more sediment than those shorter ones draining into Lake Erie from headward positions at or below the escarpment face on the lake plains. This is illustrated in the profiles of Figure 5. Beaver Creek, only 10.5 km (6.5 mi) in length, drains the face of the escarpment where only small amounts of drift overlie bedrock. Slippery Rock Creek, farther south (Figure 6), is only somewhat larger at 11.6 km (7.2 mi) length, but reaches some much thicker surficial deposits in the buried topography of the escarpment. Canadaway Creek, a larger basin with channel length of 29.8 km (18.5 mi),

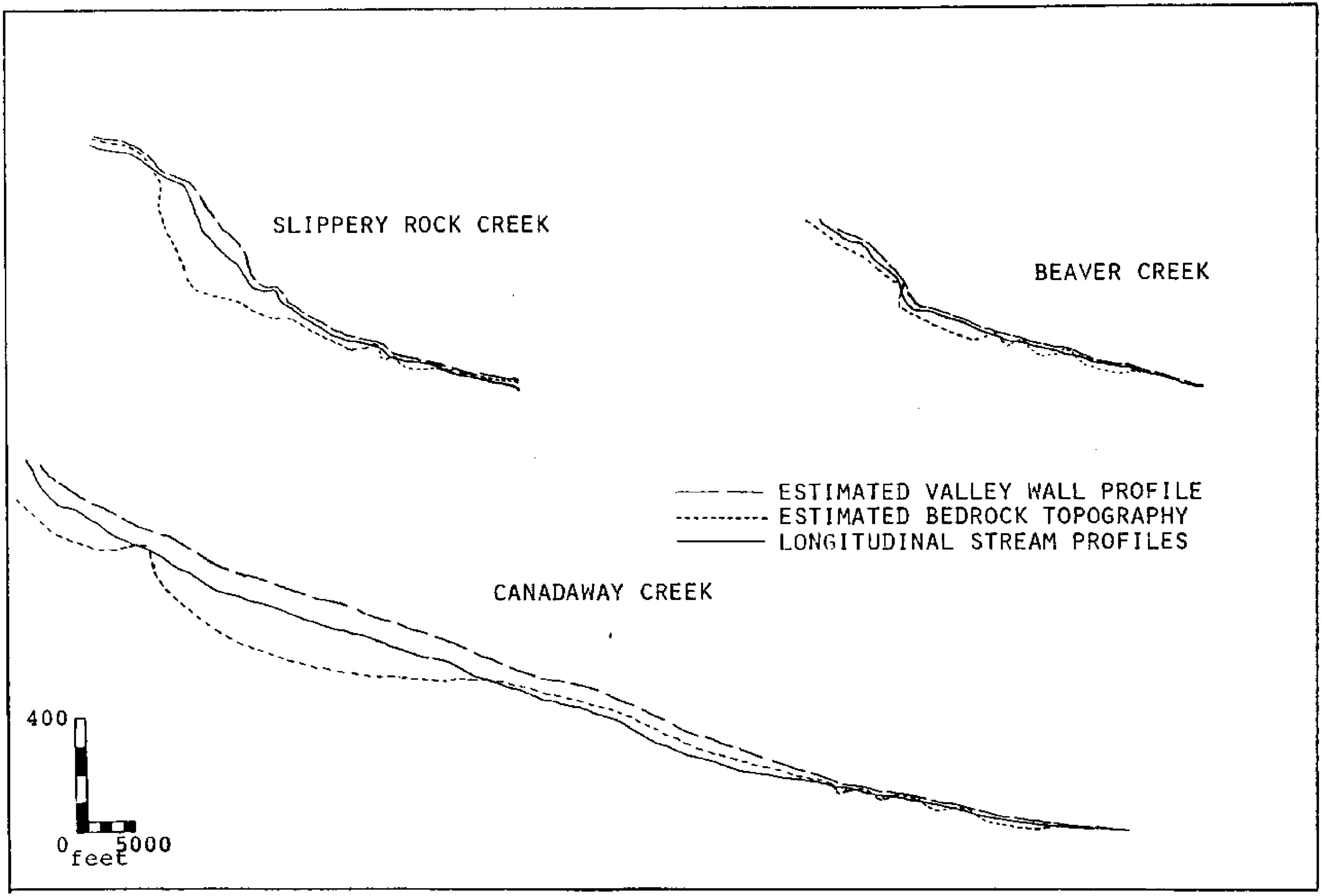


FIGURE 5 Longitudinal Stream Profiles Showing Bedrock Topography and Thickness of Surficial Material for Three Streams Located in Figure 2

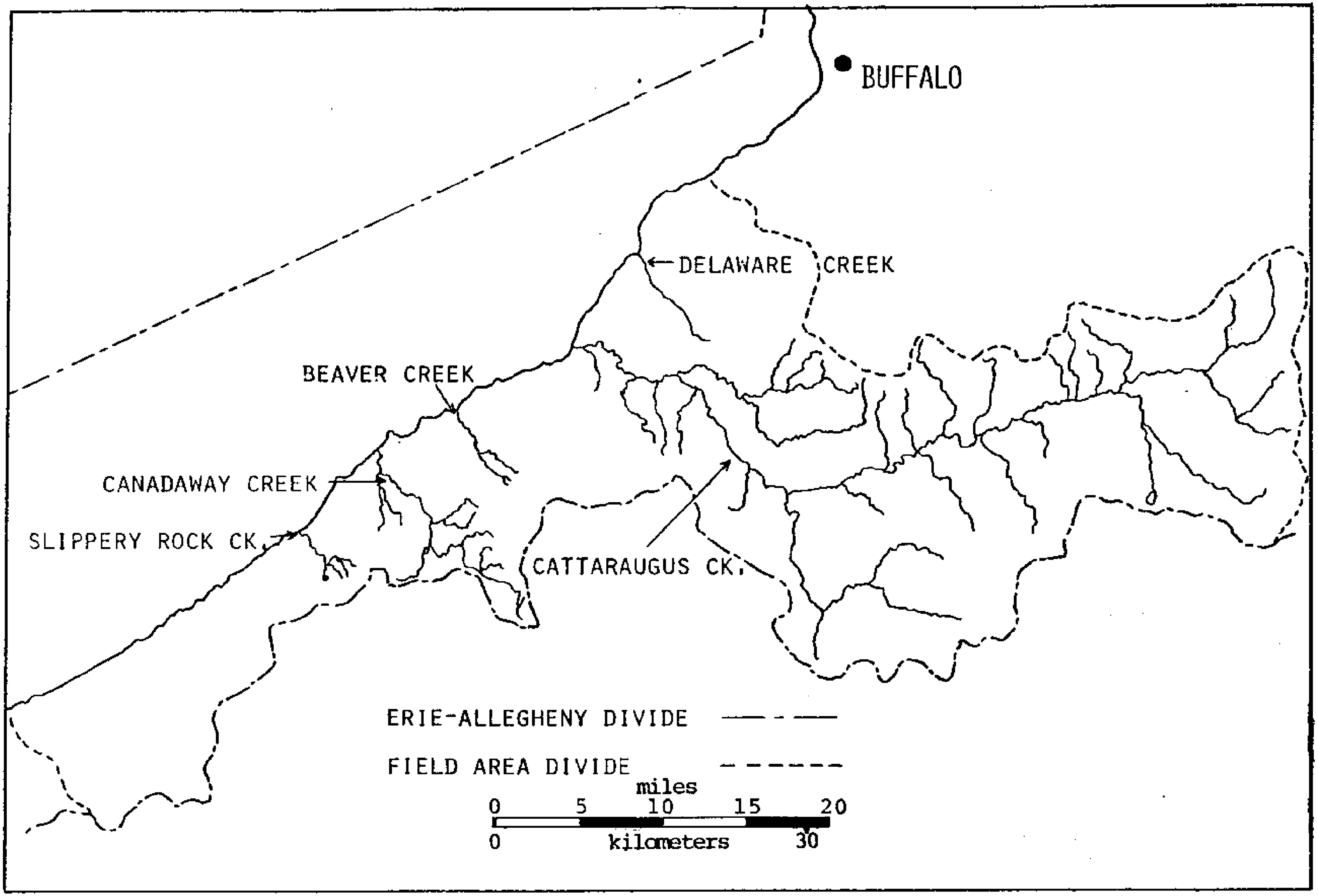


FIGURE 6 Locations of Staff Gage Sites and Sampled Reaches in the Representative Basins

reaches well into areas of buried topography and thick surficial deposits. The downstream reaches of all three streams encounter only thin surficial materials overlying the bedrock.

QUANTITATIVE ANALYSIS OF BASIN GEOMORPHOLOGY

Discussion of Parameters

In order to estimate the individual contributions of each drainage basin in the field area to the total sediment budget, it was necessary for us first to characterize the basins on the basis of parameters that would reflect the variations in the stream flow and sediment discharge characters. These parameters include:

- drainage area and main stream length
- relief ratio and longitudinal stream gradient
- area-altitude relationships
- drainage density (Chow 1964; Gregory and Walling 1973; Morisawa 1959; Schumm 1956; Strahler 1957)

Our main source of all quantitative data was a composite of 7 1/2 minute US Geological Survey topographic maps for the entire field area. We compared glacial features for each of the basins using Muller's 1:250,000 Quaternary geology map of the Niagara sheet (1977). The data are presented in Table 1.

Drainage Area and Stream Length

Drainage area (Table 1) shows the greatest contrast among basins. Cattaraugus Creek, with a drainage area of 1435 km^2 (554 mi^2) and stream length of 110 km (68.9 mi) is by far the largest. Five intermediate-size drainage areas ranged from 88 to 137 km^2 (34 to 53 mi^2), with an average stream length of 28.6 km (17.8 mi). The remaining 23 basins range from 5 to 31 km^2 (2 to 12 mi^2) with main stream lengths between 4.3 and 12.4 km (2.7 and 7.7 mi).

Relief

We compared relief ratio and longitudinal stream gradient to better understand the relative relief of the basins throughout the field area. Relief ratio is the ratio between the total elevation of the basin (from mouth to maximum elevation of divide) and the horizontal distance along the longest dimension of the basin parallel to the principal drainage. Schumm (1956) has shown that relief is of great importance in determining annual sediment yields. Relief ratios vary from 31 to 253 (ft/mi) with a definite trend toward decreasing values as one proceeds north through the field area.

Longitudinal stream gradient is the average slope of the entire main stream channel from mouth to source. Values range from 27 to 181 (ft/mi) and also show a trend of decreasing gradients going north. These results imply increasing slopes and a greater capacity to erode and transport sediment as

TABLE 1 Quantitative Geomorphic Data

Geomorphic Group	Stream Name	Drain Area (mi^2)	Stream Length (mi)	Relief Ratio (ft/mi)	Long. Stream Grad. (ft/mi)	Max. Elev. Divide (ft)	% Area >1100'	Drainage Density
E	Pike	7.3	5.4	49	33	790	0	1.33
E	Lit.Sister	9.8	6.6	31	27	790	0	1.68
B	Big Sister	50.1	18.9	69	34	1335	17	1.66
E	Delaware	9.8	7.7	45	39	900	0	2.49
E	Muddy	11.6	5.5	32	30	760	0	2.25
A	Cattaraugus	554	68.9	-	-	-	-	-
E	Halfway	4.7	2.7	75	69	820	0	1.28
B	Silver	53.1	16.2	140	65	1850	60	2.12
D	--	8.3	--	110	--	1145	0	1.21
D	Beaver	10.0	6.5	131	93	1295	16	1.25
C	Scott	6.6	6.8	174	89	1650	42	2.05
D	Hyde	4.8	3.9	119	77	1170	2	1.38
D	Crooked Bk.	5.5	5.6	98	73	1100	0	1.50
B	Canadaway	41.7	18.5	106	73	1975	59	1.77
D	--	3.7	--	98	--	983	0	1.73
C	Lt.Cndwy	6.9	7.6	201	68	1540	52	2.21
C	Slip.Rock	8.5	7.2	193	122	1500	37	1.95
C	Corell	6.7	5.3	195	133	1430	12	--
C	Walker	3.3	4.8	199	181	1490	33	2.83
C	--	3.4	--	253	--	1535	23	2.87
C	--	1.5	--	251	--	1475	26	3.33
C	Bournes	3.6	3.5	216	148	1330	23	2.87
C	Spring	2.5	3.5	188	148	1270	12	2.15
C	Doty	2.9	3.9	186	152	1280	18	2.82
B	Chautauqua	36.2	18.0	207	60	1775	87	2.04
C	Vorce	2.1	3.8	221	136	1390	12	2.16
C	Freelings	2.0	3.4	236	173	1400	18	4.10
C	--	4.1	6.5	208	--	1615	71	2.40
B	Twentymile	33.8	18.0	169	58	1772	91	1.90

one goes south through the field area.

Area-altitude Relationships

The amount of surficial material available to stream transport increases headward toward the escarpment and Allegheny Plateau, as discussed in the previous section. The maximum elevation of basin divides for each of the basins appears to reflect the probability of their reaching and draining areas of surficial material. We determined area-altitude relationships in accordance with the method of Strahler (1957) and calculated percent of the drainage areas for the following intervals:

- below 244 m (below 800 ft)
- between 244 and 335 m (800 and 1100 ft)
- 335 and 427 m (1100 and 1400 ft)
- above 427 m (1400 ft)

We reported only the percent areas above the 335 m (1100 ft) contour on the assumption that this contour best separates low-lying areas of thin surficial cover from higher areas of thicker sediment cover.

The intermediate-size basins with drainage areas from 88 to 138 km^2 (34 to 53 mi^2) reach higher elevations south of the escarpment and have greater percentages of their drainage areas above 335 m (1100 ft). The remaining smaller basins show a trend toward decreasing maximum elevation of divides and a lower percentage of their areas above 335 m (1100 ft) as one goes north through the field area.

These results demonstrate that the intermediate-size basins should have the largest amount of sediment available for transport. Also, of the remaining small drainage basins, those in the southern portion of the field area are expected to have the highest availablity of sediment.

Drainage Density

We measured drainage density by the "blue-line" method of Gregory and Walling (1973) where it is defined as the ratio of total length of mapped stream channels to drainage area.

It is a sensitive parameter reflecting topographic, lithologic, pedalogic, and vegetative controls, as well as man's influence on drainage basin processes. Due to this complex interrelationship, the effect of drainage density on sediment yield is not fully understood. Measurements in this area show a trend toward decreasing drainage density as one proceeds north through the field area.

Geologic Significance

The effect of the escarpment on the local topography explains the north to south increases of the following geomorphic parameters:

- maximum elevation of basin divides
- percent area above 335 m (1100 ft)
- relief ratio and longitudinal stream gradient

In the southwestern extreme of the field area, the base of the escarpment is no more than five kilometers (3.1 mi) inland across the lake plain; however, as one follows the shoreline to the northeast, the escarpment diverges to the east, widening the lake plain to 12 km (7.5 mi) (Figure 27).

