THE UNIVERSITY OF MANITOBA

ALLUVIAL FAN GEOMORPHIC SYSTEMS:
THE RIDING MOUNTAIN ESCARPMENT MODEL

by

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ABSTRACT

This study investigates the relationships between watershed morphology, stream hydrology and the parameters which represent the alluvial fans located at the base of the Riding Mountain Escarpment.

A partial synthetic systems model has been used in the first part of this study to suggest theoretical linkages between selected watershed morphometric parameters and the alluvial fan slope. Later this general systems model was expanded to include several variables considered to be representative of the stream subsystem. Initially, the variables were examined separately, employing simple regression and correlation techniques. Later, they were collapsed into two theoretically independent variables (catchment area and unit area effective fan building discharge), and subjected to stepwise multiple regression techniques. The resulting mathematical models support the primary assumption of systematic equilibrium. Since this is the case, the alluvial fan geomorphic systems operating on the eastern slopes of Riding Mountain are considered to be in a state of dynamic equilibrium.

Further examination of the multiple regression models, indicate that the watershed area is the dominant component of these systems, while specified stream discharge variables, associated with stream competence, are less significant.

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LIST OF SYMBOLS

Symbol	Description
A	Total planimetric drainage basin area or watershed area.
Af	Alluvial fan planimetric area.
AX	Stream channel cross sectional area. Equal to $\bar{d} \cdot \bar{w}$ and $R \cdot P$
c	Regression constent for the power function $Y = cX^n$
c'	Mean unit area storm discharge coefficient
c"	Mean unit area snowmelt discharge coefficient.
d	Stream depth of flow
$\bar{d}$	Mean stream depth
D	Bed material grain size defined by a "b" axial measurement
D_{50}	Median grain size or that size of a rock which is larger than 50% of the bed material size distribution
D_{75}	That rock size which is greater than 75% of the bed material size distribution
D_{90}	That rock size which is greater than 90% of the bed material size distribution
Deg. F	Degrees of freedom
e	The constant 2.27 or base of the natural logarithm
ei	Exact error in a measurement Xi
Ei	The limiting absolute error in a measurement Xi .
fi	The fractional or relative error in a measurement Xi
F	The F statistic
G	Total stream sediment discharge or total sediment yield

Symbol	Description
Ht	Drainage basin height . . . .
Ht/L	Drainage basin slope . . . .
$Ht/\sqrt{A}$	Drainage basin relative relief ratio . . . . .
k	Constant (runoff constant in Forsaith, 1949 model) . . . .
L	Drainage basin length . . . .
m	Exponent for the power function $Y = cX^m$ . . . .
M.A.F.	Mean annual flood discharge . . . .
Md	Median value or sample median . . . .
Md	White (1940) moment of drag. . . . .
Mw	White (1940) moment of resistance to incipient motion . . . .
n	Sample number . . . .
n	Number of years of flood record . . . .
n	Exponent for the power function $Y = cX^n$ . . . .
n	Manning roughness coefficient . . . .
N	Linsley (1958) groundwater basin lag time . . .
P	Channel wetted perimeter . . . .
Q	Stream discharge . . . .
Q/A	Unit basin area stream discharge; i.e. the discharge for 1 sq. mi. or 1 $km.^2$ . . . . . .
QD	Effective fan building discharge for erosion and transport of stream bed material . . . . .
QD_{50}	Effective fan building discharge for erosion and transport of 50% of the bed material . . .
QD_{75}	Effective fan building discharge for erosion and transport of 75% of the bed material . . .

Symbol	Description
QD_{90}	Effective fan building discharge for erosion and transport of 90% of the bed material . . .
QD/A	Unit area effective fan building discharge . .
QD_{75}/A	Unit area effective fan building discharge for erosion and transport of 75% of the bed material . . . .
QD_{90}/A	Unit area effective fan building discharge for erosion and transport of 90% of the bed material . . . .
Q M.A.F.	Mean annual flood discharge . . . .
Q/A M.A.F.	Unit area mean annual flood discharge . . . . .
r	Correlation coefficient . . . .
r_7	Correlation coefficient for 7 basin sample . .
r_{20}	Correlation coefficient for 20 basin sample . .
ri	A randon error in a measurement Xi . . . . . .
$\bar{r}$	The mean random error . . . .
r^2	Coefficient of determination . . . .
r*	Partial correlation coefficient . . . .
r^{*2}	Partial coefficient of determination . . . . .
R	Ranking in a flood frequency analysis . . . . .
R	Sample range . . . .
R	Stream channel hydraulic radius . . . .
R_{75}	The stream channel hydraulic radius estimated for an effective fan building discharge QD_{75}. .
R_{90}	The stream channel hydraulic radius estimated for an effective fan building discharge QD_{90}. .
RI	Flood recurrence interval . . . .
s	Sample standard deviation . . . .
$s/\bar{X}$	Coefficient of variability . . . .

Symbol	Description
S	Stream energy slope . . . .
Sb	Stream bed slope . . . .
Sc	Standard error in the regression constant c . .
Sn	Standard error in the exponent n . . . .
Sw	Stream water surface slope . . . .
SD	Sample standard deviation . . . .
SE	Standard error of the estimate . . . .
SK	Sample skewness . . . .
St. Dev.	Sample standard deviation . . . .
t	A real number . . . .
t	The t statistic . . . .
u	The sample mean . . . .
v	Mean cross sectional stream velocity . . . . . .
Vmc	Critical erosion velocity determined from a mean critical cross sectional velocity . . . . .
V*	Critical erosion velocity determined from a mean cross sectional velocity . . . .
V^*_{75}	Critical erosion velocity for D_{75} material . . .
V^*_{90}	Critical erosion velocity for D_{90} material . . .
Var	Sample variance . . . .
w	The surface width of a stream channel . . . . .
$\bar{w}$	The mean width of a stream channel . . . .
W	Average drainage basin width . . . .
X	The general independent variable . . . .
Xo	The true or target value of a measurement . . .
Xi	An estimate or measurement of Xo . . . .
$\bar{X}$	The mean value . . . .

Symbol	Description
Y	The general dependent variable . . . .
Z	A real number . . . .
σ	The population standard deviation . . . .
λ	The alluvial fan slope . . . .
π	3.14 . . . .

CHAPTER I

A GENERAL INTRODUCTION TO THE STUDY

1:1 The Problem

Since the draining of Glacial Lake Agassiz, the small streams rising on the Manitoba Escarpment have generally drained northeast. Frequently, their flow was disrupted by the numerous Agassiz beach ridges or impeded by low lying marsh areas located on the Agassiz lake plain. Both these barriers assist in spreading out the streams and rapidly alter the hydrometric parameters, causing sediment deposition.

The physical and chemical weathering of this sediment result in a relatively productive agricultural soil. As such, the alluvial fan deposits attracted farmers in the late 1800's to the Riding Mountain Area. Increasing settlement pressure on these areas encouraged the draining of marshes and the clearing of land progressively up the escarpment slope. Areas of recently cleared, steep sloping land offer little resistance to runoff waters and the draining of natural reservoirs such as marshes has also promoted rapid drainage up stream. It is not surprising then, that the spring runoff and runoff from intense rain storms frequently produce short lived, devastating floods in the Riding Mountain area. Gully erosion has been particularly dramatic on the upper escarpment slopes, while thick shale deposits have flooded across the crop-carrying alluvial fan surfaces and recently drained marshlands.

A drainage system established in 1909 by the Manitoba Government provided for clearing of clogged drainage ditches and dyking of potential flood streams. This became an annual task and as the streams aggraded, seepage correspondingly added to costs.

In 1947 a particularly devastating flood occurred on Edwards Creek and in the following years, the Federal and Provincial Governments undertook the construction of floodways, control structures and the improvements of channels, at a cost of approximately two million dollars. By 1957 it became apparent that high maintenance costs accompanied such flood control measures. Furthermore, the very frequent maintenance indicated that the problem had not been solved and that the flood control schemes were only localizing the hazard. The Committee on Headwater Flood and Erosion Control was established in 1957 to collect basic information on flooding, erosion, and deposition. This committee selected a watershed (Wilson Creek) for detailed hydrometeorologic measurement. However, the atypical boundary of the basin located at the east boundary of Riding Mountain National Park limits the data collection to the erosion problem area. In essence then, the committee has examined only a segment of the problem, and like earlier government attempts at control, has lost sight of the total hydrologic system.

1:2 Objective of the Study

The purpose of this dissertation is to investigate the watershed - alluvial fan geomorphic system, as developed along the Manitoba Escarpment. In particular the dissertation will attempt to outline the empirical relationships which occur between the key components defining the watershed morphometry and stream hydrology and the parameters representing the alluvial fan, in order to establish an empirical model representative of the alluvial fan geomorphic system operating on the Manitoba Escarpment.

1:3 The Study Area

A small, but representative, section of the 800 km long Manitoba Escarpment was chosen as the study area. It comprises a 15 km wide strip of land parallel to provincial highway five, extending 65 km from the town of Eden in the south to Laurier in the north (Figure 1).

This area was selected for several reasons:

i. The acute erosion and sedimentation problems were recognized as early as 1909 (MacKay and Stanton, 1964)

ii. The area is centred on an International Hydrological Decade study basin (Wilson Creek) which has provided continuous hydrometeorological information since 1959.

iii. Much research has been published on: bedrock geology (Tyrrell, 1890a; Kirk, 1930; Wickenden, 1945); surficial geology (Upham, 1895; Johnston, 1946; Klassen, 1965; Elson, 1967); soils (Ehrlich et al., 1958); and paleoecology (Ritchie, 1964; 1967, 1969; Klassen et al., 1967).

iv. Topographic maps and air photo coverage of the region are available.

