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Sediment Yield of Spring Creek Watershed, Alberta

University — Université

University of Alberta

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M.Sc.

Year this degree conferred — Année d'obtention de ce grade

1979

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THE UNIVERSITY OF ALBERTA

SEDIMENT YIELD OF SPRING CREEK WATERSHED, ALBERTA

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL, 1979

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Sediment Yield of Spring Creek Watershed, Alberta.

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Date *Oct. 18 1979*

ABSTRACT

The sediment regime of Spring Creek Watershed, a 112.7 km^2 wilderness area in west-central Alberta, was assessed using streamflow records and suspended sediment and solute concentration measurements made on Spring Creek and five of its tributaries from 1967 to 1977.

Most of the watershed contributes practically nothing to the sediment yield. Ninety percent of the sediment yield is derived from a 1.5 km^2 area near the watershed mouth; a zone of geomorphic disequilibrium developed in response to past changes in the local base level. Older, higher level disequilibrium zones on the tributary streams provide most of the remaining sediment yield.

On average, 76% of the annual sediment yield is output during spring runoff and the sediment discharge of 18 days per year accounts for 90% of the annual sediment yield. Combining spatial and temporal aspects shows that over 80% of the sediment yield is derived from 1.5% of the watershed area in less than 5% of the time.

Sediment rating curves give reasonably good prediction of sediment concentration from streamflow rates for Spring Creek, but not for its tributaries. The sediment-streamflow relationship observed for Spring Creek is largely defined within the major sediment source area near the watershed mouth.

Differences between spring and summer rating curves are minor and variations in mean monthly sediment yield are controlled by variations in monthly flow characteristics.

The impact of the construction of a pipeline right-of-way across Spring Creek was evaluated. This disturbance of .004% of the watershed area produced a 36% increase in sediment yield.

Recommendations for further research and some guidelines for land managers are presented.

ACKNOWLEDGEMENTS

This study would not have been possible without the support of numerous individuals and organizations. Alberta Environment Research Secretariat gave financial support and Alberta Environment Technical Services Division provided field transportation and accommodation. Sediment sampling equipment was kindly lent by the Department of Geography, University of Alberta. Water Survey of Canada provided analysts' reports for the sediment data gathered prior to 1977. The author is indebted to Mr. George Holecek, Head, Special Studies Section, Hydrology Branch, Alberta Environment who helped secure financial and logistic support for the study and made valuable data available to the author. Special thanks are due to Dr. Ian Campbell of the Department of Geography, University of Alberta, who acted as the author's thesis supervisor over the course of this study. His guidance, continuing interest and support were much appreciated. The author would also like to thank Mr. Gerry Coles, Mr. Neil Asmus, and Mr. Joe Ragan of the Technical Services Division, Alberta Environment for their assistance.

The assistance of Mr. Geoff Lester, Mrs. Stephanie Kucharyshyn, and Mr. Jack Chesterman of the Cartography Division, Department of Geography in preparing the maps and diagrams for this thesis was much appreciated. My wife, Diane, gave her valuable assistance and continued support through all phases of this study.

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1. INTRODUCTION

1.1 Reasons for the Study

Sediment yield is the net sediment outflow of a watershed. Sediment sources are spatially variable and the rate of sediment outflow varies over time. Complex interrelationships exist between sediment discharge and environmental factors and cause extreme regional and intraregional variations in the magnitude and nature of sediment yield. The complexity of sediment systems make it difficult to accurately predict either their net output or their response to environmental changes.

The production, transportation, and deposition of sediment affects and is affected by human activity. Erosion leads to the degradation and loss of productive soil and the formation of rills and gullies. The concentration of sediment in rivers and streams affects their water quality and the cost of processing the water to make it acceptable for an intended use. Sediment deposition influences river regime, accentuates local flooding and channel migration, and sediment deposition rates in reservoirs largely determine their effective life.

In most cases, the impact of human activity on the sediment regime of an area is negative and causes or accentuates sediment problems. In other cases, however, man aims to remedy such problems or to prevent their development. While the cost of sediment problems is difficult to assess, it is certainly significant. In order to minimize this cost, management techniques must be refined and this requires an improved understanding of sediment dynamics. Since no universal models are available, managers require information on the specific regional character of sediment systems.

Despite this need, there is a paucity of data available on the sediment yield of Alberta watersheds. This lack is most pronounced in the northern parts of the province and is due primarily to the high costs of establishing and operating sediment gauging stations. For example, the Peace River drains 175,000 km^2 in Alberta, about 25% of the total land area of the province, yet sediment data are gathered regularly at only four sites within this area (Water Survey of Canada, 1976). One station gauges the sediment discharge of the upper two-thirds of the watershed and another is situated at the watershed mouth. The measurements made provide valuable information on the sediment yield of the Peace River watershed, but they do not indicate the spatial variation of sediment production within it. Rather, they record the net sediment output of vast areas which include a wide variety of environmental conditions and land uses.

The other two sites monitor the sediment yield of small, relatively homogeneous, tributary watersheds. One is in the Rocky Mountain Foothills and the other is on the southern margin of the Peace River Region. The latter site, Spring Creek Watershed, is of particular interest since it is typical of many areas in northwestern Alberta being made available for settlement and agricultural development. In the past, development of such areas has caused erosion problems (Alberta Environment Conservation Authority, 1976).

1.2 Objectives

This thesis is a study of the sediment yield of Spring Creek Watershed. Its principal objectives are to examine and explain the sediment dynamics of this wilderness watershed. The research complements hydrologic investigations by Alberta Environment, the ultimate purpose of which is to evaluate the impact of future agricultural development within the watershed.

1.3 Scope

The thesis summarizes the environmental character of the watershed and reviews the data-gathering methods which have been employed. It then discusses the temporal aspects of the sediment regime. Annual and seasonal variations in sediment yield and sediment discharge are examined. An analysis of the spatial variation in sediment production follows, and the sources of the suspended sediment discharged from the watershed are identified. The relationship between sediment and water discharge is then investigated using sediment rating curves.

Immediately prior to the start of this study, a pipeline was constructed across Spring Creek near the mouth of the watershed. Erosion of the pipeline right-of-way was monitored over the summer of 1977 and its initial impact on the sediment yield of the watershed is reported here.

The thesis concludes with a review of the study findings, recommendations for further research, and some guidelines for land managers.

Suspended sediment is the primary concern of this study, and for the sake of brevity, it is referred to simply as sediment. Dissolved sediment is termed solute.

1.4 Previous Studies

A wide range of natural environments are found in Alberta; from the semi-arid plains in the south to the permafrost areas of the northern uplands, from the Rocky Mountains in the south-west through the foothills and prairies to the Canadian Shield in the north-east. Superimposed on this natural diversity is a wide variety of land uses. World and continental scale studies of sediment yield patterns suggest that this environmental diversity should be reflected in a diversity of sediment yields over the province.

The classic study by Langbien and Schumm (1958) relating sediment yield to mean annual precipitation found that maximum sediment yields occur in semi-arid regions and that sediment yield decreases as the climate becomes more humid. More recent studies (Douglas, 1967; Fleming, 1969; Wilson, 1973) are in general agreement with these findings although they suggest that the "Langbien-Schumm curve" may only be valid for continental climates.

Gregory and Walling (1973) reviewed previous studies to compare erosion rates for mountainous and lowland areas at the world scale. They found that erosion rates reported from mountainous areas are generally an order of magnitude greater than those of lowland areas.

The effects of land use can substantially alter sediment yield patterns (Strakhov, 1967; Wolman, 1967; Slaymaker and McPherson, 1973). Although human activity generally increases sediment yields, its impact in specific cases in highly variable (Gregory and Walling, 1973).

Scale of investigation strongly influences the results of sediment yield studies. The sediment yield per unit area of small watersheds is generally greater than that of large watersheds (Hadley and Schumm, 1961; Gottschalk, 1964) although some exceptions have been reported (Carson et al., 1973). Scale affects not only the magnitude, but also the temporal pattern of sediment yield. Ketcheson et al. (1973) found that sediment transport in small Ontario watersheds occurs primarily in the spring while movement from upland plots takes place largely in the summer. The relative importance of the various factors controlling sediment yield changes as the scale of investigation changes (Gregory and Walling, 1973). For example, while climate may be a controlling variable at the world scale, it becomes a constant at local or micro scale.

Stichling (1973) has mapped sediment yield per unit area and river sediment load patterns for Canada and has explained them in terms of geology, relief, climate and land use. The patterns observed and the explanations offered are in general agreement with findings of world scale studies.

Stichling (1973) shows little variation in sediment yield per unit area within Alberta. Almost all of the province falls into the yield category of 18-88 t/km^2/yr. However this study is based largely on data for large watersheds and as such the findings indicated only that sediment yield per unit area does not vary appreciably between the 4 or 5 major watersheds into which the province may be divided.

More variation was found in sediment yield per unit runoff than in sediment yield per unit area. This suggests that even though the quantity of sediment derived per unit area does not vary greatly among large Alberta watersheds, the pattern and character of sediment discharge may vary substantially.

Small watersheds for which Stichling (1973) was able to obtain data, appear as small anomalous areas yielding sediment at rates different from the regional norm. Again there is more diversity in sediment yield per unit runoff than in sediment yield per unit area. In contrast with the findings of previous studies, these small watersheds generally yield less sediment per unit area and per unit runoff than the larger watersheds of which they are a part.

Kellerhals et al. (1974) regressed mean daily sediment concentration on mean daily discharge for four large prairie rivers, the drainage areas of which are largely or entirely within southern Alberta. They found that the predictive ability of the regression equations could not be improved by employing a precipitation index as an additional independent variable. They conclude that this is due to the fact that no single precipitation index could reflect the short-term diversity in precipitation characteristics, runoff response and sediment production over the watersheds.

Luk (1975) made an extensive study of the erodibility of soils in the Bow River basin based on measurements from a number of erosion plots. He found that erosion rates decreased from the prairies to the mountains to the foothills. The low erodibility of the foothills soils is related to climatic factors; high rainfall produces a dense vegetation cover, high organic content in the soils, and the development of water stable aggregates in the soils. Aggregate development is inhibited in mountain soils by their sandy nature and in prairie soils by the more arid climate.

Bryan (1974) made a laboratory simulated rainfall test of the erodibility of a number of Alberta soils. He found that soil erodibility generally increased with the climatic aridity of the area from which the soil sample was taken.

McPherson (1975) estimated the mean annual sediment yield of 36 southern Alberta watersheds ranging in size from 75 km^2 to 1427 km^2. Mean annual sediment yields ranged from 223 t/km^2 to 5 t/km^2; a substantial variation about Stichling's (1973) regional norm. The highest, as well as some of the lowest sediment yields were found in the foothills. The sediment yields of the mountain watersheds were higher than those of the prairie watersheds, yet both were lower and less variable than the sediment yields of the foothills. So although foothills soils are the least erodible (Luk, 1975) the actual rate of sediment production may be highest in the foothills region.

Campbell (1977a, 1977b) has made a long-term study of the sediment yield and erosion rates of the Red Deer River watershed. The study has focussed on the badland areas of the lower watershed. Marked contrasts were found in sediment and runoff producing characteristics between the upper and lower watershed. The watershed upstream of Red Deer consists mainly of mountains and foothills and accounts for 70% of the area, 75% of the runoff but only 10% of the sediment yield of the total watershed. The lower watershed between Red Deer and Bindloss accounts for only 30% of the area and 25% of the runoff but over 90% of the sediment yield.

Erosion rates on the badland areas adjacent to the river channel in the lower watershed are 8,217 $t/km^2/yr$ and can more than account for the entire sediment yield measured at Bindloss. Large areas of the lower watershed cannot contribute either sediment or runoff to the Red Deer River. The sediment input between Bindloss and Red Deer (90% of the total sediment yield) may therefore be derived almost entirely from the badland areas (2% of the total area).

Stichling's (1973) regional study of Canadian sediment yield patterns is in general agreement with previous world and continental scale studies. It appears to indicate a homogeneity of sediment production within Alberta, yet the environmental diversity of the province suggests that there should be significant variability of sediment production within it. Upon closer examination, Stichling's (1973) study shows greater variability may exist than is at first apparent. The regional sediment yield norms are established largely on the basis of measurements from several major rivers. The few small watersheds for which data is available deviate from the regional norm and sediment yield per unit runoff is more variable than sediment yield per unit area among both large and small watersheds. Also, the sediment yield studies which have been done in southern Alberta show that substantial variations in sediment yield may exist among similar small watersheds and between physiographic regions within large watersheds.

It is expected that similar diversity exists in northern Alberta. Unfortunately there are no watershed sediment yield studies available from this part of the province. The sediment studies made in this area have been specifically problem-oriented and as such offer little information on regional sediment production and yield patterns. Wyldman and Poliquin (1973) measured soil loss from highly disturbed sites in the Swan Hills and found it to be correlated with precipitation amounts. Outhet (1976) found that the channelization of the East and West Prairie Rivers has not significantly increased sedimentation rates in the western end of Lesser Slave Lake.

This study aims to contribute to the understanding of sediment yield and production patterns within Alberta. It examines in detail the magnitude and nature of the sediment yield of a typical small watershed in the upper Peace River watershed, an area for which little information is presently available. MacIver (1966) made an inventory of the land and water resources of the study area in order to evaluate its land use potential. This study has been a valuable source of background information.

2. WATERSHED ENVIRONMENT

2.1 Location and Physiographic Setting

Spring Creek is a right bank tributary of Simonette River located 35 km southwest of Valleyview, Alberta (see Fig. 1). It drains a watershed area of 112.7 km^2 on the southern margin of the Peace River region. This is an extensive plain which is mantled largely by glacio-lacustrine deposits and supports parkland and Boreal mixed wood ecosystems (Atlas of Alberta, 1969). The plain is dissected by the deeply incised valleys of the Peace River and its major tributaries. The study area lies within the Wapiti Plain sub-division of the Alberta High Plains physiographic region (Atlas of Alberta, 1969).

2.2 Climate

The Peace River Region has a subhumid microthermal climate (Longley, 1967; Atlas of Alberta, 1969); Dfc in the Köppen system. Summers are short and cool with less than 4 months per year having mean temperatures over 10°C. Mean January temperatures can fall to -30°C while mean July temperatures can exceed 15°C (MacIver, 1966). Regional mean annual precipitation ranges approximately between 400 and 500 mm.

MacIver (1966) assessed the climate of the southern Peace River region and the following is largely a summary of his work. Other sources are referenced where appropriate.

Weather patterns largely reflect the interaction of Polar Maritime air from the Pacific Ocean and Polar Continental air from the northern interior of North America. Regional temperatures are most

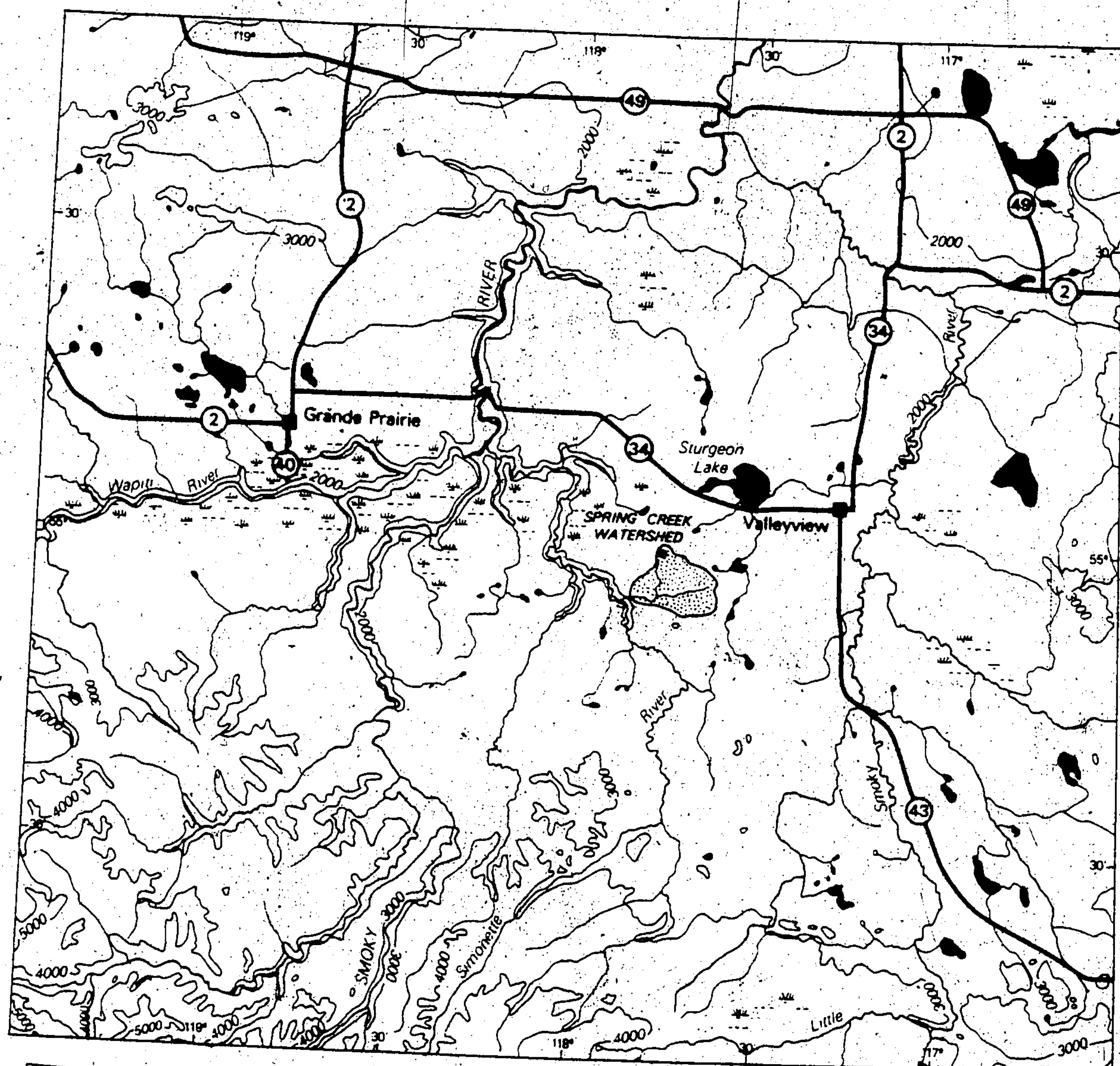


Figure 1

LOCATION MAP — SPRING CREEK WATERSHED

variable in the winter when the temperature difference between these two air masses is the largest. In contrast, precipitation is most variable in the summer when the humidity difference is largest.

In the winter, the continental high pressure system covers the region causing most storms to pass to the south. Snowfall, which accounts for about 30% of the mean annual precipitation, occurs when Polar Maritime air is forced aloft along a warm front.

This frontal activity increases in the summer as the continental high moves north. Convective storms develop in the summer as a result of surface heating. Rare incursions of Maritime Tropical air can bring extremely high precipitation. The net result of these activities is a marked precipitation maximum during the summer. About 60% of the mean annual precipitation falls during this season.

Rainfall intensity within the region is relatively low. Toogood (1963) presents rainfall intensity data for a station at Beaverlodge, about 80 km west of the study area. Of 217 rain storms which were recorded over a 7 year period, none had maximum one hour rainfall intensities greater than 40 mm/hr and only 4% had intensities greater than 10 mm/hr. The most intense rainfall was associated with convective activity and usually occurred in July.

The study area is representative of the cooler and wetter areas of the Peace River Region (Leggat, 1979). Alberta Environment used the short meteorological records from Spring Creek Watershed in conjunction with longer records from other sites in the region to compute long term annual values of temperature and precipitation. These were calculated to be 1.4°C and 538 mm respectively (Holecek, 1970).

The orographic influence of the Swan Hills, located about 120 km to the west of the study area, may be partly responsible for the fact that local precipitation is higher than the regional norm. The pattern of precipitation distribution over the year (Fig. 2) is essentially the same as that of Peace River Region.

The cause of locally cooler temperatures is not certain, although two possible contributing factors have been identified. As a result of its distance from the Rocky Mountains, the study area may not benefit from modified Pacific air masses to the same extent as other parts of the Peace River Region (Leggat, 1979). The general forest cover on Spring Creek Watershed would tend to reduce daily maximum temperature near the ground (MacIver, 1966).

While no data are available on rainfall intensity in the study area it is probably little different than that experienced in Beaverlodge. Rainfall intensity concerns this study primarily with regard to its potential to cause rain splash erosion and generate overland flow. Because the watershed is heavily forested it is unlikely that either of these phenomena occur to a significant degree even under the most intense storms.

2.3 Geology, Soils, and Vegetation

The Land Systems Map (Fig. 3) of the watershed was prepared from the Land Systems Map of the Sturgeon Lake area (Boyacioglu, 1977) and additional information from MacIver (1966), air photo interpretation and field observation.

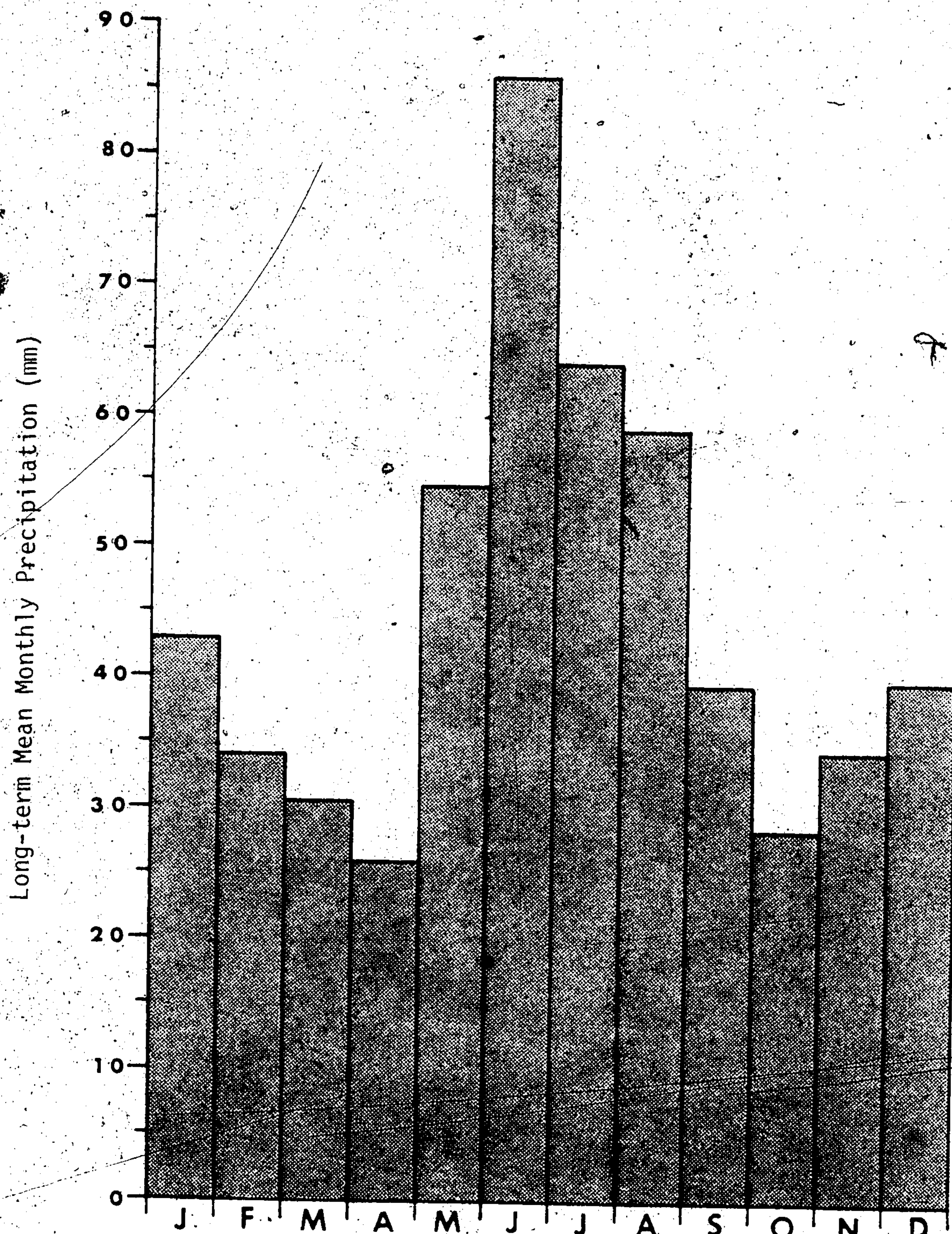
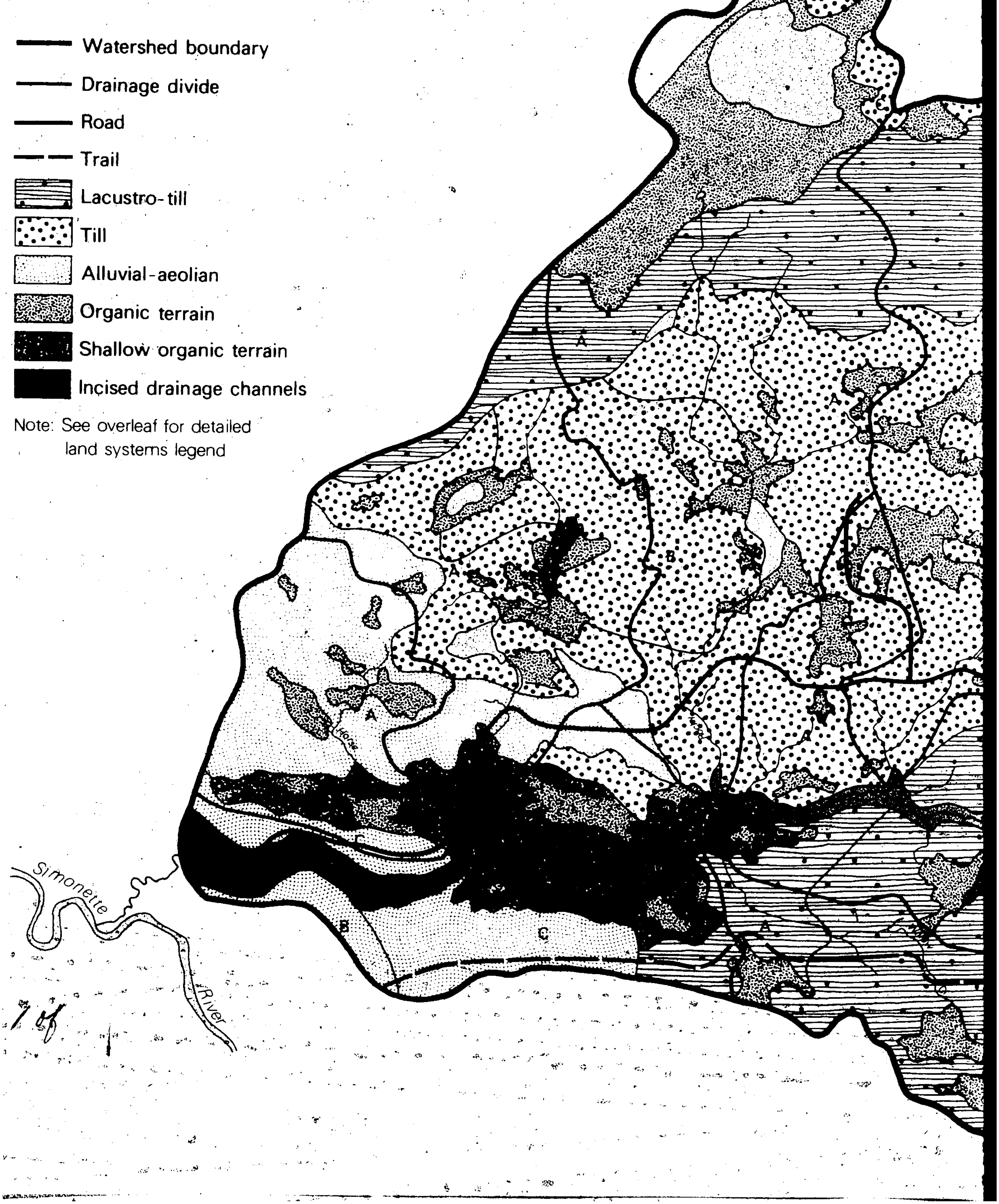