The effect of the escarpment is not as great on the five intermediate basins (Group B) as it is on the others. The reason for this diminished influence is that the streams in Group B originate in the thick sections of surficial material in the buried valleys, which lessens the effects of escarpment relief and offers vast amounts of unconsolidated material for transport.

Classification of Basins

We categorized all 29 basins in the field area according to the results of the quantitative analysis and placed them in groups of basins with similar geomorphic character. Table 2 gives mean and standard deviation of the grouped basins for the most significant parameters. Cattaraugus Creek is by far the largest basin in the field area and we classified it by itself as Group A.

We grouped the five intermediate-size basins together in Group B because of the following similarities (see Tables 1 and 2):

- sizes
- values of maximum elevation
- longitudinal stream gradients
- drainage densities

The changing width of the lake plain has less effect on these basins than the small basins even though they occur regularly from Pennsylvania to near Buffalo. The four southernmost of the intermediate-size basins head in the areas of thick buried topography in the through valleys along the escarpment, and a large percentage of each drainage basin lies above 335 m (1100 ft).

The remaining twenty-three basins are significantly smaller in drainage area and we divided them into three groups reflecting the north-south variations (Figure 2) rather than on size.

Group C represents 13 basins in the southern portion of the field area. They have high relief ratios, steep longitudinal stream gradients, and high drainage densities. They head high on the escarpment and have the greatest percent areas above 335 m (1100 ft). Slippery Rock Creek represents this group.

Group D includes five basins centrally located in the field area. They have the lowest drainage densities of all the streams in the field area (Table 3). Furthermore, they have lower relief ratios than Group C and moderate gradients. They do not reach as high on the escarpment as does the group of southernmost basins and generally have less area above 335 m (1100 ft). Beaver Creek represents this group.

Group E is the group of the five northernmost small basins. Here the escarpment is 13-16 km (8-10 mi) inland and has less effect in determining the geomorphic character of these basins. Relief ratios and longitudinal stream gradients are the lowest in the field area (Tables 1 and 2). The divides are much lower than those of the other groups. This group has no area above 335 km (1100 ft). Drainage densities for this group are abnormally high for two basins (Table 1), one of which is Delaware Creek, the representative of the group.

TABLE 2 Mean and Standard Deviation of Major Landform Parameters for Groups of Geomorphically Similar Basins

Group	Representative Basin	Elev. of Divide	Relief Ratio	Gradient	Drainage Density	% Area Above 1100'
B	Canadaway Ck.	1741-242	--	58-14	1.90-.19	63-30
C	Slip. Rock Ck.	1454-119	209-71	135-35	2.54-.71	30-18
D	Beaver Ck.	1138-113	111-14	81-10	1.41-.21	4-7
E	Delaware Ck.	812-53	46-27	40-17	1.81-.54	0-0

TABLE 3 Annual Precipitation, 1975

Rain Gage Stations*	Precipitation Annual	Precipitation Norm	Elevation (ft)
Fredonia	35.8	37.0	760
Gowanda	42.0		870
Westfield	45.2	49.5	975
Jamestown	45.0		1250
Sinclairville	46.8		1390
Sherman	50.4		1538

*Rain gage stations within and around field area are located on Figure 19.

CONTRIBUTION OF FINE MATERIAL

Data Sampling Locations

We sampled suspended sediment flood hydrographs in the following representative basins:

Group B--Canadaway Creek
Group C--Slippery Rock Creek
Group D--Beaver Creek
Group E--Delaware Creek

The data for Group A, Cattaraugus Creek, were taken from Archer and La Sala (1968).

We installed staff gages at accessible locations where road bridges control the cross sections. We selected sections as clse to the mouth as possible so that suspended sediment sampling would closely approximate the sediment contribution from the entire basin, yet still be above backwater effects of high lake levels. Figure 6 shows the locations of gage sites.

Canadaway Creek

A pre-exisiting gaging station at the Matteson Avenue Bridge on Canadaway Creek permitted the use of data acquired in previous years (Figure 7). We sampled just downstream of the bridge where the cross section is a typical straight reach with sand and gravel bed and banks. Only after scour during high flows did patches of bedrock occasionally appear. This location did not permit inclusion of the discharge of a six-square-mile tributary basin which enters downstream closer to the lake.

Slippery Rock Creek

We placed the Slippery Rock Creek gage on the Route 5 Bridge. The high resistance of the bedrock here completely controls the wide, flat-bottomed siltstone channel. We took samples just upstream of the road bridge. From here the channel falls very rapidly in a steep bedrock channel 50 m (164 ft) to the mouth (Figure 8).

Beaver Creek

We installed the Beaver Creek gage about 180 m (600 ft) upstream from the mouth, above any observed high water effects, on the old Route 5 road bridge. The reach is a broad meander against a shale cliff. Bedrock which disappears under gravel bars controls the right side of the channel; surficial deposits, the left (Figure 9).

FIGURE 7 Staff Gage Site on Canadaway Creek at the Mateson Street Road Bridge

FIGURE 8 Staff Gage Site on Slippery Rock Creek at the Route 5 Road Bridge

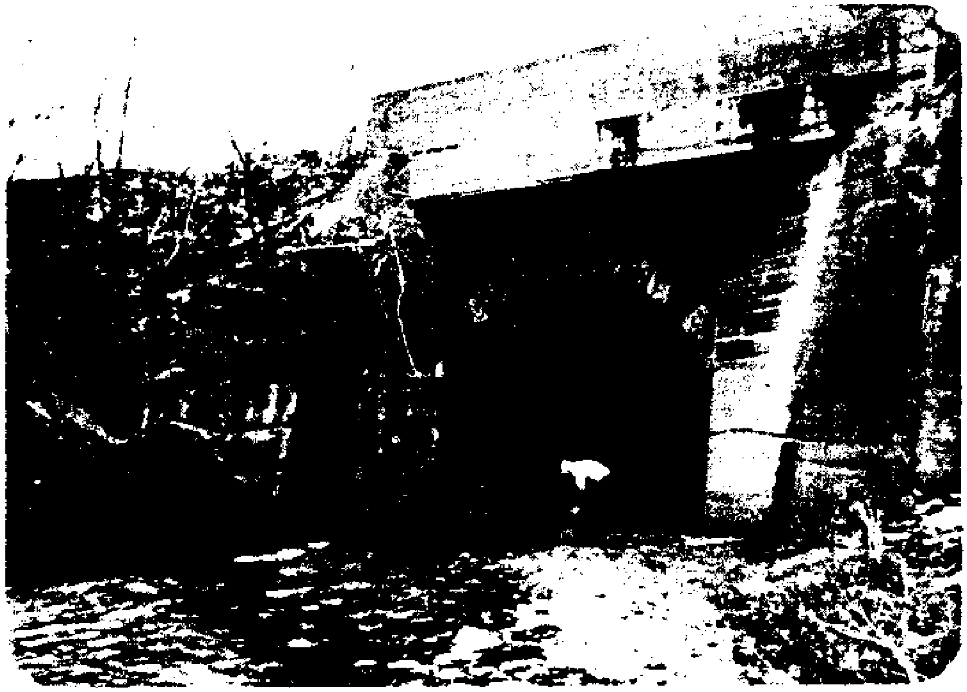


FIGURE 9 Staff Gage Site on Beaver Creek at the Old Route 5 Road Bridge (the channel geometry was disturbed when the cut stone abutment on the left bank failed before April 9, 1975)

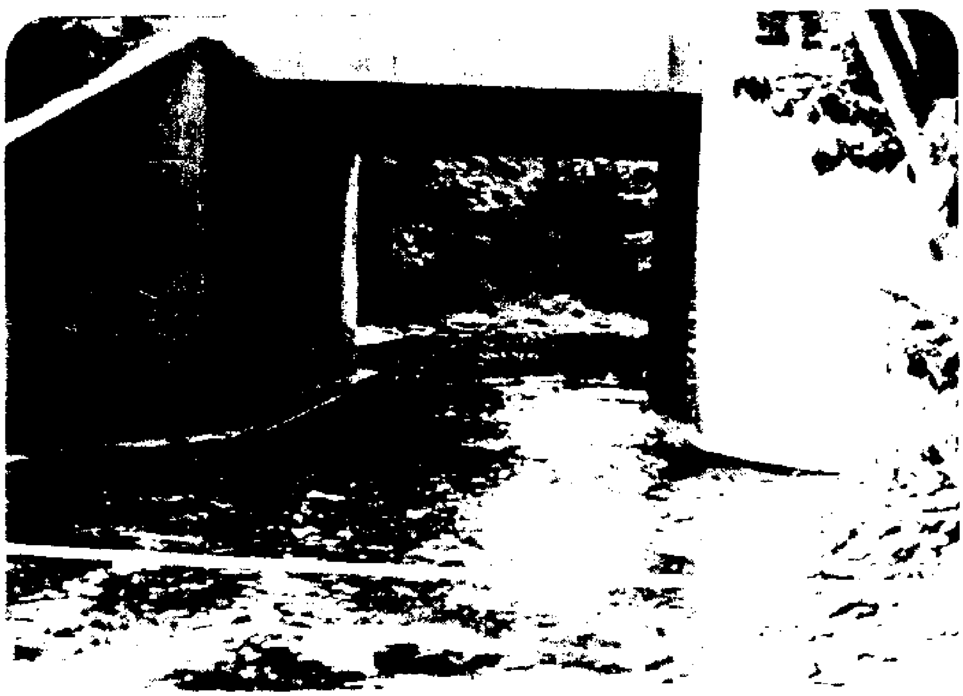


FIGURE 10 Staff Gage Site on Delaware Creek at the Herr Road Bridge

Delaware Creek

Figure 10 shows the Herr Road Bridge where we placed the Delaware Creek gage. The reach near the gage is straight for nearly 100 m (330ft) with an alluvial bed of coarse gravel, mainly shale plates. Bedrock crops out both upstream and downstream from the gage site.

Sampling Procedure

We performed sampling during most significant flow events in 1975. We were able to sample the three small basins as near to their peak discharges as possible; however, because of traveling time between streams, local precipitation differences, and the flashy nature of these small basins, we probably took many smaples on the falling stage. High water marks indicating that the flow had been higher seemed to verify this. We sampled Canadaway Creek, the intermediate-size representative basin, very close to the peak and, whenever possible, at several points on the hydrography.

We employed the standard US Geological Survey procedure for stream gaging (Buchanan and Somers 1969). We used a Price AA type current meter (hand held or with a bridge crane for high flows) and a Pygmy current meter for very low flows.

We took suspended sediment samples with a DH-48 suspended sediment sampler and the US Geological Survey equal transit rate (ETR) of collection (Guy and Norman 1970, pp. 32-33), a method geologists think produces the best approximation of instantaneous load.

In the ETR method, we divided the cross section into vertical quartiles. Then we took depth-integrated (mixed for different levels) samples at the three verticals dividing the quartiles. We sampled each of the three verticals with a constant transit time at a constant velocity. This method allows the samples to integrate variations of sediment concentration with depth as well as width of the channel.

We then ran the samples through standard millepore filters, employing the same method the US Geological Survey uses (Guy 1969).

Discharge Rating Curves

We gaged the streams only until enough points were acquired at different discharges to establish an acceptable gage height versus discharge rating curve. Figures 11 through 14 show the rating curves for the four sampled streams.

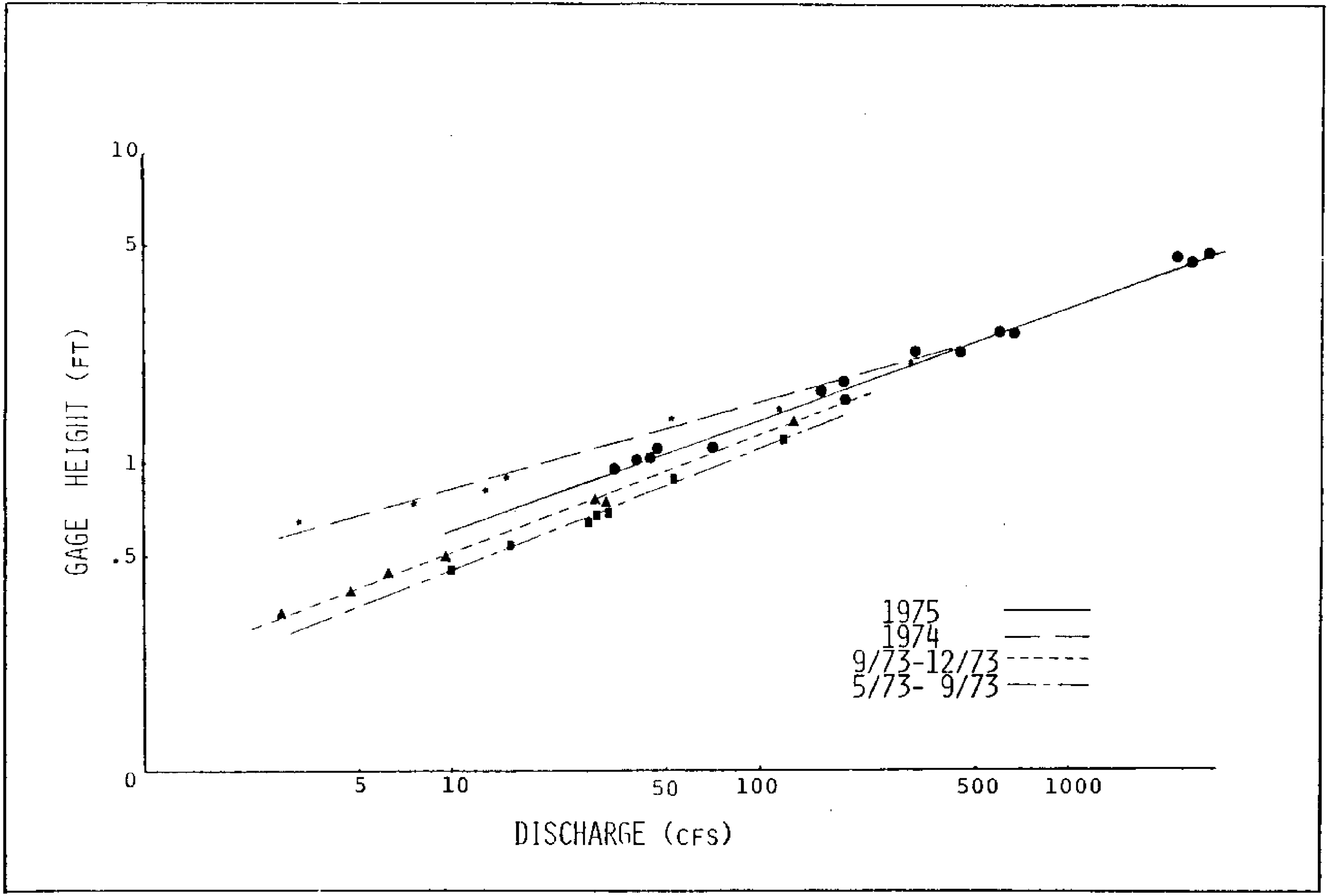


FIGURE 11 Gage Height versus Discharge Rating Curve for Canadaway Creek (curve fits equation of form: log G = a + b log Q where Q = water discharge, G_{HT} = gage height, and a and b are constants. Correlation coefficient for the presented data = .996; a = .27 and b = .36. The variation with time in the low discharge end of the rating curve is due to changes in channel cross-sectional area as gravel bars migrate downstream through the reach at the gage site)