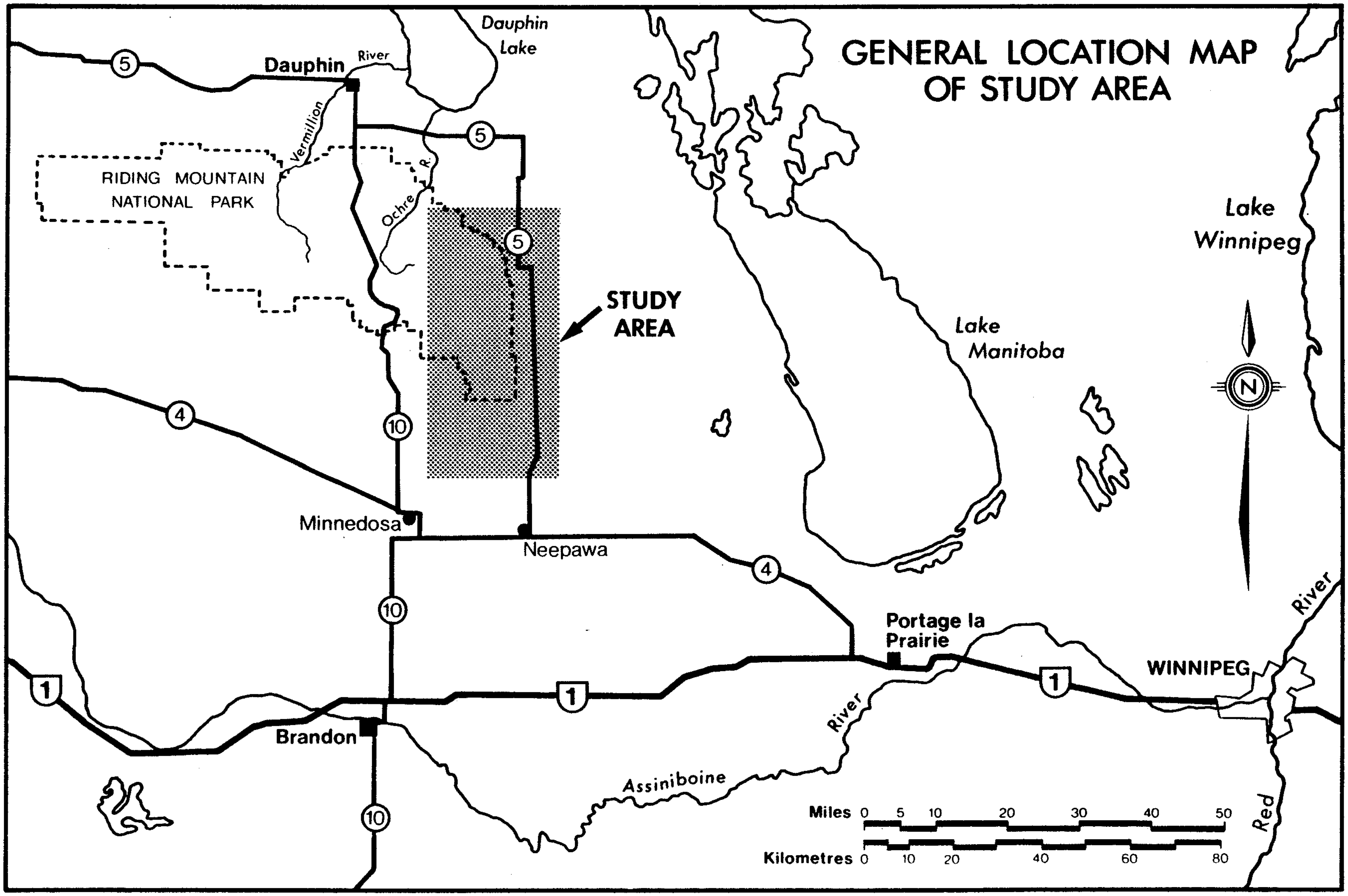

GENERAL LOCATION MAP
OF STUDY AREA
Dauphin
Lake
Dauphin
River
Vermillion
RIDING MOUNTAIN
NATIONAL PARK
Ochre R.
STUDY
AREA
Lake
Winnipeg
Lake
Manitoba
N
Minnedosa
Neepawa
Portage la
Prairie
WINNIPEG
River
Brandon
River
Assiniboine
Red
Miles 0 5 10 20 30 40 50
Kilometres 0 10 20 40 60 80

Figure 1

v. The small drainage basins selected for study are of a manageable size and accessible via numerous roads and lanes.

vi. The presence of the Riding Mountain National Park has reduced anthropomorphic factors.

vii. The area appears relatively homogeneous with respect to the physiography, geology, soils, vegetation, and climate.

1:4 Topography of the Study Area

MacKay and Stanton (1964) have subdivided the Manitoba Escarpment in the Wilson Creek area into three physiographic divisions, here designated as: (1) the catchment plateau; (2) the escarpment slope; and (3) the alluvial apron. The morphologic variations occurring in each of these divisions necessitates a more detailed description of their respective topographies than the general remarks presented in MacKay and Stanton's (1964) paper. Figure 2 illustrates the general physiography of the study area and four cross-sections in Figure 3 visually outline the morphologic variations which are summarized in Table 1.

The catchment plateau may be described as a gently rolling till plain ranging from a maximum elevation of 730 m a.s.l. in the north to 670 m in the south. From the catchment plateau, the land drops an average of 275 m in 4.0 km to the alluvial apron. In actual fact, a great deal of variation occurs in both the gradient and relative relief of the escarpment slope region. Mean slopes

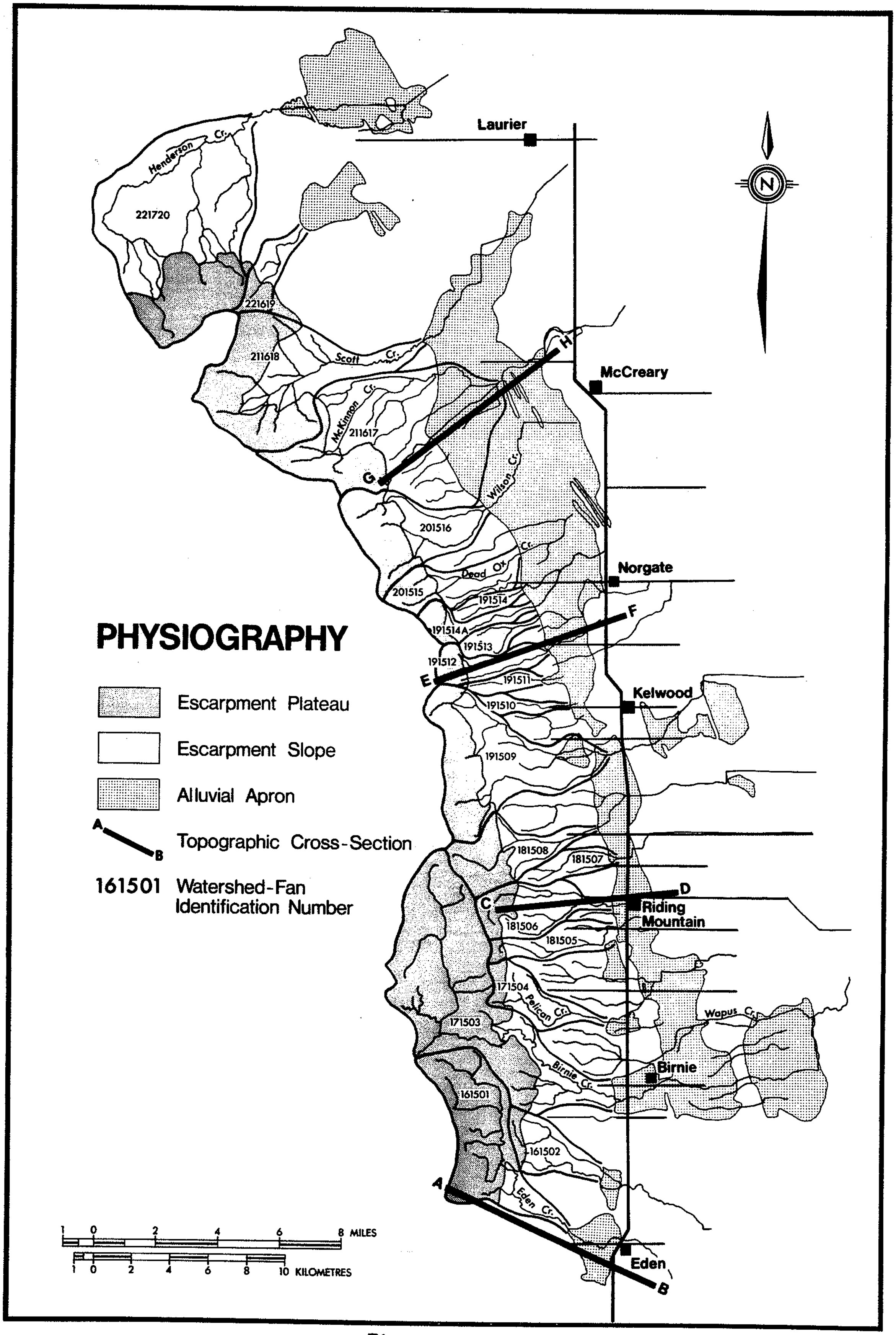
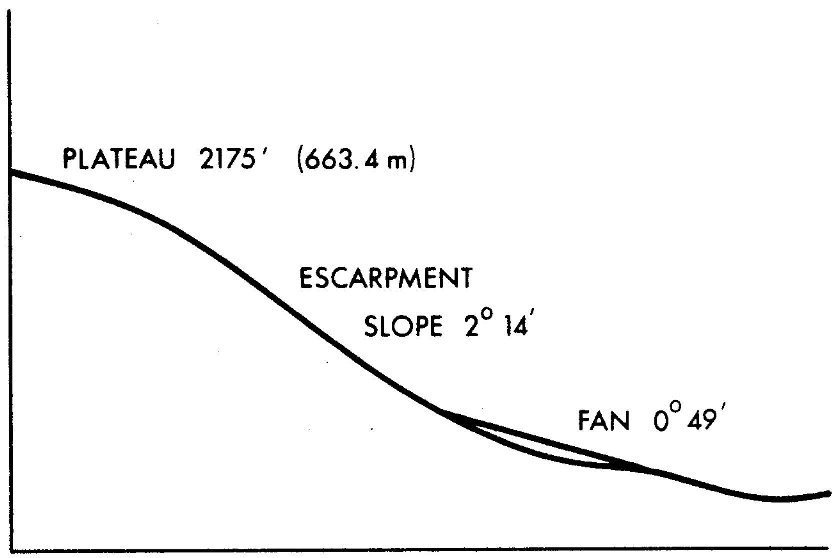

PHYSIOGRAPHY
Escarpment Plateau
Escarpment Slope
Alluvial Apron
Topographic Cross-Section
161501 Watershed-Fan Identification Number
Laurier
McCreary
Norgate
Kelwood
Riding Mountain
Birnie
Eden
Henderson Cr.
Scott Cr.
McKinnon Cr.
Wilson Cr.
Dead Ox Cr.
Pelican Cr.
Birnie Cr.
Eden Cr.
Wapus Cr.
221720
221619
211618
211617
201516
201515
191514
191514A
191513
191512
191511
191510
191509
181508
181507
181506
181505
171504
171503
161501
161502
A
B
C
D
E
F
G
H
N
MILES
KILOMETRES

Figure 2

SELECTED PHYSIOGRAPHIC CROSS-SECTIONS

Eden Cr. Section

(a)



1 : 200,000 horizontal

1 : 48,000 vertical

Riding Mountain Section

(b)

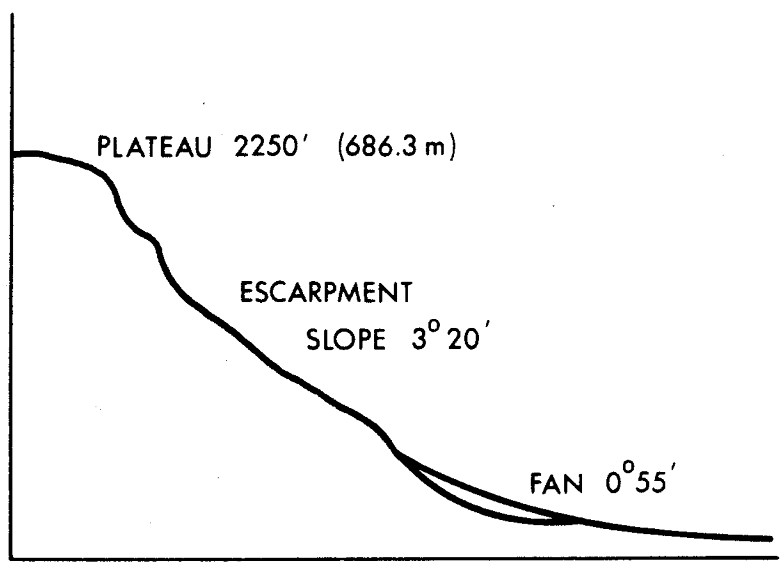
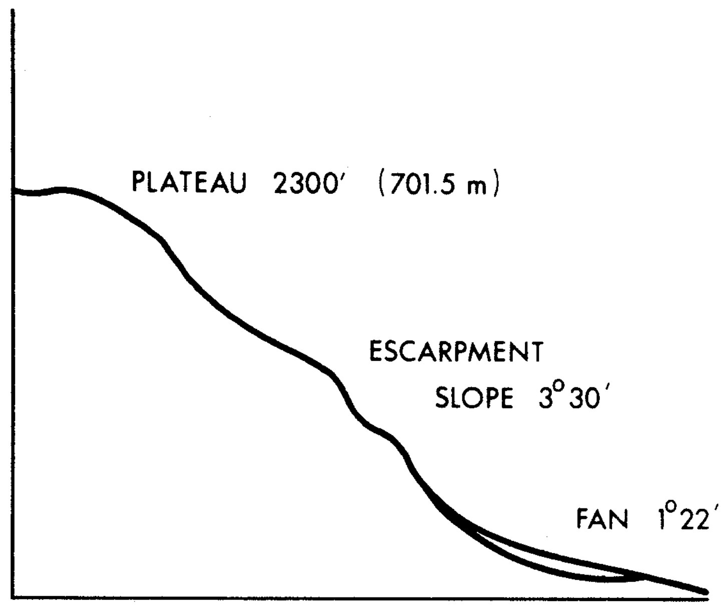