FIGURE 2: PRECIPITATION REGIME OF SPRING CREEK WATERSHED
(data from Holecek, 1970)

SPRING CREEK WATERSHED LAND SYSTEMS



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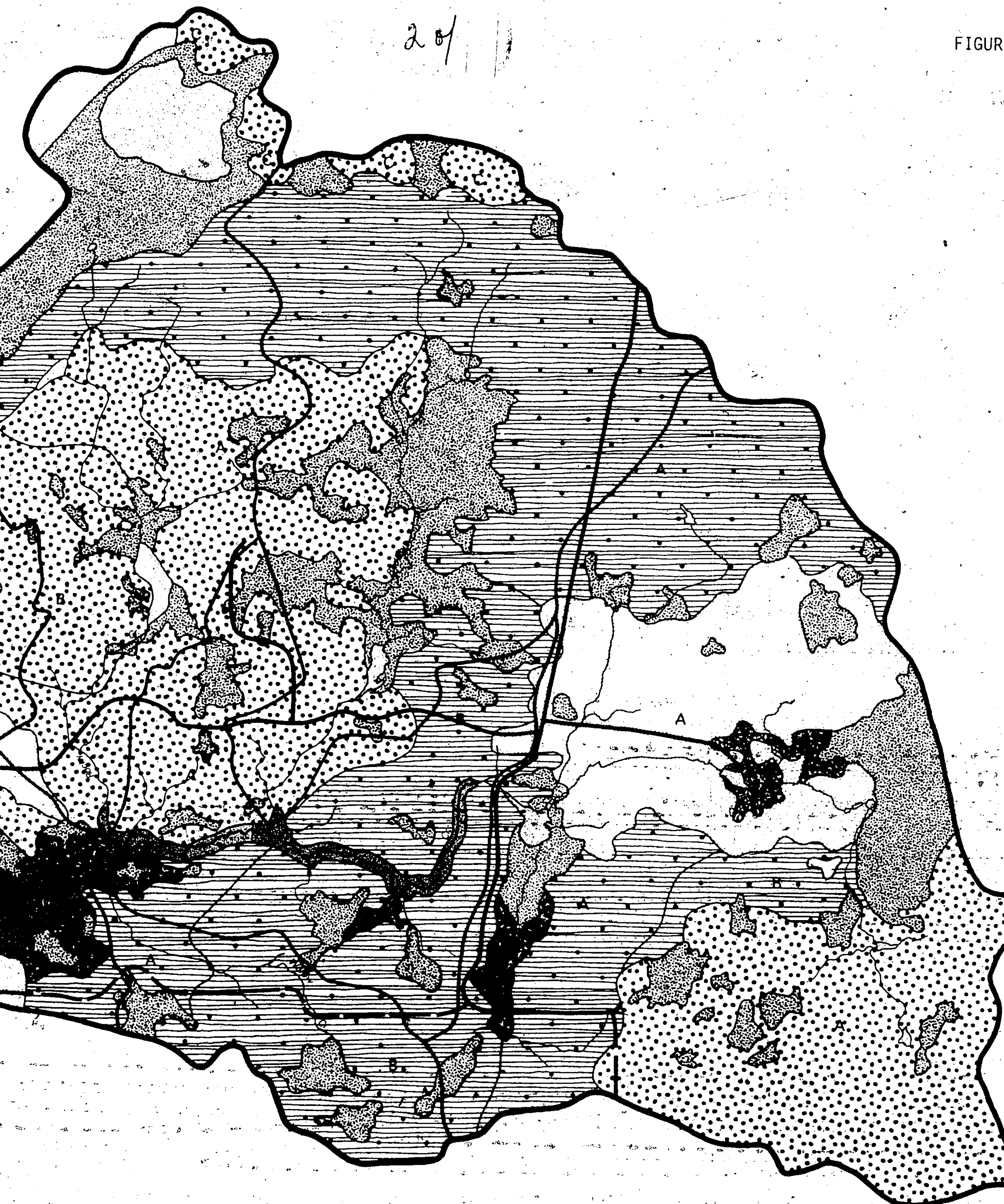
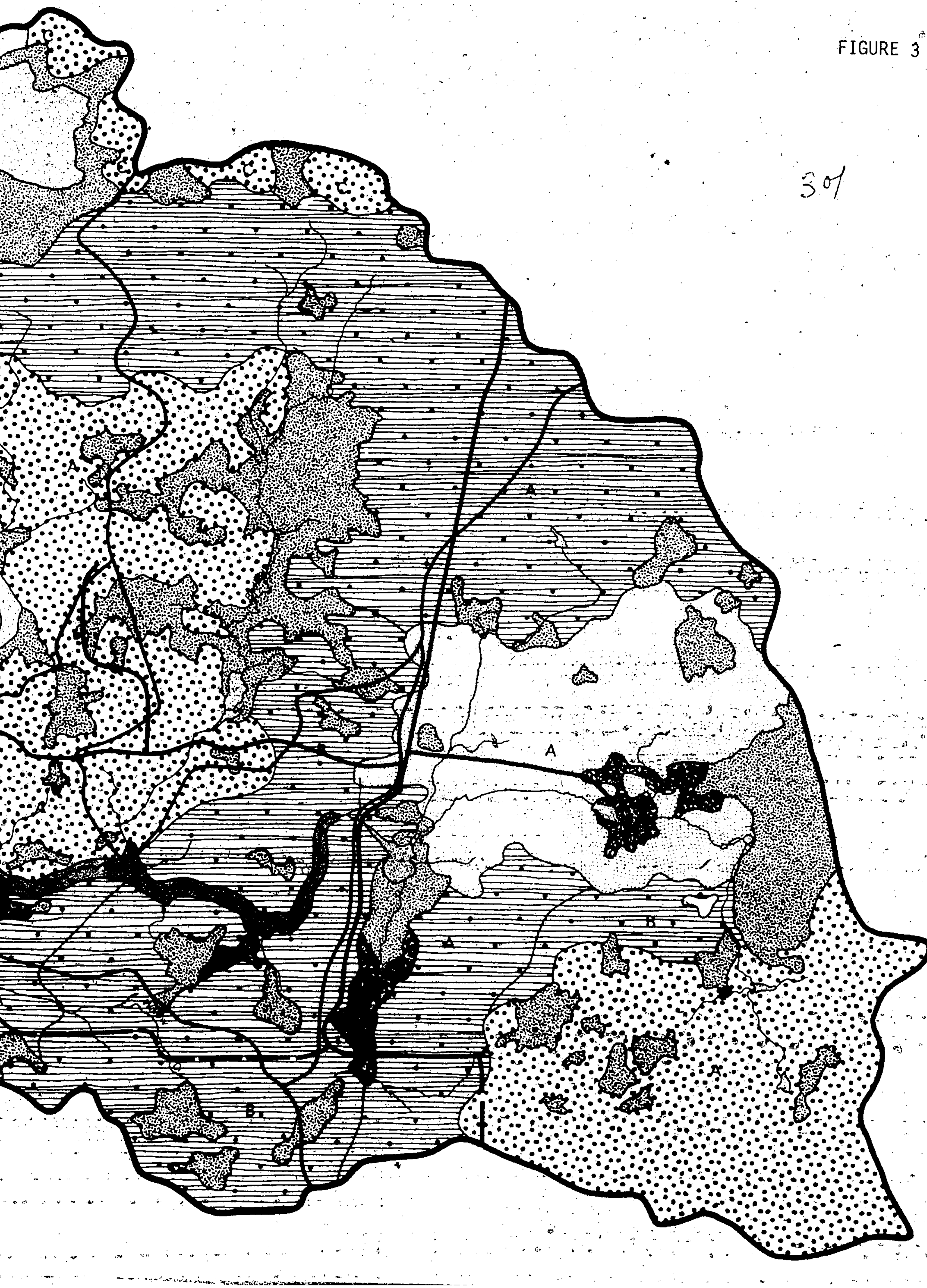


FIGURE 3



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LAND SYSTEMS – DETAILED LEGEND

Description	Drainage	Slope %	Vegetation
LACUSTRO-TILL: Fine textured stratified material containing some stones. Deposited mainly under lake-water conditions			
A Undulating to gently rolling clay loam to clay	Imperfect	2.0 - 9.0	Aspen, white spruce, native grasses
B As "A" above	Poor	2.0 - 9.0	Aspen, willow, white spruce, native grasses
TILL: Unstratified, heterogeneous glacial debris containing numerous stones			
A Gently rolling, loam to clay loam	Moderately well	2.0 - 9.0	Aspen, shrubs, native grasses
B Rolling, loam to clay loam	Well	9.0-15.0	Aspen, shrubs, white spruce, native grasses
C Gently rolling to rolling ablation till, loam to clay loam, up to 30% outwash materials	Moderately well	5.0-15.0	Aspen, shrubs, native grasses
ALLUVIAL-AEOLIAN: Stratified, water and wind sorted deposits associated with past and present watercourses			
A Undulating to gently rolling, loam to silty loam, shallow alluvial soils over fine textured material	Well	2.0 - 9.0	Aspen, shrubs, native grasses
B Gently rolling to rolling, slightly calcareous. Up to 30% organic soils	Rapid	5.0-15.0	Aspen, shrubs, native grasses, pine
C Gently rolling to rolling, sand to sandy loam	Rapid to well	5.0-15.0	Aspen, shrubs native grasses
SHALLOW ORGANIC TERRAIN: Meadow lands developed on poorly drained soils under the influence of a high or highly fluctuating water table			
A Depressional to level, sandy loam to silty loam	Imperfect to poor	0.0 - 0.5	Willow, shrubs, aspen, native grasses
B Depressional to level, loam to clay loam	Poor to very poor	0.0 - 0.5	Willow, shrubs, aspen, sedge peat, native gr.
ORGANIC TERRAIN: Marshes and muskegs consisting of coarse or fiberous peat with sphagnum mosses, sedges, tamarack and black spruce			
INCISED DRAINAGE CHANNELS: Valley sides, banks, floodplains, and channels of rivers and creeks			

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The watershed is underlain by horizontally bedded sandstone, siltstone, and shale of the Upper Wapiti formation (Holecek, 1967). Above this is till mantled by a variable thickness of stony glacio-lacustrine deposits. In the central and southeastern parts of the watershed, this mantle is very thin and patchy and thus these areas are classified as till. Much of the rest of the watershed, where the mantle is more nearly continuous, is designated lacustro-till.

Near the mouth and in the headwaters of the watershed are areas of alluvial-aeolian deposits. In part of the lower watershed, these are remnants of former floodplains of the Simonette River. Elsewhere, they are channel and floodplain deposits of glacial meltwater and more recent streams. All have been subject to some reworking by wind. Although only a limited portion of the watershed is given an alluvial-aeolian classification, thin and discontinuous patches of wind-blown sands and silts are also found elsewhere.

The "incised drainage channels" category includes two distinctly different geomorphic units. Downstream from the junction of Horse Creek and Spring Creek, it consists of the river channel and severely eroded valley sides. There is no well developed floodplain along this reach. Upstream from the junction, this category includes the river channel and its floodplain. The valley sides along this reach are relatively stable. The significance of this change in the characteristics of areas bordering the river channels is discussed later.

The dominant soil series in the watershed are Braeburn and Codesa (MacIver, 1966). Soils range from clay loam to sandy loam, reflecting variations in the parent material. The drainage characteristics of the soils are strongly influenced by topography as deep percolation of moisture is often inhibited by the occurrence of fine grained material at shallow depths.

Low lying areas are the site of marshes and muskegs which occupy about 25% of the watershed. In areas of moderately poor drainage and a high water table, meadows have developed. They support a growth of native grasses and willows and the occasional poplar bluff. The rest of the watershed has a forest cover dominated by aspen poplar. Its diversity in density and height is largely a reflection of past forest fires.

2.4 Hydrology

Six tributary watersheds have been defined within Spring Creek Watershed (see Fig. 4) and are referenced by the names of the creeks which drain them. Upper Spring Creek Watershed drains through the gauging station situated on the north-south trending road. Alberta Environment and Water Survey of Canada have measured the streamflow of Spring Creek and five of its tributaries from 1967 to the present.

Data for the 1970 to 1974 period (Table 1) are the basis of the hydrologic parameters listed in Table 2 and much of the following discussion of the spatial and temporal aspects of the watershed sediment yield. Complete records of the water and sediment discharge of Spring Creek and its gauged tributaries are available from March to October for each year of this period. The records are incomplete for at least one stream in all other years of the period of record

SPRING CREEK WATERSHED INSTRUMENTATION

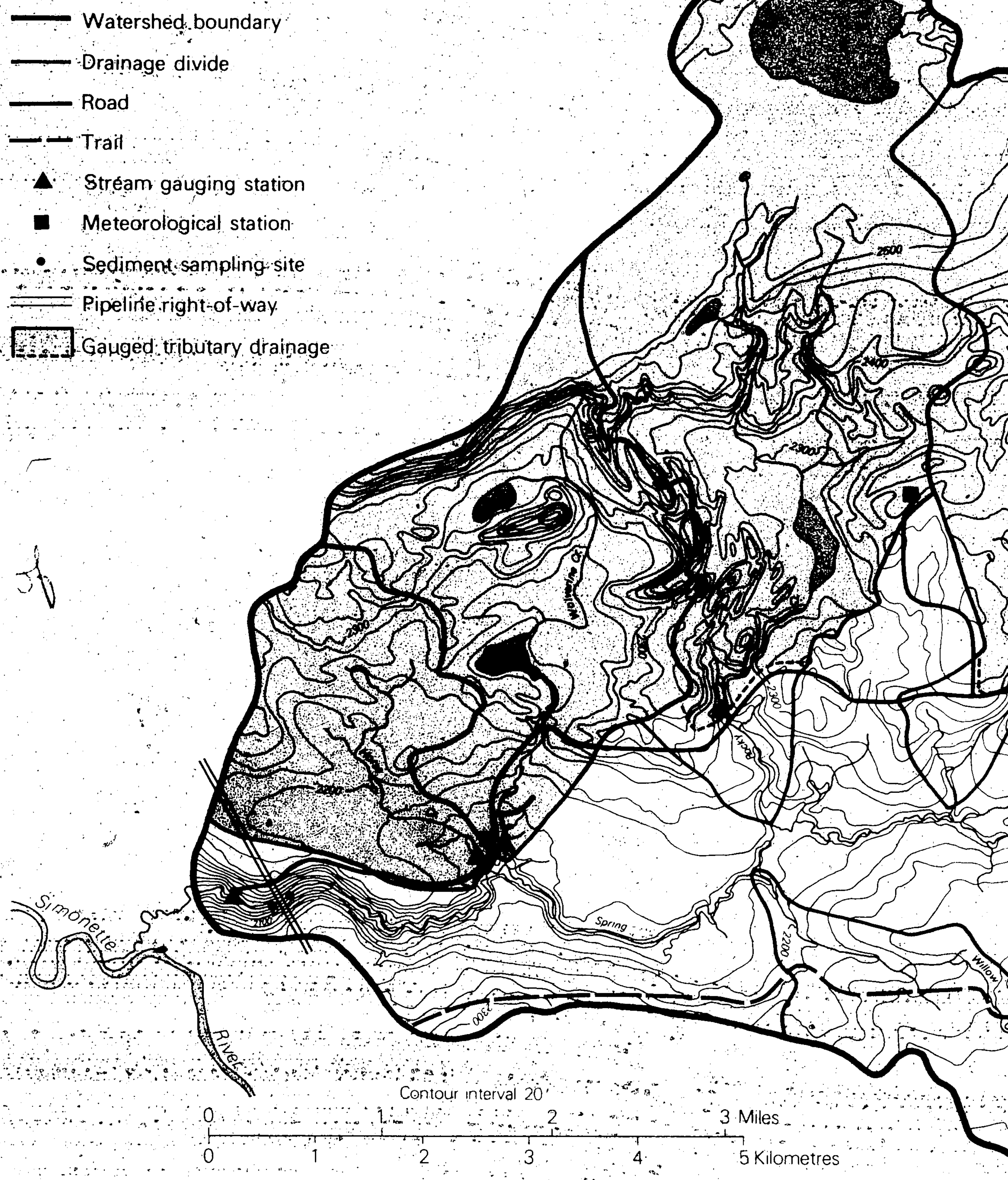

FIGURE 4

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TABLE 1: ANNUAL WATER AND SEDIMENT YIELD

YEAR	1970	1971	1972	1973	1974	MEAN
Precipitation (mm)	434	655	551	562	485	543
SPRING CREEK						
Water Yield ($m^3 \times 10^3$)	4798	9560	9510	8227	16,899	9799
Sediment Yield (t)	329	3201	2185	1460	10,244	3484
Sediment Conc. (mg/l)	69	335	230	177	606	356
HORSE CREEK						
Water Yield ($m^3 \times 10^3$)	342	464	488	485	941	544
Sediment Yield (t)	4.2	18.6	10.9	8.3	32.3	15.
Sediment Conc. (mg/l)	12	40	22	17	34	28
WOLVERINE CREEK						
Water Yield ($m^3 \times 10^3$)	460	633	807	847	1258	801
Sediment Yield (t)	105	131	160	109	252	151
Sediment Conc. (mg/l)	228	207	198	129	200	189
ROCKY CREEK						
Water Yield ($m^3 \times 10^3$)	703	1134	1214	1237	1752	1208
Sediment Yield (t)	12.7	20.9	27.2	24.5	44.5	26
Sediment Conc. (mg/l)	18	18	22	20	25	22
BRIDLEBIT CREEK						
Water Yield ($m^3 \times 10^3$)	1095	2023	2171	2069	3577	2187
Sediment Yield (t)	7.3	13.6	46.3	26.3	29.9	25
Sediment Conc. (mg/l)	7	7	21	13	8	11
UPPER SPRING CREEK						
Water Yield ($m^3 \times 10^3$)	1591	3232	3738	3036	5082	3336
Sediment Yield (t)	7.3	48.1	87.1	75.3	50.8	54
Sediment Conc. (mg/l)	5	15	23	25	10	16

TABLE 2: HYDROLOGIC INDICES

(calculated from 1970 - 1974 data)

WATERSHED	MEAN WATER YIELD (m^3/yr)	MEAN WATER YIELD ($m^3/km^2/yr$)	MEAN DISCHARGE (m^3/sec)	RUNOFF EFFICIENCY	RUNOFF DEPTH (mm)
Spring Creek	9799×10^3	87×10^3	0.31	0.16	87
Gauged Tributaries					
-Horse Creek	544×10^3	97×10^3	0.02	0.18	97
-Wolverine Creek	801×10^3	83×10^3	0.03	0.15	83
-Rocky Creek	1208×10^3	67×10^3	0.04	0.12	67
-Bridlebit Creek	2187×10^3	114×10^3	0.07	0.21	114
-Upper Spring Creek	3336×10^3	100×10^3	0.11	0.18	100
Total of Gauged Tributaries	8075×10^3	94×10^3		0.17	94
Ungauged Area	1724×10^3	64×10^3		0.12	64

TABLE 3: WATERSHED FORM AND NETWORK INDICES

WATERSHED	AREA (km^2)	DRAINAGE DENSITY (Km/km^2)	WATERSHED LENGTH (L) (km) *	WATERSHED WIDTH (W) (km) **	FORM RATIO (L/W)	RELIEF (m)	MEAN BIFURCATION RATIO
Spring Creek	112.7	2.0	15.2	10.6	1.4	180	4.0
Horse Creek	5.6	2.2	3.3	2.9	1.1	90	4.0
Wolverine Creek	9.7	2.8	5.8	3.5	1.7	130	3.9
Rocky Creek	18.7	1.9	8.7	4.2	2.1	130	3.8
Bridlebit Creek	20.3	2.3	7.4	5.3	1.4	100	3.9
Willow Creek	5.1	2.4	4.6	1.9	2.4	70	3.6
Upper Spring Creek	33.4	1.4	6.9	7.6	0.9	90	3.4

*Watershed Length: The longest straight line distance connecting the watershed outlet and the drainage divide

**Watershed Width: The longest straight line distance perpendicular to the watershed length axis connecting two points on the drainage divide (i.e. 1967 to 1977).

The 1970 to 1974 period also provides a reasonable analog of the long term watershed behavior. Over this time, the mean annual precipitation was 543 mm and the mean annual discharge rate was 0.31 cms. The calculated long-term mean values are 538 mm and 0.29 cms respectively (Holecek, 1970). Thus in terms of input and output volumes, the 1970 to 1974 period closely approximates the long-term mean. During this period 70% of the mean annual water yield was discharged in the spring months of March to May, and four years were dominated by spring runoff while one year was dominated by summer runoff. This is in agreement with the expected long-term behavior of the watershed.

The hydrographs (Fig. 5) show that in most years there are two major runoff peaks; one in the spring associated with snowmelt and one in early summer associated with the period of maximum precipitation.