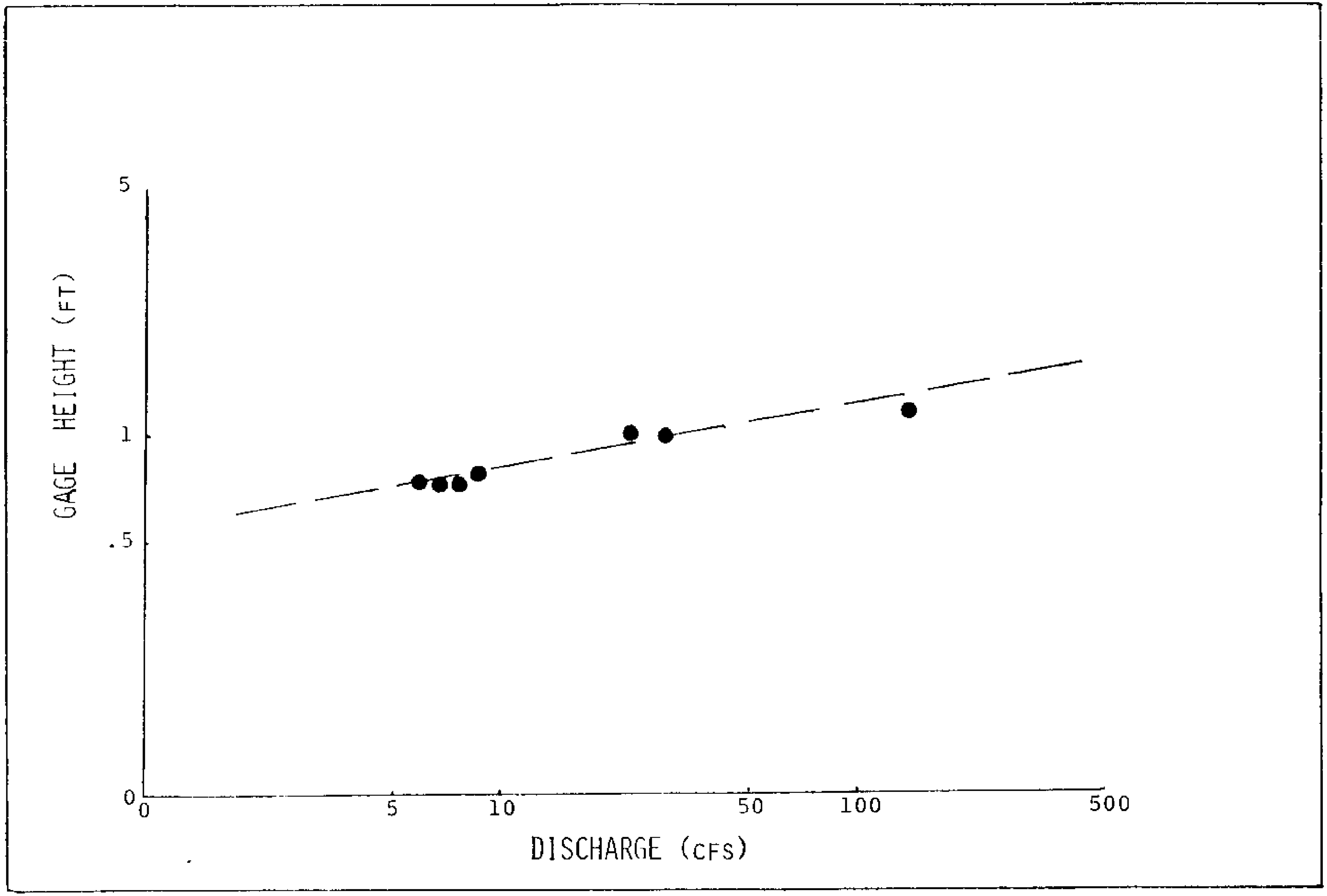


FIGURE 12 Gage Height versus Discharge Rating Curve for Slippery Rock Creek (correlation coefficient for presented data = .876; a = .39 and b = .32)

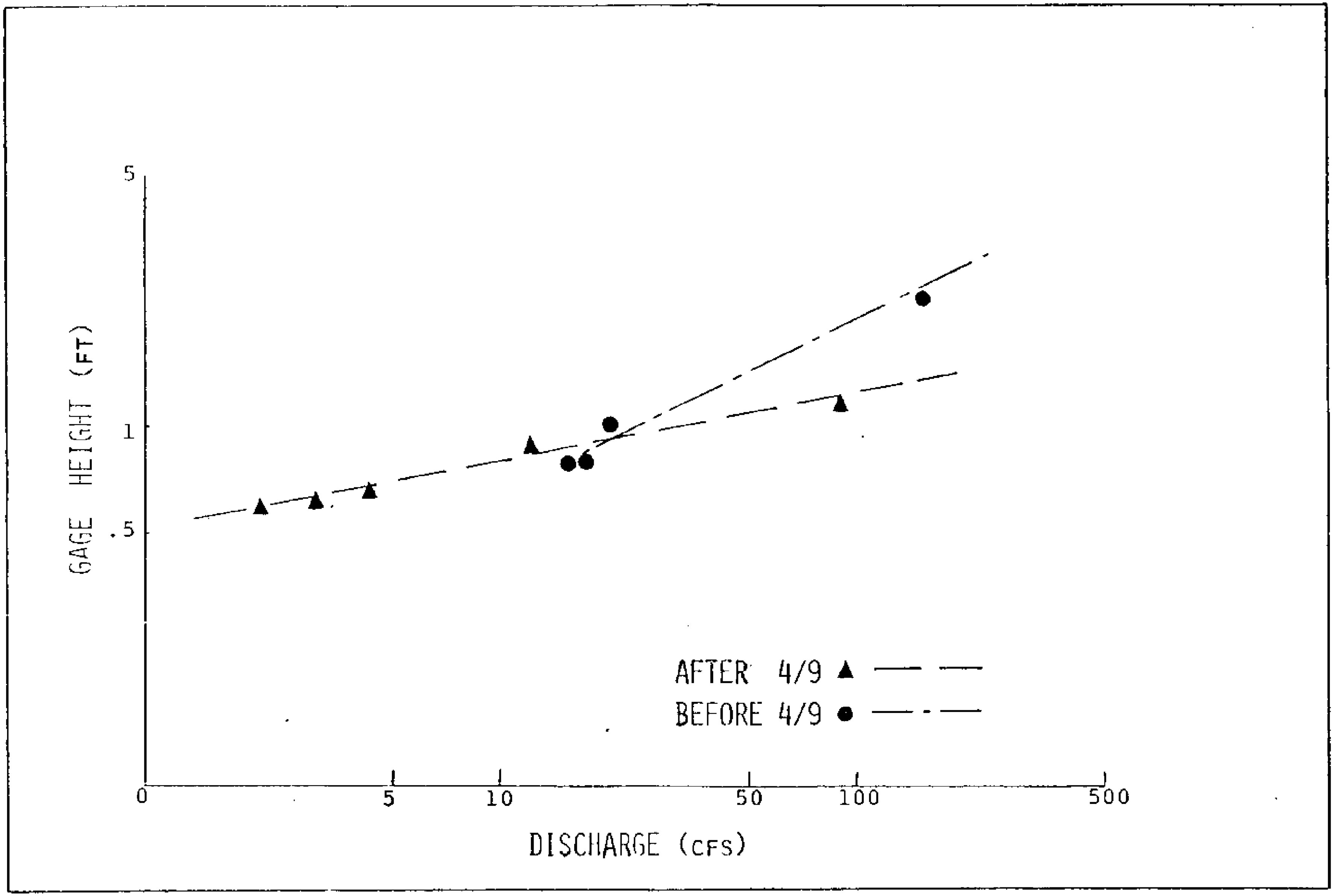


FIGURE 13 Gage Height versus Discharge Rating Curve for Beaver Creek (change in slope of rating curve is the result of radical change of cross-sectional area due to landslide which occurred before sampling of high flow on April 9, 1975) (correlation coefficient = .926; a = .43 and b = .28)

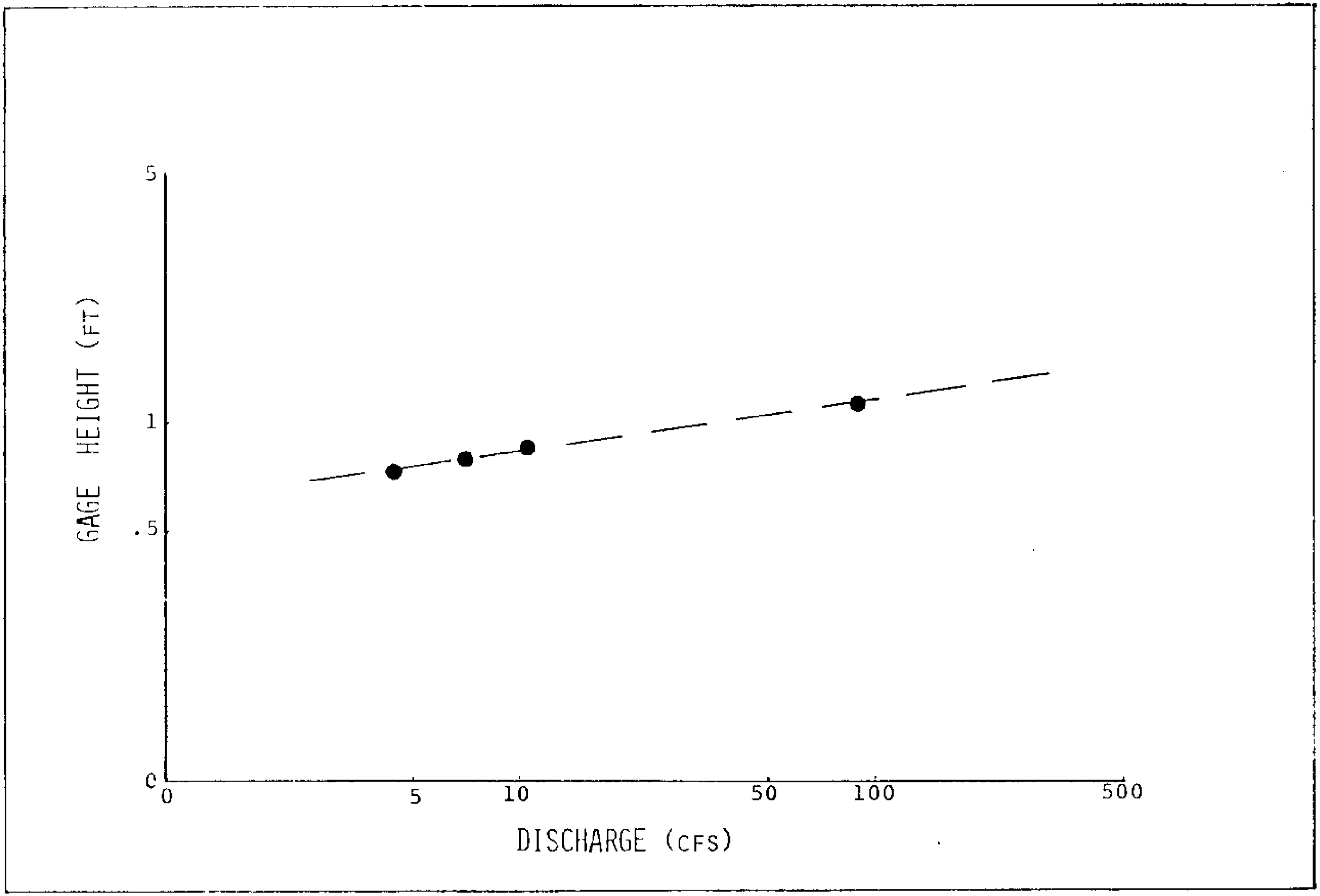


FIGURE 14 Gage Height versus Discharge Rating Curve for Delaware Creek (correlation coefficient = .999; a = .60 and b = .14)

The Beaver Creek rating curve was disrupted by the cave-in of a portion of the cut stone abutments of the old Beaver Creek road bridge at the gage (Figure 9). The obstruction altered the rating curve (Figure 13) and hindered the bulk movement of gravel downstream through the reach.

The Canadaway Creek rating curve (Figure 11) shows data already available at that gage site. The variability at the end of its rating curve is due to changes in cross section as coarse gravel bars migrated slowly downstream through the section. At higher discharges, these cross section changes are insignificant and do not affect the rating curve.

Suspended Sediment Rating Curves

Figures 15 through 18 show the sediment rating curves for the four sampled streams. These plots show discharge versus suspended sediment concentration in a logarithmic relationship

$$\log C = A + B \log Q$$

where A and B are constants, Q is discharge, and C is suspended sediment concentration (parts per million) (Abraham and Kellerhals 1973, p. 111). Correlation coefficients for the relations range from .894 to .704.

Fine sediment yields for all the sampled basins are insignificant at low discharges; however, suspended sediment concentrations increase rapidly as discharge increases. As a result, a single high flow event may contribute a sizable percentage of the annual sediment yield.

Snowmelt runoff did not exhibit suspended sediment concentrations as high as runoff from rainstorms of the same magnitude. In winter, the frozen ground is more resistant to sheet and gully erosion and a snow blanket protects the ground from raindrop impact. Furthermore, farming in summer disturbs the soil's natural resistance to erosion. Soil desiccated by long dry periods between rainfalls is more susceptible to erosion, landslides, and bank failure. Even in spite of frozen ground in winter and desiccated soil in summer, the exceedingly large winter flows, by virtue of their size, supply most of the sediment contribution for the year.

Figures 15 through 18 show seasonal variations in suspended sediment concentration, especially at low discharges where summer concentrations lie above the regression and winter concentrations below.