Figure 3

Kelwood Cr. Section

(c)



1:200,000 horizontal

1:48,000 vertical

McCreary Section

(d)

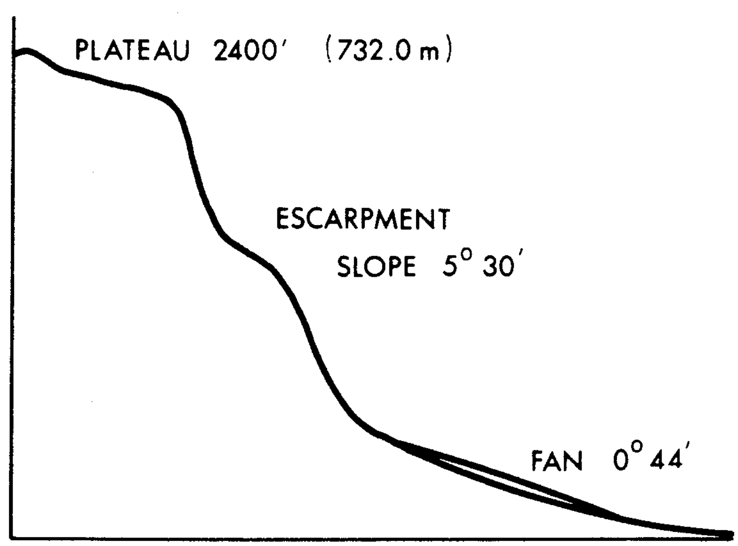


TABLE 1

SUMMARY OF THE TOPOGRAPHY OF THE STUDY AREA

Topographic Parameter	Approximate cross-section location			
	Eden	Riding Mountain	Kelwood	McCreary
Fan Slope	0.82°	0.92°	1.37°	0.73°
Escarpment Slope	2.23°	3.33°	3.50°	5.50°
Plateau Height	2175 ft 665 m	2250 ft 685 m	2300 ft 700 m	2400 ft 730 m
Fan Apex Height	1450 ft 440 m	1350 ft 410 m	1375 ft 420 m	1325 ft 405 m
Relative Relief	900 ft 275 m	1075 ft 330 m	1150 ft 350 m	1400 ft 425 m
Escarpment Slope Relief	725 ft 225 m	900 ft 275 m	925 ft 280 m	1075 ft 325 m

may be as low as 2.25° in the southern portion of the study area and as high as 6.00° in the north with relative relief varying from 225 m in the south to 325 m in the north. The escarpment slope region is also characterized by deeply incised intermittant streams. Stream incisions of between 30 m and 60 m are common and these account for the numerous stream bank exposures of partially weathered shale (Plate I).

The alluvial apron generally begins at a height of between 395 m and 460 m a.s.l. and slopes at an average of 1.00° towards the east or northeast. Fanhead entrenching of the streams is common in the predominantly silty deposits.

1:5 The Geology of the Study Area

Riding Mountain, the segment of the Manitoba Escarpment in this study, is formed by the outcroppings of Cretaceous shales rising 230 m to 425 m above the Manitoba Plain (Bostock, 1964). Figure 4 is derived from the bedrock topography map of Klassen, Wyder and Bannatyne (1970) and illustrates the bedrock geology of the study area.

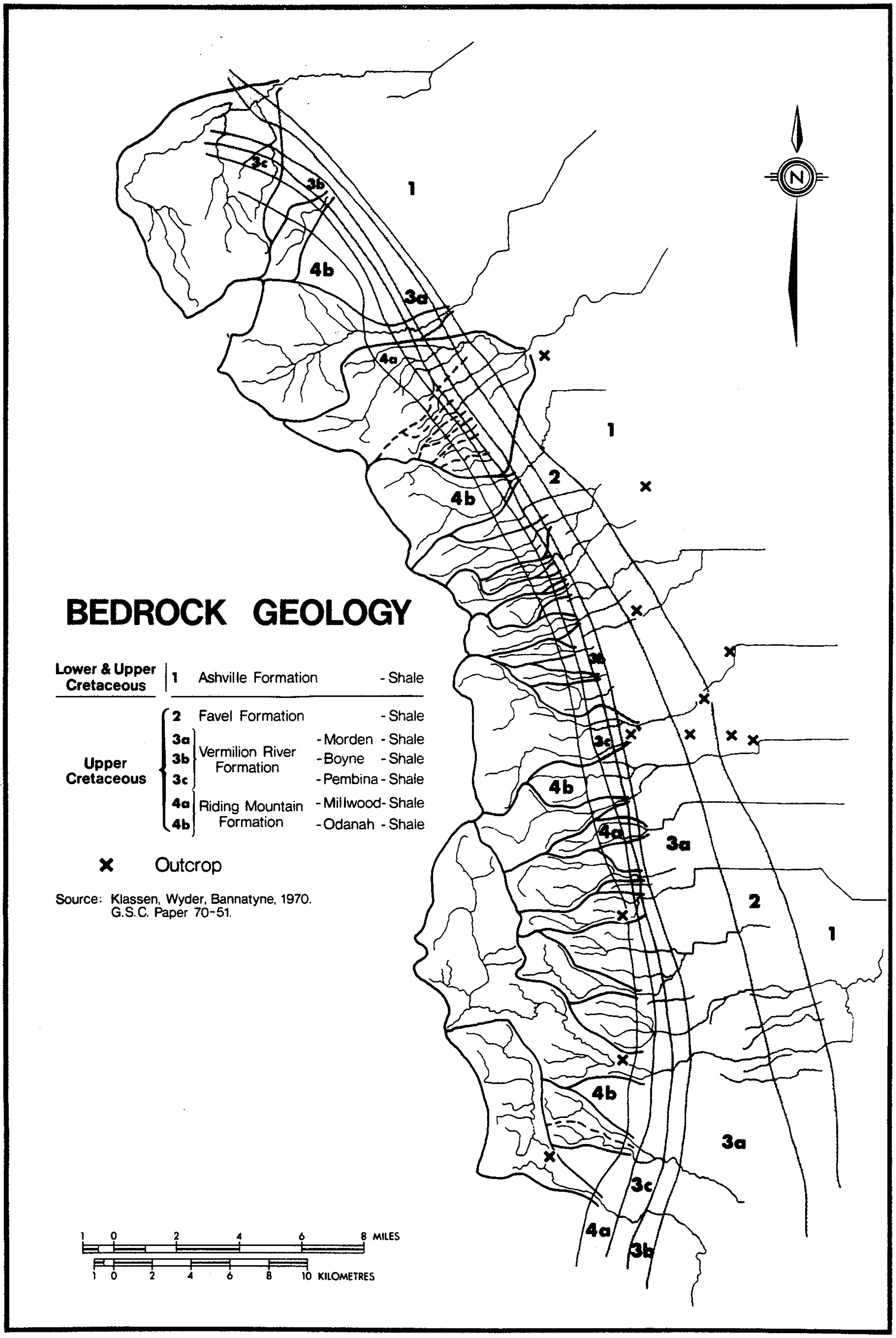
The basic stratigraphic nomenclature of the Manitoba Escarpment was formulated by Tyrrell in 1890. Since then, additional descriptive information and subsequent revisions have been presented by Leith, 1929; Kirk, 1930; Wickenden, 1945; and Kerr, 1949. Bannatyne (1963, 1970) has further investigated the properties of the Cretaceous shales and summarized the stratigraphy of the Manitoba Escarpment. Table 2 lists the formations and members present in the Riding Mountain area and Appendix I provides additional information regarding the physical characteristics of these members.

Following an interval of erosion of Jurassic rocks, deposition of the Cretaceous beds began. The sandstone and shale beds of the Cretaceous

PLATE I

A Shalebank Exposure in the Escarpment Slope Region

Stream incisions of between 100 and 200 feet deep are common in the escarpment slope region. The deep valleys account for numerous and sometimes extensive streambank exposures of weathered shale. These shalebanks are believed to represent the primary source of the alluvial fan sediments (MacKay and Stanton, 1964, 47).



BEDROCK GEOLOGY
Lower & Upper Cretaceous
1 Ashville Formation - Shale
Upper Cretaceous
2 Favel Formation - Shale
3a Vermilion River Formation - Morden - Shale
3b - Boyne - Shale
3c - Pembina - Shale
4a Riding Mountain Formation - Millwood - Shale
4b - Odanah - Shale
× Outcrop
Source: Klassen, Wyder, Bannatyne, 1970. G.S.C. Paper 70-51.
1 0 2 4 6 8 MILES
1 0 2 4 6 8 10 KILOMETRES
N
1
1
1
2
2
3a
3a
3a
3b
3b
3b
3c
3c
3c
4a
4a
4a
4b
4b
4b
4b

Figure 4

TABLE 2

CRETACEOUS STRATIGRAPHIC CHART FOR RIDING MOUNTAIN AREA

Era	Period	Epoch	Formation	Member	Approximate Thickness
MESOZOIC	CRETACEOUS	UPPER	Riding Mountain	Odanah	400 ft. 120 m
				Millwood	200 ft. 60 m
			Vermilion River	Pembina	40 ft. 12 m
				Gammon Ferruginous	120 ft. 36 m
				Boyne	80 ft. 25 m
				Morden	80 ft. 25 m
			Favel	Assiniboine	50 ft. 15 m
				Keld	50 ft. 15 m
			Ashville	Upper (base of fish scale zone)	100 ft. 30 m
		LOWER		Lower	70 ft. 20 m
			Swan River		

Swan River Group are thought to indicate a transition from the terrestrial Jurassic environment to a marine environment (Wickenden, 1945). Throughout most of the Cretaceous, continued subsidence resulted in the deposition of marine shales and limestone beds. The members of the Ashville, Favel, and Vermilion River formations were deposited during this interval. Near the end of the Cretaceous the axis of deepest sedimentation, formerly centred in Saskatchewan, shifted eastward and resulted in the deposition of the Riding Mountain Formation shales. This displacement is believed due to initial orogenic uplift of the Rocky Mountains. The main uplift resulted in the withdrawal of the seas from the Interior Plains and cessation of Cretaceous sedimentation.

The advent of the Tertiary is characterized by continued emergence and subsequent erosion and pediplanation, (Douglas et al., 1970). Bird (1972) suggests that the general process of scarp retreat in Tertiary times established the Manitoba Escarpment at its present-day geographical location - approximately 190-240 km west of the Precambrian Shield. No Tertiary deposits have been found in the study area and it is believed that the pre-Pleistocene topography of the Riding Mountain Area is closely approximated by the bedrock topography (Klassen et al., 1970).

1:6 The Surficial Geology

The lack of extensive stratigraphic sections in Manitoba has restricted Quaternary research to studies concerning the Wisconsinan glaciation. Major works by Klassen (1965) and Elson (1955) have substantially added to the previous studies of Tyrrell (1890b, 1891), Antevs (1931) and Johnston (1921, 1934, 1946). These studies have focused on two aspects of Wisconsinan stratigraphy: the pre - 12,000 years B.P. Wisconsinan glaciations; and the post - 12,000 years B.P. Glacial Lake Agassiz history.

The Wisconsinan stratigraphy of Western Manitoba has been summarized by Klassen (1969) and is illustrated in Figure 6.