The nature of spring runoff in any year is a function of the water equivalent of the snowpack at the beginning of snowmelt, temperature conditions, rainfall, and the saturation condition of the watershed. The long-term mean values for various water balance elements during spring runoff are given by Holecek (1979) as follows:

1. Water equivalent of the snowpack at the beginning of spring runoff =	119 mm
2. Rainfall during spring runoff =	27 mm
3. Evapotranspiration during spring runoff =	32 mm
4. Watershed storage increase =	63 mm
5. Spring runoff =	51 mm

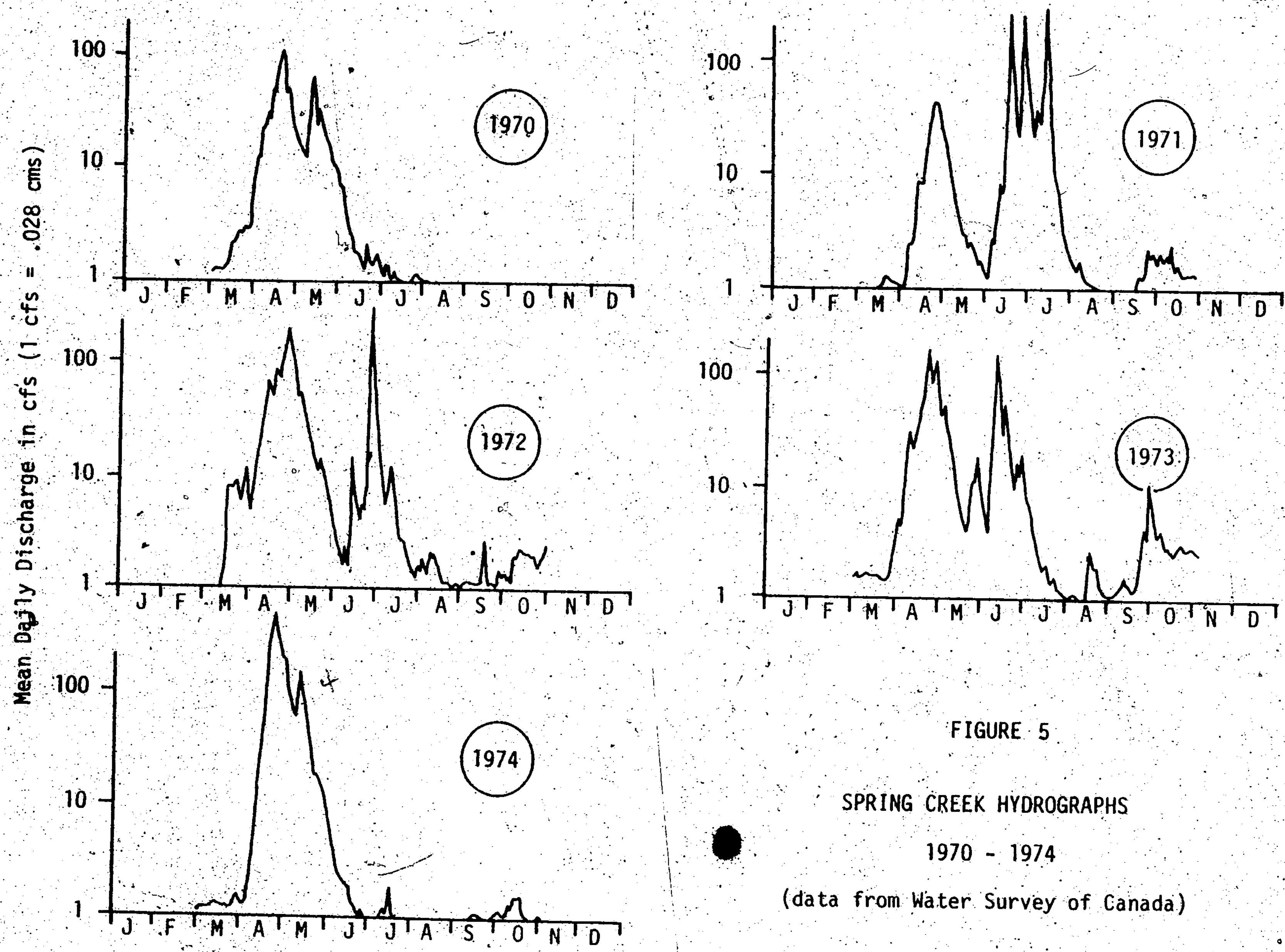


FIGURE 5

SPRING CREEK HYDROGRAPHS

1970 - 1974

(data from Water Survey of Canada)

The nature of spring runoff in any given year reflects the annual variation of these elements.

The mid-summer runoff peak primarily represents the interaction of the rainfall and the saturation condition of the watershed. The values of the water balance elements have not been isolated for this event but Holecek (1979) gives the long term mean annual values as follows.

1. Precipitation = 538 mm
2. Evapotranspiration = 315 mm
3. Storage increase = 141 mm
4. Runoff = 82 mm

In comparing these annual values to the spring values, it is apparent that runoff generation is much less efficient in summer than in spring. The runoff efficiency (i.e. ratio of precipitation to runoff) for the spring is 0.35 compared to 0.15 for the year as a whole. This is due primarily to increased evapotranspiration during the summer and soil moisture recharge which occurs in the fall.

During the 1970 to 1974 period, 87 mm of the mean annual precipitation was output by streamflow to give a runoff efficiency of 0.16 for the watershed as a whole. The runoff efficiency of the gauged tributaries range from 0.21 for Bridlebit Creek to 0.12 for Rocky Creek. Runoff efficiency is inversely related to the proportion of landlocked or enclosed drainage agea of the watersheds (Holecek, 1970).

2.5 Drainage Network

Drainage network indices are given in Table 3 along with watershed form indices. Drainage densities were computed by the "contour crenulation" method. The drainage network given on the topographic base map was first expanded as indicated by the contour configuration and then drainage densities were computed for the expanded network. Elsewhere, this method has produced results in close agreement with field surveys (Morisawa, 1957). However, this may not be the case for Spring Creek Watershed. Air photo interpretation reveals that a number of the synthetic drainage lines are interrupted by muskegs through which no distinct stream channel exists. Therefore the drainage density values should be treated as a measure of the relative watershed dissection by both past and presently active stream channels.

Spring Creek Watershed as a whole has a drainage density of 2 km/km^2. The values for its tributaries range from 2.8 km/km^2 in Wolverine Creek to 1.4 km/km^2 in Upper Spring Creek.

When the synthesized drainage network was ordered by the Strahler (1964) method, Spring Creek was designated a fifth order stream. The bifurcation ratios of the network are well within the range expected for watersheds in which geologic structure is not a dominant influence on drainage patterns.

Log jams and beaver dams which obstruct the stream channels are water and sediment storage sites. Several larger lakes have been created by beaver dams and are now permanent features of the landscape.

2.6 Watershed Morphology

Spring Creek Watershed is roughly semi-circular in shape with a length to width ratio of 1.4. Its outlet is 610 m above sea level and it has a relative relief of 180 m.

A hypsometric curve of the watershed (Fig. 6) was constructed by measuring the area enclosed between contours drawn at 6 m intervals. The hypsometric integral of 0.63 indicates that much of the relative relief of the watershed is concentrated in a small area near its mouth. Such a large hypsometric integral implies that the watershed is in a state of geomorphic disequilibrium (Strahler, 1952).

Figure 7 shows the channel profiles of Spring Creek and its tributaries. There is a distinct knickpoint on all the streams near the elevation of 690 m a.s.l. Another knickpoint is seen on the Spring Creek profile just downstream of its junction with Horse Creek. Since no geologic controls are acting directly on the profile configuration, it is inferred that these knickpoints mark episodes of channel incision in response to local base level lowering by the Simonette River. The present disequilibrium condition of the watershed can be attributed mainly to the incision of the lower reaches of Spring Creek channel.

The term "geomorphic disequilibrium", as it is used here, does not imply a total lack of mutual adjustment among the various elements of watershed hydrology, sediment yield, and morphology. Rather it refers to the fact that at the scale of geologic time, the watershed is presently undergoing a rapid readjustment to a change in boundary conditions.

2.7 Land Use

Environmental disturbances have been limited and the watershed

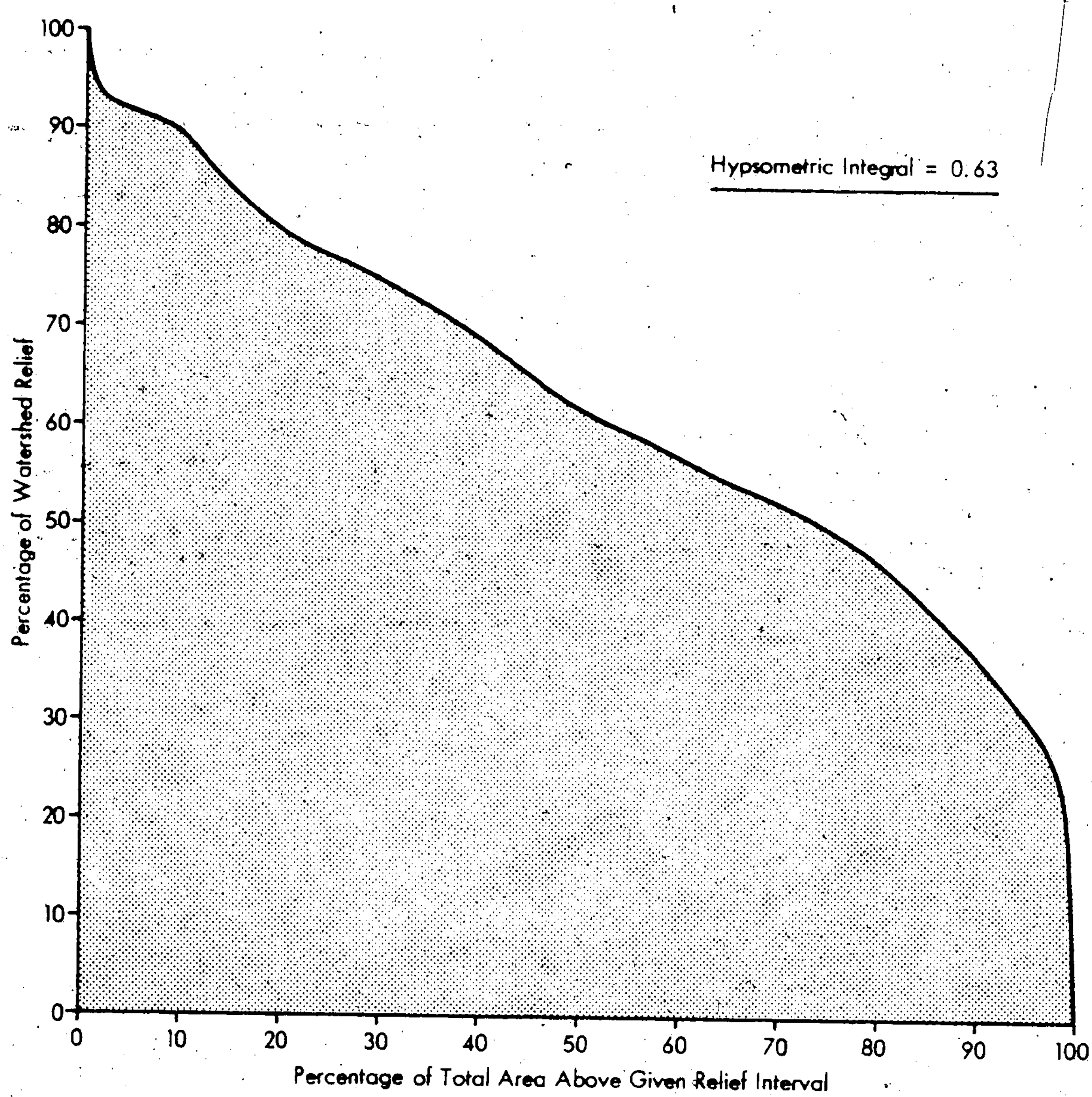
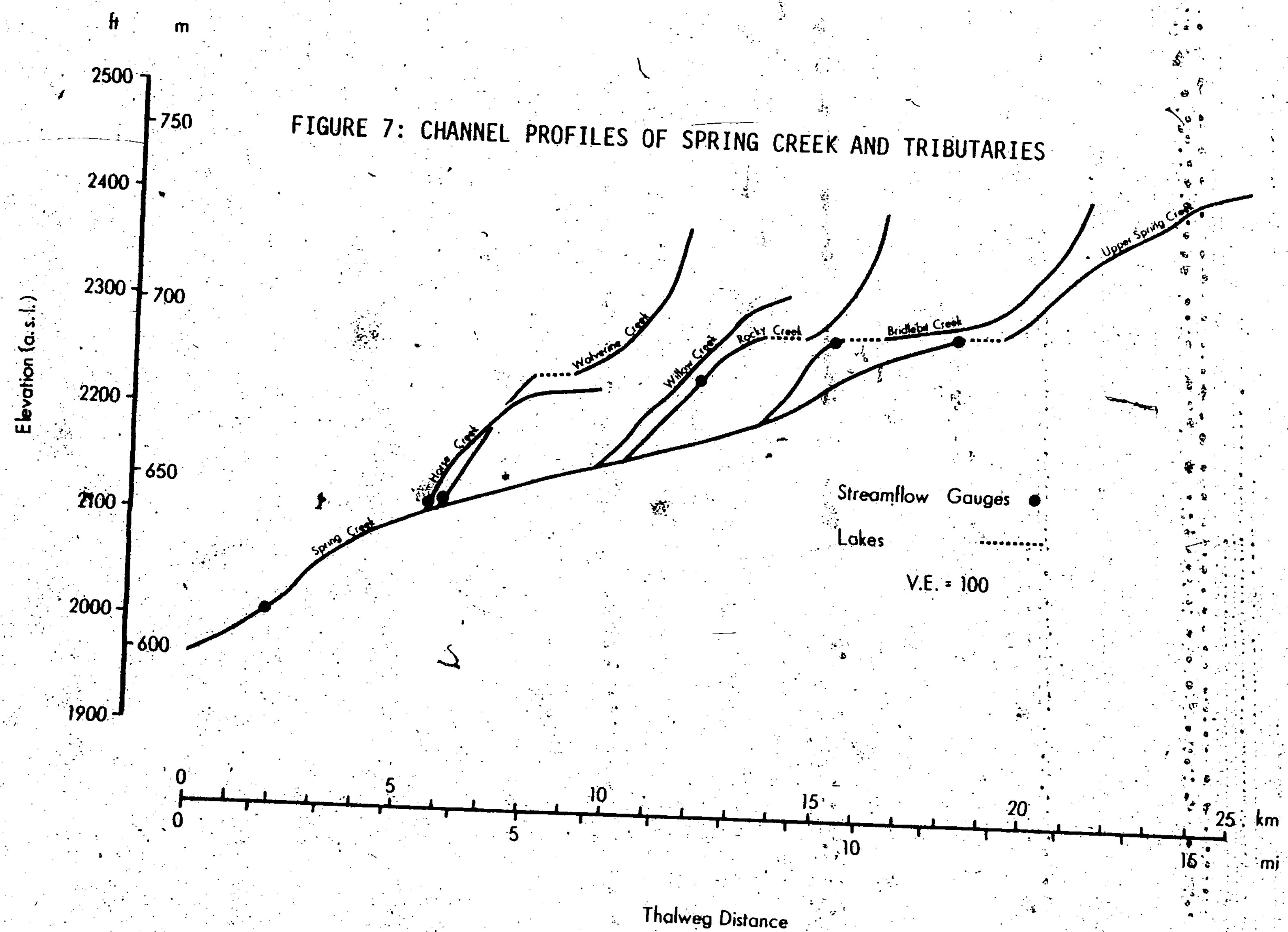


FIGURE 6: HYPSOMETRIC CURVE OF SPRING CREEK WATERSHED

FIGURE 7: CHANNEL PROFILES OF SPRING CREEK AND TRIBUTARIES



is essentially in a wilderness state. The forest cover is now well recovered from major fires which occurred prior to 1950. Livestock grazing in the meadow lands adjacent to Horse and Wolverine Creeks was discontinued in 1966 when the watershed was selected as a research area. At this time, Alberta Environment constructed the main access road through the watershed. Previously existing roads established by timber and oil interests were not maintained and are now more appropriately designated as trails. While there is no record of logging within the watershed, oil exploration involved clearing of siesmic lines and well sites. These areas are fully revegetated although they can still be recognized by the relative youthfulness of their forest cover. Several cleared right-of-ways, presumably established for survey purposes, cross the watershed. They support a lush vegetation cover. In the winter of 1977, a pipeline was constructed through the watershed and crosses Spring Creek near its mouth. The pipeline right-of-way is not revegetated.

3. SAMPLING AND MEASUREMENT TECHNIQUES

3.1 Streamflow Measurement

Alberta Environment measured streamflow at the Spring Creek Watershed mouth and on five tributary streams from 1967 to the present. River stage was recorded over most of the open water period and then converted to streamflow rates by the use of stage-discharge relationships. It should be noted that streamflow measurements were taken at the mouth of Horse and Wolverine Creeks but on Rocky and Bridlebit Creeks, the gauging stations were situated some distance upstream of the junction with Spring Creek (see Fig. 4).

3.2 Sampling Sites

Alberta Environment took aperiodic sediment and solute samples immediately downstream of each streamflow gauging station. On Bridlebit, Rocky, and Upper Spring Creek, samples were obtained downstream of "V" notch weirs. These structures act as sediment traps and therefore, samples taken downstream of them would not usually provide a reliable measure of sediment output from the watershed area upstream. However, this is not true in the study watersheds.

The weirs are located in streams which support a succession of beaver dams. Often, one beaver dammed pond merges into the next with no connecting channel and tangled masses of brush and logs choke the channels in those few places where beaver dams do not. In every case, a large lake is located a short distance upstream of the weirs. Therefore, the weirs can be considered as artificial features which affect the water and sediment flow very much as the natural features of the channel do. In fact, two of the weirs have been adopted by beavers which make their presence known by a continuing effort to dam the weir notch. On Horse, Wolverine and Spring Creek, the structural controls do not dam streamflow and thus have no sediment trapping effect.

The main access road crosses all of the tributary streams near the streamflow gauging and sampling sites. At the Spring Creek station, the cumulative input of sediment from the main road is measured. On all of the tributaries except Wolverine and Rocky Creek, samples are taken immediately downstream of the points where the main road crosses the streams. On Rocky Creek the samples are taken upstream of the road crossing and on Wolverine Creek, they are taken approximately 1.5 km downstream of the road crossing.

3.3 Sampling Procedure

In general, samples were taken on a daily basis during peak flow events and otherwise taken once every week or two. This provided an average of 23 samples per year for Spring Creek over the period 1967 to 1976. A slightly lower frequency of samples is available for the tributary streams.

Samples were usually taken in a single vertical at the centre of the stream using a DH-48 depth-integrating sampler. At very low flows sample bottles were simply dipped in the streams, and at very high flows, a DH-59 cableway sample was used to sample Spring Creek.

3.4 Sample Analysis

The samples were analyzed by the procedure given by Guy (1969), which involved determination of the sample volume and subsequent filtration to extract the suspended sediments. The sediment was then oven-dried and its weight measured. The sediment concentration was computed and expressed in mg/l. In addition, an aliquot of the filtrate was evaporated. The weight of the residue per aliquot volume gave the solute concentration. This was also expressed in mg/l.

3.5 Sediment Discharge Computations

Water Survey of Canada (1976) used the sediment concentration data in conjunction with the streamflow records to compute sediment discharge. No such operation was done with the solute data. Sediment discharge computations essentially followed the method given by Porterfield (1973). A mean daily sediment concentration value for sample days was determined by consideration of the measured sediment concentration and the hydrograph shape for that day. Mean daily concentration values for the intervening period were then derived by interpolation and adjusted for streamflow characteristics.

3.6 1977 Sediment Measurements

During summer of 1977, a more detailed sampling program was conducted by this researcher. Samples were taken on a once or more daily basis during high flows and less frequently during low flows. A total of 750 samples were obtained for an average of 27 samples per station per month. The previously established sampling sites were used on all of the tributary streams. The construction of a pipeline corridor across Spring Creek near its mouth necessitated a re-establishment of the main sampling site. Samples were taken immediately upstream and downstream of the pipeline right-of-way (see Fig. 5 for location).

Sampling and analysis procedures followed those previously established by Alberta Environment. Solute concentrations were, however, not determined.

4. TEMPORAL ASPECTS

4.1 Mean Annual Sediment Yield

Between 1970 and 1974, the annual sediment yield of Spring Creek Watershed ranged from 329 tonnes to 10,244 tonnes and averaged 3484 tonnes. The annual sediment concentration varied between 69 mg/l and 606 mg/l with a mean of 356 mg/l (see Table 1 for annual data).

Annual water yield and annual sediment concentration over this period are highly correlated (r = .98). A regression line fitted to this data predicts that for a year with a mean streamflow rate of 0.29 cms (i.e. the long term mean rate calculated for Spring Creek) the sediment concentration will be 254 mg/l. As there are few data in the analysis, a high standard error of prediction is associated with the regression. The product of the water yield and sediment concentration for the "mean" year gives the mean annual sediment yield to be 2326 t/yr ± 878 tonnes, or in areal terms, 21 $t/km^2/yr$ ± 8 tonnes.

An alternate estimate of the mean annual sediment yield was made by the sediment rating - flow duration curve method (Miller, 1951; Piest, 1964). A sediment rating curve relating instantaneous sediment concentration to instantaneous streamflow rates was developed (see Chapter 7). This was applied to a mean daily flow duration curve (Fig. 8 from Holecek, 1970) such that the sediment load for small increments of the duration curve were computed and then summed to obtain a mean annual sediment yield estimate of 1594 t/yr. While it is not possible to place realistic confidence limits on this

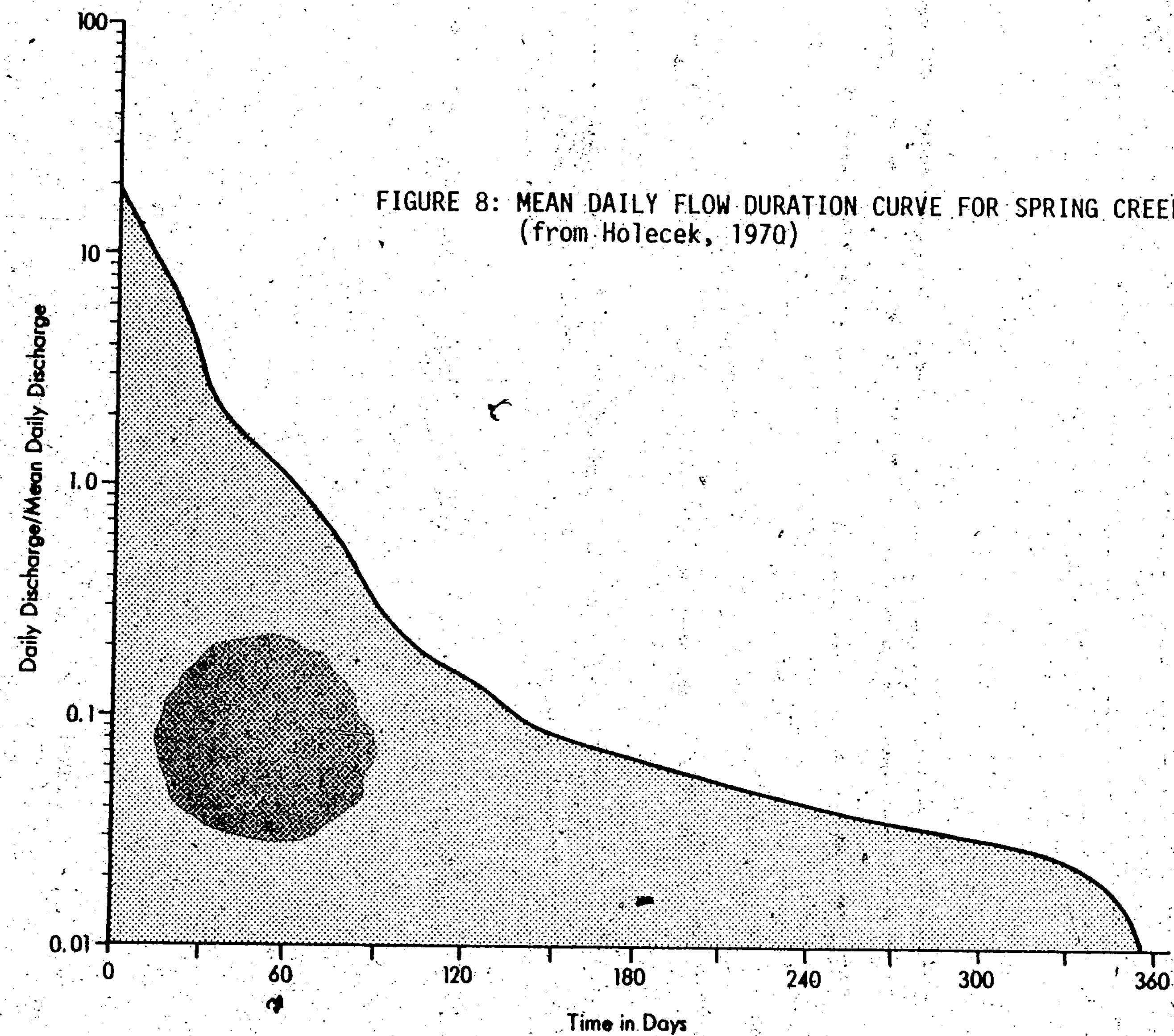


FIGURE 8: MEAN DAILY FLOW DURATION CURVE FOR SPRING CREEK WATERSHED
(from Holecek, 1970)

estimate, it has been shown (Walling, 1971, in Gregory and Walling, 1973) that in small watersheds, the use of an instantaneous rating curve with mean daily streamflow data will underestimate the sediment yield and that this underestimate may be as great at 50%.

This is likely due to the fact that mean daily streamflow values fail to account for the peak flows which produce the highest sediment concentrations. For Spring Creek, the sediment concentration values generated in the sediment rating - flow duration curve calculations range from 271 mg/l to 12 mg/l, yet the range which has been measured and is shown in the rating curve is 2306 mg/l to 4 mg/l. Accepting that this method has underestimated the mean annual sediment yield and that the underestimate may be as high as 50%, the true value should lie between 1594 t/yr and 3188 t/yr. These values are in agreement with those estimated previously.

Significant relationships do not exist between the annual water and sediment yields of the tributaries, and their sediment rating curves are either insignificant or have very poor predictive abilities. Therefore, estimation of their mean annual sediment yields by the methods applied to the Spring Creek data was impossible. The mean annual sediment yield of the tributaries over the 1970 to 1974 period is given in Table 4.