Annual Discharge Hydrograph

To calculate the annual discharge of the field area, we monitored the annual discharge hydrograph of the streams sampled in 1975. We made daily staff gage observations for Canadaway Creek and observed storm hydrographs for all four sampled streams. In addition to our own data, we used the National

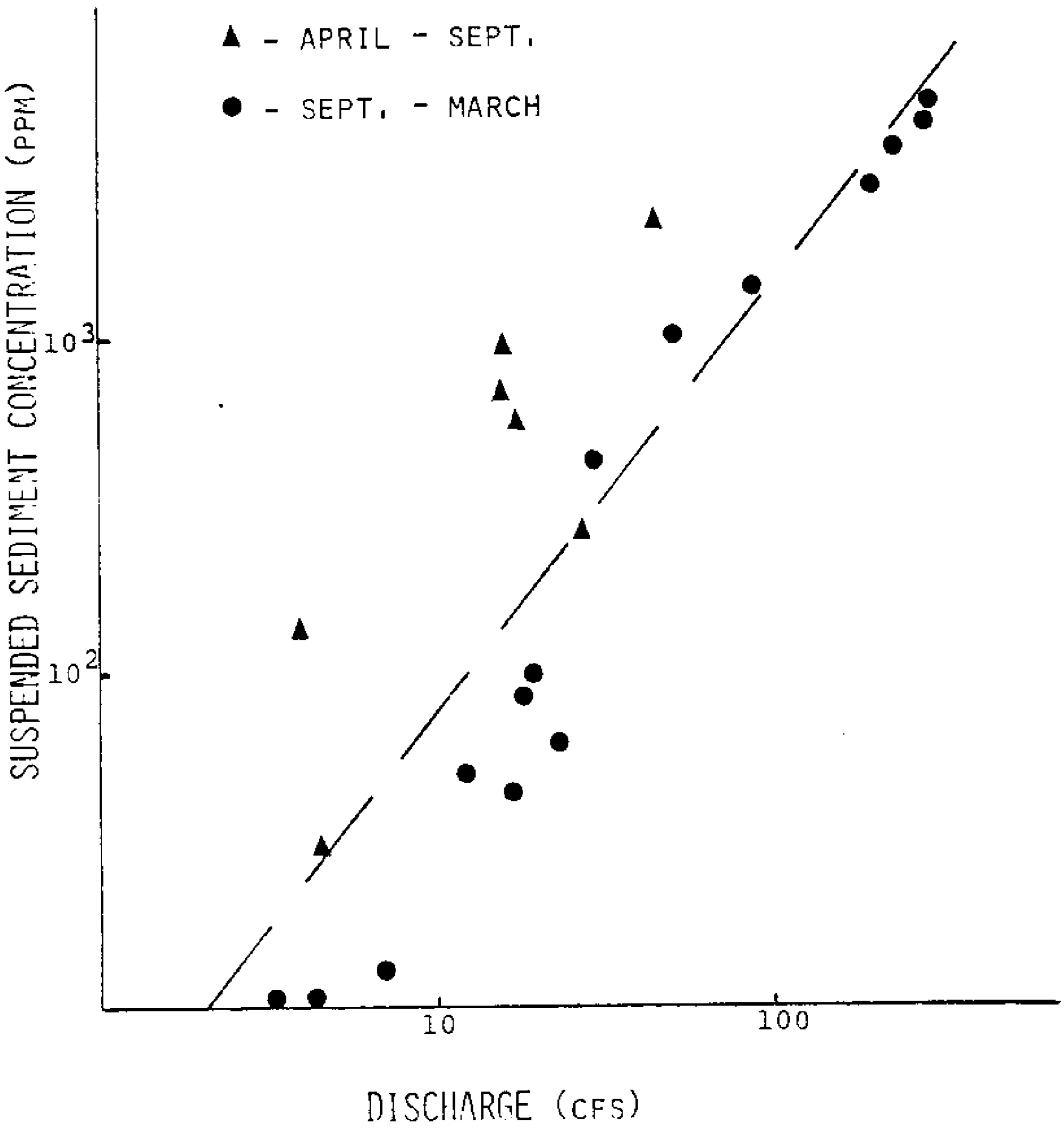


FIGURE 15 Suspended Sediment Rating Curve for Canadaway Creek (fit to equation: log C = a + b log Q, where Q = water discharge, C = suspended sediment concentration in ppm, and a and b are constants) (correlation coefficient for the plotted data is C_c = .894; a = .23 and b = 1.27)

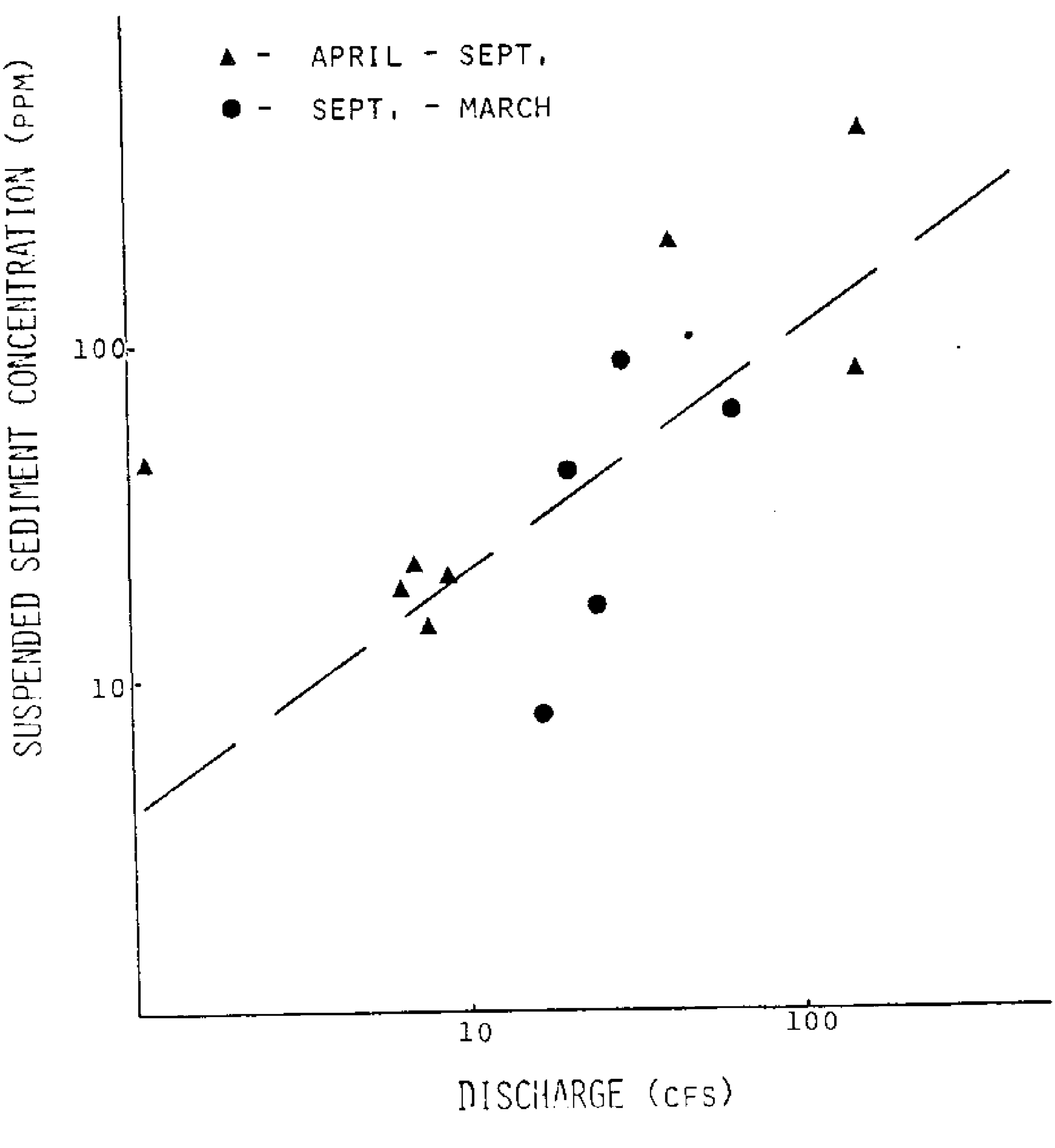


FIGURE 16 Suspended Sediment Rating Curve for Slippery Rock Creek (correlation coefficient for the plotted data is C_c = .804; a = .72 and b = 3.98)

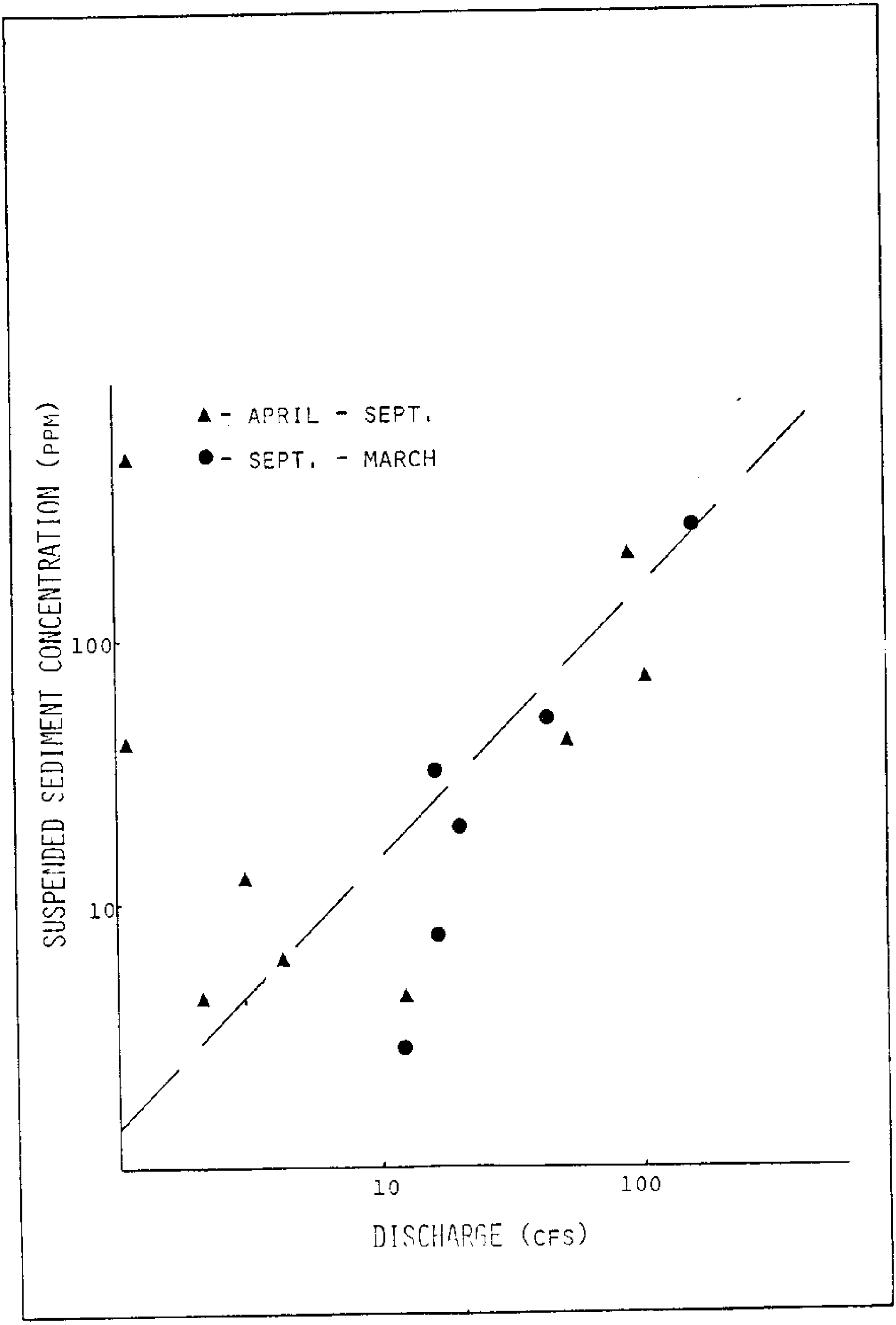


FIGURE 17 Suspended Sediment Rating Curve for Beaver Creek (correlation coefficient for the plotted data is C_c = .786; a = 1.42 and b = 1.03)

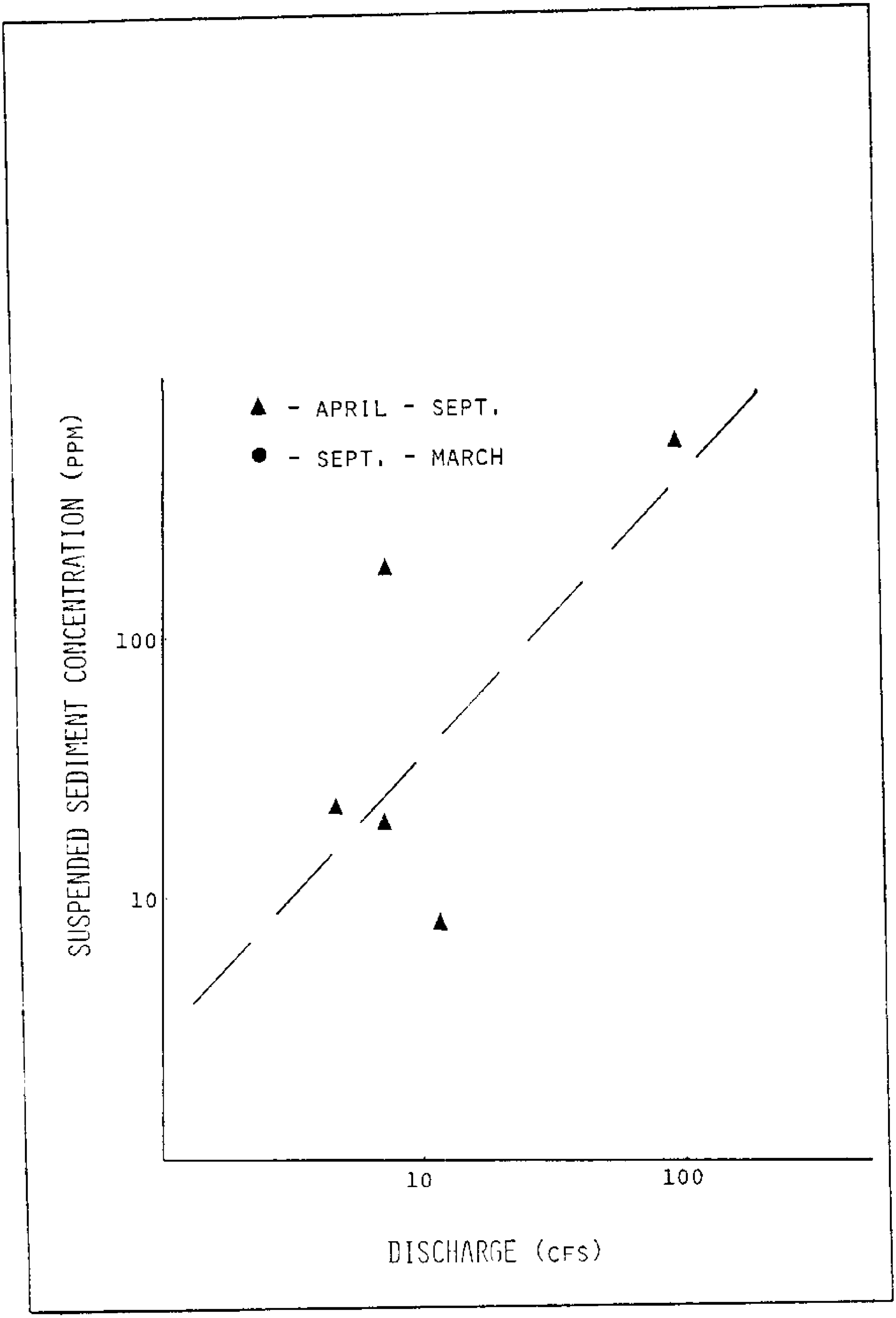


FIGURE 18 Suspended Sediment Rating Curve for Delaware Creek (correlation coefficient for the plotted data is C_c = .704; a = 2.88 and b = 1.13)

Oceanographic and Atmospheric Administration's 1975 climatological information (US Department of Commerce 1975). These data include:

- o daily precipitation data at four stations of varying elevations in or close to the study area
- o snow-on-ground readings at two stations
- o maximum and minimum temperatures

Figure 19 shows the locations of the NOAA stations.