The Shell Till overlies unnamed deposits of glacial and non-glacial origin which are believed to be pre-Wisconsinan in age. This till represents an early Wisconsinan glacial advance from east to west over the study area. The Shell Till is overlain by Roaring River Clay deposits, primarily of lacustrine origin and containing pollen, ostracods and molluscs. Klassen et al. (1967), on the basis of pollen and ostracod assemblages, postulated that the Roaring River Clay deposits were of interstadial origin. The interstadial was followed by a northeast to southwest glacial advance resulting in the deposition of the clay-silt rich Minnedosa Till. A second interstadial followed and has been dated (Klassen, 1969) at 40,000 B.P. An unnamed till and stratified glaciofluvial deposits comprise a stratigraphic unit described as "unnamed middle deposits" (Klassen, 1969). The Lennard Till overlying these "unnamed middle deposits" was laid down by the most recent glacial advance approximately 20,000 years B.P. The till is somewhat sandier than the previously deposited Minnedosa Till and has a northwest to southeast fabric. Following the deposition of the Lennard Till, the general glacial retreat of the late Wisconsinan took place. In Manitoba, this retreat is associated with the history of Glacial Lake Agassiz. Elson (1967) summarizes this history (Appendix II) and Prest (1970) presents an illustrated sequence of the Late Wisconsinan in Manitoba.

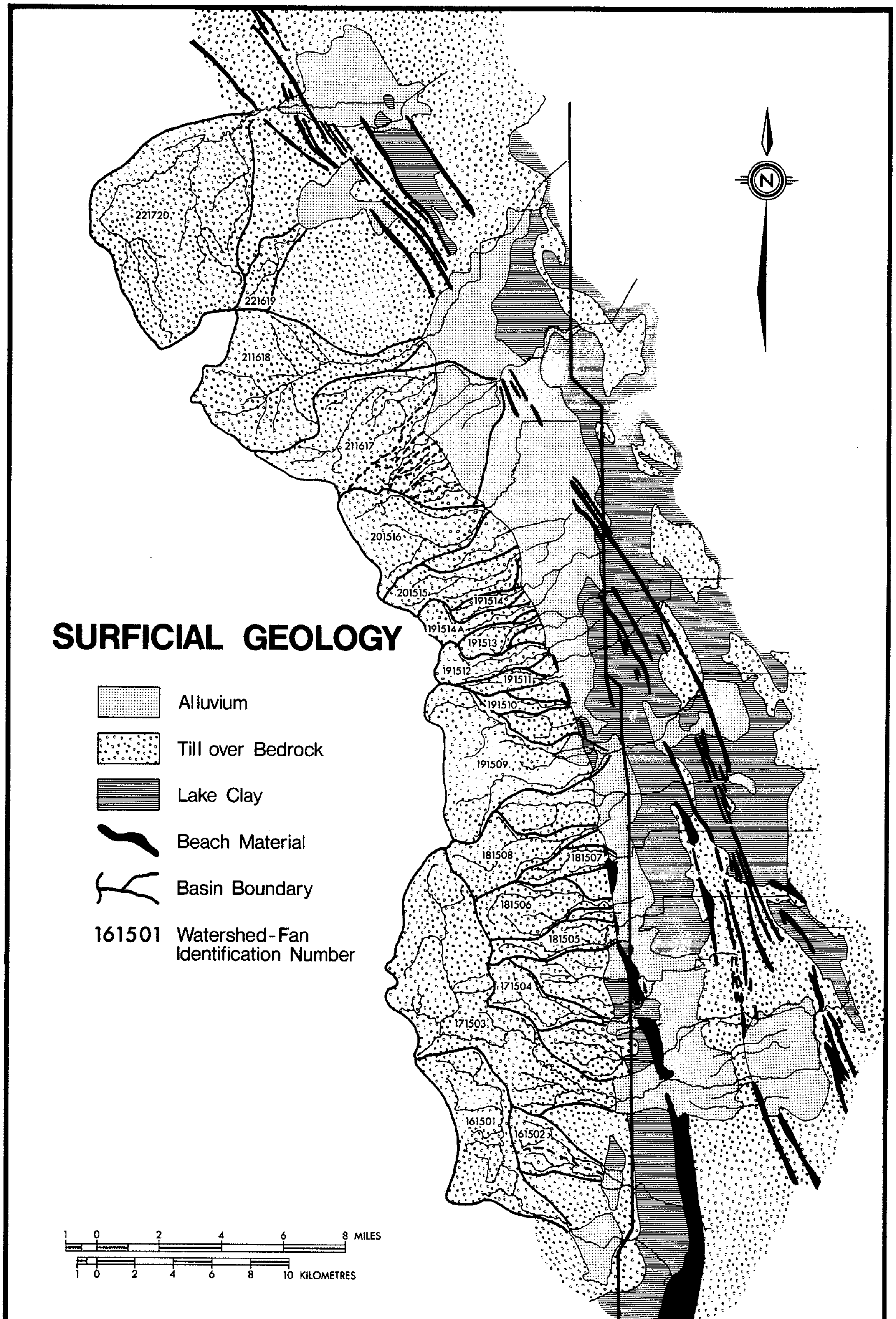

SURFICIAL GEOLOGY
Alluvium
Till over Bedrock
Lake Clay
Beach Material
Basin Boundary
161501 Watershed-Fan Identification Number
221720
221619
211618
211617
201516
201515
191514
191514A
191513
191512
191511
191510
191509
181508
181507
181506
181505
171504
171503
161501
161502
N
0 2 4 6 8 MILES
0 2 4 6 8 10 KILOMETRES

Figure 5

WISCONSINAN STRATIGRAPHY OF THE WESTERN MANITOBA

	Stratigraphic Unit		Date
Late Wisconsinan	Assiniboine Valley Sediments	unnamed upper deposits	10,000 B.P.
25,000 B.P.	Lennard Till		20,000 B.P.
Mid Wisconsinan	sand and gravel Till silt, sand and gravel	unnamed middle	40,000 B.P.
	Minnedosa Till		> 40,000 B.P.
55,000 B.P.	Roaring River Clay (interstadial)		
Early Wis-con-sinan 70,000 B.P.	Shell Till		
Pre Wisconsinan	Souris River Sand & Gravel (interglacial)	Unnamed lower deposits	

Source: Klassen 1969
Prest 1970

Time scale - Flint 1971

Figure 6

1:7 Soils and Vegetation

The soils formed on the catchment plateau and escarpment slope regions overlie a medium textured till containing shale, limestone and Precambrian Shield rocks (Ehrlich et al., 1958).

Grey wooded soils - the Granville Association - are well developed in the catchment plateau region and range in texture from fine, sandy loam to clay loam. The Granville soils are found in an area of hardwood and white spruce forest with an undergrowth of hazel, wild rose and allied shrub species (Ehrlich et al., 1958).

The improved drainage of the escarpment slope accounts for a transition from the Granville Association to the grey wooded Clarksville Association. The Clarksville soils vary in texture from fine, sandy loams to loams. The improved drainage accounts for a greater depth of leaching in these soils than in the Granville soils.

Associated with the Clarksville soils in the upper escarpment slope region is the Wapus Association. Wapus soils have developed on thin shaly till over shale rock. The better quality Wapus soils are fine, sandy loams. Ehrlich et al. (1958) indicate that Wapus soils are extremely susceptible to wind and water erosion and suggest that they not be cultivated.

In the lower segment of the escarpment slope region, dark grey wooded soils of the Erickson Association predominate. The finer texture of these soils reflect the glacio-lacustrine origin of the parent materials. The greater moisture retention and subsequently, lesser degrees of leaching, have resulted in a characteristic dark grey A_2 horizon.

A relatively closed cover of mixed forest of aspen poplar and white birch, with local stands of white spruce, constitutes the natural vegetation of the escarpment slope. The conifers are common to the upper slopes; the aspen stretch along numerous gully slopes; and white birch dominates the relatively more stable interfluve areas (MacKay and Stanton, 1964).

The alluvial soils of the Edwards Association have developed on the alluvial fans and alluvial apron in the study area (Figure 2). Ehrlich et al. (1958) have divided the Edwards Association into three associates. The Edwards Silt, Clay Loam to Silty Clay is characterized by several dark grey bands in the subsoil, believed to "represent weakly developed A horizons subsequently covered by additional alluvium" (Ehrlich et al.,1958) (Plate II). The Edwards Shaly Phase is similar to the above described associate with the exception that a large percentage of shale gravel is found in the parent material. Lastly, the Edwards Semi-Mature Phase soils represent the poorest drained soils in the Edwards Association, due to a greater clay percentage. However, like the previous mentioned Edwards phases, the Edwards-Semi-Mature Phase soils also contain several dark organic bands in the lower horizons.

The poorly developed A horizons and organic layers, common to the Edwards Association, may provide data relating to climatic change and sedimentation in the study area over the last 8000 years.

The natural vegetation on the alluvial apron is described as a parkland of elm, ash, Manitoba maple, willow, and assorted herbaceous shrubs and grasses (MacKay and Stanton, 1964). However, the agriculturally productive soils of the Edwards Association have

PLATE II

The Edwards Association Soil

The Edwards Association Soils have developed on the alluvial fans and alluvial apron in the study area. These soils are characterized by several dark grey bands in the subsoil, "believed to represent weakly developed A horizons subsequently covered by additional alluvium" (Ehrlich et al., 1958).

attracted farmers since the early 1900's and as such, the natural vegetation has been removed.

1:8:0 A General Statement on Alluvial Fan Research

Tricart and Cailleux (1972, 165) postulate that the landforms of an area are a function of specific morphogenic systems which themselves are dependent on the climatic factors associated with the area. In view of this hypothesis they have regionalized the continents into morphoclimatic zones; each characterized by climate, soils, vegetation and dominant geomorphic processes.

Traditionally, alluvial fans have been associated with the arid cycle of erosion (Davis, 1905). Consequently, many studies of these physiographic features have been concentrated in the Dry Morphoclimatic Zone. Since alluvial fans have been recognized in other morphoclimatic zones, the Geomorphic Systems Model postulated by Tricart and Cailleux (1972) would imply that different morphoclimatic variables are involved in producing these alluvial fans.

Within the last decade geomorphologists have begun to investigate the nature of alluvial fans in both the Cold Morphoclimatic Zone and the Forested Mid Latitude Zone.

1:8:1 American Southwest (Dry Morphoclimatic Zone)

A large majority of the published works on alluvial fans has been based on research in the American southwest. Several of these studies have made major contributions to the understanding of alluvial sedimentation.

Historically, Blackwelder (1928) and Eckis (1928) were among the first to describe in detail the fan-forming processes. Blackwelder's narrative style documents mudflow and alluvial fan processes while Eckis' study outlines the physiography and geology of alluvial fans. Eckis (1928) also commented on the nature and causes of fanhead entrenchment. Longwell (1930) investigated segmented fans and attributed the segmentation to tectonic activity and subsequent faulting. Rich (1935) applied the Davisian concept of the cycle of erosion to the development of rock fans and pediment surfaces.

Prior to 1959, the majority of alluvial fan research emphasized the importance of mudflows in alluvial deposition (Chawner, 1935; Jahns, 1949; and Sharp and Nobles, 1953). However, Blissenbach (1952, 1954) extended his study to encompass the nature of the alluvial deposits. Blissenbach (1954) concentrated on several aspects of the spatial distribution of fan sediments; namely, the relationship between distance from the apex, and the size, composition, sphericity, roundness, and sorting of the sediment. An abstract by Buwalda (1951) indicates that he also was interested in the sediment characteristics of alluvial fans.

In 1959, Bull published an abstract outlining his studies of alluvial fans in Southern California. In a following series of articles he discussed the morphometry, the hydrology and the sediment characteristics of alluvial fans and their associated drainage basins. The morphometric aspects of fan slope, fan area and drainage basin area were investigated thoroughly in U.S.G.S. Professional Paper 450 B (Bull, 1962a). Bull also considered the effects of lithological variation in alluvial fan morphometry. In later papers (1964a and 1964b), he restated his earlier findings and presented additional morphometric relationships.

Prior to Bull's work on alluvial fans it was believed that the change in the gradient of a stream emerging from the mountain front onto the plain, resulted in a decrease in stream velocity and alluvial sedimentation. However, Bull's investigations into the hydrology of alluvial streams (1964b) indicated that the stream gradient does not change radically and furthermore, he postulated that it is a change in the width-depth ratio and consequent reduction in velocity which accounted for deposition. Bull (1964b) also suggested that the alluvial deposits themselves can promote sediment deposition through the infiltration of stream discharge and consequent reduction in stream capacity.