4.2 Mean Annual Solute Yield

The sediment rating - flow duration curve method is better suited to the calculation of solute yield than sediment yield, at least in this instance. Rating curves (see Chapter 7) show that solute

TABLE 4 - SEDIMENT YIELD (Calculated from 1970-1974 data)

Watershed Name	Mean Annual Sediment Yield (t/yr)	Mean Annual Sediment Yield ($t/km^2/yr$)	Mean Sediment Concentration (mg/l)	Mean Sediment Load (t/day)
Spring Creek	3484	31.0	356	9.50
Gauged Tributaries				
Horse Creek	15	2.7	28	0.04
Wolverine Creek	151	16.0	189	0.41
Rocky Creek	26	1.4	22	0.07
Bridlebit Creek	25	1.3	11	0.07
Upper Spring Creek	54	1.6	16	0.15
Total of Gauged Tributaries	271	3.2		
Ungauged Tributary Area*	3213	119.0		

* Area gauged indirectly as the difference between the measured values for "Spring Creek" and "Total of Gauged Tributaries"

concentrations are negatively correlated with discharge and vary only slightly at higher flows. Therefore the volume of water yield is more important than its flow distribution in determining solute yield. The Spring Creek solute rating curve covers a range of concentrations from 333 mg/l to 110 mg/l while the solute rating - flow duration curve calculations employ a range of 322 mg/l to 138 mg/l. For the above reasons, the mean annual solute yield estimate of 1484 tonnes obtained by this method is considered reliable. This gives a mean solute concentration of 162 mg/l. Assuming a mean annual sediment yield of 2326 tonnes, the ratio of sediment yield to solute yield is 1.6:1.

4.3 Seasonal Patterns

Mean monthly water and sediment discharge of Spring Creek for the 1970 to 1974 period are given in Table 5. Figure 9 illustrates this data in the form of a sedi-hydrogram which is constructed by plotting mean monthly sediment yield per unit area against mean monthly water yield per unit area and then joining the points sequentially. Only the four months of April to July are plotted but these account for 99% of the mean annual sediment yield.

April provides 68% of the annual sediment yield but only 49% of the water yield. In contrast, May contributes only 8% of the sediment yield but 22% of the water yield. This can be explained by the difference in runoff characteristics between the two months. The rising limb and the peak of the spring runoff hydrograph usually occur during April. Therefore much of the runoff in this month is

TABLE 5 - MEAN MONTHLY SEDIMENT YIELD - SPRING CREEK (Calculated from 1970-1974 data)

Month	Mean Water Yield (m^3/km^2)	Mean Water Yield % of total	Mean Sediment Yield (t/km^2)	Mean Sediment Yield % of total	Mean Concentration (mg/l)
March	978	.9	.27	.9	276
April	51,376	49.0	21.0	68.0	408
May	23,366	22.0	2.4	8.0	103
June	19,528	19.0	4.8	15.0	246
July	8,557	8.0	2.5	8.0	289
August	204	.2	.002	0.0	10
September	316	.3	.004	0.0	13
October	827	.8	.007	0.0	8

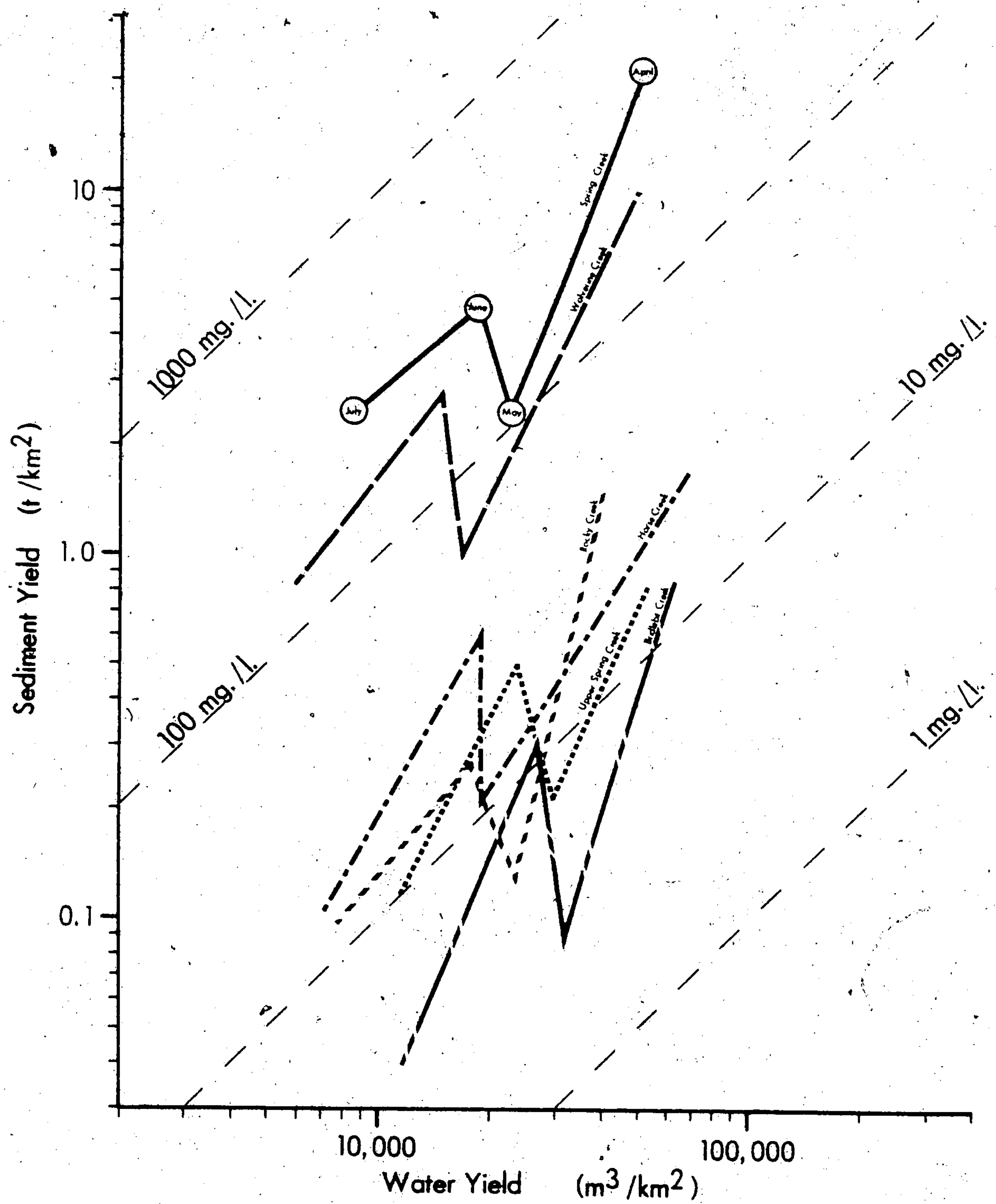


FIGURE 9: SEDI-HYDROGRAM OF SPRING CREEK WATERSHED

discharged under peak flow conditions which generate the highest sediment concentrations. Most of the May runoff can be considered part of the recession limb of the spring hydrograph and is characterized by sustained moderate flows with a large baseflow component. It produces a substantial volume of runoff but only generates intermediate sediment concentrations.

During June and July, runoff is usually less and is marked by a number of minor peaks. Both months show a balance between rising and falling flows. As a result, sediment discharge occurs in roughly the same proportion as water discharge.

The sedi-hydrogram shows that the monthly pattern of sediment and water discharge is the same for the tributaries as it is for Spring Creek. This is expected since they share a similar runoff pattern and experience their highest sediment concentrations during the peak flows of spring.

Spring runoff is even more important in sediment production than in runoff production. April and May (1970-1974) account for 71% of the mean annual water yield and 76% of the mean annual sediment yield.

4.4 Time Distribution

Most of the sediment discharge of the watershed occurs in a very short period of time each year (see Table 6). Between 1970 and 1974, the sediment discharge of an average of four days per year (i.e. 1% of the time) accounted for 50% of the annual sediment discharge. As well, 90% of the annual sediment yield could be accounted for by the sediment discharge of an average of 18 days per year (i.e. 5% of the time).

TABLE 6 - TIME DISTRIBUTION OF SEDIMENT DISCHARGE - SPRING CREEK

Year	(A) Minimum number of days required to account for 50% of the annual yield	(B) Minimum number of consecutive days required to account for 50% of the annual yield	Time of B	Minimum number of days required to account for 90% of the annual yield
1970	4	4	April 20-23	24
1971	3	13	June 15-26	11
1972	4	5	April 26-30	17
1973	6	8	April 23-30	28
1974	4	4	April 23-26	12
Mean	4	7		18

In contrast, the solute discharge is much more evenly distributed over time. The solute rating - flow duration curve calculations show that over 75 days per year (i.e. 25% of the time) are required to account for 90% of the solute yield.

5. SPATIAL ASPECTS

5.1 Spatial Variation in Sediment Yield

An attempt was made to explain the variation in sediment yield among the tributary watersheds on the basis of several physical factors. Sediment yield per unit area was related to runoff efficiency, drainage density, watershed relief, and watershed area. No significant correlations were found. An examination of the Land Systems Map (Fig. 3) indicates that neither surficial geology or forest cover can explain the variation in sediment yield among the tributary watersheds.

It was previously noted that Spring Creek Watershed is in a state of geomorphic disequilibrium. The knickpoint on Spring Creek near its mouth marks the most recent response of the watershed to a reduction in its base level. The stream channel downstream of this knickpoint is steep (9 m/km) and is incised in a deep, narrow valley which lacks a floodplain. The valley sides are steep, convex, and despite forest cover, are subject to massive and extensive slumping. Upstream from the knickpoint, Spring Creek has a gentler slope (3.5 m/km), a broader valley, and meanders largely within its own floodplain.

The knickpoints on the tributaries mark the watershed response to an older drop in its base level. A distinct difference similar to that on Spring Creek is apparent between the stream valley characteristics upstream and downstream of these knickpoints. However the valleys downstream of the knickpoints on the tributaries appear to be less unstable than the comparable reach of Spring Creek. They are not as deep and narrow, and slumping does not occur on the same massive scale.

The knickpoints on Spring Creek and its tributaries subdivide the watershed into zones of varying stability or intensity of geomorphic activity. It is in the context of this zonation that the variation in sediment productivity within the watershed can be explained.

5.2 Bridlebit Creek and Upper Spring Creek

Bridlebit Creek and Upper Spring Creek are gauged upstream of their respective knickpoints. Both watersheds produce similarly low amounts of suspended sediment; Bridlebit Creek yields 1.3 $t/km^2/yr$ and Upper Spring Creek yields 1.6 $t/km^2/yr$. It is probable that not all of their sediment output is the product of erosion.

Organic material was observed to be carried in suspension in the streamflow. Some of this material is the organic component of soils which have been eroded, but most is likely the product of biologic activity within the lakes and streams. The warm, shallow, nutrient-rich lakes support algal and other aquatic growth in the summer months and some of this material is carried in suspension in the lake outflow.

As sample analysis involved drying the filtered suspended solids at a temperature insufficient to ignite the organic material (i.e. 110°C), this material was measured as sediment. Therefore, the sediment yields of these watersheds, low as they are, do not represent the products of erosion only, but rather the cumulative effects of erosion and biologic activity.

For these watersheds, there is a tendency for sediment concentrations to be negatively correlated with discharge (see Chapter 7). This pattern is most marked in Upper Spring Creek during the summer. Biologic sediment production probably occurs at a relatively constant rate in the lakes during the summer and as discharge increases sediment concentration is reduced by a dilution effect.

The fact that the sediment output of these watersheds is very low does not necessarily imply that erosion rates everywhere within them are low. There may be small areas of intense erosion in their more rugged headwater regions. However, the products of this erosion never reach the watershed outlet, at least not in terms of the time scale with which human activity is concerned. The muskegs and beaver dammed ponds along the stream channels act as filters of variable efficiency which allow the throughflow of water but block the passage of most sediment.

Sediment measurements on Bridlebit and Upper Spring Creeks are made downstream of road crossings. There is very little relief in the vicinity of the Upper Spring Creek gauging station and it is unlikely that substantial amounts of surface runoff or sediment are derived from the road. Yet the sediment concentration at this site is nearly the same as that measured on Bridlebit Creek where relief in the vicinity of the gauging station is much greater. This implies that the stable and well-designed road crossings on these creeks contribute relatively little sediment to the streams.

5.3 Horse, Wolverine, and Rocky Creeks

Horse, Wolverine, and Rocky Creeks are gauged downstream of their respective knickpoints. The watershed areas upstream of the knickpoints on Horse, Wolverine and Rocky Creeks have environmental characteristics similar to those of the gauged areas of Bridlebit and Upper Spring Creeks. Most especially, they have in common the presence of "filters" in their streams which inhibit sediment movement. Therefore it is expected that all these areas will have similarly low sediment yields.

A number of samples were taken on Wolverine Creek during 1977 at the channel knickpoint (see Figure 4 for location). In every case, the sediment concentrations of the samples were comparable to those taken concurrently on Bridlebit and Upper Spring Creeks. It follows that the sediment yield of the watershed area upstream of the knickpoint on Wolverine Creek must be of the same order as that measured for Bridlebit and Upper Spring Creeks.

The sediment yield per unit area and the mean sediment concentration values measured at the mouths of Horse and Wolverine Creeks are much greater than those expected at their knickpoints. Therefore the sediment yield downstream of the knickpoints must be higher than that upstream of them.

Horse and Wolverine Creeks differ in their sediment dynamics. The mean sediment concentration and yield per unit area of Wolverine Creek is six times that of Horse Creek. The application of both the sediment rating curve and the sediment yield per unit area values for Horse Creek to Wolverine Creek predict a mean sediment yield of 25 t/yr in contrast with its measured sediment yield of 151 t/yr. Obviously the difference in sediment yield is not explained by the difference in water yield or watershed area. It then follows that Horse Creek is an anomalously low sediment producer, or that Wolverine Creek is anomalously high, or both.

It appears that Horse Creek more closely represents the norm. In Rocky Creek Watershed where sediment output is measured midway between the knickpoint and the watershed outlet, the mean sediment concentration is 22 mg/l. Also, when the large enclosed drainage area in its northern portion is excluded from analysis, Rocky Creek has a measured sediment production of 1.9 t/km^2/yr. These values are much closer to those of Horse Creek than to those of Wolverine Creek (see Table 4).

The sedi-hydrogram (Fig. 9) also illustrates the difference between the sediment dynamics of Wolverine Creek and the other tributaries. The line representing Wolverine Creek shows that it produces much more sediment per unit runoff and unit area than the other tributaries.

There are several features of Wolverine Creek Watershed which could account for its high sediment production. The lower portion of Wolverine Creek Watershed was used for livestock grazing for a number of years following a forest fire and this inhibited the regrowth of willows and other shrubs along the stream channel (MacIver, 1966). Valley side stability was thereby reduced and extensive slumping followed. MacIver (1966) also shows that cattle trails leading down to Wolverine Creek suffered severe erosion and developed into gullies. While grazing was discontinued in 1966, its impact was no doubt felt for a number of years thereafter.

Wolverine Creek Watershed contains approximately five times the length of road that is present in Horse Creek Watershed. The road crosses Wolverine Creek at two sites. The crossing closest to the watershed mouth is quite unstable. During the summer of 1977, the bridge approach at this crossing was twice lost by mass movement and in each case about 5 m^3 of material was transported into the stream channel. A vehicle approach to the stream channel exists at the streamflow gauging site and, between the main road crossing and the gauging station, the road is crossed by several culverts. The road and the culverts channelize the runoff from meadow lands to the west of Wolverine Creek, which previously moved toward the stream via numerous smaller channels and subsurface drainage.

In 1971 a small area (6 ha) in the lower portion of Wolverine Creek Watershed was cleared of its natural vegetation cover and converted to pasture as part of an experimental project (Holecek and Noujaim, 1971). This reduced the duration and increased the volume of spring runoff from this area.

It is impossible to precisely quantify the effect of land use on the sediment yield of Wolverine Creek, but environmental disturbances in the lower portion of its watershed, a zone of geomorphic disequilibrium, have been greater than elsewhere and have produced a substantial increase in sediment yield. There are no major differences between the natural environmental character of the lower portions of Horse and Wolverine Creek Watersheds and therefore it is reasonable to assume that the higher sediment productivity of Wolverine Creek is largely due to land use impacts.

5.4 Spatial Sediment Budget

The measured contribution of each gauged tributary and the ungauged tributary areas to the total water yield, sediment yield, and area of Spring Creek Watershed is given in Table 7. This is a spatial sediment and water budget. It shows that 92.2% of the Spring Creek sediment yield is derived from the ungauged tributary portion of the watershed, 23.9% of its total area. Figure 10 illustrates the discrepancy between the sediment yield of the tributaries and that of the watershed as a whole and the discrepancy between the water and sediment yield of the ungauged tributary area. In order to refine the sediment budget the ungauged portion of the watershed was subdivided on geomorphic grounds and the sediment yield of these subdivisions was estimated on the basis of the measurements made in gauged portion of the watershed.

First, mean water yields of the ungauged portions of Rocky and Bridlebit Creeks were estimated by dividing the water yields measured at their gauging stations by the effective runoff generating areas (i.e. the watershed areas topographically connected to the stream channels) given by Holecek (1970) and then applying this rate to the area of the ungauged portion of the watersheds.

The Horse Creek sediment rating curve indicates a sediment yield of 48 t/yr at the mouth of Rocky Creek and 99 t/yr at the mouth of Bridlebit Creek. Applying the sediment yield per unit area of Horse Creek to the drainage areas of Rocky and Bridlebit Creeks upstream of their junction with Spring Creek predicts yields of 50 t/yr and 55 t/yr respectively.

TABLE 7. - MEASURED SPATIAL SEDIMENT AND WATER BUDGET (Calculated from 1970-1974 data)

Watershed	Area % of total	Area km^2	Mean Sediment Yield % of total	Mean Sediment Yield t/yr	Mean Water Yield % of total	Mean Water Yield m^3/yr
Spring Creek	100.0	112.7	100.0	3484	100.0	9799×10^3
Gauged Tributaries						
Horse Creek	5.0	5.6	0.43	15	5.6	544×10^3
Wolverine Creek	8.6	9.7	4.3	151	8.2	801×10^3
Rocky Creek at gauging station	16.0	18.0	0.75	26	12.3	1208×10^3
Bridlebit Creek at gauging station	16.9	19.1	0.72	25	22.3	2187×10^3
Upper Spring Creek	29.6	33.4	1.5	54	34.0	3336×10^3
Total of Gauged Tributaries	76.1	85.8	7.8	271	82.4	8075×10^3
Ungauged Tributary Area*	23.9	26.9	92.2	3213	17.6	1724×10^3

* Area gauged indirectly as the difference between the measured values for "Spring Creek" and "Total of Gauged Tributaries".

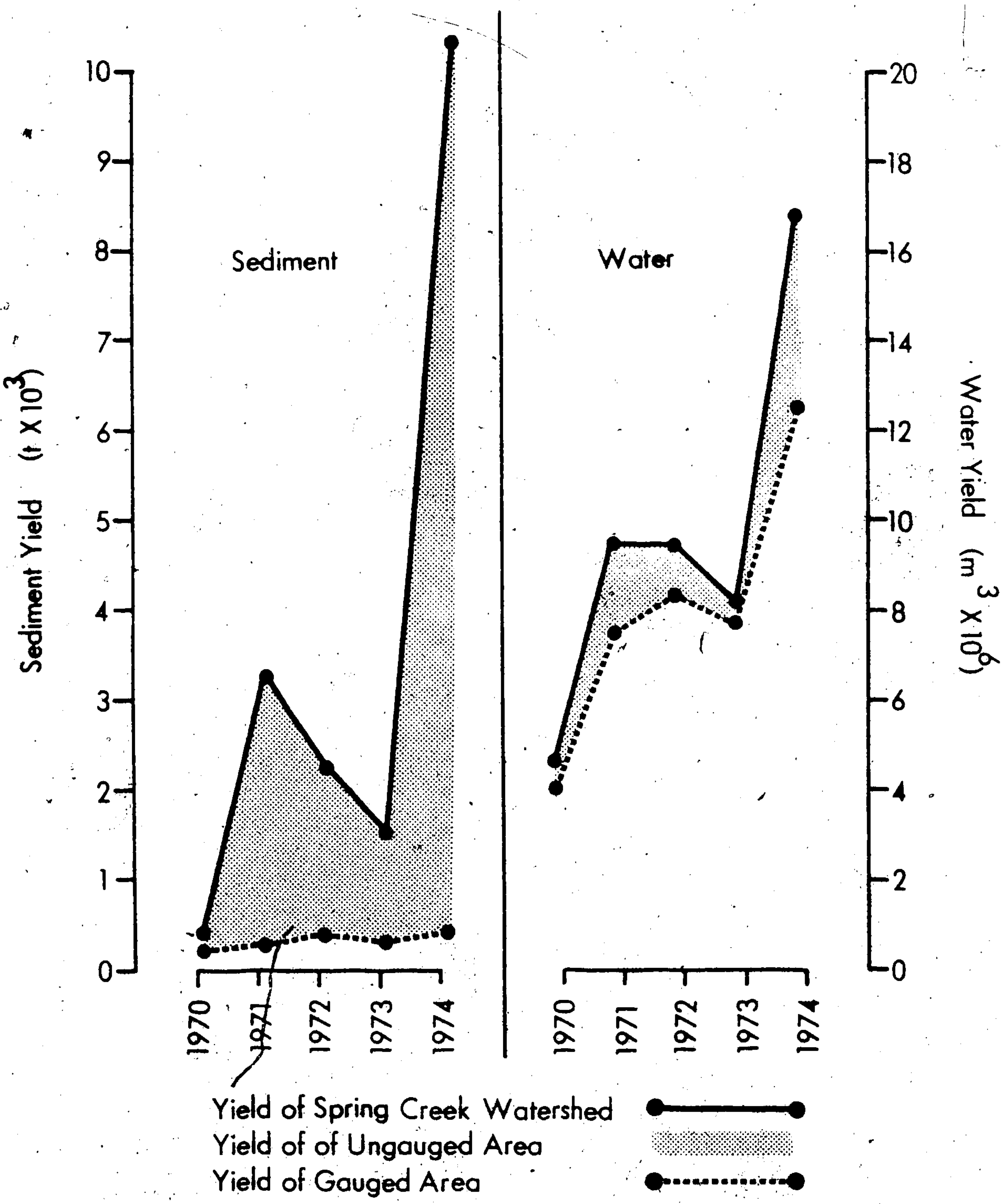


FIGURE 10: RELATIVE CONTRIBUTION OF GAUGED AND UNGAUGED AREAS OF SPRING CREEK WATERSHED

The mean sediment concentration measured at the Rocky Creek gauging station is 22 mg/l. This measurement is taken about one km downstream of the knickpoint. Leopold, Wolman, and Miller (1964) show that elsewhere sediment load increases downstream as the 0.8 to 1.3 power of discharge. In other words, sediment concentration changed very little in the downstream direction even though discharge increased substantially. Of course, this would only hold true where environmental conditions did not change drastically in the downstream direction. Since this is the case for Rocky Creek downstream from its gauging station, the mean sediment concentration at the watershed mouth should be little different from that measured at the sampling site.

Between 1970 and 1974, the measured mean annual sediment concentrations of Rocky Creek was not significantly correlated with its annual water yield, and only ranged between 18 mg and 25 mg/l (i.e. range is approximately ± 15% of the mean) while the annual water yield ranged from 703,000 m^3 (i.e. range is approximately ± 45% of the mean). Also, sediment concentration is only very weakly or insignificantly related to water discharge in this watershed (see Chapter 7). Sediment concentration, then, changes little despite large fluctuations in annual water yield and is poorly correlated with streamflow rates.

This is also true of Bridlebit Creek. Therefore the difference in the mean annual water yield of these streams should not of itself produce a substantial difference in their mean sediment concentrations. Since Bridlebit and Rocky Creeks share virtually identical environmental conditions along their lower reaches, they are expected to have nearly the same mean sediment concentrations at their mouths.

In order to estimate the sediment yield at the mouth of Rocky and Bridlebit Creeks, two assumptions were made. First, it was assumed that the mean sediment concentration at the mouth of Rocky Creek was the same as that measured at its gauging station (i.e. 22 mg/l). Secondly, the mean sediment concentration at the mouth of Bridlebit Creek was assumed to be the same as that of Rocky Creek.

The product of the mean sediment concentration and the estimated water yield at the mouth of each watershed gave a mean annual sediment yield of 52 t/yr for Bridlebit Creek and 31 t/yr for Rocky Creek. These values are slightly less than those calculated previously by applying the relationships from Horse Creek. The heavy forest cover and numerous beaver dams present in the lower watersheds of Rocky and Bridlebit Creeks but absent from that of Horse Creek are expected to inhibit sediment production. Therefore estimates calculated using the measured sediment concentration of Rocky Creek are considered more correct.

The sediment yield from the ungauged portion of Bridlebit Creek is 27 t/yr or 22 t/km^2/yr. This is the difference between the measured sediment yield of the gauged area and estimated sediment yield of total watershed, and corresponds to the sediment contribution of the watershed area downstream of the knickpoint. In contrast, the area upstream of the knickpoint only yields 1.3 t/km^2/yr.

Assuming the sediment concentration of the outflow from the upper portion of Rocky Creek Watershed is the same as that of Bridlebit Creek, the sediment yield of this area is 8 t/yr. Therefore the sediment yield from the lower portion of Rocky Creek Watershed is 23 t/yr or 12 t/km^2/yr.

The water yield of Willow Creek, the largest ungauged tributary, was estimated by using the runoff per unit area figure for Upper Spring Creek. Since Willow Creek is similar in most respects to Rocky Creek, it is expected to have about the same mean sediment concentration. The product of estimated water yield and sediment concentration of Willow Creek gave a sediment yield of 11 t/yr.