Table 3 gives the precipitation data for the four stations of various elevations. The results support the observation of Harding and Gilbert (1968) that precipitation increases substantially with a rise in elevation. From these results, one would expect higher discharge from streams with greater areas at high elevation.

We used all available climatological data and staff gage readings to complete the 1975 daily discharge records for the sampled streams. For all days with significant precipitation we used the Soil Conservation Service procedure, for approximation of peak runoff and mean daily discharge from rainstorm activity (Soil Conservation Service 1971a,b).

From the data collected, we concluded that greater runoff occurs in winter when evapotranspiration is very low and great amounts of water are released during snowmelt. Because of the very high rate of evaporation from May through August, the higher summer precipitation does not produce as much runoff as does winter precipitation.

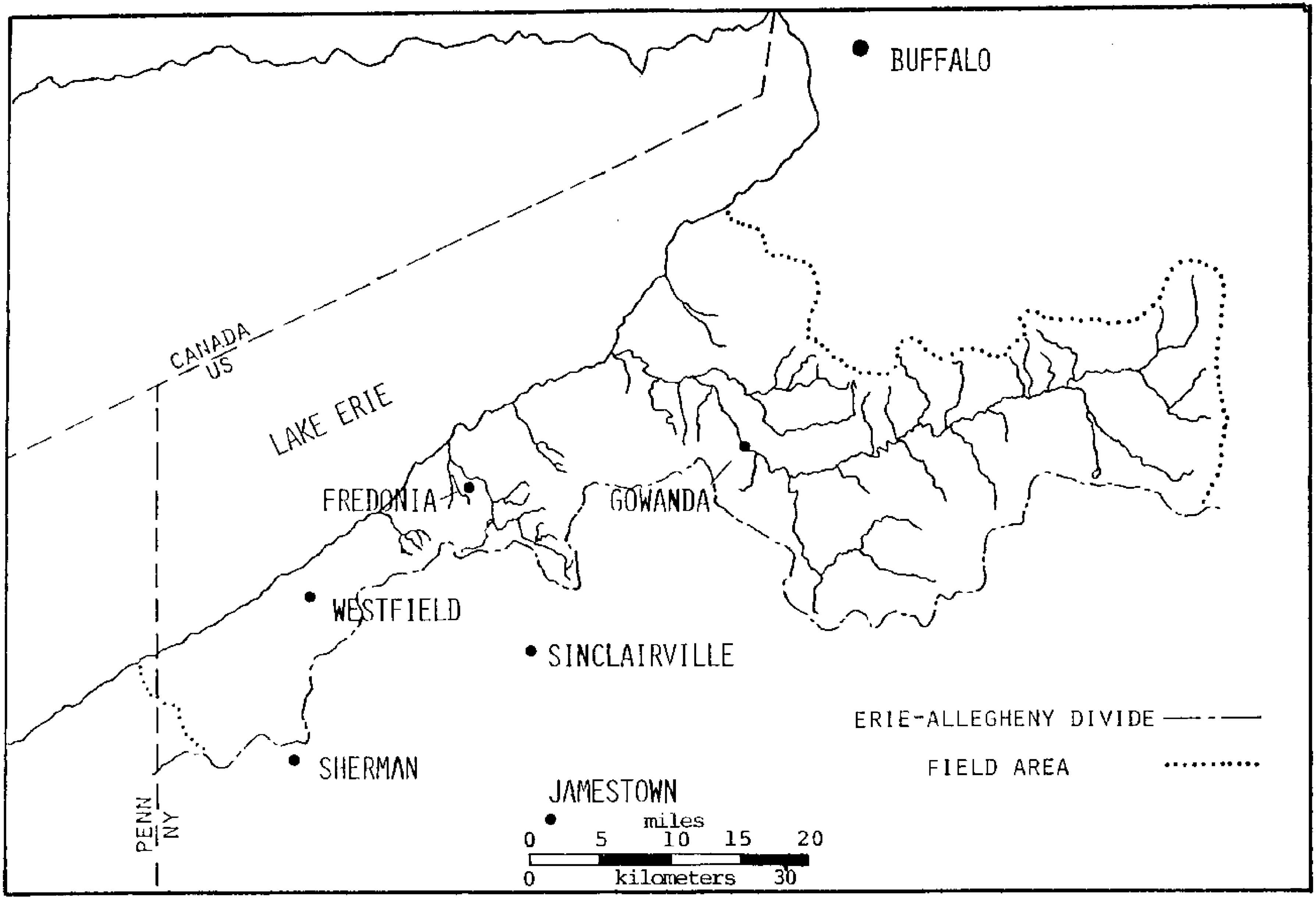


FIGURE 19 Rain Gage Stations

Annual Suspended Sediment Yield

The daily discharge records and suspended sediment rating curves were used to calculate the annual suspended sediment yield for each sampled basin. We found that sediment contributions are largest from large flow events. For example, in Canadaway Creek:

- Four high flow days contributed 96% of January's sediment.
- Three high flow days contributed 99% for February.
- Two high flow days contibuted 73% for March.
- These nine days collectively made up 73% of Canadaway's contribution for the entire year.

Table 4 lists annual suspended sediment yields for the sampled basins plus those of Cattaraugus Creek. This table shows:

- Canadaway Creek, an intermediate-size basin, contributes a sizable portion of the total yield.
- Slippery Rock and Beaver Creek, two of the smaller basins, yield insignificant amounts of suspended sediment.
- Delaware Creek, a small basin, shows an unexpectedly high production rate, but this is probably unreliable since we took few samples and those during summer when suspended sediment is most concentrated.
- The sediment yield from the largest basin, Cattaraugus Creek (Archer and LaSala 1968), dwarfs the contributions of the smaller basins though its sediment production rate is comparable.

Evaluation of Sediment Yield Data

Chow (1964) published the results of sediment yield calculations for 1,096 basins of various size in the United States (Table 5). These data show considerably higher sediment production rates than do the figures obtained in our study and by that of Archer and LaSala (1968) from western New York basins (Tables 4 and 6). In addition, Chow's figures show that decreasing sediment production rates occur with increasing drainage area. The production-area relationship derived from our study is clearly contrary; data from several small basins showed very low sediment production rates (Table 4). Support for our sediment yield to basin size relationships has been presented previously by Winter (1974) and Jagoda (1973). Their study of two small basins in western New York suggested that much higher flows are needed to modify channel geometry of small basins than larger ones and that major erosional events are more frequent on large basins. However, data of Archer and LaSala (1968) (Table 6) show no relationship between drainage area and sediment production rate.

That our results (Table 4) contrast strongly with broad-based averages calculated by Chow (1964) may suggest that geomorphic influences and availablity of sediment as well as basin size strongly influence sediment

TABLE 4 Annual Suspended Sediment Yield, 1975

Sampled Stream	Drainage Area (mi^2)	Sediment Yield (tons)	Sed. Prod. Rate ($tons/mi^2$)
Canadaway Ck.	38	40,500	1,080
Beaver Ck.	10	3,300	330
Slippery Rock Ck.	9	2,800	310
Delaware Ck.	10	11,600	1,160
Cattaraugus Ck.*	554	710,000	1,270

*Data from Archer and La Sala (1968)

TABLE 5 Average Sediment Production Rates for Various United States Drainage Basins *

Drainage Area (mi^2)	Sed. Prod. Rate ($tons/mi^2$)	Number of Measurements
Under 10	9,800	650
10-100	4,130	205
100-1000	2,610	123
over 1000	1,290	118

*(Chow 1964)

TABLE 6 Annual Sediment Production Rates for Local Western New York Basins *

Greater than 100 (mi^2)		Less than 100 (mi^2)	
Drainage Area (mi^2)	Prod. Rate ($tons/mi^2$)	Drainage Area (mi^2)	Prod. Rate ($tons/mi^2$)
22.1	50	134	1,500
23.6	250	144	1,000
29.3	1,300	171	350
37.2	780	231	160
40.7	80	352	90
72.4	60	432	1,400
78.4	420		
80.1	250		
94.9	1,200		

*(Archer and La Sala 1968, p. 11)

yield. The lower sediment production rates in our Erie basin study may be related to the effects of shallow bedrock in much of our field area.

CONTRIBUTION OF COARSE MATERIAL

So far we have discussed only the transportation of suspended or fine sediment load to Lake Erie. There is, however, much evidence of the transportation of coarse sediment (bedload) in the sampled basins.

Coarse material consisting of sand through boulders, which is transported downstream and through the mouth of streams in the field area, nourishes Erie's coastal sediment budget. The material is heavy enough to remain in the high energy (littoral) zone near shore without being washed away. Therefore, the transport of coarse material is critically important to this study.

Bedrock and till cutbanks contribute a great deal of coarse material. Undercutting, avalanching, slumping, and other mass wasting processes provide varying quantities of coarse plates and erratics for storage in numerous locations along the stream course in the form of longitudinal, diagonal, and point bars. Figure 20 shows a section of Canadaway Creek which, in spite of semi-annual dredging for the past several years, constantly collects new gravel bars. Figure 21 shows the same section of Canadaway Creek after Hurricane Agnes in June 1972.

In investigating coarse sediment (bedload) transport, we used observational criteria and theoretical bedload transport equations as well as channel geometry and critical transport velocities.

Observational Criteria for Bedload Transport

Using criteria from Lane and Borland (1951, pp. 619-620) and Sheppard (1965, pp. 275-276), paraphased below, in conjunction with Maddock's classification for determining bedload, shown in Table 7, we estimated the percentage of coarse material in the total sediment yield.

Criterion 1. The smaller the actual concentration of suspended material, the higher the percentage of bedload.

Criterion 2. The smaller the difference in the particle sizes of the bedload material and suspended load material, the higher the percent of bedload.

Criterion 3. The ratio of bedload to suspended load is likely to be larger for low or moderate stages than for high stages.

Criterion 4. Streams with wide, shallow channels carry a higher proportion of sediment as bedload than streams with deep, narrow channels.

Criterion 5. Stream channels with a high degree of turbulence tend to have smaller amounts of bedload.

Criterion 6. Sediment derived from sheet erosion tends to be fine; therefore, streams which derive much of their total load from sheet erosion tend to have a smaller amount of bedload.

TABLE 7 Maddock's Classification for Determining Bedload*

Concentration of suspended load	Type of Material forming the channel of the stream	Texture of the suspended material	Percent bed load in terms of measured suspended load
Less than 1,000 ppm	Sand	Similar to bed material	25 to 150 percent
Less than 1,000 ppm	Gravel, rock, or consolidated clay	Small amount of sand	5 to 12 percent
1,000 to 7,500 ppm	Sand	Similar to bed material	10 to 35 percent
1,000 to 7,500 ppm	Gravel, rock, or consolidated clay	25 percent sand or less	5 to 12 percent
Over 7,500 ppm	Sand	Similar to bed material	5 to 15 percent
Over 7,500 ppm	Gravel, rock, or consolidated clay	25 percent sand or less	2 to 8 percent

*(Leopold et al. 1964)

FIGURE 20 Reach Just Upstream of the Gage Site on Canadaway Creek Just after Removal by a Gravel Operation of a Large Gravel Bar (photo taken just before Hurricane Agnes, early spring 1972)

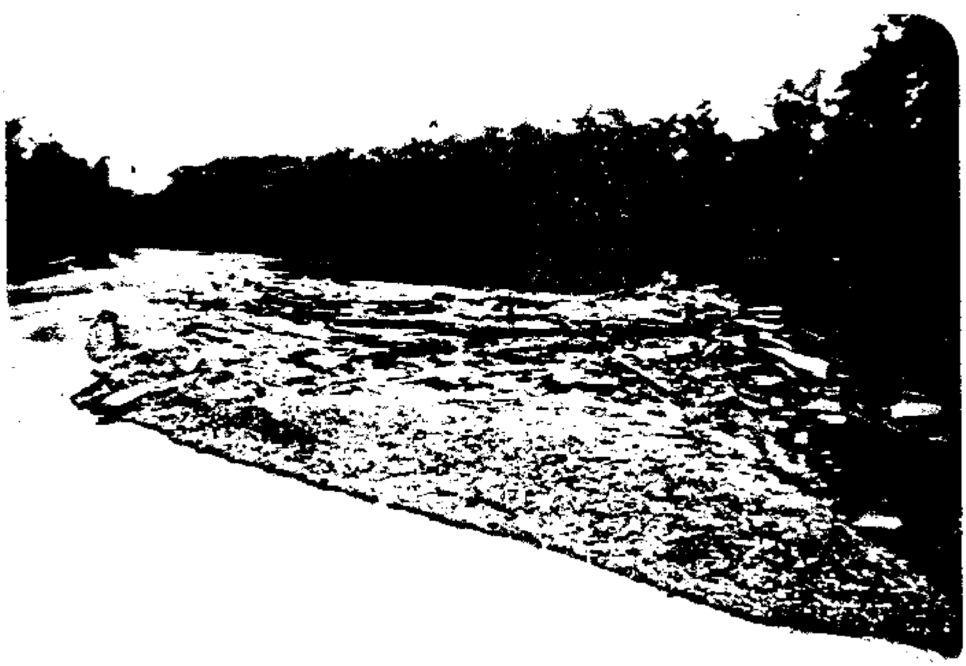


FIGURE 21 Reach Just Upstream of the Gage Site on Canadaway Creek after Hurricane Agnes in July 1972 (boy standing on shale plates shows size of bar and material)

Criterion 7. Gully erosion and bank cutting are likely to produce coarser material than sheet erosion and thus produce a greater percentage of bedload.