In 1961, Bull divided alluvial fan sediments into three groups; mudflow deposits, water laid deposits, and intermediate deposits; and in later articles outlined the textural character (1962b), physical characteristics (1963) and sedimentary structures (1963) associated with each group. Bull's morphogenetic classification of alluvial fan sediment was presented in articles in 1964 and 1968. In 1977, Bull published a very informative paper summarizing existing information on alluvial fans. Bull's research stimulated interest in various facets of alluvial sedimentation and in following years publications concerning alluvial fan research increased. Ruhe (1962 and 1967) investigated relationships between fan gradient, sediment size, basin lithology and basin geometry. Denny (1965) extended Bull's morphologic studies to include discussions of relationships between stream geometry, drainage basin characteristics, sediment parameters, and fan size, volume and slope. In a later paper (1967), he proposed an open system development of fans and suggested that buried soils are the result of the normal fan forming process.

Melton (1965) refined morphometric studies of alluvial fans and explained the necessity for employing logarithmic transformations and dimensionless numbers in linear regression analysis. Cooke (1970a, 1970b), and Cooke and Reeves (1972) applied Melton's concepts to the morphometric study of mountain pediments and associated alluvial plains. Cooke (1970b) is particularly concerned with the development of precise operational definitions and measurement procedures, and compliments the quality of the earlier alluvial fan research of Bull, Denny and Melton.

Both Denny (1967) and Melton (1965) emphasized the importance of the hydrologic character of the alluvial stream in the fan forming process and Hooke (1968) suggests that the alluvial stream maintains a steady-state relationship between the morphometry of the basin and the physical characteristics of the alluvial fan. Hooke's research (1965, 1967) included investigations into the stream hydrology and fan-basin morphometry. He applied engineering hydraulic formulae in order to explain sediment transport and deposition on alluvial fans. Lustig (1965, 1967) also utilized hydraulic formulae in his studies of sediment transport on alluvial fans.

Bluck (1964) investigated the spatial distributions of sediment size, shape, and sphericity, and related these parameters to mudflow and streamflow phases in fan development.

Beaty (1963) investigated debris flow, sheetflow and regular streamflow deposits and later (1970) examined rates of accumulation of such materials on alluvial fans.

The previously cited studies are concentrated on the arid region alluvial fans located in the American Southwest. Limited and geographically scattered research on alluvial fans has occurred outside this region.

Anstey (1966) compared the alluvial fan deposits in West Pakistan and Beaumont (1972) studied several alluvial fans in Iran, but both studies shed no new light on the formation of arid region alluvial fans.

1:8:2 Alluvial Fans in Arctic Regions (Cold Morphoclimatic Zone)

Alluvial fans have been studied in the Canadian Arctic by Leggett and Brown (1956), Leggett, Brown and Johnston (1966), Keeble (1971), and Church and Ryder (1972). These studies emphasize the importance of frost shattering as a means of providing a continual and abundant supply of sediment for alluvial streams.

1:8:3 Forested Mid-Latitude Zone

Studies of alluvial fans located in the forested mid-latitude morphoclimatic zone (Tricart and Cailleux 1972) are also few in number. Murata (1966) conducted a theoretical study of alluvial fan forms in Japan. Suggate (1963) and Carryer (1966) briefly studied fan surfaces and their formation in New Zealand. Hirst (1971) and later Hodgkins (1972) investigated the alluvial fans in the deeply entrenched North Saskatchewan River Valley near Saskatoon and Winder (1965) studied mudflow fans in the Canadian Rockies.

Ryder (1970 and 1971a) developed a morphometric and hydrologic model based on the findings of Bull (1963), Denny (1965), Melton (1965), and Hooke (1968) and undertook similar morphometric studies in southern British Columbia. Investigation of fan sediments (Ryder, 1971b) and morphology (Ryder, 1971a) have led to the introduction of a new type of alluvial fan. This fan, termed "paraglacial" (Ryder, 1970), is characterized by a sediment supply (in Ryder's case, till) which becomes exhausted within a finite period of time resulting in cessation of major alluvial sedimentation.

1:8:4 Recent Theoretical Studies

Price (1974) attempted to simulate the alluvial fan geomorphic system. He derived theoretical functions for mountain uplift, rock weathering, stream discharge, and channel shifting and produced a sequence of computer maps illustrating the spatial development of a theoretical alluvial fan over time.

Miall (1973) employed a Markovian chain probability model to synthesize alluvial fan stratigraphy. He then tested his model on the sequential deposits of an alluvial fan.

The large amount of "hard" data required to derive Price's mathematical functions and to produce Miall's probability matrix, generally limits this type of theoretical research to specific alluvial fans located in well documented geomorphic environments.

CHAPTER II

THEORETICAL CONSIDERATIONS AND MODELLING THE ALLUVIAL FAN GEOMORPHIC SYSTEM

2:1 Definition of an Alluvial Fan

"An alluvial fan is a body of stream deposits whose surface approximates a segment of a cone that radiates down slope from a point where the stream leaves a mountainous (highland) area" (Bull, in Fairbridge [ed.] 1968).

2:2 Deposition on Alluvial Fans

Henderson (1966, 3) points out that stream discharge is the product of stream width, stream depth, and stream velocity. Bull (1964b) postulates that as a stream emerges from a highland area onto a plain, increases in stream width and corresponding decreases in depth of flow and velocity account for a reduction in competence and subsequent sediment deposition. Bull (1961) classifies alluvial fan deposits of this nature as the waterlaid sediments of shallow bars and braided channels, consisting of poorly sorted gravels and crossbedded sand.

Stream discharge does not always remain constant when flowing over coarse alluvial sediments. Often, the waters will infiltrate and flow through these coarse gravels. Such a reduction in discharge decreases stream capacity and results in sediment deposition. Hooke (1968) refers to deposits of this nature as sieve deposits.

When the sediment concentration of a stream is approximately equal to the volume of water, streamflow becomes a debris flow or mudflow (Sharpe, 1938). Debris flows compared to streamflows have a higher density and viscosity and are therefore, capable of transporting large boulders for some distance. Debris flow sediments are a common type of alluvial deposit in areas with: intense sporadic precipitation; steep slopes with sufficient vegetation to retard rapid runoff and erosion; and a source of fine material necessary to produce a mud matrix for the flows (Blackwelder, 1928; Sharp and Nobles, 1953).

The various types of alluvial fan deposits are recognizable in the stratigraphy. Debris flows, sieve deposits and water-laid sediments are usually deposited as narrow tongues, radiating downslope from the fan apex (Bull, 1968). As such, these deposits may be traced for considerable distances downslope; yet, their lateral extent is generally limited to a few hundred metres.

2:3 Changes in Loci of Deposition

The tongue-like nature of alluvial fan deposits suggest that only a small area of the fan - that adjacent to the main stream - is actively aggrading at any particular time. Therefore, in order to construct an alluvial fan, it is necessary to shift the area of deposition. The shifting of the loci of deposition may occur laterally or along a radial line from the apex to the fan edge.

Lateral migration of the loci of deposition takes place when deposition has raised the fan surface sufficiently to favour shifting of the stream channel to a lower segment of the fan (Bull, 1968). The geometry of a cone dictates that a minor change in the stream channel

PLATE III

The Loci of Deposition on an Alluvial Fan Surface

As the small streams emerge from the escarpment slope onto the alluvial plain, the decrease in stream velocity results in a corresponding reduction in stream competence and subsequent shale sediment deposition. Frequently, these shale deposits flood across the crop-carrying alluvial fan surfaces and recently cleared marshlands.

position near the apex produces major fluctuations in channel position on the lower fan areas.

Migration of the loci of deposition along a radial line is also common on alluvial fans. Positive changes or migration up slope are generally due to gradual decreases in discharge and subsequent backfilling of the principal stream-channel. Sieve deposits (Hooke, 1967) account for local small scale fluctuations in the loci of deposition that, over a period of time, may result in a major shift. Negative changes (migrations downslope) are basically the result of stream entrenchment. Generally, two theories prevail: Eckis (1928) postulates that under uniform conditions, a stream will ultimately dissect the upper segment of the fan because of continued downcutting of the stream in the highland area. This theory is closely associated with the evolutionary theory of fan formation. A second theory proposes that entrenching of alluvial channels and major backfilling may be a natural response of the steady state alluvial fan (Hooke, 1968) to climatic, tectonic, or man-induced changes. Bull's (1964c) study on rainfall intensity and its variation over time tends to support this hypothesis. Whatever the cause, channel entrenching is a primary means of enlarging fan area, as the loci of deposition are shifted sufficiently far downslope to allow moderate flows to deposit material on areas which previously received sediment only during periods of major flooding.

2:4:0 Theories of Fan Growth

The traditional response of researchers to the complexities of geomorphology has been to create abstract systemizations which provide simplified yet intelligible overviews of real world situations. These are known as models. A model may be defined as "a simplified structuring of reality which presents supposedly significant features or relationships in a generalized form" (Haggett and Chorley, 1969, 22).

2:4:1 <u>The Evolutionary Model</u>

The evolutionary model of alluvial fan growth and development assumes that alluvial fans are a function of structure, process and time (Davis, 1899). This model postulates that, if no 'accidental' alterations (Davis, 1899) in the environment take place, be they climatic, tectonic or man-induced, an alluvial fan will develop along a generalized evolutionary path, progressing from stages of youth to maturity to old age. The physiography of the alluvial fan defines each stage of development. Youthful alluvial fans are small in area and volume and are steep sloping. They are associated with an initial period of rapid degradation of the highland area (Davis, 1905). Mature alluvial fans are much larger in both area and volume and their gradients are generally less steep. Frequently, adjacent alluvial fans coalesce during the mature stage and form an alluvial apron. The mature stage is considered to be the period of maximum geomorphic activity associated with multishifting of the loci of deposition and initiation of fanhead entrenching. Alluvial fans which have progressed to a stage of old age are characterized by a decrease in sediment deposition, a major downslope shift of the loci of deposition and development of a dendritic drainage pattern on the upper segment of the fan (Eckis, 1928). Although the primarily descriptive evolutionary model of alluvial fan development has been replaced by more intricate equilibrium models, several authors utilize the basic concept and terminology in their descriptions, and theories (Eckis, 1928; Rich, 1935; Blissenback, 1954; and Lustig, 1965).

2:4:2 Equilibrium Model of Alluvial Fan Development

The concept of dynamic equilibrium states that for a given set of interrelated conditions, energy and matter input equals energy and matter output. Furthermore, changes in any one condition result in adjustments in the other related conditions in order to maintain the input/output equality. Applied to geomorphology: "every geometric element [landform parameter] is a product of adjustment between materials and process" (Tanner, In: Fairbridge, 1968, 316). This equilibrium is known as the steady state relationship. The concept of the steady state does not refer to static conditions. It is the complex geometric element (landform) which appears to remain static, but in fact can change as the equilibrium shifts in response to changes in material and process (Tanner, 1968, 316). Several authors have employed the equilibrium model as a basis for research into the morphometric relationships between alluvial fans and associated drainage basins. Bull suggests that alluvial fans act as open systems because changes in drainage basin conditions cause changes in fan characteristics (1964a, 94). Denny's research is founded on his belief that an alluvial fan is related to some sort of balance or interaction between mountain degradation and valley alluviation - perhaps to a condition of dynamic equilibrium between a fan area, Af, and drainage basin area, A. Hooke (1968, 609) suggests that this relationship $Af = cA^n$ "results from a tendency toward a steady state among coalescing fans in the same lithologic, tectonic, and geographic environment". Hooke also attempts to evaluate the constant c and exponent n in this empirical relationship, and extends his studies to include hydrological parameters.