Just as the tributary watersheds are divided into two distinct units by a knickpoint, so is the interbasin area (i.e. the ungauged tributary area less the area of Willow Creek Watershed and the lower portions of Rocky Creek and Bridlebit Creek watersheds). The entire interbasin area has a mean annual water yield of 829,000 m^3 (i.e. difference between sum of estimates for tributaries and total measured for Spring Creek). Assuming that the interbasin area upstream of the major knickpoint on Spring Creek (i.e. the upper interbasin area) has a water yield of 825,000 m^3 with a mean sediment concentration equivalent to that of Rocky Creek, it would have a sediment yield of 18 t/yr.

Recalculating the sediment budget (Table 8), all of the Spring Creek watershed upstream of the major knickpoint on Spring Creek channel has a sediment yield of only 332 t/yr. The area downstream of this knickpoint (i.e. the lower interbasin area) has a sediment yield of 3152 t/yr which must be derived almost entirely from the channel and the valley sides, an area of approximately 1.5 km^2.

5.5 Sediment Sources

Data from the revised spatial sediment budget (Table 8), was used to construct the Sediment Contributing Zones Map (Fig. 11). This map shows the contribution of sediment by tributary areas to that measured at the watershed mouth, it does not show erosion intensity. It

TABLE 8 - REVISED SPATIAL SEDIMENT AND WATER BUDGET

Watershed Name	Area % of total	Area km^2	Mean Sediment Yield % of total	Mean Sediment Yield t/yr	Mean Water Yield % of total	Mean Water Yield m^3/yr
Spring Creek (measured)	100.0	112.7	100.0	3484	100.0	9799×10^3
Horse Creek (measured)	5.0	5.6	0.43	15	5.6	544×10^3
Wolverine Creek (measured)	8.6	9.7	4.3	151	8.2	801×10^3
Rocky Creek at mouth (estimated)	16.6	18.7	0.89	31	14.3	1403×10^3
Bridlebit Creek at mouth (estimated)	18.0	20.3	1.5	52	24.0	2356×10^3
Willow Creek (estimated)	4.5	5.1	.32	11	5.2	511×10^3
Upper Spring Creek (measured)	29.6	33.4	1.5	54	34.0	3336×10^3
Upper Interbasin Area* (estimated)	15.4	17.3	0.52	18	8.5 (Upper and Lower Interbasin Areas combined)	829×10^3 (Upper and Lower Interbasin Areas combined)
Lower Interbasin Area* (estimated)	2.4	2.7	90.5	3152		

* see text for definition of terms

SPRING CREEK WATERSHED SEDIMENT CONTRIBUTING ZONES

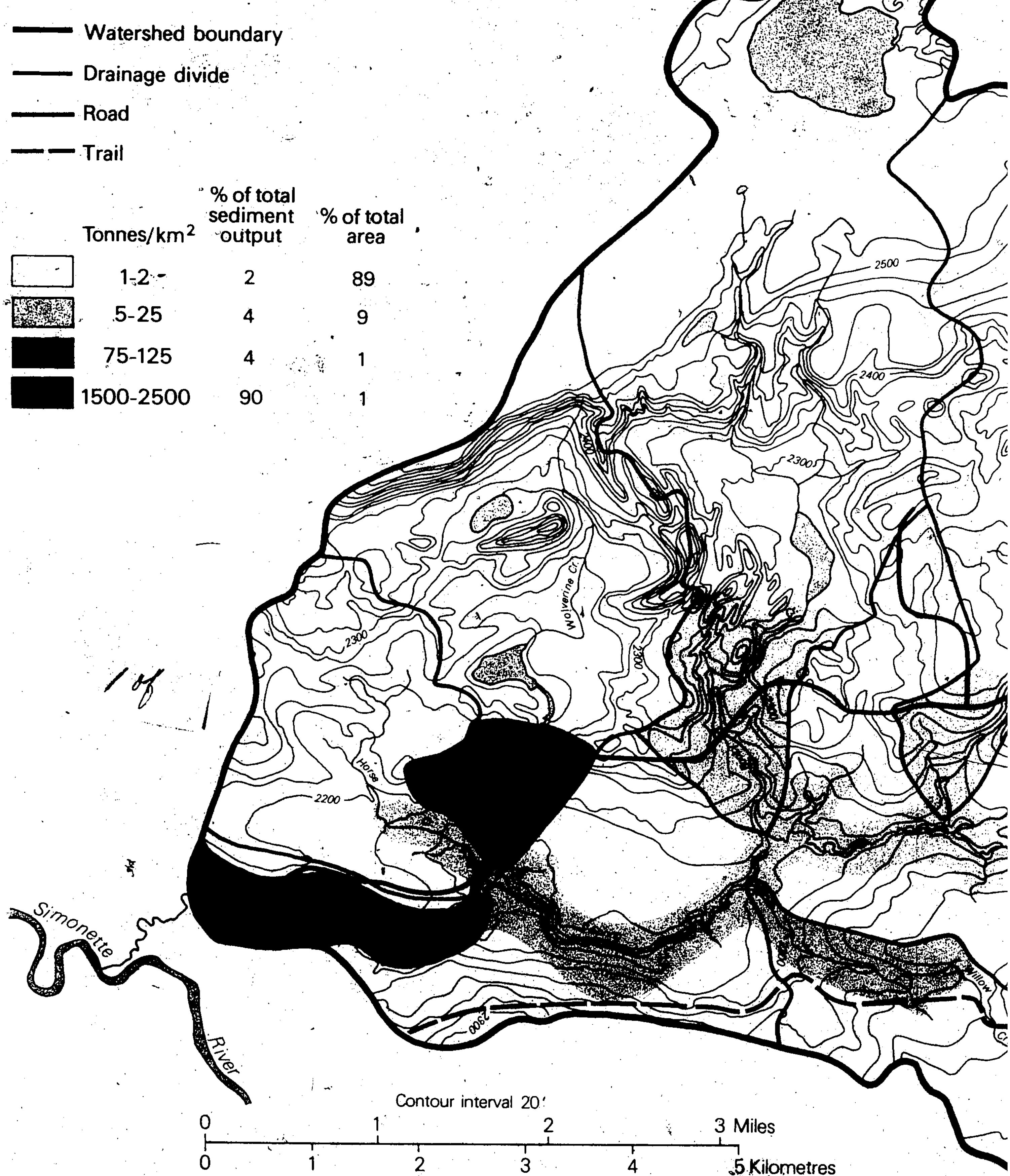


FIGURE 11

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illustrates the net sediment output remaining after the various sediment filters have acted on the products of erosion.

The majority of the watershed contributes little or nothing to the total sediment output. In fact, a part of the measured sediment output from the upper watershed is not derived through erosion but rather through biologic activity in streams and lakes.

The intermediate zone, containing the lower portions of the tributary watersheds, contributes sediment at a higher rate. The lower portions of the tributary watersheds and the area immediately downstream of the Upper Spring Creek gauging station are in disequilibrium, that is, the stream channels are still adjusting to past changes in base level.

The lower portion of Wolverine Creek is classified separately due to its high sediment production. If it were not for the land use impacts in this area, sediment production would probably be of the same order as that observed in the other tributaries.

The Spring Creek valley downstream of the Horse Creek junction provides over 90% of the total sediment output of the watershed. The channel in this zone is in disequilibrium; it is readjusting to past changes in the elevation of the Simonette River channel. The sediment productivity of this area is further enhanced by the fact that the channel is partly incised through older fluvial deposits, namely terraces of the Simonette River.

5.6 Factors Controlling the Spatial Pattern

In the development of the spatial sediment budget and the Sediment Contributing Zones Map (Fig. 11), three dominant factors have been identified as controlling the pattern of sediment production.

First, the anomalously high sediment yield of Wolverine Creek is attributed largely to land use impacts. Relatively minor and spatially limited environmental disturbances which produced instability along the stream channel have probably caused a substantial increase in the watershed sediment output.

Second, the beaver dams protect the stream channels and reduce the sediment delivery ratios of the watersheds by acting as sediment traps. They also limit channel erosion and sediment production downstream by serving as water storage sites and thereby reducing peak flows.

Third, sediment sources are most especially defined by the watershed morphology. Changes in base level have caused the channels to readjust by removing vast quantities of material in order to maintain accordance with the new base level. The zones of highest sediment production are coincident with the disequilibrium knickpoints.

6. IMPACT OF THE PIPELINE RIGHT-OF-WAY

During the winter of 1977 a pipeline was constructed across Spring Creek near the watershed mouth (see Fig. 4 for location). The erosion of the pipeline right-of-way and its sediment contribution to Spring Creek were monitored between April 9th and 11th and between May 5th and August 24th of 1977.

6.1 Site Characteristics

The pipeline right-of-way is 30 m wide and follows the fall line of the slope. It was cleared of vegetation over its full width in order to facilitate the movement of construction equipment.

In an attempt to protect the right-of-way surface from erosion, it was covered with the forest debris obtained from the clearing operation. To divert runoff away from the slope, a berm was constructed across the right-of-way at the crest of the south valley side and a tractor trail running diagonally across the right-of-way was left on the north valley side.

The pipeline crossing is located shortly downstream of the knickpoint on Spring Creek channel. The valley sides in this area have overall slope angles of 20° to 25°. The slopes are convex and become steeper near the stream. Extensive valley side slumping occurs upstream and downstream of the right-of-way despite a dense spruce and poplar growth.

6.2 Sediment Yield

Between May 5th and August 24th of 1977, Spring Creek Watershed upstream of the right-of-way yielded 10,652 x 10^3 m^3 of runoff with a mean sediment concentration of 428 mg/l. This is a sediment yield of 4559 tonnes. Immediately downstream of the right-of-way, the mean sediment concentration was 583 mg/l and the sediment yield was 6209 tonnes. The difference of 1605 tonnes is the sediment yield of the pipeline right-of-way. This is a 36% increase of the sediment yield of the watershed.

The total amount of material eroded from the right-of-way was greater than 1605 tonnes. Only the sediment which was discharged in suspension was measured and not material which was transported by traction along the stream bed.

The sediment yield of the right-of-way must have been derived from the area between the berm on the south valley side and the main road crossing on the north side since these features blocked any sediment input from upslope. This is a sediment contributing area of .005 km^2. Therefore the sediment yield of the right-of-way, in areal terms, was 33,000 t/km^2. In contrast, the sediment yield of the watershed upstream of the right-of-way was 40 t/km^2.

6.3 Erosion Processes

The erosion of the right-of-way followed a different sequence on each side of the valley. Soil pipes developed on the south valley side. These collapsed and provided channels for subsequent mudflows. On the north side of the valley, most slope wasting occurred as massive slumps. Overland runoff produced rills and small channels on both slopes but these were minor in comparison with the major slope failures.

The surficial materials above the crest of the south valley side are of alluvial-aeolian origin. The slope of the right-of-way surface on this side of the valley was reduced by cutting into the crest of the valley and moving the excavated material downslope. This covered the right-of-way surface with sand and silt. As less permeable materials exist below this surface cover, precipitation percolated rapidly through the surface materials and then moved downslope along a less permeable horizon. This runoff process on the steep slope of the right-of-way surface led to the rapid and extensive development of soil pipes. These subsequently collapsed and provided channels for mudflows.

Under such conditions, the construction of a berm across the upper portion of the right-of-way was of limited value. Most runoff moved toward the stream in subsurface channels and the catchment area of the right-of-way slope on the south valley side was determined more by the configuration of the underlying strata than by that of the ground surface.

A road crosses the right-of-way just above the crest of the north valley side. The pipeline right-of-way follows a minor drainage course for a short distance upslope from the road. Runoff is funnelled to the crest of the right-of-way slope by the drainage course and the road ditches. Here it is blocked by the road and ponds. In order to reach the stream channel, the ponded water must percolate sufficiently deeply to pass beneath the packed road bed. These conditions produced a shallow groundwater system which helped develop and lubricate shear planes at depth and reduced slope stability.

Figure 12 shows that the products of the right-of-way erosion were discharged from the watershed intermittently. In the course of runoff events, the sediment contribution from the right-of-way was greatest during the rising stages and decreased at the peak and during the initial recession stages.

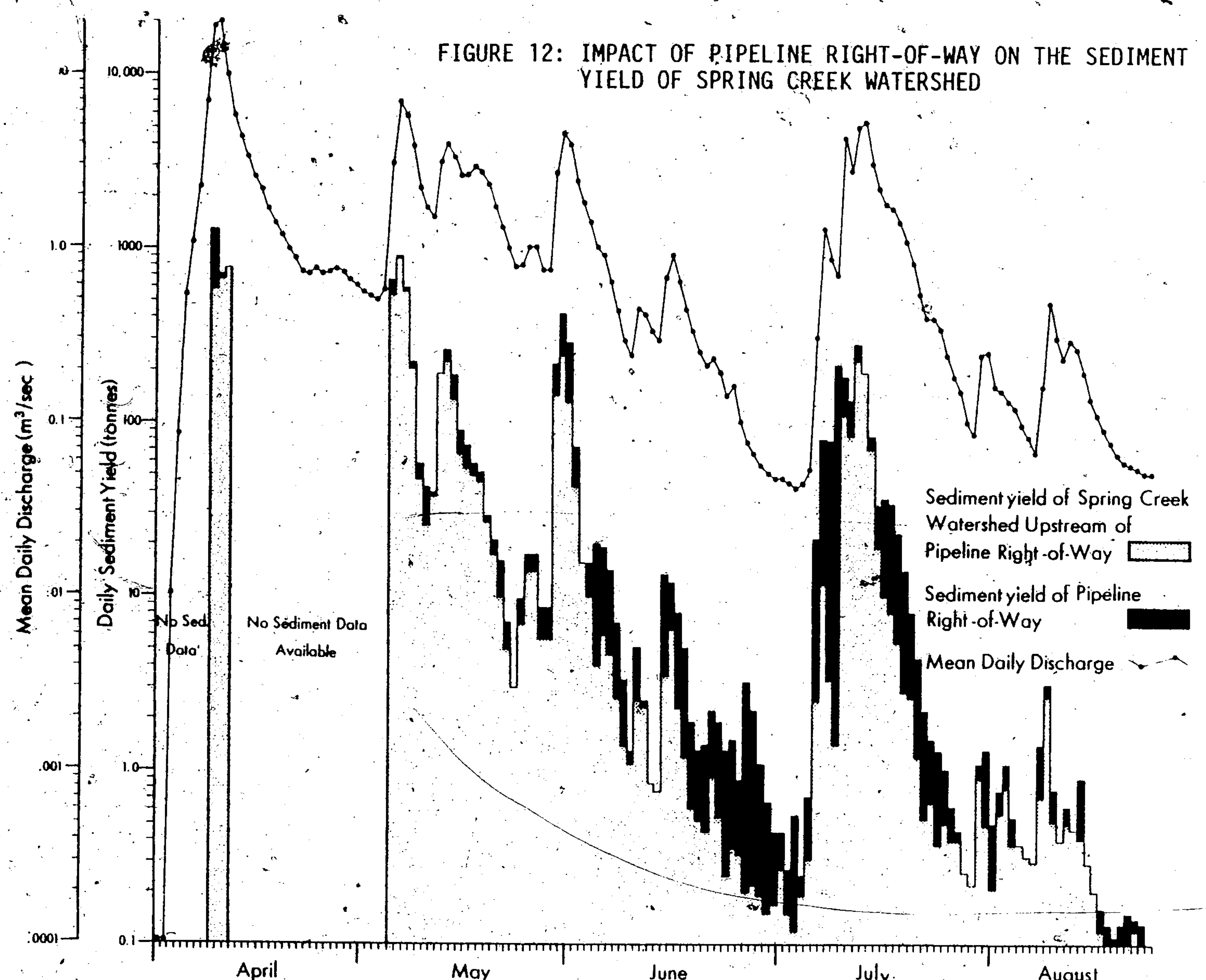
Material moved downslope into the channel during low flow periods, but the rate of supply exceeded the capacity of the stream and thus much of the material remained in storage within the channel. During rising stages, this material increased the stream capacity by restricting the flow, and provided a ready supply of sediment. As peak flow conditions were attained, the channel was cleared and the sediment supply largely depleted. The direct input of sediment from the right-of-way became insignificant in relation to the high sediment loads which were associated with peak flows.

When flows receded, the sediment contribution from the right-of-way gradually increased in relative importance as the natural sediment load decreased. Also, slope failure occurring in the aftermath of major runoff events placed sediment in transport and constricted the stream channel.

6.4 Erosion Prevention

It is apparent that surface protection measures were inadequate to prevent serious erosion of the pipeline right-of-way. The pipeline crossing was constructed through a zone in which the valley side

FIGURE 12: IMPACT OF PIPELINE RIGHT-OF-WAY ON THE SEDIMENT YIELD OF SPRING CREEK WATERSHED



slopes have been oversteepened by the rapid incision of the stream channel. The slopes are therefore unstable even under natural conditions as is evidenced by the extensive slumping on the forest-covered slopes adjacent to the right-of-way. The forest removal and surface disturbance associated with the construction of the pipeline aggravated this situation and accelerated the rate of slope wasting.

The surface protection measures applied were of limited value in the face of major slope instability. The runoff diversion berm constructed on the south valley side failed since most runoff was occurring below the ground surface. The road at the crest of the right-of-way slope on the north valley side effectively blocked runoff. However, it did not divert the water away from the right-of-way slope but rather caused it to move downslope at depth, aggravating slope instability.

The erosion problems could have been avoided, or at least very much reduced, by a different choice of site. In this case, however, the range of available sites was limited by the research nature of Spring Creek Watershed. The primary consideration in locating the pipeline right-of-way was to minimize its impact on the watershed as a whole. For this reason, the pipeline was constructed as near as possible to the watershed mouth where its overall impact was minimized and easily monitored.

Ideally the crossing should have been located some distance upstream of the knickpoint where the valley sides have attained a greater degree of natural stability. Under such conditions, properly applied surface protection measures of runoff diversion, debris cover, and revegetation could have been effective in preventing serious erosion problems from developing. As it was, major and expensive slope stabilization works have been required to correct these problems.

7. SEDIMENT AND SOLUTE RATING CURVES

A sediment rating curve illustrates the relationship between the water and sediment output of a watershed. Changes in this relationship through space and time provide clues to the operation of sediment related processes in a watershed. Further, if the sediment rating curves exhibit consistent shifts or changes, these can be employed to advantage in predicting sediment yield.

7.1 Theoretical Considerations

Sediment rating curves take several forms. Either sediment discharge rates or sediment concentrations are plotted against water discharge rates. Instantaneous, mean daily or mean monthly values are the most commonly used. The relationship between the two variables employed in a sediment rating curve is usually quantified by means of simple linear regression.

Plotting sediment discharge rates against water discharge rates can lead to spurious correlations as this approach is equivalent to the regression of xy on x (Benson, 1965). Meaningful sediment rating curves should relate sediment concentration to water discharge.

For a number of statistical reasons, log values of the variables are generally used. This is done on the grounds that the background populations show a log normal distribution and more importantly, in order that the distribution of residuals about the regression line have a mean of zero and a constant variance (see Kellerhals et al., 1974 for further discussion).

The most severe shortcoming of sediment rating curves revolves about the fact that both of the variables employed in the analysis are serially correlated. This poses difficulties in the assessment of the strength and significance of the regression. Serial correlation can be considered equivalent to reducing the number of degrees of freedom below that defined by the sample size. The amount by which it is reduced may not be readily determined and as a result none of the standard significance tests can be validly employed.

In the case of this study, the number of samples is large and thus the regressions are considered quite robust. Also, the samples taken from 1967 to 1976 are spaced aperiodically through time. It nevertheless remains that the outcome of the statistical tests must be treated cautiously.

The choice of using instantaneous, mean daily or other values should consider the character of the data base and watershed hydrology. Spring Creek is a relatively small watershed with rapid fluctuations in streamflow which are masked by mean daily flow values. This characteristic is even more marked in the tributaries. Also, the method of computing mean daily sediment concentration is based to a degree on subjective judgement and requires the assumption of some relationship between streamflow rates and sediment concentrations. For these reasons, instantaneous values are used in the analyses presented here.

7.2 Data Base

Sediment sample analysis reports for the years 1967 to 1976 furnished by Water Survey of Canada gave the solute and sediment concentrations for each sample and the stream stage at the time of sampling. Samples were rejected if the analyst's report noted possible contamination or damage. Equivalent data for 1977 were gathered by the author.

The stage was converted to a discharge rate by the use of the appropriate stage-discharge table and the required correction factors. These were provided by Water Survey of Canada and by Alberta Environment.

7.3 Model Definition

Initial analysis was made of the Spring Creek data in order to define the form of the relationship between suspended sediment concentration and streamflow rates. This and all other statistical analyses were done using the MIDAS statistical program package (Fox and Gutre, 1976).

The set of all samples for Spring Creek was plotted in the form of the log to the base 10 of sediment concentration in mg/l (LOGCS) against the log to the base 10 of water discharge in cfs (LOGQ). This showed a non-linear relationship between LOGCS and LOGQ (see Fig. 13). A set of curves was fitted to the data by the use of polynomial regressions of LOGCS on LOGQ. An F-test of the reduction of the sum of squares of the deviations from the regression lines (SSE) showing a very significant reduction was attained in moving from a first degree polynomial regression (i.e. linear regression) to a second degree polynomial regression. A third degree polynomial regression gave a further reduction which was significant at the .005 level but not at the .001 level. A fourth degree polynomial regression did not give a further significant reduction in SSE. Thus, the rating curve for all Spring Creek samples was established to be curvi-linear, and while a third degree polynomial form could have been accepted, a second degree polynomial was chosen in the interest of simplicity.

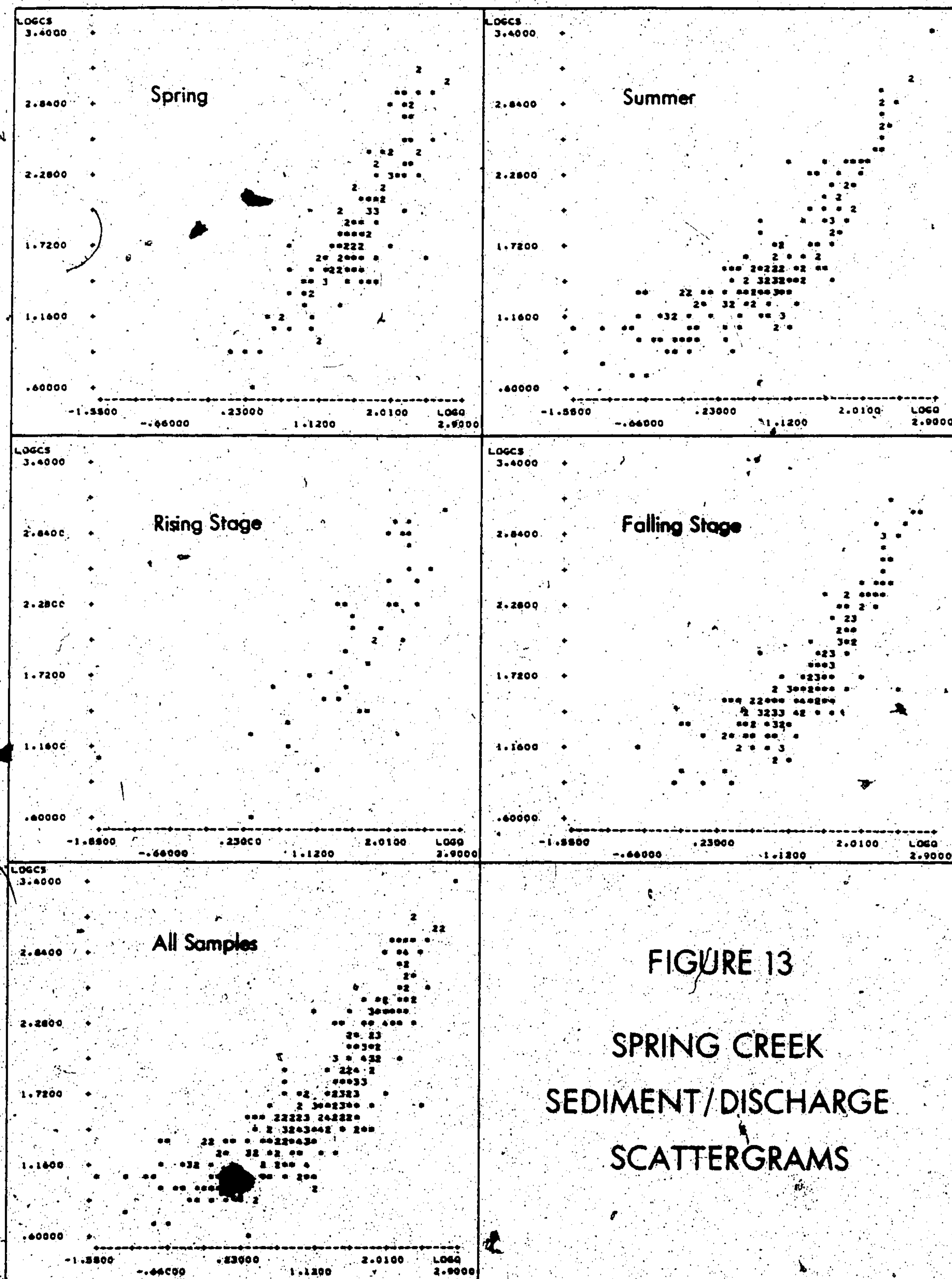


FIGURE 13

SPRING CREEK

SEDIMENT/DISCHARGE

SCATTERGRAMS

This type of regression was used because of its ability to fit the data, not because there is any theoretical reason to believe that the relationship between LOGCS and LOGQ is of this form. Therefore the polynomial regression equations presented here should not be used to make predictions beyond the range of the data from which they were developed.