Criterion 8. The nature of the sediment available for transport, both as bedload and suspend, including grain size, fall velocity, resistance to erosion, and so on, plays a major role in determining the character of sediment transport in a stream.

For the most part, the streams of this study have suspended sediment concentrations less than 1,000 ppm and include very small amounts of sand even at high discharges. Gravel and bedrock channel reaches predominate with bed material much coarser than the suspended load. Under these circumstances Maddock's classification (Table 7) calls for a bedload contribution amounting to 5 to 12 percent of the measured suspended load. Because most of the stream channels are wide, shallow, and bedrock floored, and turbulence is low, somewhat higher percentages of the total load than normal may be transported as bedload.

Sediment is derived by sheet erosion, gullying, and cutbank erosion from glacial drift and siltstone and shale bedrock. The glacial drift supplies silts and clays as well as sand and gravel. The shale and siltstone bedrock is a good source of gravel plates; however, the shale plates break down rapidly after prolonged exposure.

The coarse plates are abundant in the beds of the sampled streams, and appear to have an armoring effect, protecting the bed material from transport. Imbricated on the bed, the large plates trap silt and clay-size sediments which remain in place until there is enough turbulence (critical velocity) to move the coarse grains. This results in the transportation of the coarse sediment in pulses. The plates store the sediment during times of base flow until high flow events flush the sediment through the channel.

Based on the observational criteria, we assumed an estimated 10 percent of the total annual sediment load of the sample is bedload. Archer and LaSala (1968) also used this figure in a transport study of selected western New York basins north of the field area.

Theoretical Bedload Transport Equations

Theoretical equations were also used to determine the amount of coarse sediment that the field area contributes to Lake Erie. We used a number of equations to determine the coarse sediment yield as did Hubbell and Matejka (1959) and Colby and Hembree (1955). Fahnestock et al. (1974) made similar estimates for Cattaraugus Creek, the largest stream in the field area.

We chose sample reaches on each of the representative streams to obtain data for use in the transport equations. We selected reaches near the gage sites and as close to the mouth as possible without introducing backwater effects from high lake levels. The reaches range from 100 to 200 m (330 to 660 ft) long--as long as possible while still maintaining some uniformity of channel geometry (a description of a given cross section within a limited reach of a river channel).

Bedrock determines the character of the stream channels near the mouth of the lake plain. The slopes of the channels are more a function of the resistance of bedrock than the result of an equilibrium of sediment transport. To avoid this condition, we chose reaches with a veneer of gravel in the channel on the assumption that the presence of gravel shows some balance between the transport capacity of the reach and the amount of sediment available for transport.

We surveyed cross sections at the upstream and downstream ends of the reaches. Figure 22 shows the upstream and downstream cross sections and base flow water levels. We also surveyed base flow water surface slopes and thalweg (steepest stream gradient) slopes at each of the reaches. We chose bankfull depth for each of the cross sections based on the definitions of Leopold et al. (1964, p. 319) and Wolman and Miller (1960, p. 72). Using the Manning equation (see Table 8a), we calculated the water surface slopes and bankfull discharges for the streams. Table 8 shows some of the important characteristics for Beaver, Slippery Rock, Delaware, and Canadaway creeks:

- bankfull discharges
- mean velocity
- cross sectional area
- hydraulic radius
- width-depth ratio

We took three 9 to 14 kg (20 to 25 lb) samples of bed materials at the downstream cross section of each of the reaches with a cylindrical sampler (25.4 cm) (10 in) in diameter which penetrates at least 12 cm (5 in) into the gravel. We analyzed the size distributions using the sieve method. Figure 23 shows the cumulative frequency curves for Beaver, Slippery Rock, Delaware, and Canadaway Creeks.

Because of their ease in calculation, we used the Schoklitsch, Duboys, Meyer-Peter, Kalinske, and Meyer-Peter Muller equations to determine the amount of coarse sediment transported by the field area. The most reliable equation for small gravel-bearing streams is the Schoklitsch equation. The other equations are more successfully used for streams that carry predominantly sand-size bedload. Graf (1971), Gray (1970), Shen (1971), and Vanoni et al. (1961) provide detailed explanations of these equations. Table 9 gives the results of the calculations.

Each of the equations has its own inherent prejudices. The Schoklitsch and Meyer-Peter equations are critical discharge equations. Critical shear stress needed to set the bed material in motion is the basis for the Duboys and Meyer-Peter Muller equations. Water surface slopes are heavily weighted as can be seen by the large predicted load for Slippery Rock Creek, a high gradient stream. The Kalinske equation, based on tractive force theory, gives a much smaller range in sediment yield for different discharges.

The results of the calculations show very similar values for the different equations. The average values of calculated bedload transport on the estimated bankfull discharge days are as follows:

- 50 Mg (55 tn) per day or 24 percent of the total load for Beaver Creek
- 835 Mg (920 tn) per day or 4 percent of the total load for Canadaway Creek

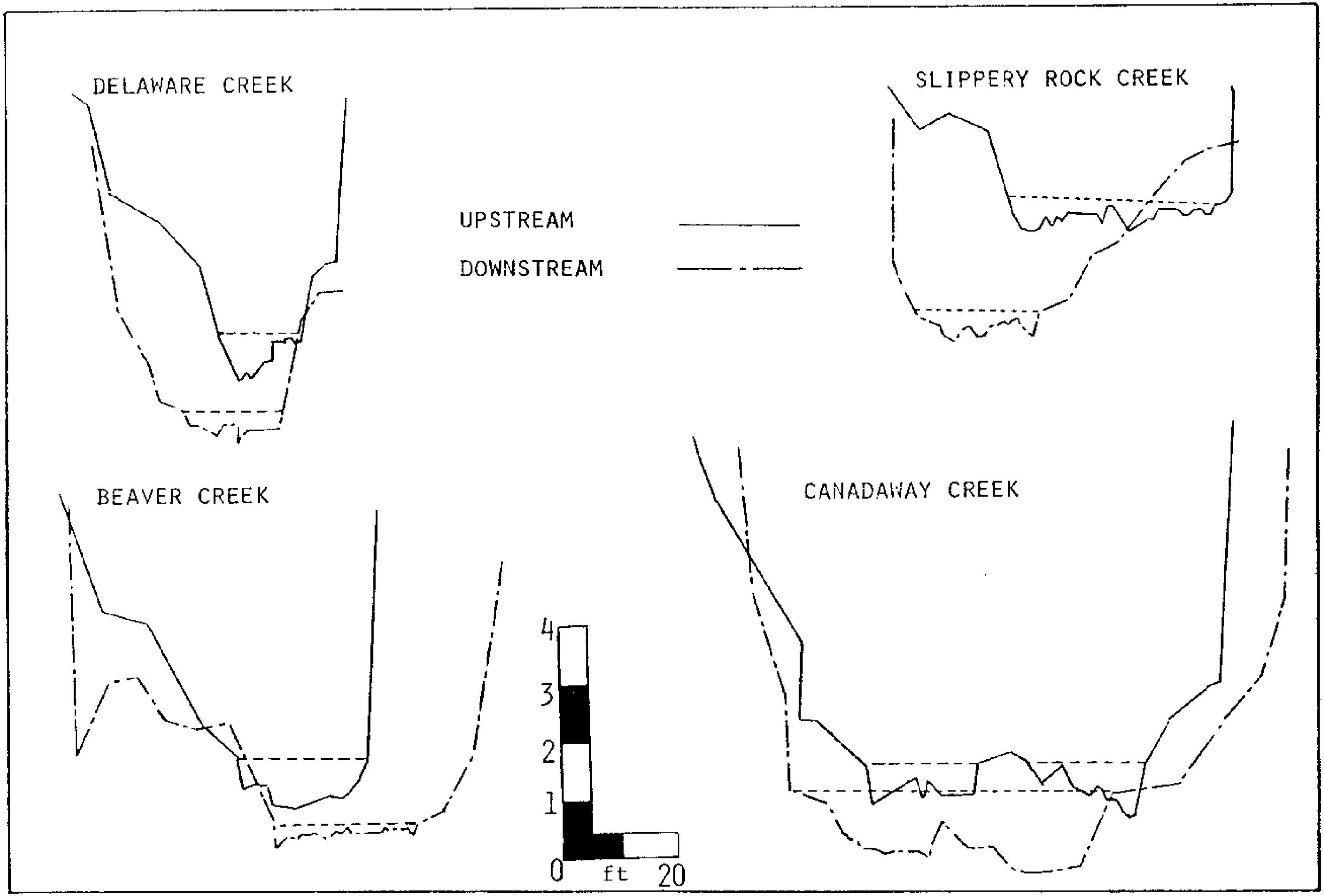


FIGURE 22 Cross-Sectional Profiles of Sampled Streams at Upstream and Downstream Ends of Surveyed Reaches (reach between these extremes was always a weighted average of the two displayed cross-sections. Dashed line is base flow water level)

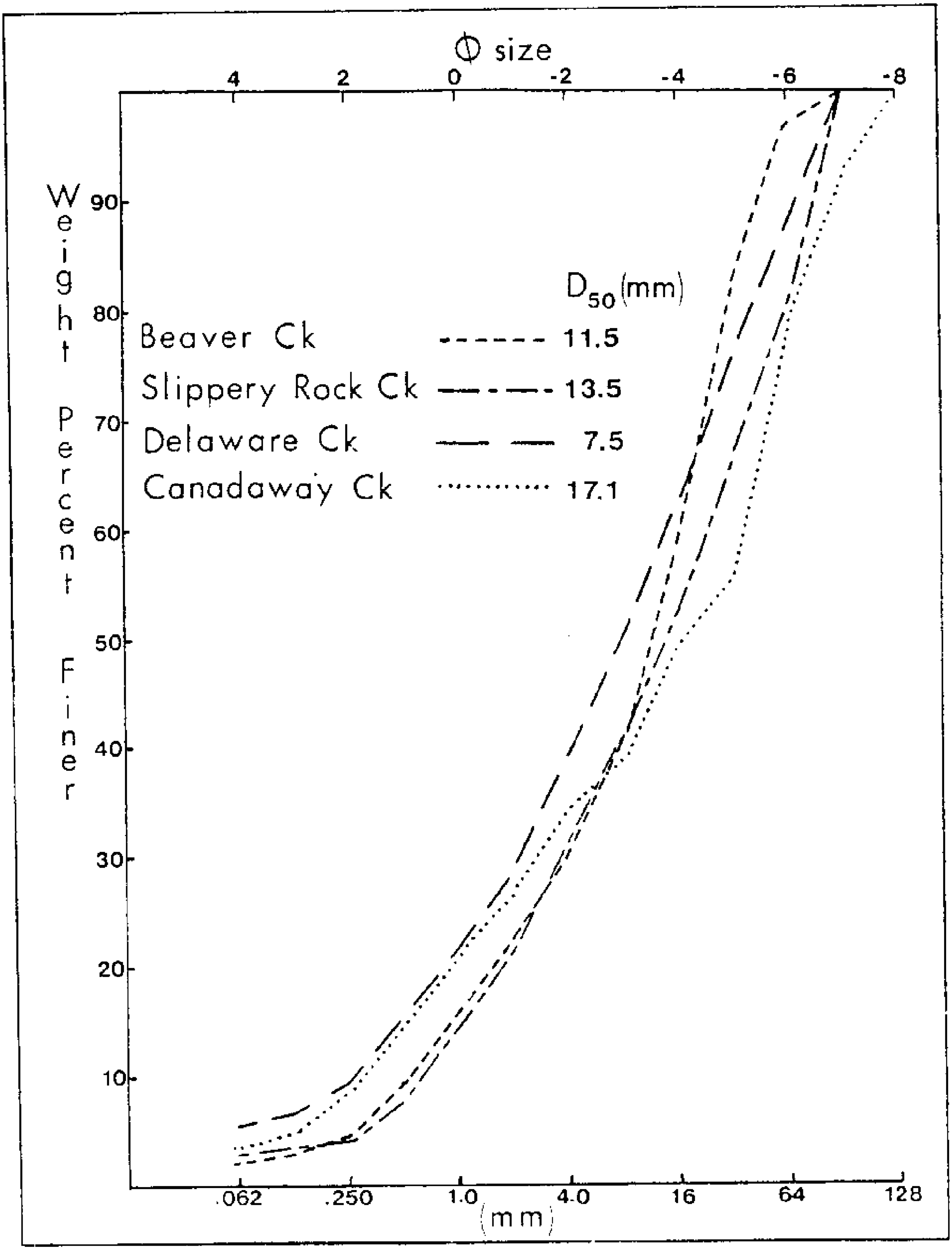


FIGURE 23 Cumulative Frequency Curves for Bed Material Grain-Size Distributions (each curve is the average of three samples taken at the sampled reaches of the representative streams)

TABLE 8 Various Parameters of Channel Geometry at Estimated Bankfull Discharge

Table 8a

MANNING EQUATION
For calculating water surface slopes and bankfull discharges

$$V = \frac{1.49}{n} Rh^{2/3} S^{1/2}$$

Rh = Hydraulic radius

S = Water surface slope

n = Manning's roughness coefficient
(n = 0.35 as per channel descriptions in Gregory and Walling 1973, p. 129)

V = Mean velocity

TABLE 8b

VARIOUS PARAMETERS OF CHANNEL GEOMETRY

Stream Name	Q_b (cfs)	V (fps)	Depth (ft)	Width (ft)	XSA (ft^3)	R_h	W/D	Slope (ft/mi)
Beaver Ck	190	2.59	2.70	41	73	.83	15.2	21.9
Slip. Rock Ck	330	4.10	2.65	54	85	.84	20.4	49.7
Delaware Ck	200	2.66	2.76	38	76	.96	14.3	21.8
Canadaway Ck	2300	3.67	7.75	97	600	2.95	12.5	17.6

Q_b = bankfull discharge, V = mean velocity, XSA = cross sectional area, R_h = hydraulic radius and W/D = width-depth ratio

TABLE 9 Theoretical Estimate of Bedload Transport

Stream Name	Q_b (cfs)	Bedload Discharge (tons/day) A	B	C	D	E	Avg.	% of Total Load
Beaver Ck.	190	60	40	33	88	49	55	24
Slip. Rock Ck.	330	1200	1660	169	677	160	770	--
Delaware Ck.	200	207	202	44	38	42	110	16
Canadaway Ck.	2300	1417	1590	302	--	356	920	4

Bedload discharge estimated for a day of mean bankfull discharge (Q_b), as calculated by the Schoklitsch (A), Meyer-Peter (B), DuBoys (C), Meyer-Peter and Muller (D) and Kalinske (E) theoretical bedload discharge equations.