2:5 The Equilibrium Model and General Systems Theory

A geomorphic system, according to Chorley (1969, 77), is an integrated complex of landforms operating together. If the concept of equilibrium is applied, it can also be stated that the energy and/or matter inputs of the geomorphic system give rise to predictable responses in terms of the internal organization of the system and the resulting energy/matter outputs (Chorley, 1969, 77). It becomes clear that the descriptive term 'state' be it constant or variable, represents the instantaneous condition of the geomorphic system. Furthermore the 'state' is defined by the internal organization, composition, and energy transfer of the system. The variable state of a geomorphic system, described as a positive feedback system, occurs when changes in the inputs result in complementary changes in the outputs (Chorley 1969, 78).
However, input changes in the 'steady state' system do not produce changes in the outputs but are absorbed by the internal organization of the system. This is referred to as a negative feedback system Chorley, 1969, 78). The self-regulation of the negative feedback system requires a time interval described as the 'relaxation time' (Langbein and Leopold, 1964, 782). This time interval may be of any duration, from virtually instantaneous to millions of years. Considering the previous statement, one might say that all geomorphic systems have both positive and negative feedback characteristics. After the initial flux in inputs, there is an immediate positive feedback for a variable period of time - the relaxation time - and during this time interval, readjustment in the internal organization of the system takes place which results in a gradual return to the steady state. If the relaxation time is relatively

short the system is described as a negative feedback system. If the relaxation time is of relatively long duration, say several thousand years, the system is referred to as a positive feedback system (Chorley, 1969, 78).

From the previous statements, it is apparent that the relaxation time of a geomorphic system is a primary factor in determining the feedback property of the system. The relaxation time is believed to represent the degree of the relationships between the components of a system (Chorley, 1969, 79). Therefore, an evolutionary model of alluvial fan development would be considered a positive feedback system characterized by low correlations between the components of the geomorphic system. A steady state or equilibrium model would imply a short term relaxation time reflecting high correlations between the system's components.

In the past, geomorphologists have explored the internal organization of drainage basin systems and found correlative linkages between several components (for numerous examples see Gregory and Walling, 1973). Hydrologists have employed the principles of dynamic equilibrium and the steady state in river mechanics since early 1900's and have derived numerous empirical relationships between the stream parameters. It remains for the geomorphologist and hydrologist to investigate the common linkages of these two subsystems and their relationship to the parameters of the alluvial fan.

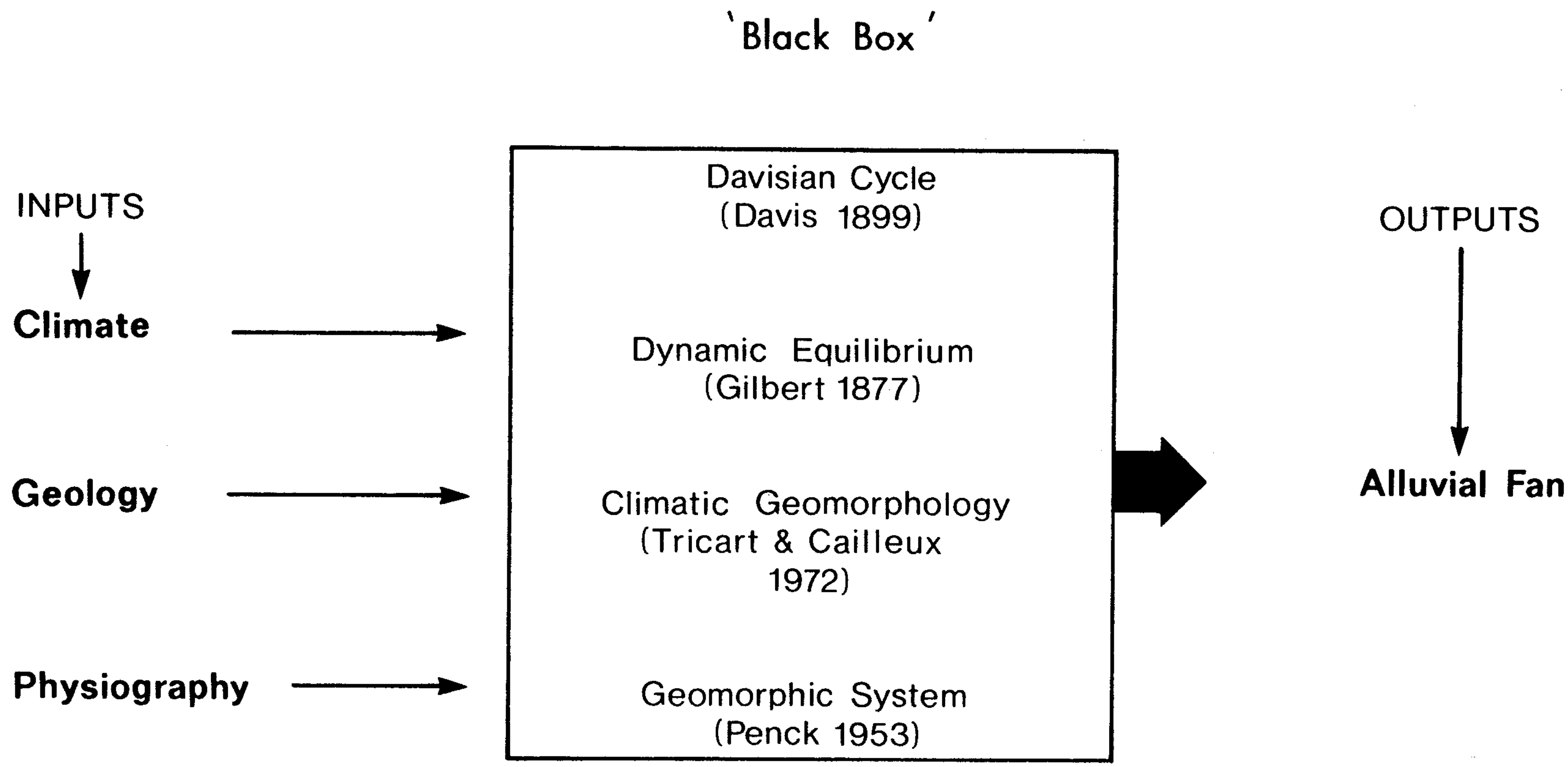
2:6 The General Systems Approach to Alluvial Fan Research

The alluvial fan geomorphic system is composed of subsystems, each with their respective input/output linkages. The subsystems are also interconnected in that the outputs of one become the inputs of another.

The general systems approach to alluvial fan geomorphology can be subdivided into three type models: a synthetic systems model; a partial synthetic systems model; and a 'black box' model.

A 'black box' model requires little or no information as to the internal organization and operation of the system. Instead, it focuses on the nature of the inputs and outputs. This type of model may be described as an impulse-response model and there are generally two kinds; a negative feedback model, where an impulse produces no measurable variation in output response (dynamic equilibrium), and a positive feedback model, where the impulse produces measurable variation in outputs. Figure 7 illustrates the black box model applied to alluvial fan development. This model has been particularly useful in the early alluvial fan research. Drew (1873) recognized that large fans appear to have a gentler slope than small fans. Blackwelder (1928) suggests that mudflows on alluvial fans are a result of a favourable combination of material, slope, water and vegetative cover. Eckis (1928) essentially arrives at a similar conclusion with respect to alluvial fan formation (Figure 7, "inputs"). Longwell (1930) invokes a black box model and attributes fan segmentation to tectonic disturbances, and Rich (1935) suggests an evolutionary cycle of fan building. Bull (1964a), Denny (1965), and Hooke (1968) refer to a steady state or equilibrium condition and on this basis initiated their respective studies into the operations in the black box. Studies of the internal workings of the black box produce synthetic system models of the alluvial fan processes (Figures 8 and 9).

A 'BLACK BOX' MODEL OF AN ALLUVIAL FAN GEOMORPHIC SYSTEM



ADAPTED FROM ECKIS 1928

Figure 7

The synthetic systems model (Chorley, 1969, 80-81) begins by establishing the key elements of the general set (components of the system or subsystems) and the nature of the linkages between these components. Studies are directed toward determining the strength, and direction of the impulse and whether there is any secondary feedback loop. The goal of the synthetic systems model is to establish the primary, secondary, etc., responses of each variable in the system to a given impulse, and knowing these to be able to predict the fluctuations, if any, in the output. The major problem with this model is in determining the number of variables (elements or components) within the system. For this reason the synthetic system is considered to be open-ended so that variables may be added at any time as new linkages are established. However practical researchers have favoured the less complex solution of restricting their studies to those parts of the general system which appears to have more significant responses to the impulses. These abridged versions of the synthetic systems model are referred to as partial synthetic systems.

Partial synthetic systems models cannot and do not fully explain the internal organization of the black box. However, they are often used to identify and predict the responses of the general system to particular impulses. Bull (1964a) and Denny (1965) employ a simplified partial synthetic systems model to arrive at the log-linear relationship $Af = cA^n$. This relationship states that the area of an alluvial fan is exponentially related to the area of the associated drainage basin. The constant c represents the area of a fan with a drainage basin area of one square mile, and n represents the rate at which fan area varies with drainage