7.4 Annual Variations in Sediment Rating Curves

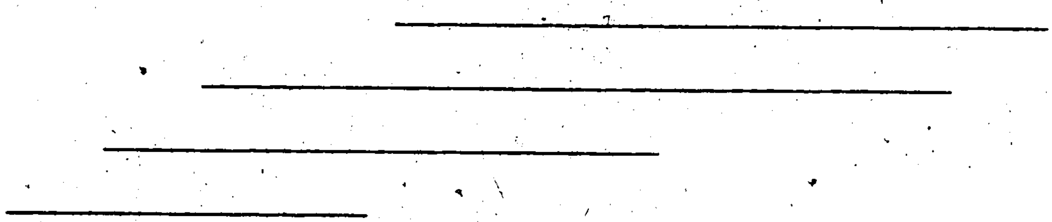
The Spring Creek sampling site was moved between 1976 and 1977, and therefore the question arises as to whether the 1977 data is comparable to that of previous years. This was investigated by comparing the sediment rating curves for different years by means of covariance analysis (Snedecor and Cochrane, 1967). The rating curve for the 1977 data was compared with that of the 1967 to 1976 data. Also, rating curves for each year were compared with each other.

The annual rating curves were constructed and compared only for the upper range of discharge (i.e. LOGQ is greater than 0.7) where they could be defined by linear regressions. This was done because sediment samples for lower discharges were not available in some years and therefore it would have been misleading to use polynomial regressions to define the rating curves for all years.

The 1977 rating curve has the same slope but a significantly different intercept (at the .05 confidence level) than the 1967 to 1976 rating curve. However the annual rating curves also have the same slopes but significantly different intercepts. The relationship between the intercepts as illustrated by the results of a Neuman-Kuel

Studentized Range Test (Snedecor and Cochrane, 1967) given graphically below.

1970 1971 1974 1969 1972 1976 1973 1968 1975 1967 1977



The years represent the rank of intercept values from lowest to highest and the lines define groups of intercepts which are not significantly different from each other at the .05 confidence level. Thus moving the sampling site does not appear to have caused any greater displacement of the 1977 rating curves than might have otherwise occurred.

Explanations for the lack of similarity of the intercepts were sought. The rank of the intercepts is not related to the rank of annual water yields, the proportion of annual runoff produced in spring, or the proportion of samples taken by depth-integrating samplers, nor does it follow a time trend. The variation is not due to measurement error as the same sampling method and sample analysis procedure was employed in each year. Apparently, significant differences in the value of the intercepts is the result of the operation of variables which have not as yet been identified. The data from all years were pooled for further analysis in the belief that it reflects the long term average relationship between LOGCS and LOGQ.

7.5 Seasonal and Hydrologic Factors

Differences may exist between spring and summer rating curves

(Guy, 1964; Brown, 1972), and between rising stage and falling stage rating curves (Walling, 1977). In order to investigate this for Spring Creek and its tributaries, the sample sets were subdivided by season and stage.

Spring was defined as the months March, April, and May while summer was defined as the months of June to October inclusive. No samples were available for the remaining months.

Rising and falling stage classification was based on the mean daily discharge hydrograph. If the mean daily flow rate on a sample day had changed significantly from that of the previous day, and if the direction of that change continued into the next day, the sample was placed into the appropriate rising or falling stage category. If not, the sample was placed in a residual category. It was arbitrarily decided that a change in the mean daily flow rate of .0057 cms for Spring Creek and .0014 cms for the tributaries would be considered significant. This classification system was chosen because it ignores minor fluctuations in discharge and places samples taken during transitional period (i.e. at peaks and troughs of the hydrograph) in the residual category.

7.6 Spring Creek

It was previously shown that the rating curve for the set of all Spring Creek samples is curvi-linear and that it can be defined by a second degree polynomial regression equation. The summer data plots in the same fashion and can be fitted by an equation of the same type. In the spring, however, the relationship between LOGCS and LOGQ is linear (see Fig. 13 and Table 9).

Figures 14 and 15 show that over most of the range of streamflow rates for which sediment samples are available, there is very little difference between spring and summer sediment concentrations. Above flows of LOGQ = .70 (i.e. .15 cms or 5.0 cfs) the summer rating curve conforms to a linear regression model; that is no significant reduction in the SSE is achieved by the use of a polynomial regression. Further, covariance analysis shows that for this range of streamflows, there is no significant difference (at .05) between the spring and summer rating curves.

Below LOGQ = .70, the spring and summer rating curves diverge. Over their common range (i.e. LOGQ .06) the spring and summer rating curves are different in that one conforms to a linear regression model while the other does not. For the summer data a significant reduction in SSE is achieved in moving from a first degree to a second degree polynomial regression. Therefore, the spring and summer rating curves are different from each other but the difference is restricted to low flows less than approximately 50% of the mean streamflow rate.

At low flows, intense summer thunder showers may cause a measureable increase in sediment concentration without appreciably increasing streamflow. Dam building activity by beavers accelerates at low flows as they attempt to maintain favorable water levels. Such activity produces sporadic sediment inputs. Low summer flows are also associated with a more stable aquatic environment, higher water temperatures (i.e. 15°-20°C) and thus with more prolific biologic sediment production. These three factors combine to maintain a minimum sediment

TABLE 9: SEDIMENT REGRESSION ANALYSIS

	Regression Equation	N	R^2	Level of Significance*
SPRING CREEK				
All Samples	$Y = .21147\ X^2 + .17090\ X + 1.0726$	290	.81467	.0000
Spring	$Y = .91276\ X + .43033$	121	.77034	.0000
Summer	$Y = .18936\ X^2 + .21546\ X + 1.1098$	169	.83785	.0000
Rising Stage	$Y = .18568\ X^2 + .26658\ X + 1.0094$	37	.71362	.0000
Falling Stage	$Y = .26607\ X^2 - .00248\ X + 1.1701$	163	.82097	.0000
HORSE CREEK				
All Samples	$Y = .15263\ X^2 + .39181\ X + 1.0408$	159	.43232	.0000
Spring	$Y = .53324\ X + 1.0447$	68	.56803	.0000
Summer	$Y = .12789\ X^2 + .34610\ X + 1.0711$	90	.14165	.0013
Rising Stage	$Y = .06913\ X^2 + .23741\ X + 1.1932$	16	.39105	.0398
Falling Stage	$Y = .23664\ X^2 + .30494\ X + .97123$	74	.35433	.0000
WOLVERINE CREEK				
All Samples	$Y = .33260\ X^2 + .52804\ X + 1.3201$	180	.52199	.0000
Spring	$Y = .66233\ X + 1.5867$	84	.47942	.0000
Summer	$Y = .37617\ X^2 + .43584\ X + 1.1684$	96	.30297	.0000
Rising Stage	$Y = -.14031\ X^2 + .71696\ X + 1.5478$	17	.29280	.0885
Falling Stage	$Y = .25550\ X^2 + .69528\ X + 1.1928$	67	.82372	.0000
ROCKY CREEK				
All Samples	$Y = -.07439\ X + .85610$	191	.03131	.0143
Spring	$Y = .01047\ X + .80958$	87	.00024	.8858
Summer	$Y = -.13585\ X + .82645$	102	.11672	.0004
Rising Stage	$Y = -.04796\ X + .97997$	40	.00713	.6043
Falling Stage	$Y = -.08574\ X + .76789$	81	.03572	.0911
BRIDLEBIT CREEK				
All Samples	$Y = .02538\ X + 1.0947$	225	.00362	.3690
Spring	$Y = .23628\ X + .90640$	83	.12900	.0009
Summer	$Y = -.02316\ X + 1.1120$	141	.00335	.4957
Rising Stage	$Y = .13864\ X + 1.2187$	39	.06923	.1056
Falling Stage	$Y = -.06968\ X + 1.0038$	104	.02543	.1059
UPPER SPRING CREEK				
All Samples	$Y = -.10387\ X + .97013$	189	.08131	.0001
Spring	$Y = -.02644\ X + .92189$	80	.00336	.6096
Summer	$Y = -.18160\ X + .96596$	107	.21158	.0000
Rising Stage	$Y = -.00595\ X + 1.0520$	31	.00017	.9449
Falling Stage	$Y = -.10534\ X + .89634$	97	.07894	.0053

Y = log to the base 10 of sediment concentration in mg/l

X = log to the base 10 of water discharge in cfs

* attained significance of the null hypothesis

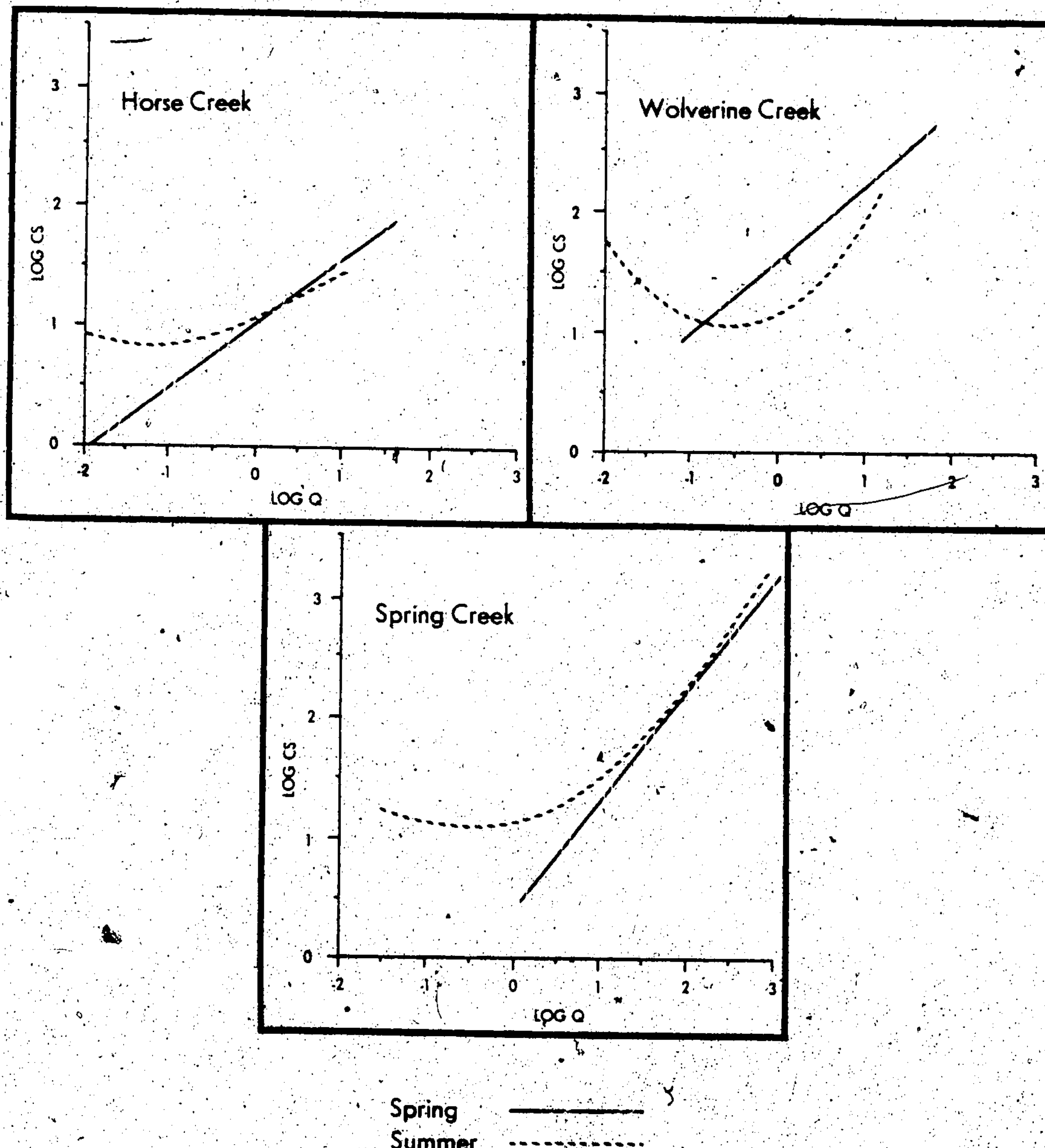


FIGURE 14: SEASONAL SEDIMENT RATING CURVES

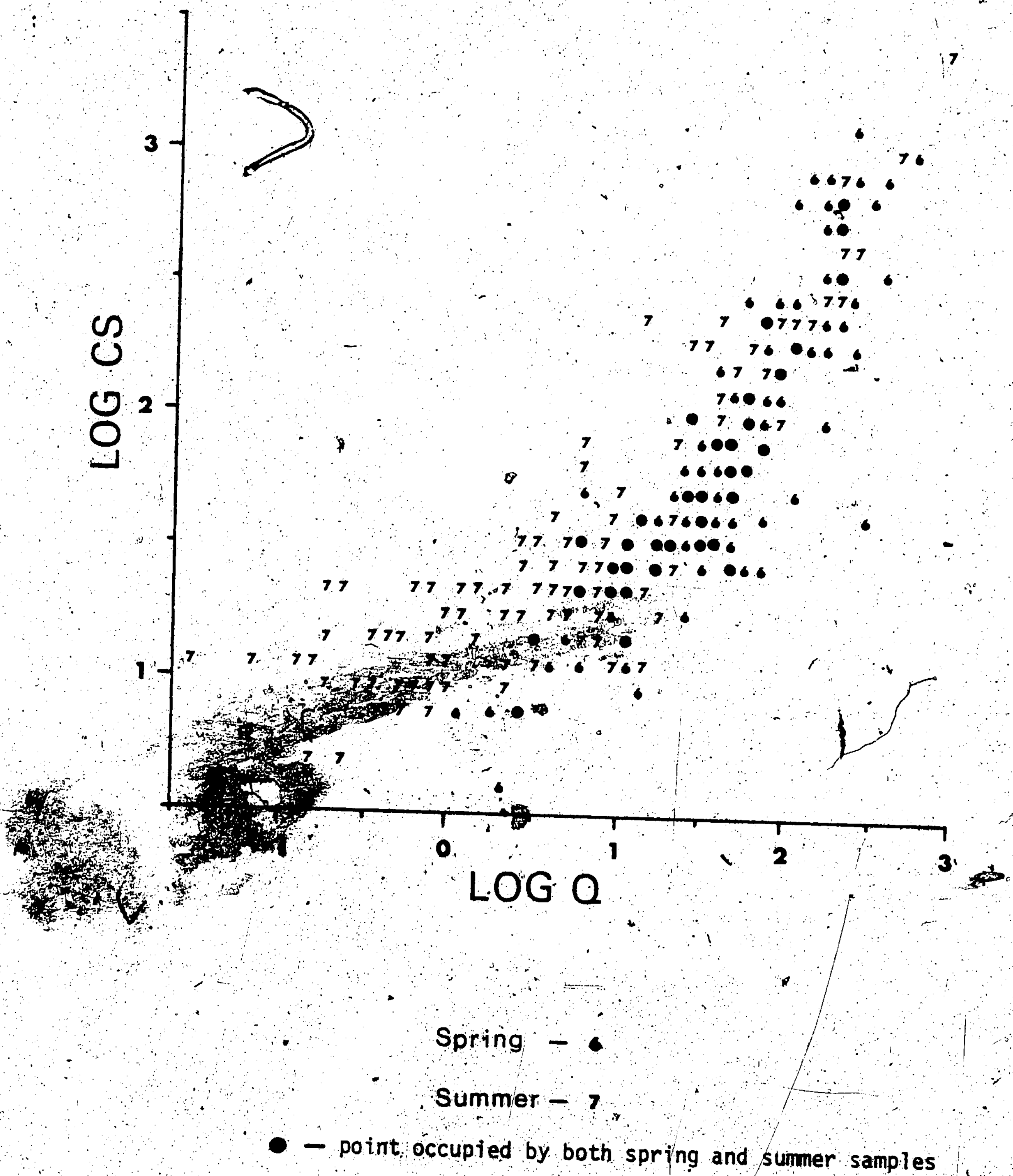


FIGURE 15: SEASONAL SEPARATION OF SPRING CREEK SEDIMENT/DISCHARGE SCATTERGRAM

concentration during the summer months and thereby cause curvilinearity in the summer rating curve.

The maintenance of a minimum concentration during the summer months does not substantially affect the annual sediment output of the watershed. The sediment rating - flow duration curve calculations using the rating curve for the set of all samples shows that flows less than 0.15 cms contribute under 8 t/yr to the mean annual sediment yield of Spring Creek.

The summer rating curve shows a stronger correlation between LOGQ and LOGCS (r^2 = .84) than the spring rating curve (r^2 = .77). However this difference is not great and does not necessarily indicate seasonal differences in the strength of the sediment-discharge relationship. It may simply reflect differences in the ability of linear and polynomial regressions to fit a given set of data.

Both rising stage and falling stage rating curves are curvilinear and covariance analysis shows no significant difference between them. Correlation is somewhat better on falling stage (r^2 = .82) than on rising stage (r^2 = .71). It is expected that on the rising stages sediment concentration will be affected by variations in antecedent supply and the nature of runoff generation. As a result, sediment concentration is more variable at the beginning of a runoff event. On falling stages, the differences in initial conditions will have been largely "damped out" and the sediment load is better adjusted to the carrying capacity of the stream.

The unstable valley sides in the lower interbasin area provide substantial sediment inputs to Spring Creek. Because the sediment concentration is seldom limited by the available supply, it is rather well predicted by a measure of the stream's carrying capacity, and there is very little difference between the seasonal and stage-differentiated rating curves. This also implies that the Spring Creek sediment rating curves largely reflect the sediment - discharge relationship through the lower interbasin area of the watershed.

7.7 Horse Creek

The plot of LOGCS against LOGQ for the set of all Horse Creek samples (Fig. 16) is curvi-linear and shows a high degree of scatter. The rating curve is defined by a second degree polynomial (Table 9).

The spring rating curve is linear while the summer rating curve is curvi-linear. As in Spring Creek, the real seasonal differences are apparently restricted to low flow periods, presumably for the same reasons (see Fig. 14). However, unlike Spring Creek, there is a large difference in the regression coefficient of the spring (r^2 = .57) and summer (r^2 = .14) curves. Since Horse Creek has such a low mean sediment concentration, variations in rainfall intensity during the summer are more likely to be reflected in the sediment concentration. Variations in the sediment input from the upper watershed due to beaver activity and algal growth rates also have a strong impact in the summer. These types of variations are masked in Spring Creek, except at very low flows, by the high sediment production of the lower interbasin area.

The rising stage rating curve has a higher r^2 value (.39) than the falling stage rating curve (.35), but it is only based on 16

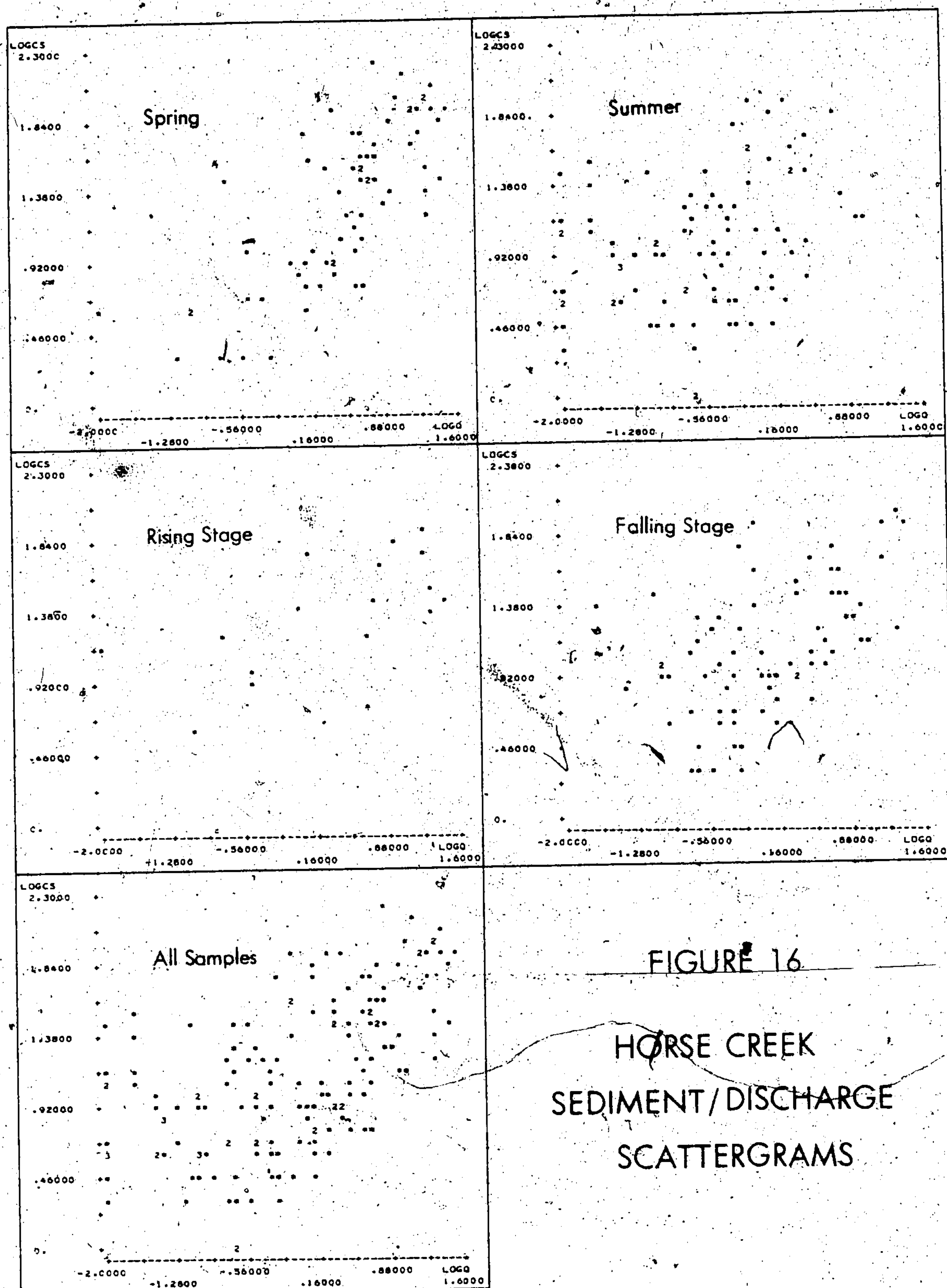


FIGURE 16

HORSE CREEK
SEDIMENT/DISCHARGE
SCATTERGRAMS

samples and can be considered not significant at the .01 confidence level (see Table 9).

7.8 Wolverine Creek

A curvi-linear rating curve defined by a second degree polynomial is indicated for the set of all Wolverine Creek samples (see Fig. 17). Scatter about the curve is high.

As before, the spring curve is linear while that for the summer is curvi-linear. Unlike before however, the seasonal curves are significantly different over the upper range of discharge to which linear regressions can be fitted to both the spring and summer data. This was tested by covariance analysis at the .05 confidence level. Figure 14 shows that over most of the range of discharge, sediment concentrations are higher in the spring than in the summer. This is probably due to the sensitivity of the disturbed areas of the watershed to seasonal changes in vegetation cover. These areas lack the protective cover of organic debris and shrub growth which is present in the undisturbed portions of the watershed, and as a result they are more susceptible to erosion and minor slumping in the spring. As new vegetation becomes established in the summer, the erosion resistance of these disturbed areas is increased, at least at moderate flows.

At high flows the spring and summer curves converge. Under the high hydraulic stresses applied to the channel banks and lower valley sides at these times, the summer vegetation cover on the areas disturbed by land use fails to provide protection against erosion.