• 100 Mg (110 tn) per day or 16 percent of the total load for Delaware Creek

The results for Slippery Rock Creek are probably too high due to the exaggerated effect of the steep bedrock-controlled slopes. All of the results show a substantial capacity to transport coarse sediment and fair agreement with the percent bedload estimates made according to accepted observational criteria (Lane and Borland 1951; Sheppard 1965)

Critical Transport Velocities

We compared the mean velocities calculated for bankfull discharge in the sample reaches with the critical velocities needed to transport the median (D 50) grain size on the bed (Fahnestock 1963; Lane 1955; Soil Conservation Service 1971a, Figure 6-1) as a check on the stream's ability to transport the coarse material found on the bed.

Table 10 shows that the mean velocity is capable or very nearly capable of transporting the mean grain size on the bed.

Other factors are important when using critical transport velocities in estimating the stream's ability to transport coarse material in the bed. First, threads of higher current velocity in the thalweg or line of strongest flow in the stream have the capacity to transport even larger grain sizes. Second, the normal velocity profile shows a decrease in velocity at the bed and banks; however, gravel caving in off undermined cutbanks is already in motion as it enters the flow. Third, particles packed or imbricated on the bed are more difficult to set in motion. Fourth, the shape of the particles sometimes determines their transport ability just as much as size does.

TABLE 10 Critical Transport Velocities

Stream Name	D_{50} (mm/in)	Velocity (fps) A	B	C	Measured
Beaver Ck.	11.5/.449	3.4	3.6	2.9	2.59
Slippery Rock Ck.	13.5/.527	3.6	4.0	3.3	4.10
Delaware Ck.	7.5/.293	2.9	3.1	2.7	2.66
Canadaway Ck.	17.1/.668	3.9	4.3	3.5	3.67

Measured mean channel velocities are compared to calculated critical transport velocities for median grain size of bed material on sampled basins; critical velocities as measured by (A) Lane (1955), (B) Soil Conservation Service (1971a) and (C) Fahnestock (1963).

TOTAL SEDIMENT YIELD

We were able to estimate the total fluvial sediment contribution from the 29 basins of the field area to the Lake Erie sediment budget for 1975 based on our extrapolation of sediment production rates obtained from the five represented basins.

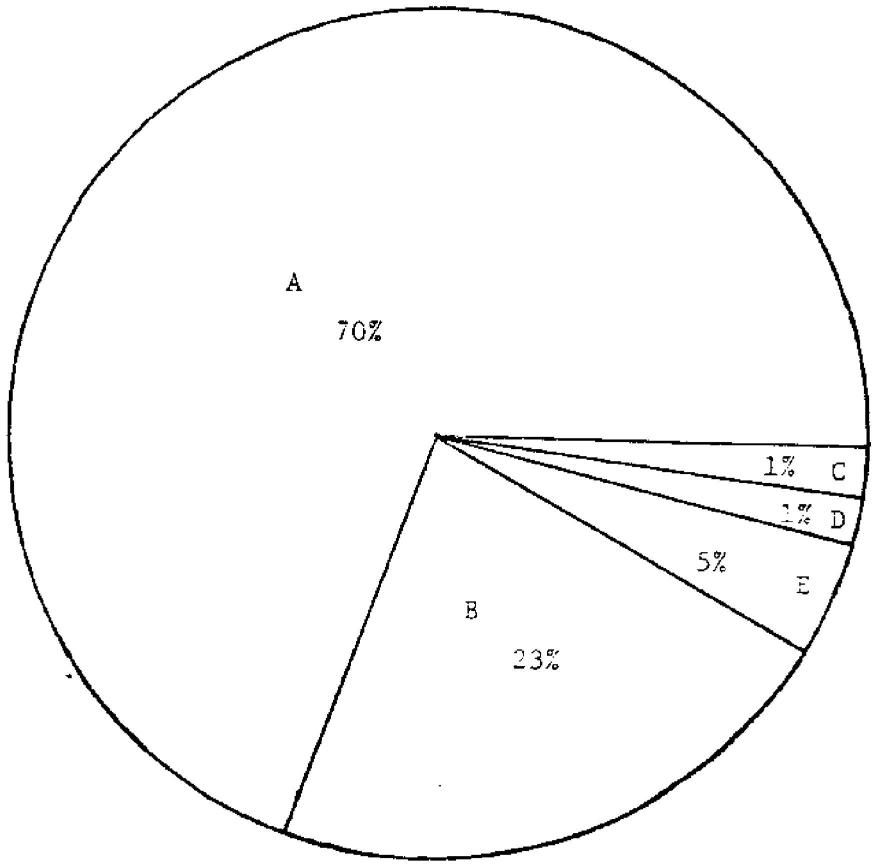
The results of the total yield calculations appear on Table 11 and Figure 24. The table shows the comparable yields of the individual groups and total yield for the field area. All figures include 10 percent addition for the bedload transport as we estimated in the previous section. Precipitation records from established rain gage stations (Table 3 and Figure 19) showed that 1975 was an average precipitation year. Thus sediment yields may also have been average.

The high sediment production rates in the intermediate-size basins, Group B (represented by Canadaway Creek), combine with the large total drainage area of the five basins in this group to contribute an estimated 235,000 Mg (260,000 tn) of sediment per year to Lake Erie. Groups C and D, small basins, have very low sediment yields. Calculations for group E, the remaining small basins, show a slightly higher yield. The total yield for the three groups of small basins, 23 streams totaling 337 km^2 (130 mi^2) is 75,000 Mg (82,500 tn) of sediment per year, much less than that of group B.

The "Erosion and Sediment Inventory" (EASI) (Soil Conservation Service 1974) of western New York estimated 380,000 Mg (420,000 tn) of sediment eroded from the field area excluding Cattaraugus Creek. This compares well with the 308,000 Mg (340,000 tn) annual sediment yield which we estimated in our study.

The annual sediment yield for Cattaraugus Creek according to the modified data of Archer and LaSala (1968, pp. 7-9) is 708,000 Mg (780,000 tn) (Table 11) although the EASI study estimates 472,000 Mg (520,000 tn) per year. Our data and those of Archer and LaSala (1968) suggest that this is by far the largest contributor of stream sediment to Lake Erie from western New York. The Buffalo Creek basin, north of the field area, may carry in excess of 417,300 Mg (460,000 tn) per year to its mouth making it second in importance as a single output (Archer and LaSala 1968). However, there is in addition a sizable contribution from the intermediate-size basins as exhibited in this study, which should not be overlooked, particularly with respect to its potential for beach sediment replenishment along the coast.

The total fluvial sediment contribution of 2,300 km^2 (900 mi^2) field area as rounded from Table 11 is approximately 1,018,000 Mg (1,123,000 tn) per year with a 10 percent or 101,800 Mg (112,000 tn) coarse fraction. Geier and Calkin (in press) estimate that erosion of western New York coast contributes a total of 323,000 Mg (356,000 tn) to Lake Erie. Of this amount, 42,000 Mg (46,000 tn) are sand and gravel from unconsolidated deposits. Added to this amount will be



Group A (Cattaraugus Creek)	780,000 short tons per year
Group B (represented by Canadaway Creek)	260,000 short tons per year
Group C (represented by Slippery Rock Creek)	16,500 short tons per year
Group D (represented by Beaver Creek)	16,000 short tons per year
Group E (represented by Delaware Creek)	50,000 short tons per year

FIGURE 24 Total Sediment Yield of Streams within the Field Area to Lake Erie

TABLE 11 Total Sediment Yield

Group	Representative Basin	Streams in Group	Sed. Prod. Rate[a] (tons/yr/mi^2)	Total Group Area (mi^2)	Total Yield[a] (tons/yr)
B	Canadaway Ck.	5	1,200	215	260,000
C	Slip. Rock Ck.	13	345	48	16,500
D	Beaver Ck.	5	366	44	16,000
E	Delaware Ck.	5	1,290	38	50,000
Total		28		346	342,500
A	Cattaraugus Ck.[b]	1	1,400	554	780,000

[a]We used total group areas and calculated sediment production rates to estimate the annual sediment contribution from the four groups of geomorphically similar basins. Yields and production rates include an estimated 10 percent for bedload.

[b]Modified from data of Archer and La Sala (1968) to include basin above mouth of Cattaraugus Creek at Lake Erie.

most of another 184,000 Mg (202,000 tn) consisting of eroded shale bedrock which will together be available as coarse load for beach nourishment.

The total contribution of fluvial sediment, therefore, is nearly three times that of local shoreline erosion. The component of coarse stream sediment may be as little as half of that derived at the coast. However, it is of sufficient amount to become a critical part of the littoral drift and a deterrent to Lake Erie shoreline recession.

ESTUARY EFFECTS

There is a complex interaction of streamflow and wave forces at the mouths of many streams which are tributaries of Lake Erie. The mouths of many streams have become estuaries (drowned river mouths) during the postglacial increase in Lake Erie level controlled by rebound of its spillway outlet at Niagara Falls (Calkin and Brett 1978). In addition, recent high lake levels such as those in 1973 through 1975 temporarily lengthen estuaries. The wave current activity of Lake Erie has built bars, spits (narrow points of land extending into a body of water), or berms (narrow ledges or shelves) across the mouths of the streams that block the flow of water to the lake and restrict the natural mixing of lake and stream waters. Wave activity drives the berms onshore where they join up with the beaches and extend across the mouths of the sample basins. Wave attack, streamflow, and longshore drift modify the berms. The results vary depending upon streamflow, sediment supplied from upstream, wave attack, longshore drift, and sediment supplied from offshore bars.

Because of the obstructions at the mouths of the sampled streams, the estuaries act as settling ponds and sediment transported to this reach is deposited in the deep, slow-moving waters. The sediment remains there until there is a flow which is strong enough to break the obstructions and flush the stored sediment into the lake (see also Archer and LaSala 1968).

The small basins have less streamflow and therefore less power to flush out the sediment that obstructs the mouth under normal flow conditions. The wave activity of Lake Erie dominates and allows the sediment to build up across the mouths of the streams. The large berms block the streamflow almost entirely except for groundwater. The small basins are able to flush through the obstruction only at times of high flow. Therefore, the actual transport of fluvial sediment from the field area to Lake Erie occurs in an intermittent manner. The recurrence of floods of a magnitude great enough to overcome the effects of high lake level and wave-induced obstructions at the mouths of the streams determine the frequency of sediment transport.

Figure 25 shows the mouth of Beaver Creek following the high flow event of June 5. A 2 to 3 m (7 to 10 ft) incision was cut through the existing beach berm during the high flow. The water in this channel is approximately 1.5 m (5 ft deep and has a bedrock floor. This demonstrates the stream's competence through this reach during the high flow. However, note that wave action and littoral sediments have already blocked the stream from flowing to the lake.

The intermediate-size basins have a consistently greater flow which overtops the berms and forces some of the sediment offshore. The result is less accumulation of sediment across the mouth. This allows streamflow and wave action to modify the berm into a spit or narrrow point of land extending into the stream. The prevailing drift direction determines the orientation of the spit.

FIGURE 25 The Mouth of Beaver Creek after a Significant Flow Event Eroded 2 m (6.6 ft) through the Beach Berm (flushing all sediment previously trapped in the estuary and obstructing the mouth out into the lake. The shoreline is at the left border of this photo)

FIGURE 26 The Mouth of Silver Creek on October 25, 1974 after a Period of Prolonged Low Flows (wave activity and longshore drift have deposited much sediment obstructing flow to the lake)

Figure 26 shows the mouth of Beaver Creek after the June 5 flow which eroded six feet of beach berm and flushed all of the sediment previously trapped in the estuary out into Lake Erie. Figures 26 and 27 show the mouth of Silver Creek, an intermediate basin, before and after a high flow event freed the mouth of the channel. Figures 28 and 29 show similar before and after scenes at the mouth of Cattaraugus Creek.

The obstruction of the mouths of the streams which causes the transport of sediment in pulses creates a number of problems. Prolonged base flow conditions, when wave activity drives in the spit oriented across the mouth of the creek, blocks small-craft access to refuge at Cattaraugus Harbor (Fahnestock, Hayes, and Nummedal 1974). The Army Corps of Engineers proposed a multimillion-dollar structure to alleviate this condition, but the project has now been dropped.

The present Fredonia sewage treatment plant discharges its effluent into Canadaway Creek. The obstruction at the mouth prevents natural mixing and dilution of the polluted water. As a result, the pollution becomes quite concentrated and unhealthy. A new treatment plant under construction on the lake shore will eliminate this problem.

The obstruction of the stream mouths causes some other problems. The bars or berms across the creeks keep Lake Erie's game fish from spawning in the small and intermediate-size streams.

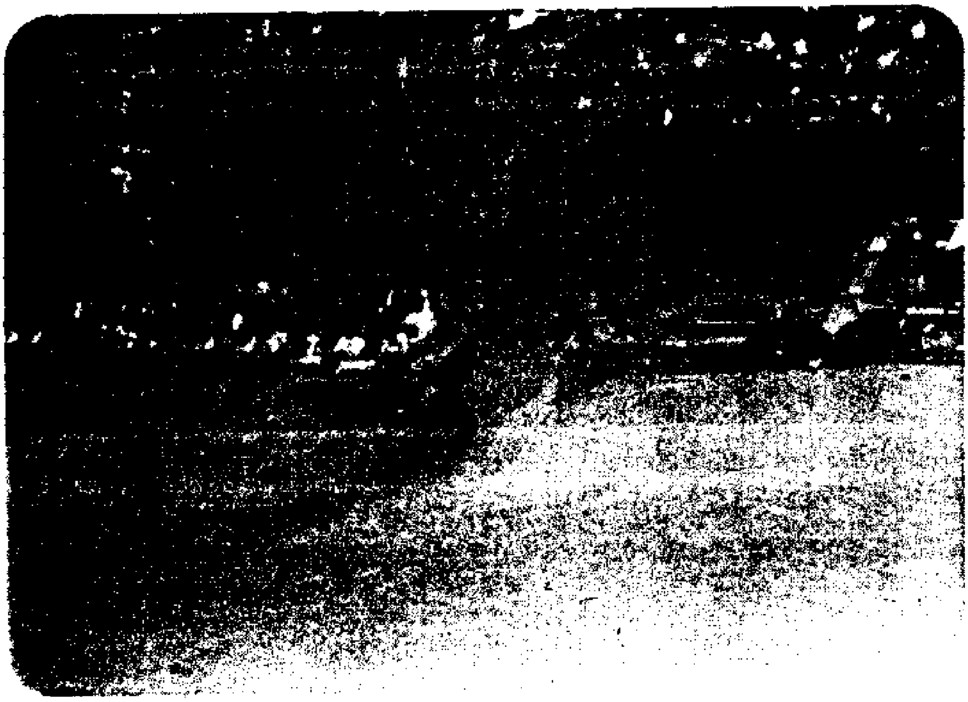


FIGURE 27 The Mouth of Silver Creek on March 23, 1975 after a High Flow Event Flushed all Sediment Obstructing the Mouth and Trapped in the Estuary out into the Lake

FIGURE 28 The Mouth of Cattaraugus Creek on October 25, 1974 after a Period of Prolonged Low Flows (wave activity and longshore drift have deposited enough sediment at the mouth to obstruct the flow significantly)

FIGURE 29 The Mouth of Cattaraugus Creek on March 23, 1975 after a High Flow Event Flushed all Sediment Obstructing the Mouth and Trapped in the Estuary out into the Lake

SUMMARY AND CONCLUSIONS

It was our main purpose in this study to investigate the fluvial contribution of small western New York drainage basins to the whole Lake Erie sediment budget of western New York. However, our goal was also to document the major coarse sediment component from streams that remains within the littoral zone and is available for beach nourishment. Our field area encompassed 20 drainage basins including most of western New York drainage in position to furnish beach material to its Lake Erie shore.