A SYSTEMATIC MODEL OF AN ALLUVIAL FAN GEOMORPHIC SYSTEM

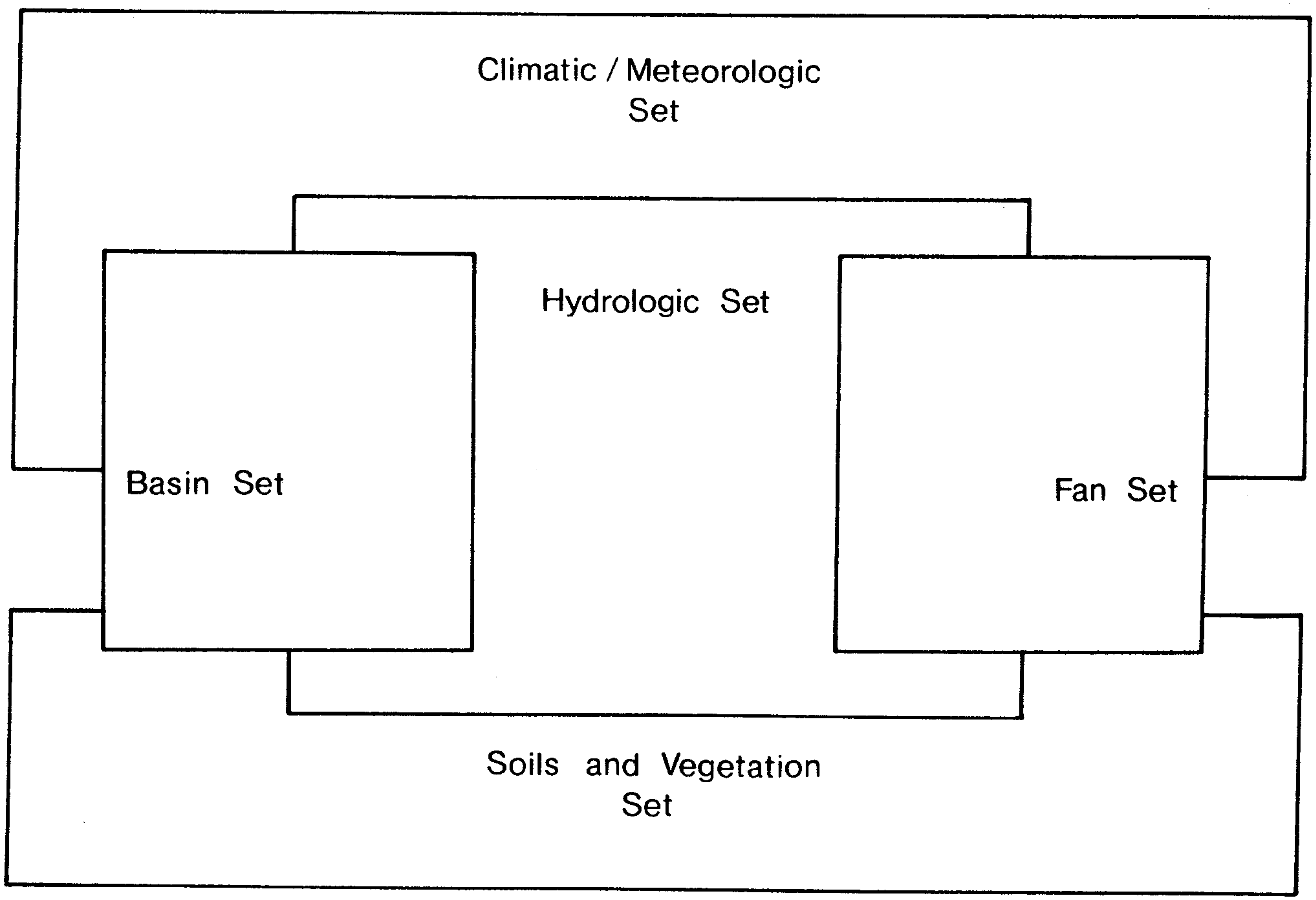


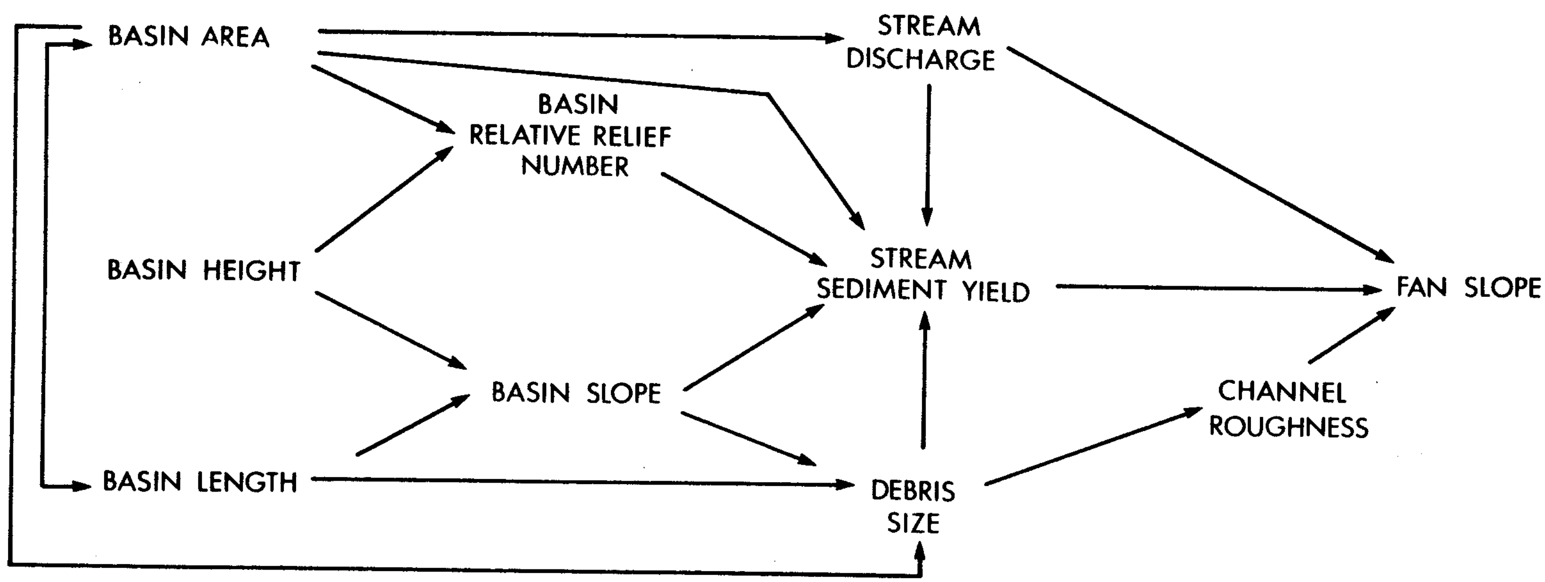
Figure 8

basin area. Hooke (1968) substantiates the empirical relationship between fan area and basin area postulated by Bull and Denny, and suggests factors which influence c and n. These additional variables are reviewed in Cooke and Warren (1973). Briefly, c is influenced by: the ratio of potential erosion area to potential deposition area; differing response to tectonic activity within a basin; the erodibility of the basin material; local climatic variation; and physical barriers to local depositional areas. The value of the regression coefficient n is usually less than unity, implying that a large drainage basin contributes proportionately less sediment to the alluvial fan geomorphic system than a smaller basin. Langbein and Schumm (1958, 1079) suggest that storage of sediment on the less steep valley slopes of large basins can impede weathering, and Hooke concludes that the consequent reduction in the potential fan material will be reflected by the sediment yields in these larger basins. He also postulates that larger basins are less frequently covered by a single storm and as a result the sediment yield is derived from only a portion of the total basin area.

Melton (1965) clarified the partial system model by pointing out that the fans in his study were a sample of a large population of alluvial fans and as such were subject to statistical inference. Melton then defined the variables to be examined and established that the linkages were of a positive or negative log-linear relationship. The parameters studied include fan slope, basin area, and basin height. Regression and correlation models were employed to study the nature of the linkages and in particular the variance in fan slope explained by the basin area and basin height. A prominent outcome of the study was the proposal of the relative relief dimensionless number as a significant variable in the fan-basin morphology. Hooke (1968) investigated Bull's (1964a) and Denny's (1965) basin-fan areal relationship and recognized the importance of the alluvial stream as a physical link between the drainage basin and respective alluvial fan. Employing a hydrologic 'hardware model' (Chorley, 1969, 63), Hooke investigated the effect of stream discharge, sediment yield, and particle size on the respective fan slope. Hooke also proposed linkages between these three hydrologic variables, the drainage basin area and lithology.

Ryder (1970) reviewed the research of Bull (1964a), Denny (1965), Melton (1965), and Hooke (1968) and drafted a working partial synthetic systems model of the alluvial fan geomorphic system (Figure 9). This model proposes that linear or log-linear relationships exist between the alluvial fan slope and specific basin parameters. Ryder also incorporates Hooke's hydrologic parameters as intermediate variables, linked to the fan slope and basin parameters. For the purposes of this study an adaptation of Ryder's 1971 model is employed (Figure 9).

A PARTIAL SYNTHETIC SYSTEM MODEL OF ALLUVIAL FANS



ADAPTED FROM RYDER (1971)

Figure 9

CHAPTER III

MORPHOMETRY OF ALLUVIAL FANS AND ASSOCIATED DRAINAGE BASINS

3:1 Introduction

Certain "a priori" assumptions are implied in a study of the morphometric relationships in an alluvial fan geomorphic system. Specifically, a steady state or equilibrium exists which maintains the proportionality between the fan parameters and the parameters of the associated drainage basin. In the past, several authors have investigated the nature of the statistical relationships and interpreted their results as indicators of the equilibrium state. (For example: Bull, 1964a ; Denny, 1965 ; Melton, 1965 ; Hooke, 1968 ; and Ryder, 1971a).

The fan-basin morphometric relationships outlined in the partial synthetic systems model (Figure 9) were investigated in the study area. For valid comparison with other research (i.e. Hooke and Melton in the American Southwest and Ryder in British Columbia), similar operational definitions of the measured parameters must be applied.

3:2 Operational Definitions and Measurement of Morphometric Parameters

A measurement is made for a specific purpose and it is this purpose which determines the procedure or set of rules for obtaining the measurement. The operational definition of the measured parameter specifies this procedure (Krumbein, 1958).

3:3 Fan Parameters

Throughout the literature, various morphometric parameters of alluvial fans have been measured. These include length, width, area, volume, shape and slope. In this study an accurate estimate of each parameter is desirable. However, the numerous beach ridges of Glacial Lake Agassiz found in the study area often disrupt the natural extensions of the alluvial fans, making estimations of fan length difficult and unreliable. More important, coalescence of many of these fans seriously hinders any attempt to accurately estimate the width, area, shape, and volume.

A measurement of the fan slope, taken near the apex and along the medial radial profile, avoids influences of spatially adjacent alluvial fan forming processes. It has also been suggested (Melton, 1965; Hooke, 1968; Cooke, 1970b; and Ryder, 1970) that fan slope is a composite morphometric parameter which is particularly sensitive to fluctuations in stream hydrology and basin morphology. For these reasons fan slope (λ) has been selected as the parameter characteristic of alluvial fans in the study area.

The slope of each alluvial fan is operationally defined as the rise divided by the run, measured along the mid-radial line in the upper one fourth of the fan. This corresponds to a similar zone of measurement utilized by Melton (1965) and Ryder (1971a). Both authors point out that the fan slope measured in this zone is closely controlled by the drainage basin characteristics. It should be noted that Bull (1964a), Denny (1965) and Hooke (1968) employ the total fan slope (apex to edge) and as a result arrive at relatively lower fan slope values. The profile of the measured mid-radial line was derived using the GK 1 Small Engineers Level (Kern and Company Limited). This instrument of medium precision has a maximum levelling error of 0.02 feet over a one mile circuit. The instrument was calibrated before and at the conclusion of the measurements. All measurements were observed by the same instrument operator and rod-man. Each profile was constructed and examined for major anomalies in slope. No unaccountable irregularities were found to exist and the specific fan profiles were assigned a mean slope value which was recorded in degrees.

3:4:0 Basin Parameters

According to the model postulated by Ryder (1971a), there are three fundamental basin parameters controlling fan slope; drainage basin area; basin height; and basin length.

3:4:1 Drainage Basin Area (A)

Although drainage basin area is operationally defined in rigid terminology as the total (plane) area of the drainage basin upstream from the fan apex (Ryder 1971a), the exact delineation of this area on a 1:50,000 topographic map becomes somewhat subjective. Therefore, the limiting absolute error value may be relatively large and this allows for potentially large deviations from the target value (Appendix III). Since all other basin parameters employed in this study are defined within the drainage basin area, basin area delineation is extremely important with respect to the measurement of these other basin parameters.

The drainage basin area of each fan was outlined on two different occasions and measured with a Koizumi Compensating Planimeter Type KP-23. Each area was measured five consecutive times and the mean of these values calculated. Standard deviations and variance were also calculated as estimates of the precision. An analysis of variance of the paired samples indicated no significant difference at the 0.001 probability level. Basin areas were measured in square miles.

3:4:2 Basin Length (L)

Basin length is defined by Krumbein and Graybill (1965) and Ryder (1971a) as the longest axis from the basin mouth (apex of the fan) to the divide. This axis was measured on a 1:50,000 topographic map and evaluated on a rule calibrated in millimeters. The measurement was observed three times in succession before being converted to miles and recorded.

3:4:3 Basin Height (Ht)

Basin height is defined (Ryder 1971a) as the maximum difference in elevation between the basin mouth (fan apex) and the highest point on the divide. This measure was obtained by subtracting the estimate of fan apex elevation from that of the elevation of the highest point on the divide. The elevation estimates were obtained from the 1:50,000 topographic map. The contour interval is 25 feet, giving a rounded off threshold of sensitivity (Appendix III) of 12.5 feet for each estimate.

Topping (1972) introduces a term titled 'most probable value' which is useful when investigating measures which are the result of a sum or a difference. Topping defines 'most probable value' as the square root of the sum of squares of the limiting absolute errors. Since basin height is the difference of two measures having limiting absolute errors of 12.5 feet, the 'most probable value' may be calculated for the relative error in basin height. Basin height was recorded in miles.

3:4:4 Composite Basin Parameters

The above three fundamental basin parameters allow for the derivation of several other basin parameters; in particular, the basin slope (Ht/L) defined as basin height divided by basin length; and the relative relief ratio, ($Ht/\sqrt{A}$), basin height divided by the square root of the basin area (Melton, 1965).

3:5 Sample Size and Location

Twenty-one basin/fan systems were investigated in the study area. Figure 10 illustrates the relative location of these systems. Basin/fan system number 221619 (designated as Fan 19 by the last two digits) proved to be inaccessible to slope measurement according to the operational definition outlined above and has been removed from the study. This leaves a sample size of 20.