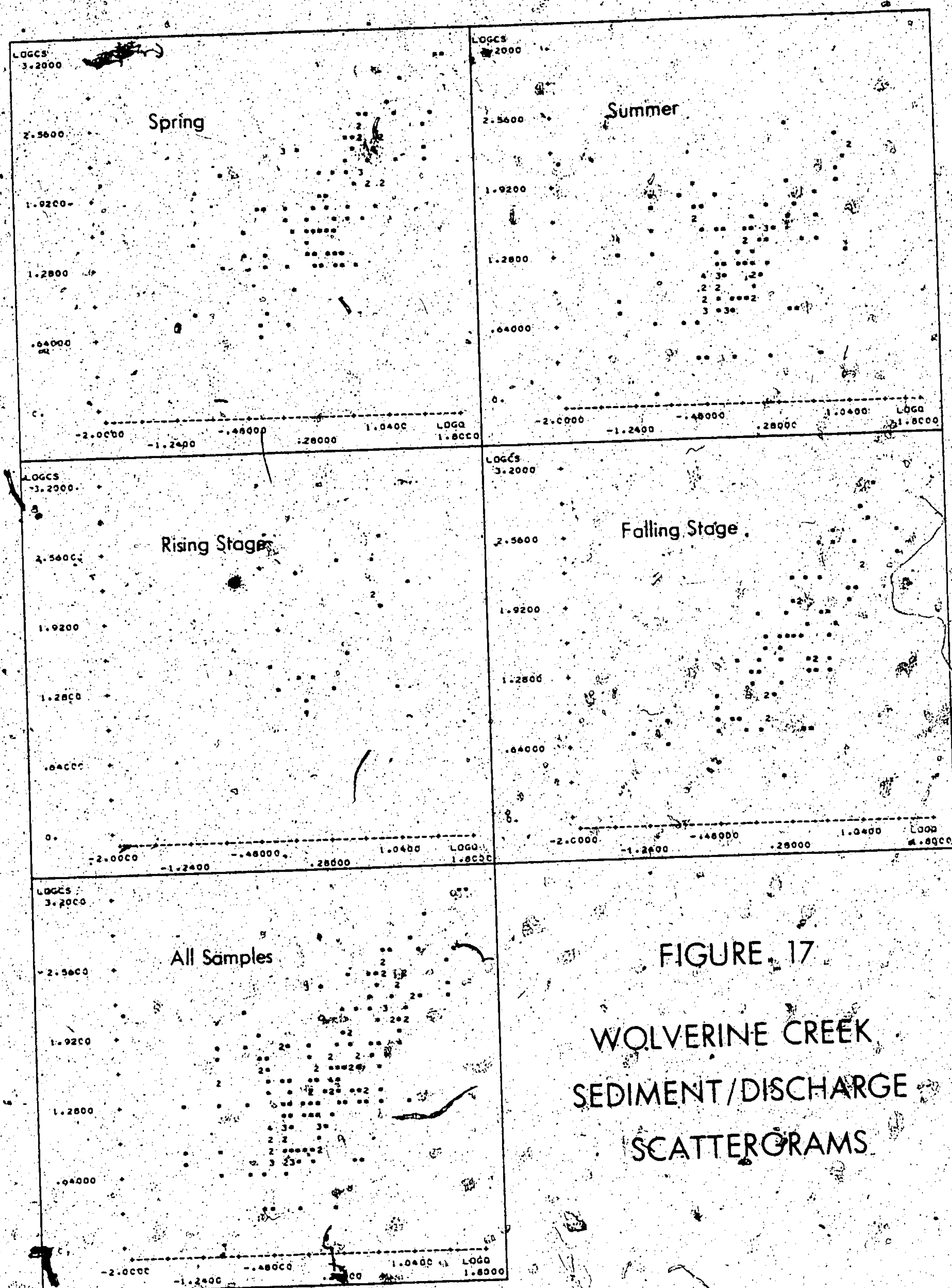


FIGURE 17

WOLVERINE CREEK
SEDIMENT/DISCHARGE
SCATTERGRAMS

The spring rating curve (r^2 = .48) has a higher r^2 value than the summer rating curve (r^2 = .30). The same factors that act in Horse Creek to produce more scatter about the summer curve than the spring curve also act in Wolverine Creek.

Scatter about the rising stage rating curve (r^2 = .29) is greater than that about the falling stage curve (r^2 = .62). Also, the regression equation defining the rising stage rating curve is not significant at the .05 confidence level (see Table 9).

7.9 Other Tributaries

Scattergrams show that for Rocky, Bridlebit, and Upper Spring Creeks the relationship between LOGCS and LOGQ is very weak (see Figs. 18 to 20). Since the data have a great deal of scatter and no clear non-linear patter is apparent, the use of curve fitting techniques could not be justified and the data were only subjected to simple linear regression analysis.

Subdividing the data on seasonal and hydrologic grounds did not greatly improve the predictive ability of the regression equations but it did indicate certain trends. Over the summer months, LOGCS is negatively correlated with LOGQ. As was discussed previously, this is due to the importance of biological sediment production at this time of the year. For Rocky and Bridlebit Creeks, LOGCS and LOGQ are positively, although weakly, correlated in the spring. It is at this time of the year that the highest water discharge rates and the highest sediment concentrations occur.

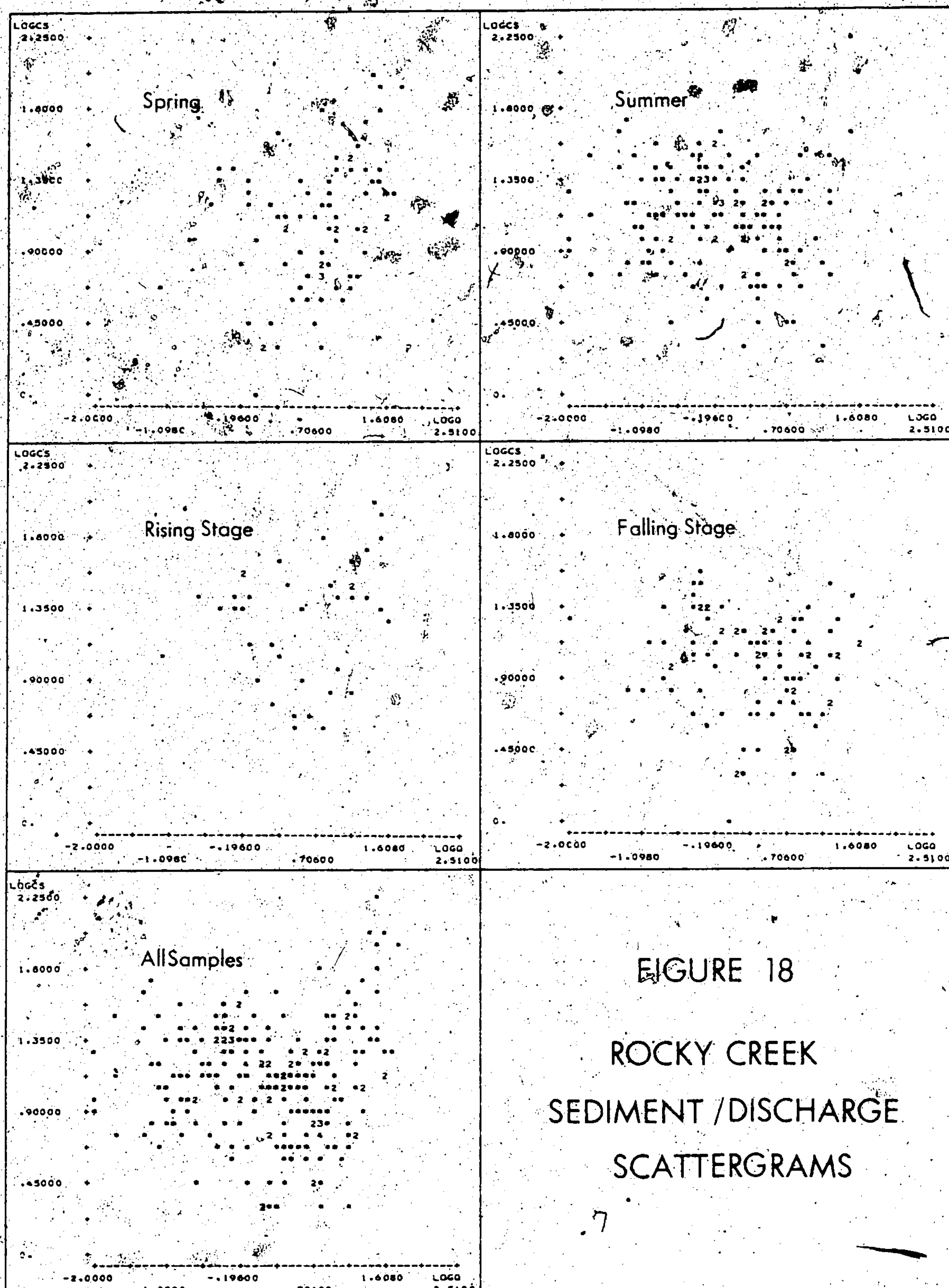
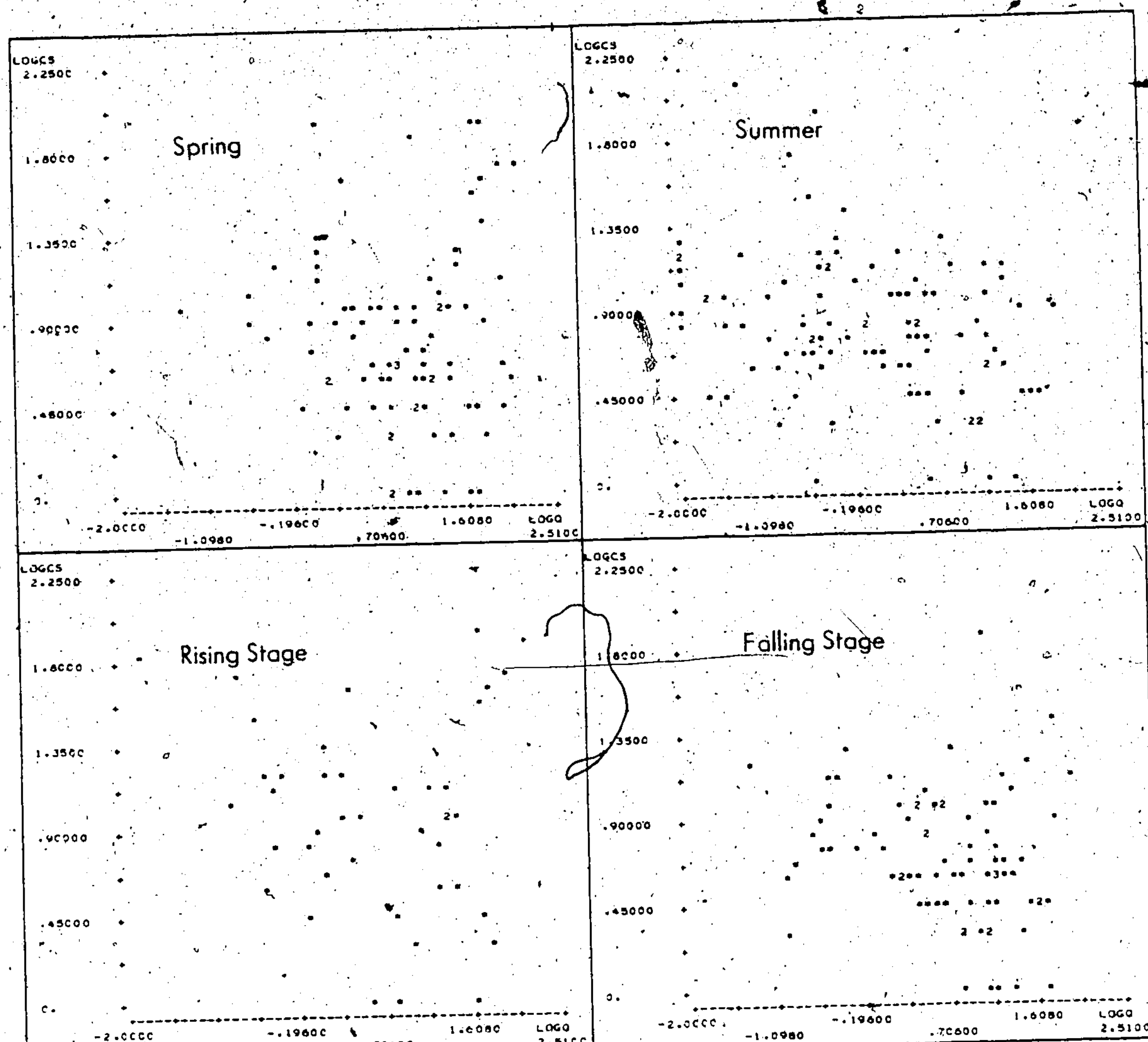


FIGURE 18

ROCKY CREEK

SEDIMENT / DISCHARGE

SCATTERGRAMS



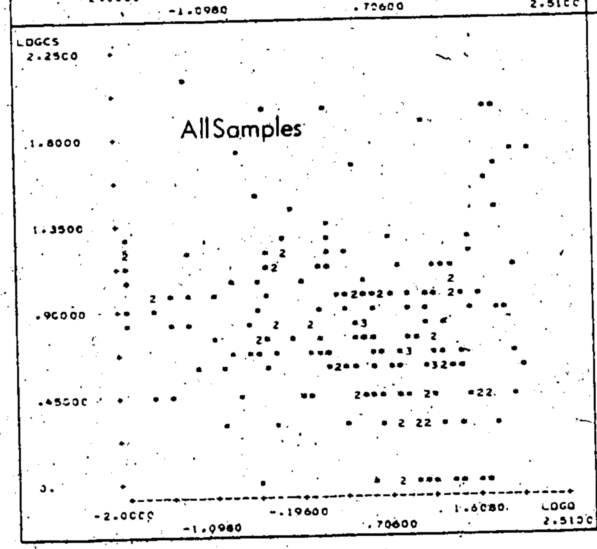


FIGURE 19

BRIDLEBIT CREEK
SEDIMENT/DISCHARGE
SCATTERGRAMS

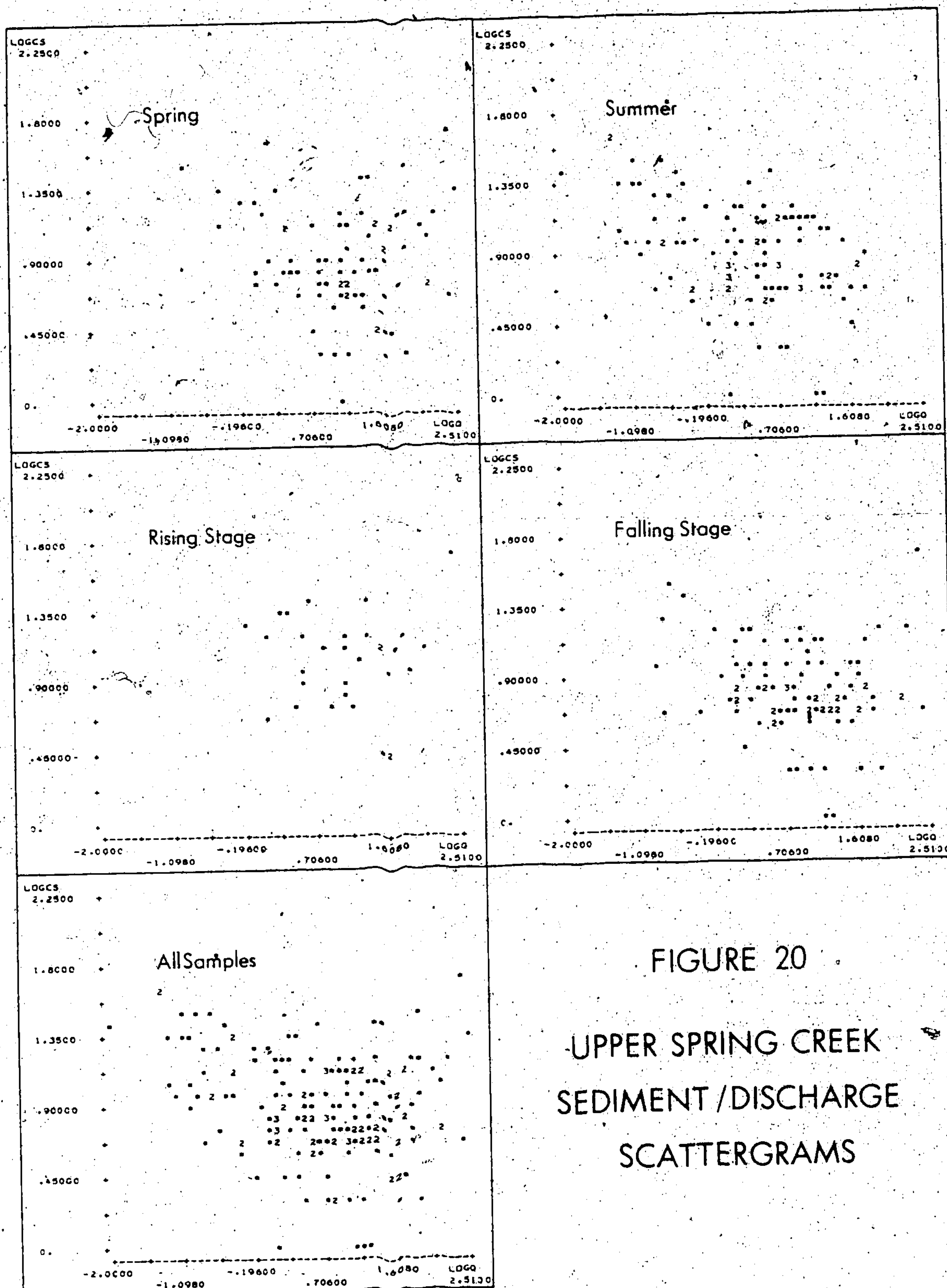


FIGURE 20

UPPER SPRING CREEK
SEDIMENT / DISCHARGE
SCATTERGRAMS

7.10 Discussion of Sediment Rating Curve Analysis

It was previously established that sediment productivity within Spring Creek Watershed increases from headwaters to mouth through three geomorphic zones. The location of gauging stations in relation to these zones affects the predictive ability of the corresponding sediment rating c[illegible]. As progressively higher sediment producing zones are inclu[illegible] the gauged watershed area, the erratic sediment inputs from the upper watershed are overridden and the correlation between sediment concentration and streamflow rates improves.

It seems to follow then that since Wolverine Creek has a much greater sediment yield than Horse Creek, it should also have better defined rating curves. This is not the case. Over the period of record, Wolverine Creek Watershed was subject to a number of disturbances which produced non-stationarity in its sediment system and the associated series of sediment measurements. Under such conditions, the correlation between sediment concentration and streamflow rates is expected to be weak.

Wolverine Creek behaves differently from Horse and Spring Creeks in that its seasonal rating curves are different from each other in both form and position. Although data from this single watershed are an inadequate basis for generalization, they suggest that disturbance of a watershed will not only increase its sediment yield but may also affect other aspects of the sediment regime, such as the pattern of sediment output and the overall sediment/discharge relationship.

The rating curves of Rocky, Bridlebit and Upper Spring Creeks poorly illustrate the erosion processes which are acting in these watersheds. Erosional inputs of sediment to the streams are blocked by the numerous "filters" in the drainage network. Much of the measured variation in sediment concentration is due to variations in the amount of organic material in transport and is therefore largely independent of streamflow rates. The use of sediment rating curves for predictive purposes in this and similar watersheds is not feasible.

The Horse Creek rating curves reflect erosion processes in the lower watershed area. However, variations in sediment concentration unrelated to streamflow are introduced by inflow from the upper watershed area and produce "noise" in the measured sediment - streamflow relationship. This results in weakly defined rating curves which would give poor results if used for prediction.

The Spring Creek rating curves give reasonably good predictions of sediment concentration from streamflow rates. Since the gauged tributary streams, which account for over 80% of the total water yield, have such poor rating curves, it is apparent that the sediment - streamflow relationship measured at the mouth of Spring Creek must be largely controlled by factors operating outside the gauged tributary watersheds. As streamflow enters the lower interbasin area, its capacity to transport sediment increases and sufficient sediment is usually available to match that capacity. The processes acting in this small zone provide most of the sediment yield and dominate the sediment regime measured at the mouth of Spring Creek Watershed.

7.11 Solute Rating Curves

The relationship between solute concentration and discharge for

Spring Creek and its tributaries is illustrated in Fig. 21. Note that actual solute concentrations in mg/l are plotted against the log values of discharge. The correlation between these variables is negative and the data plot follows a straight line. In other words, solute concentration is inversely related to discharge, and its rate of change, which is initially very rapid, decreases toward higher discharges.

During low flow periods, most of the runoff from these watersheds is derived from baseflow and therefore solute concentrations are high. When discharge increases, solute concentrations are rapidly reduced as the baseflow is diluted by storm or snowmelt runoff. This dilution effect becomes less pronounced at higher flows as the streamflow solute concentration approaches the maximum attainable by storm or snowmelt runoff.

The data sets for each watershed were subdivided on the basis of season and stage using the same criterion that were applied to the sediment data. This produced no change in the form of the rating curves and covariance analysis failed to identify any significant difference between the seasonal and stage-differentiated curves.

Figure 22 shows that there is considerable variation in the slopes and intercepts of the solute rating curves of Spring Creek and its tributaries. Peak solute concentrations are greatest in Wolverine Creek and least in Upper Spring Creek. Although during moderate and high discharges, concentrations are highest in Spring Creek, for any given frequency of flow, discharge is higher in Spring

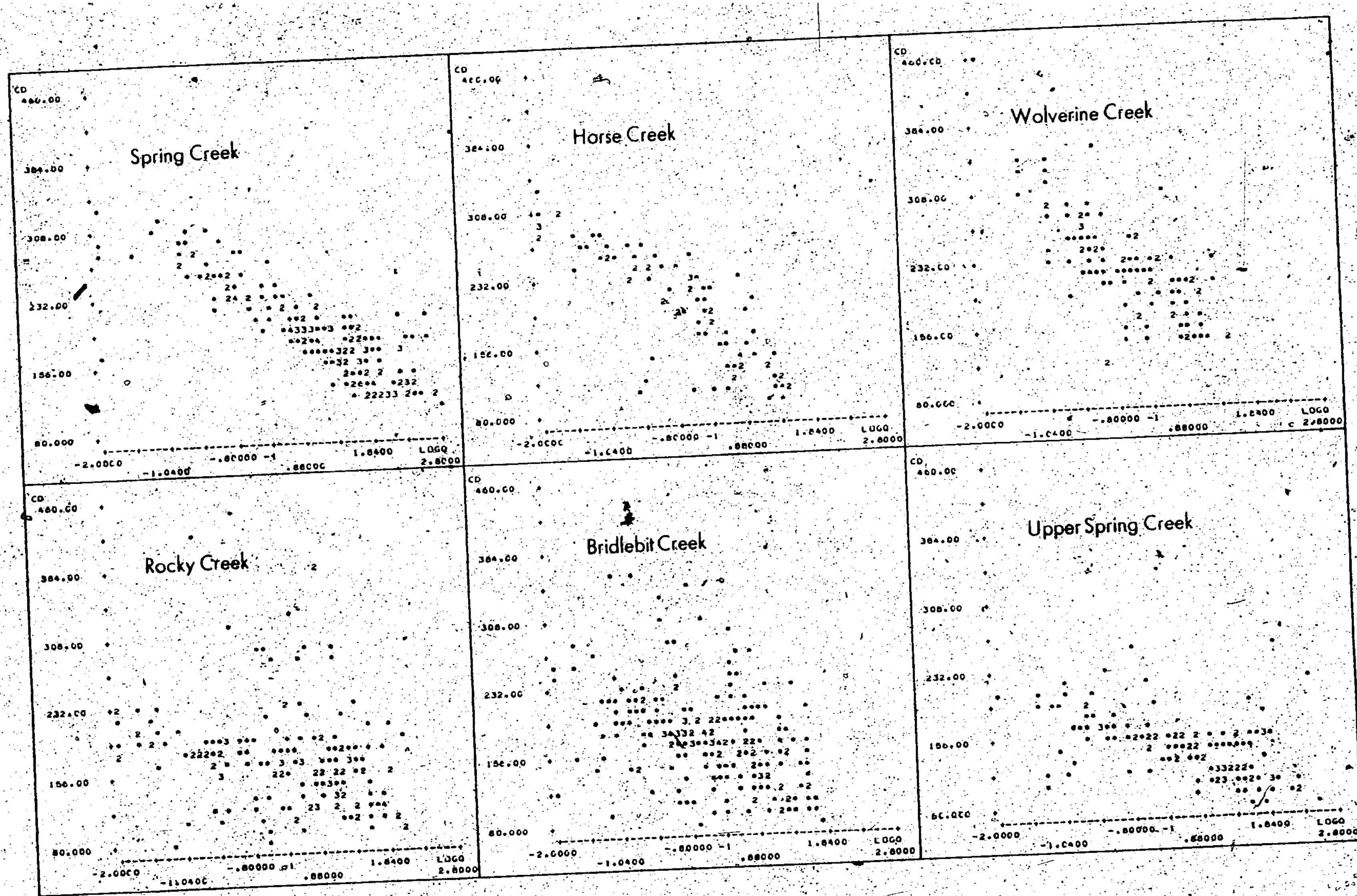


FIGURE 21: SOLUTE/DISCHARGE SCATTERGRAMS

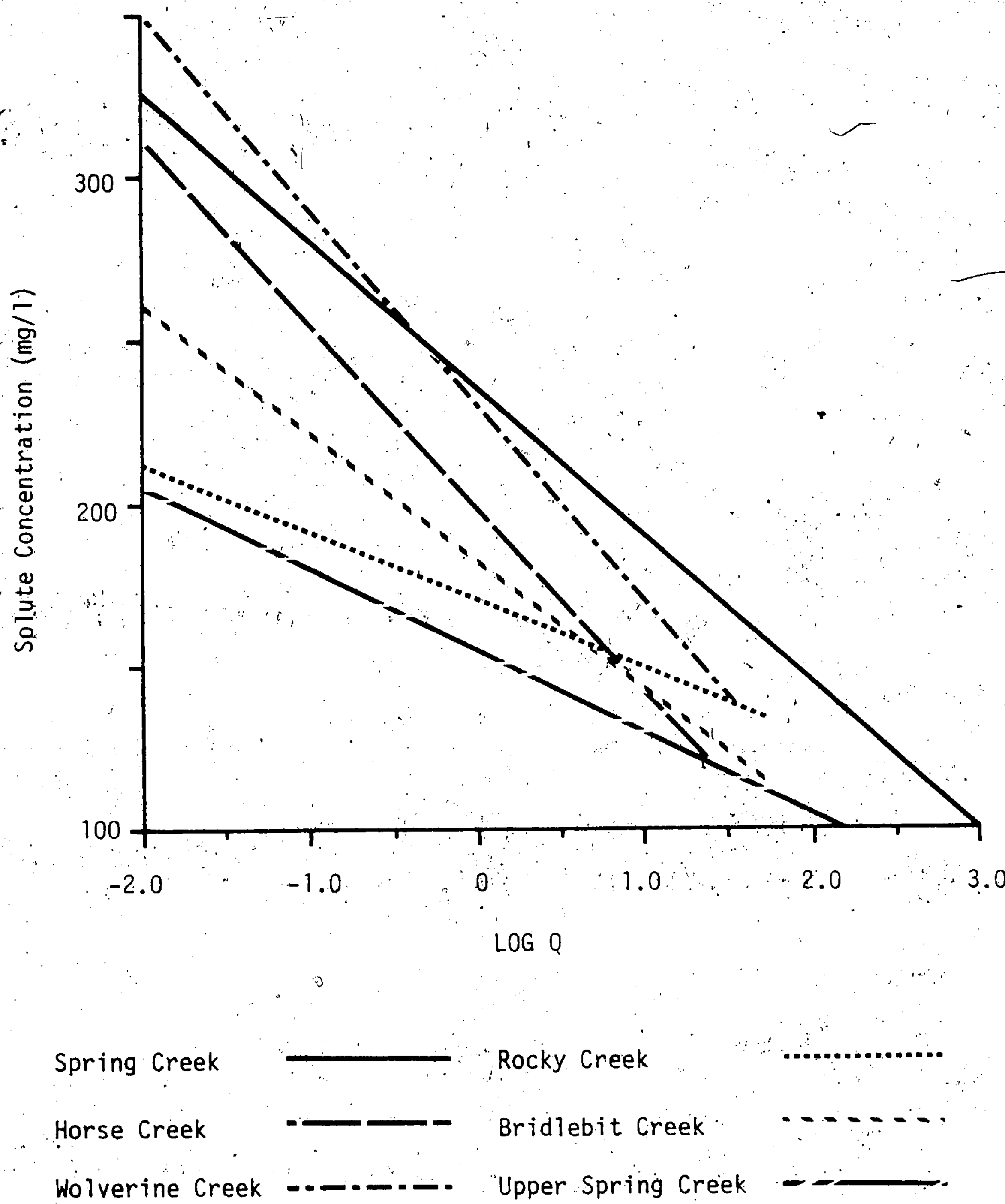


FIGURE 22: SOLUTE RATING CURVES

Creek than in any of its tributaries. Therefore it is not expected that the mean solute concentration of Spring Creek (i.e. 162 mg/l) will be appreciably higher than that of its tributaries.