We divided these 29 basins into five categories and, except for Group A (Cattaraugus Creek), sampled a representative of each category through most high flow events for calendar year 1975. We estimated that the total amount of sediment contributed annually to Lake Erie from western New York field area is almost three times that provided by coastal erosion. The coarse sediment stream load may be as little as half of the coarse load contributed from the bluffs; however, it is of sufficient amount to be critical in beach and bluff maintenance. Data for Cattaraugus Creek were taken with modification from Archer and LaSala (1968).

The results of the suspended sediment sampling show that the sediment contributions of large flow events are by far the most significant in determining annual sediment yield. Although summer suspended sediment concentrations are consistently higher for similar discharges than winter concentrations, winter flows contribute the majority of suspended sediment to the Lake Erie sediment budget.

We found much higher sediment production rates in the intermediate-size basins than in the small ones. We believe this to be the result of a higher availability of sediment in the intermediate basins, which drain large areas of buried topography and moraine belts, than in the smaller basins, which cover sediment-starved regions on the slopes of the escarpment and on the lake plain.

The transport of coarse material as bedload in these streams occurs only at high flows. Only then does the stream reach the velocity required to move the coarse plates which form the channel beds of all the area's streams.

The estuarine nature of the mouths of many field area streams poses a problem in calculation of the actual contribution of fluvial sediment to the lake. Sediment from all parts of the stream gets caught at the mouth of an estuarine stream. Only at times of high flow when a sufficient gradient compensates for high lake levels does the sediment go through these reaches and flush the obstructing beach sediments into the lake.

Most significant influxes of fluvial sediment from the small and intermediate-size basins occur during high flows when sediment, previously stored under the armoring effects of the coarse fraction of the bed material and in the settling pond-like estuaries at the stream mouth, can move to Lake Erie.

REFERENCES

Abraham, A.D., and Kellerhalls, R., 1973. Correlations between water discharge and concentrations of suspended solids for four prairie rivers: Fluvial Processes and Sedimentation, Inland Water Directorate, Department of the Environment, Canada, pp. 96-114.

Archer, R.J., and LaSala, A.M., 1968. A reconaissance of stream sediment in the Erie-Niagara basin, New York: State of New York Conservation Department and Water Resources Commission, Basin Planning Report ENB-5, 34 p.

Buchanan, T.J., and Somers, W.P., 1969. Discharge measurements at gaging stations: US Geol. Survey, Techniques of Water-Resources Investigations, book 3, chapter A8, 65 p.

Buehler, E.J., and Tesmer, I.H, 1963. Geology of Erie County, New York: Buffalo Society of Natural Sciences Bull. 21(3).

Calkin, P.E., 1970. Strandlines and chronology of the glacial Great Lakes in northwestern New York: Ohio Jour. Sci. 70: 78-96.

Calkin, P.E., and Brett, C., 1978. Ancestral Niagara River drainage: stratigraphic and paleontologic setting. Geol. Soc. America Bull. 89: 1140-1154.

Calkin, P.E., and McAndrews, J.H., 1980. Geology and paleontology of two late Wisconsin sites in western New York. Geol. Soc. America Bull. 91: 295-306.

Chow, V.T., 1964. Handbook of applied hydrology: McGraw-Hill, New York, 29 chapters.

Coates, D.R., 1958. Quantitative geomorphology of small drainage basins of southern Indiana: US Department of the Navy, Office of Naval Research, Geography Branch, Technical Report No. 10, 67 p.

Colby, B.R., and Hembree, C.H., 1955. Computations of total sediment discharge, Niobrara River near Cody, Nebraska: US Geol. Survey Water Supply Paper 1357, 187 p.

Fahnestock, R.K., 1963. Morphology and hydrology of a glacial stream, White River Mt. Rainier, Washington: US Geol. Survey Prof. Paper 472-A, 70 p.

Fahnestock, R.K., and Metzger, W.J., 1972. Buried valleys in western New York: Geol. Soc. America Abstracts, v. 4, p. 1.

Fahnestock, R.K., Hayes, M.O., and Nummedal, D., 1974. Littoral processes and sedimentation in the Cattaraugus Embayment, New York: US Army Corps of Engineers, report for contract DACW 49-74-C-0118, 246 p.

Fahnestock, R.K., Nummedal, D., Apmann, R.P., and Brownlie, W.R., 1974. Sediment transport in Cattaraugus Creek, New York: US Army Corps of Engineers, report for contract DACW 49-74-C-0018, 99 p.

Geier, R.J., and Calkin, P.E. Stratigraphy and bluff recession along the Lake Erie coast, New York. New York Sea Grant Institute, Albany, in press.

Graf, W.H., 1971. Hydraulics of sediment transport: McGraw-Hill, New York.

Gray, D.M., 1970. Handbook on the principles of hydrology: Water Information Center, Inc., Port Washington, New York.

Gregory, K.J., and Walling, D.E., 1973. Drainage basins: form and process. John Wiley and Sons, New York.
Guy, H.P., 1969. Laboratory theory and methods for sediment and analysis: US Geol. Survey, Techniques of Water-Resources Investigations, book 5, chapter C1, 58 p.
Guy, H.P., and Norman, V.W., 1970. Field methods for the method of fluvial sediment: US Geol. Survey, Techniques of Water-Resources Investigations, book 3, chapter C2, 59 p.
Harding, W.E., and Gilbert, B.K., 1968. Surface water in the Erie-Niagara basin, New York: State of New York Conservation Department, Water Resources Commission, Report No. ENB-2, 118 p.
Hubbell, D.W., and Matejka, D.W., 1959. Investigations of sediment transport, Middle Lamp River, Dunning, Nebraska: US Geol. Survey, Water Supply Paper 1476, 195 p.
Jagoda, J.L., 1973. Hydrology and morphology of Hunter Creek (Holland, NY Quadrangle), a small gravel-bearing stream in western New York: MS thesis, Department of Geology, State University College, Fredonia, New York, 82 p.
Lane, E.W., 1955. Design of stable channels: Am. Soc. of Civil Engineers, v. 120, pp. 1234-1279.
Lane, E.W., and Borland, W.M., 1951. Estimating bedload: Amer. Geophys. Union Trans., v. 28, pp. 615-620.
Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964. Fluvial processes in geomorphology: W.H. Freeman, San Francisco.
Morisawa, M.W., 1959. Relation of quantitative geomorphology to stream flow in representative watersheds of the Appalachian Plateau Province: United States Dept. of the Navy, Office of Naval Research, Geography Branch, Technical Report No. 20, 94 p.
Muller, E.H., 1963. Geology of Chautauqua County, New York, part 2, Pleistocene geology: NY State Mus. and Sci. Service Bull., 392 p.
Muller, E.H., and Fahnestock, R.K., 1974. Glacial geology and buried topography in the vicinity of Fredonia, Gowanda, and Zoar Valley, NY: NY State Geol. Assn. Guidebook, 46th Annual Meeting, pp. F1-F17.
Muller, E.H., 1975. Physiography and Pleistocene geology. In Tesmer, I.H., Geology of Cattaraugus County, New York: Buffalo Society of Natural Sciences Bull. 27: 10-20.
Muller, E.H., 1977. Quaternary geology of New York, Niagara sheet: New York State Museum and Science Service Map and Chart Series, no. 28, scale 1:250,000.
Schumm, S.A., 1956. The evolution of drainage systems and slopes in badlands at Perth Amboy, NJ: Geol. Soc. America Bull. 67: 597-646.
Schumm, S.A., 1969. River metamorphosis: Proc. ASCE Journ. Hyd. Civ., HY1, 6352, pp. 255-273.
Shen, H.W., 1971. River mechanics: published by Hsieh Wen Shen, Fort Collins, Colorado, v. 1, chapters 11 and 13.
Sheppard, J.R., 1965. Methods and their suitability for determining total sediment quantities: Agricultural Research Service, US Dept. of Agriculture, Miscellaneous Publication 970, Paper No. 32, pp. 272-286.
Soil Conservation Service. 1971a. Allowable velocities for unprotected earth channels: Engineering Field Manual for Conservation Practices, Engineering Branch-Hydrology Branch, Washington Advisory Eng. 67, pp. 2.1-2.71.
Soil Conservation Service, 1971b. Engineering handbook: US Dept. of Agriculture, section 4, Hydrology, supplement A, pp. 10.1-10.21.

Soil Conservation Service, 1974. Erosion and sediment inventory, New York: US Dept. of Agriculture, 114 p.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology: Amer. Geophys. Union Trans., v. 38, pp. 913-920.

Tesmer, I.H., 1963. Geology of Chautauqua County, New York, part 1, stratigraphy and paleontology: NY State Mus. and Sci. Service Bull. 391, 65 p.

Tesmer, I.H., 1975. Geology of Cattaraugus County, New York: Buffalo Society of Natural Sciences Bull. 27: 21-105.

US Department of Commerce, 1975. Climatological data: National Oceanic and Atmospheric Association, Environmental Data Service, v. 87, no. 1-13.

Vanoni, V.A., Brooks, N.H., and Kenedy, J.F., 1961. Lecture notes on sediment transportation and channel stability: Agricultural Research Service, US Dept. of Agriculture, Report No. KH-R-1.

Winter, R., 1974. Form and process of a small gravel-bearing stream in western New York: MS Thesis, Dept. of Geology, State University College, Fredonia, New York, 72 p.

Wolman, M.G., and Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes: Jour. Geol. 68(no. 1): 54-74.

GLOSSARY

Alluvial--Pertaining to sediment transported and deposited by a stream.
Anticline--A fold of rocks which is convex upward or with youngest material on convex portion.
Bankfull discharge--The elevation of the water surface of a stream at channel capacity.
Bar--A ridge-like accumulation of sand, gravel, or other sediment.
Basin--An area capable of collecting, storing, and discharging water by reason of its shape.
Berm--A narrow, impermanent, nearly horizontal ledge or shelf formed of material thrown up and deposited by waves.
Channel geometry--A description of a given cross section within a limited reach of a stream or river channel.
Channel line--The line of the fastest current or the strongest flow of a stream; it generally coincides with and is sometimes called the thalweg.
Delta--A low, nearly flat, alluvial tract of land near the mouth of a river or stream.
Divide--The ridge or tract of high ground which marks the boundary between two adjacent drainage basins and which divides the surface waters that flow naturally in one direction from those that flow in the opposite direction.
Drift--Surficial debris transported from one place and deposited in another--usually glacial deposits.
Drumlinized--Sculptured into low, smoothly rounded hills, mounds, or ridges by a glacier.
Epeiric sea--An inland sea.
Erratic--A rock fragment carried by glacier ice and deposited, when the ice melted, at some place distant from its place of origin.
Escarpment--A long continuous slope facing in one direction.
Estuary--A drowned river mouth such as may be formed by a rise in the lake level.
Fissile--Capable of being split along closely spaced planes.
Fluvial--Produced by the action of a stream or river.
Fold--A ripple in the land surface; either a low rounded hill or a shallow depression.
Geomorphic--Pertaining to the description, nature, origin, development, and classification of the earth's surface features and shapes.
Groundwater--Subsurface water.
Gully erosion--Erosion by running water that forms distinct narrow channels.
Gullying--Gully erosion.
Head--The source, beginning, or origin of a stream.
Hummocky--Characterized by mounds or knolls; uneven.
Hydrograph--A graph showing stage, flow, velocity, or other characteristics of water with respect to time.
Ice marginal--Along the margin of a glacier.
Imbricated--Arranged in a slanting or overlapping pattern.
Kame knob--A hill of gravel formed by meltwater from a retreating glacier.
Kettle--A shallow basin formed in gravel during retreat of a glacier.

Longshore drift--Gravel, sand, shell fragments, and other material moved along the shore by a current which runs parallel to the shore.
Moraine--A mound or ridge depositing of a glacier usually consisting mostly of till--for example, an end moraine marks a former position of a glacier margin.
Outcrop--To appear exposed or visible at the earth's surface.
Plate--A thin, flat, smooth rock fragment.
Proglacial--Immediately in front of or just beyond a glacier or ice sheet.
Reach--A straight, continuous, or extended part of a stream.
Reentrant--A prominent or high and pointed horizontal projection of the land/surface.
Reworked--Transported and acted upon by earlier geologic agents--for example, earlier stream transport.
Scour--The clearing or digging action of water or ice.
Sediment--Solid fragmental material transported by water, air, or ice.
Sediment budget--The total amount of sediment being added and removed from the water system
Shale--A finely stratified, fine-grained sedimentary rock formed from clay, silt, or mud.
Shear stress--Opposite but parallel force.
Sheet erosion--Erosion in which broad continuous sheets of running water on slopes remove thin layers of surface material.
Siltstone--Hardened silt sediment.
Spit--A small point or narrow embankment of sand or gravel extending into a body of water.
Staff gage--A type of gage containing a graduated scale for measuring water-surface elevation.
Syncline--A fold of rocks which is concave upward or with youngest material in the concave portion.
Thalweg--The line connecting the lowest or deepest points along a stream bed and usually swiftest-moving flow.
Through valley--A flat-floored depression eroded across a divide by glacier ice or meltwater streams.
Till--Poorly sorted and poorly stratified glacial drift consisting of clay, sand, gravel, and boulders deposited directly in contact with glacial ice.
Undercutting--Removal of material at the base of a steep slope or cliff or other exposed rock by falling or running water.
Watershed--A drainage basin; the region drained by, or contributing water to, a stream, lake, or other body of water.
Winnowed--Sorted with the coarser materials left behind.

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cover design: Matthew Arnold
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editors: Janie Rahman
Margaret Koontz
Department of Technical Communication
Rensselaer Polytechnic Institute

New York Sea Grant Institute
State University of New York
and Cornell University
411 State Street
Albany, NY 12246