For Spring Creek, the ratio between the mean solute concentration and the mean sediment concentration (as determined by regression analysis in section 4.1) is 0.6:1. A first approximation of the solute/sediment ratios of the gauged tributaries can be made assuming that they all have a mean solute concentration of 162 mg/l; the same as Spring Creek. This assumption cannot be truly justified but it does not seem entirely unreasonable in view of the relationship between the solute rating curves. The ratios of the tributaries range from 6:1 for Horse Creek to 15:1 for Upper Spring Creek. The indication is that solute production is far more significant among the gauged tributary streams than it is for Spring Creek Watershed as a whole.

The r^2 values of the regression equations which define the rating curves range from .75 for Spring Creek to .30 for Rocky Creek (see Table 10). The variation in the predictive ability and the position of the solute rating curves is related to the geologic and goundwater flow characteristics of the watersheds. Very little data regarding these variables are available, and therefore it is impossible to develop detailed explanations of the solute-discharge relationships.

TABLE 10 - SOLUTE REGRESSION ANALYSIS

	Regression Equation	n	r^2	*Level of Significance
Spring Creek	Y = -43.686 X + 233.44	196	.75075	.0000
Horse Creek	Y = -55.393 X + 197.36	95	.71015	.0000
Wolverine Creek	Y = -57.615 X + 227.42	105	.52804	.0000
Rocky Creek	Y = -20.069 X + 170.57	131	.29978	.0000
Bridlebit Creek	Y = -38.311 X + 179.76	142	.45636	.0000
Upper Spring Creek	Y = -23.508 X + 154.50	119	.45462	.0000

Y = Solute concentration in mg/l

X = $\log_{10}$ of discharge in cfs

* = attained level of significance of the null hypothesis

8. CONCLUSIONS

8.1 Most of the sediment yield of Spring Creek Watershed is derived from a small area within a short period of time. A 1.5 km^2 area of the Spring Creek Valley near the watershed mouth provides 90% of the sediment yield. The sediment discharge of an average of 18 days per year accounts for 90% of the annual sediment yield. Combining spatial and temporal aspects, shows that over 80% of the sediment yield is derived from 1.5% of the watershed area in less than 5% of the time.

8.2 The well-defined annual and instantaneous relationships between sediment and streamflow observed at the mouth of Spring Creek Watershed are established outside the gauged tributary watersheds, primarily in the lower interbasin area.

8.3 The contribution of tributary areas to the sediment yield of the watershed as a whole is extremely variable. The headwater areas yield less than 2 $t/km^2/yr$ while a small portion of the Spring Creek Valley yields nearly 2000 $t/km^2/yr$.

8.4 Distributing the sediment yield measured at the mouth of Spring Creek over the watershed area gives an unrealistic erosion rate per unit area. It is not applicable to the vast majority of the watershed area. Erosion rates calculated in this fashion should not be used to predict the sediment yield of smaller units within the watershed.

8.5 The dominant control on the spatial pattern is a series of past base level changes which are expressed as knickpoints on the channel of Spring Creek and its tributaries. The areas immediately downstream of the knickpoints are considered to be zones of geomorphic disequilibrium and are identified as the major sediment sources within the watershed.

8.6 The portion of the watershed upstream of the older knickpoints, 85% of the area, contributes practically nothing to the sediment yield of the watershed. A heavy forest cover limits sediment production and numerous beaver dams along the stream channels act as filters which transmit water but little sediment. Much of the sediment discharged from this area is derived through biological rather than erosional action.

8.7 The ratio of solute production to sediment production for Spring Creek Watershed is 0.6:1 but among the gauged tributary streams the ratio ranges from 6:1 to 15:1. Solute production is believed to be fairly constant over the watershed, and variation in solute/sediment ratios largely reflects the variation in sediment production.

8.8 On average, 76% of the sediment yield of Spring Creek is discharged during spring runoff. A similar pattern exists among the tributaries. The importance of spring runoff in the sediment regime was expected in view of its importance in the regional hydrologic regime. Seasonal variations in sediment concentration can be explained in terms of variation in flow characteristics.

8.9 Sediment rating curves give reasonably good predictions of sediment concentration from streamflow rates for Spring Creek but not for its tributaries. Much of the variation in sediment concentration in the tributary streams is related to biologic activity which is largely independent of streamflow.

8.10 No significant differences exist between rising stage and falling stage sediment rating curves for Spring Creek and its tributaries.

8.11 Spring sediment rating curves are defined by linear regressions while the summer curves are non-linear and defined by second degree polynomial regressions. However, in Spring Creek and Horse Creek no significant differences exist between the seasonal rating curves over moderate and high flows. Seasonal differences exist only at low flows and are attributed to the operation of variables not directly related to discharge. Principal among these variables is organic sediment production which is favored by the higher water temperatures and relatively stable aquatic environment associated with low summer flows.

8.12 Seasonal differences in Wolverine Creek are not restricted to low flows, but exist at moderate and higher flows. This suggests that watershed disturbances can not only increase sediment yield but may also affect other aspects of the sediment regime, such as the pattern of sediment output and the overall sediment/discharge relationship.

8.13 The prediction of sediment discharge from rating curves in this type of watershed faces a number of difficulties. Simply fitting a straight line to a number of samples will probably fit the data poorly and will not accurately reflect the sediment-discharge relationship. Anomalously high sediment concentrations at low flows will not appreciably affect the net sediment yield of the watershed, but if a linear regression is used, they will shift the position of the lower end of the rating curve and thereby increase its intercept and reduce its slope. If insufficient samples are available to define the curvi-linear summer curve, a rating curve based on spring samples could probably give reasonable estimates if applied over the entire year. Extrapolation of the spring curve can be done more easily and with more confidence than extrapolation of the summer curve. Alternatively, summer data could be used omitting samples taken at flows less than 50% of the mean streamflow rate.

8.14 The analysis presented here further supports the hypothesis that the use of instantaneous sediment rating curves in conjunction with mean daily flow data will underestimate sediment discharge. Instantaneous rating curves should be used only with instantaneous (or nearly so) streamflow data.

8.15 Annual shifts in the position of the Spring Creek rating curve occurs, although the reason for this is not understood. It is desirable that rating curves be based on samples taken over a number of years.

8.16 Any attempt to model the sediment dynamics of the tributary streams must incorporate other variables in addition to streamflow. Attention should be given to factors which affect the organic sediment load.

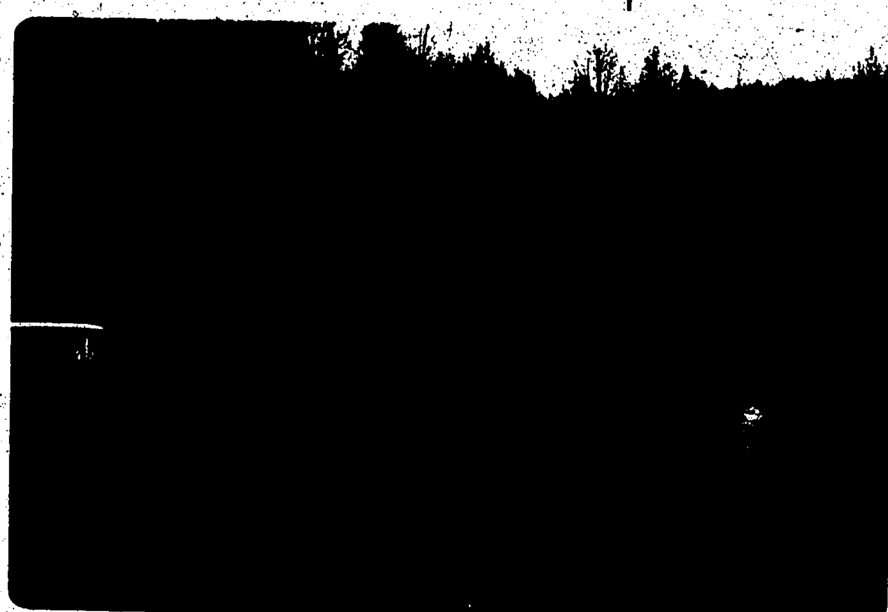
8.17 More complex models of the sediment discharge of Spring Creek should concentrate especially on the factors which are operating in the lower inter-basin area since this is the source of the vast majority of the sediment yield of the watershed. For the same reason, a model which aims to predict the spatial variation in the sediment yield between watersheds similar to Spring Creek should focus on the conditions that exist in the disequilibrium zones connecting the upland areas with the major rivers into which the watersheds drain.

8.18 Land use impacts on the watershed sediment yield have been variable. The main access road does not seem to contribute a substantial amount of the watershed sediment yield. The road surface drains to ditches which support a lush vegetation growth and the stream crossings, with one exception, are well-designed and stable. On the other hand gullying and willow destruction caused by past livestock grazing are seen as the major cause of the anomalously high sediment yield of Wolverine Creek. The most severe and problematic land use impact was caused by the construction of a pipeline corridor across Spring Creek. This disturbance of .004% of the watershed area produced an increase in the watershed sediment yield of 36% in 1977.

8.19 This research has several implications for land managers involved in erosion control. Primarily, disturbances in the disequilibrium zones of watersheds should be avoided if at all possible. Aggravating the natural instability of these areas will lead to the rapid development of erosion problems. The severity of the problems will depend on the nature of the disturbance. Accelerated erosion of these areas could also be caused by action outside the disequilibrium zones. The development of land drainage works and the removal of beaver dams in upstream areas can increase flow volumes and peak flows through the sensitive reaches. In this situation, channel protection works and artificial water storage sites should be provided if erosion problems are to be avoided.

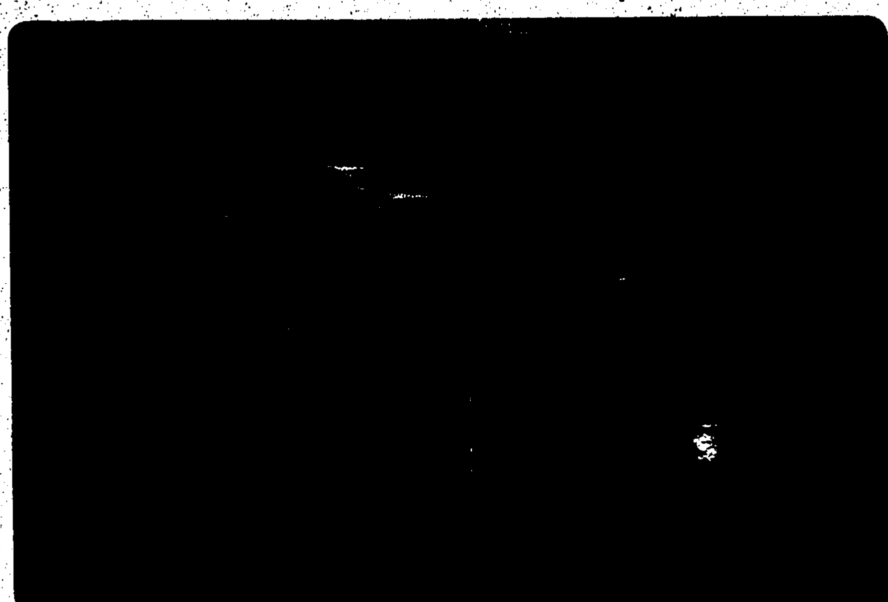
9. PHOTOGRAPHS

1. Junction of Spring Creek and Simonette River. Circle marks the junction. Note road and pipeline right-of-way in background.



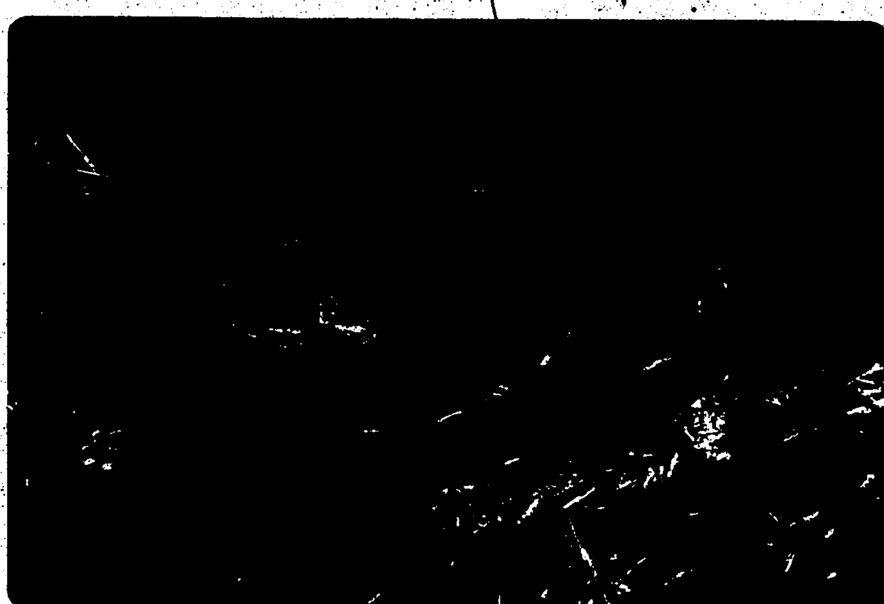
2. Spring Creek (Main) Gauging Station

5. Rocky Creek Gauging Station.



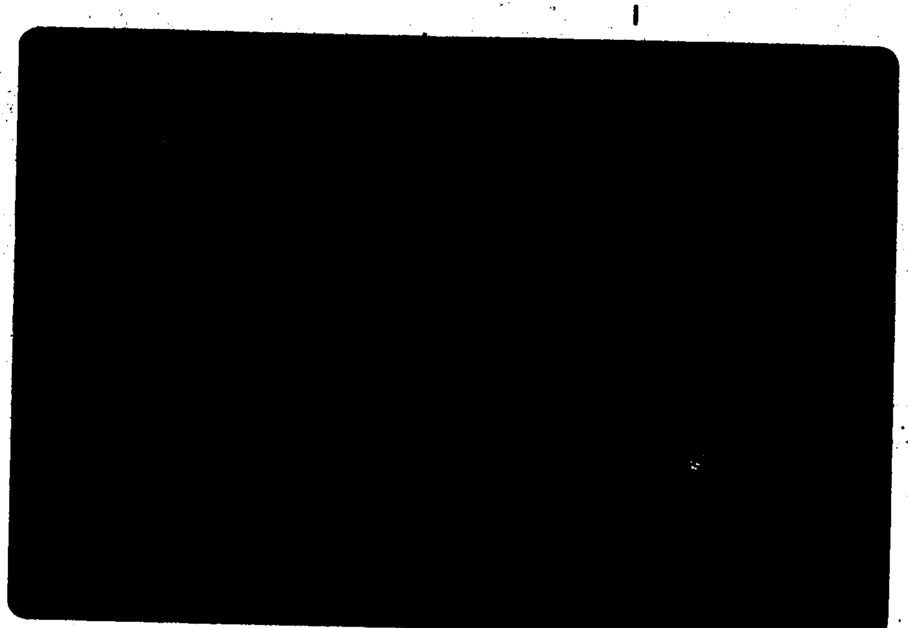
6. Bridlebit Creek Gauging Station. Note debris from beaver dam downstream from gauge.

7. Upper Spring Creek Gauging Station. Note lack of relief in surrounding area.

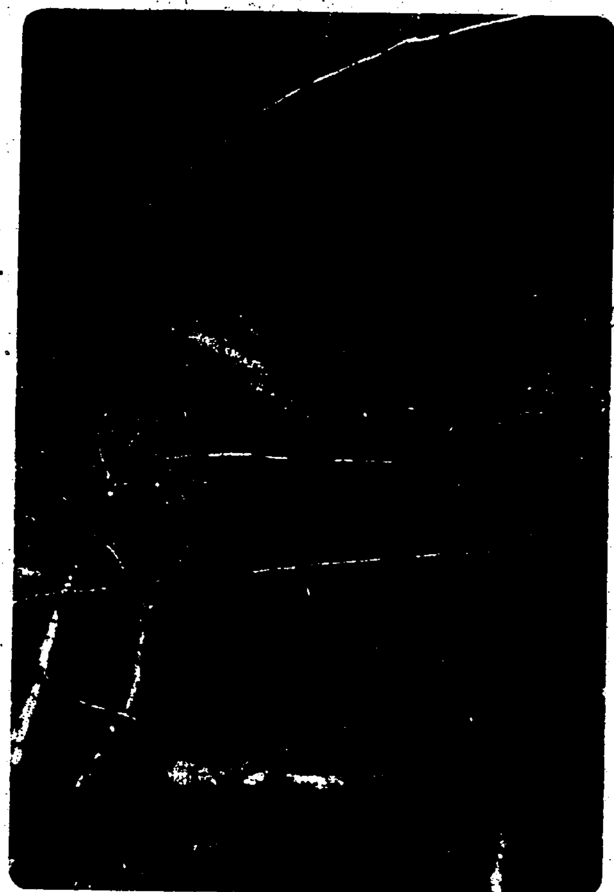


8. Sediment Sampling Site Upstream of Pipeline. Looking upstream across pipeline right-of-way. Samples taken from foot bridge.

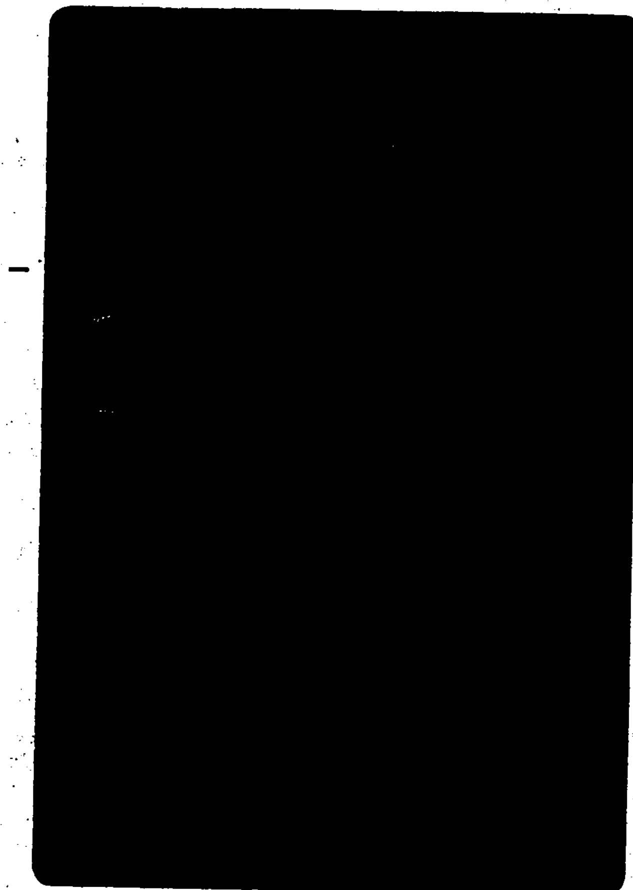
9. Sediment Sampling Site Downstream of Pipeline. Looking downstream across pipeline right-of-way. Samples taken from foot bridge.



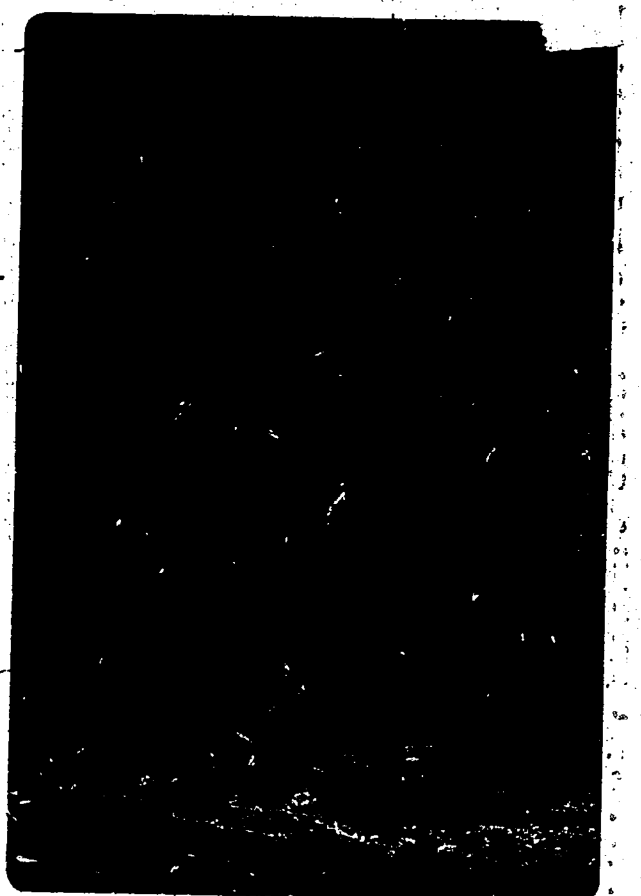
10. Slumping on Wolverine Creek. Slump is adjacent to main channel approximately 200 m upstream of gauge.



11. Slumping on Spring Creek. Slumping is along main channel about 100 m upstream of pipeline. Typical of lower reach of Spring Creek.

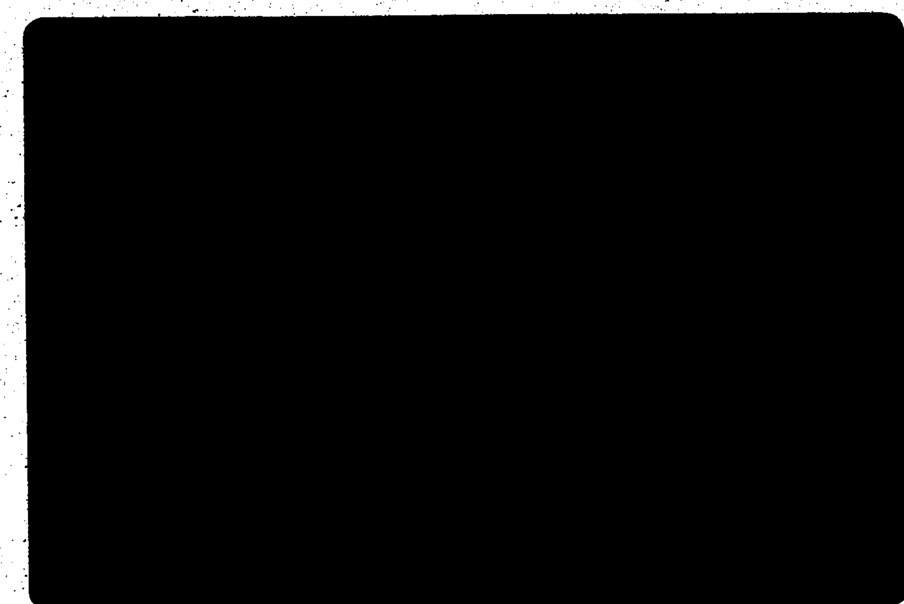


12. Pipeline Right-of-Way: North Valley-side. Taken July, 1977. Note tractor trail on which helicopter has landed. Road at crest of slope.



13. Pipeline Right-of-Way: South Valley-side. Taken May, 1977. Note soil pipe outlets at mid-slope and berm at crest of slope.

14. Junction of Spring Creek and Wolverine Creek. Circle marks the junction.



15. Outlet of Lake on Bridlebit Creek. Note beaver dam and floating organic material.

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