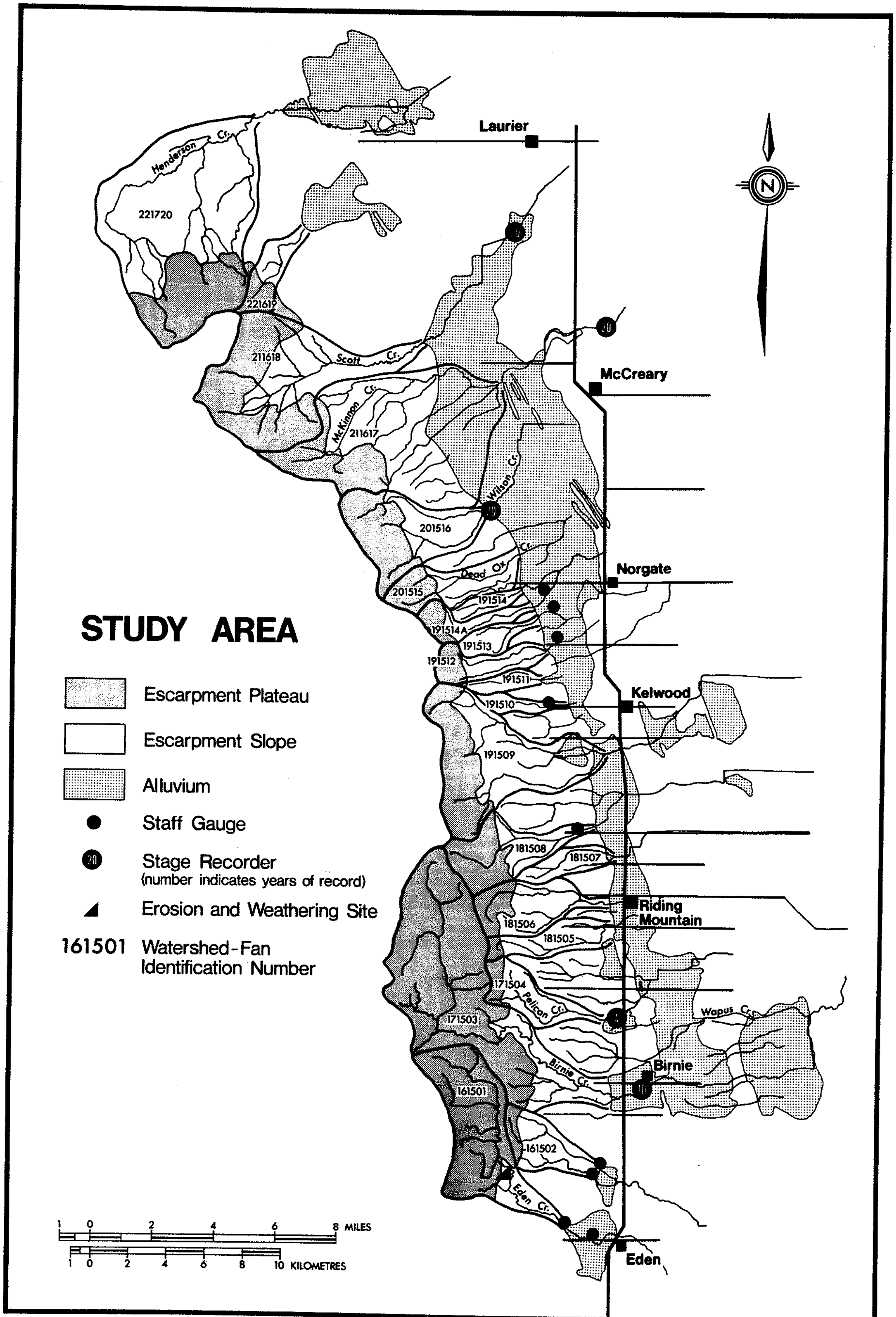
3:6 The Data

For comparative reasons, the morphometric data used in this part of the study, was recorded in imperial units and is presented in Table 3.

3:7 The Degree of Error in Measured Morphometric Parameters

Since the classic paper by Horton (1945), there has been a multitude of studies examining the morphometric parameters of drainage basins. Some of the more prominent include Strahler (1952, 1958), Melton (1957, 1958), Shreve (1967), and Hack,(1965). Often, the problems involved in obtaining a specific measure, say basin height or basin area, are neglected and the errors associated with their measurement are left unrecognized. The specific measures are then accepted as true values without question, rather than as estimates. For this reason Tables 5 through 10, involving the evaluation of measurement error, are included in this study. A brief review of the types of error, propagation of error and error theory relevant to the morphometric analysis is found in Appendix III.

Accidental error (Appendix III, p. 208) is eliminated by verifying all measures and calculations. This was attained through repetition of each measure and calculation. Observer bias is hopefully reduced to


STUDY AREA
Escarpment Plateau
Escarpment Slope
Alluvium
Staff Gauge
Stage Recorder
(number indicates years of record)
Erosion and Weathering Site
161501 Watershed-Fan Identification Number
Laurier
McCreary
Norgate
Kelwood
Riding Mountain
Birnie
Eden
Henderson Cr.
Scott Cr.
McKinnon Cr.
Wilson Cr.
Dead Ox Cr.
Pelican Cr.
Wapus Cr.
Birnie Cr.
Eden Cr.
221720
221619
211618
211617
201516
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191514
191514A
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191509
181508
181507
181506
181505
171504
171503
161501
161502
MILES
KILOMETRES

Figure 10

TABLE 3a

MORPHOMETRIC DATA
(Imperial Units)

Fan No.	λ °	A (mi^2.)	Ht (mi.)	L (mi.)	Ht/L	Ht/$\sqrt{A}$
1	1.03	11.40	0.16	7.19	0.0225	0.0473
2	1.03	4.95	0.12	5.30	0.0226	0.0541
3	0.63	23.45	0.18	9.72	0.0185	0.0372
4	1.12	3.39	0.17	3.47	0.0490	0.0924
5	1.07	2.72	0.18	4.03	0.0447	0.1091
6	0.83	5.15	0.18	4.13	0.0436	0.0793
7	1.62	1.68	0.16	2.47	0.0648	0.1231
8	1.10	5.63	0.18	4.88	0.0369	0.0759
9	1.03	14.02	0.23	7.69	0.0299	0.0615
10	1.73	1.00	0.14	2.25	0.0622	0.1400
11	1.82	1.37	0.18	3.50	0.0514	0.1538
12	1.38	3.06	0.19	3.84	0.0495	0.1086
13	1.47	1.01	0.15	2.38	0.0630	0.1485
14	1.35	1.18	0.17	2.41	0.0705	0.1565
14a	1.63	2.12	0.19	3.57	0.0532	0.1305
15	0.70	3.07	0.20	3.91	0.0512	0.1143
16	1.05	8.35	0.23	5.09	0.0452	0.0793
17	0.63	26.20	0.26	8.22	0.0316	0.0508
18	0.65	15.34	0.22	7.06	0.0312	0.0561
20	0.63	27.72	0.19	7.84	0.0242	0.0361

TABLE 3b
MORPHOMETRIC DATA
(Metric Units)

Fan No.	λ	A	Ht	L	Ht/L	$Ht/\sqrt{A}$
1	1.03	29.53	0.26	11.57	0.0225	0.0473
2	1.03	12.82	0.19	8.53	0.0226	0.0541
3	0.63	60.74	0.29	15.64	0.0185	0.0372
4	1.12	8.78	0.27	5.58	0.0490	0.0924
5	1.07	7.04	0.29	6.48	0.0447	0.1091
6	0.83	13.34	0.29	6.65	0.0436	0.0793
7	1.62	4.35	0.26	3.97	0.0648	0.1231
8	1.10	14.58	0.29	7.85	0.0369	0.0759
9	1.03	36.31	0.37	12.37	0.0299	0.0615
10	1.73	2.59	0.23	3.62	0.0622	0.1400
11	1.82	3.55	0.29	5.63	0.0514	0.1538
12	1.38	7.93	0.31	6.18	0.0495	0.1086
13	1.47	2.62	0.24	3.83	0.0630	0.1485
14	1.35	3.06	0.27	3.88	0.0705	0.1565
14a	1.63	5.49	0.31	5.74	0.0532	0.1305
15	0.70	7.95	0.32	6.29	0.0512	0.1143
16	1.05	21.63	0.37	8.19	0.0452	0.0793
17	1.63	67.86	0.42	13.23	0.0316	0.0508
18	0.65	39.73	0.35	11.36	0.0312	0.0561
20	0.63	71.79	0.31	12.61	0.0242	0.0361

A - Measured in km^2

Ht - Measured in km

L - Measured in km

TABLE 4

LOG TRANSFORMATION OF MORPHOMETRIC DATA

Fan/Basin No.	λ	A	Ht	L	Ht/L	Ht/√A
1	0.01284	1.05690	-0.79588	0.85673	-1.64782	-1.32514
2	0.01284	0.69461	-0.92082	0.72428	-1.64589	-1.26680
3	-0.20066	1.37014	-0.74473	0.98767	-1.73283	-1.42946
4	0.04922	0.53020	-0.76955	0.54033	-1.30980	-1.03433
5	0.02938	0.43457	-0.74473	0.60531	-1.34969	-0.96218
6	-0.08092	0.71181	-0.74473	0.61545	-1.36051	-1.10073
7	0.20952	0.22531	-0.79588	0.39270	-1.18842	-0.90974
8	0.04139	0.75051	-0.74473	0.68842	-1.43297	-1.11976
9	0.01367	1.14675	-0.61979	0.97035	-1.59007	-1.19246
10	0.23805	0.00000	-0.85387	0.35218	-1.20621	-0.85387
11	0.26007	0.13672	-0.74473	0.54407	-1.28904	-0.81304
12	0.13488	0.48572	-0.72125	0.58433	-1.30539	-0.96417
13	0.16733	0.00432	-0.82391	0.37658	-1.20066	-0.82827
14	0.13033	0.07188	-0.76955	0.38202	-1.15181	-0.80688
14a	0.21219	0.32634	-0.72125	0.55267	-1.27393	-0.88439
15	-0.15490	0.48714	-0.69897	0.59218	-1.29073	-0.94095
16	0.02119	0.92169	-0.63827	0.70672	-1.34486	-1.09909
17	-0 20069	1.41830	-0.58503	0.91487	-1.50031	-1.29414
18	-0.18709	1.18583	-0.65758	0.84880	-1.59585	-1.25104
20	-0.20066	1.44279	-0.72125	0.89432	-1.61618	-1.44249

insignificant amounts. All measures and calculations were made by one observer or in the case of fan slope one team of observers.

Table 7 indicates that the relative instrument error is less than 2% in all measurements. Random error (Table 9) is assumed to be normally distributed about a mean of zero. Table 8 restates each operational definition and indicates any mathematical operations involved in estimating the required measure. Table 8 also summarizes the effects of the arithmetic on the error involved.

Table 10 illustrates the maximum relative error (expressed as percentage error) in each measured parameter which occurs in this study. Before the conversion to logarithms the maximum relative error in any measurements is never greater than 3%. This is considered significantly small.

3:8:0 Data Description

Table 11 statistically summarizes the morphometric data found in Table 3. A brief discussion of these descriptive statistics and their significance follows.

3:8:1 Fan Slope (λ)

The measured slopes of the sample alluvial fans range from 1.82 degrees to 0.63 degrees with a mean value of 1.13 and a median value of 1.06 degrees. The variance was calculated to be 0.14 and the standard deviation is 0.38 degrees. The near equality of the sample mean and median values is reflected by the coefficient of skewness (0.05) and indicates a near normal distribution (normal distribution: SK = 0.00). Generally, it may be said that the sample alluvial fan slopes in the study area are normally distributed about a mean value of 1.13 degrees with a standard deviation of 0.38 degrees.

TABLE 5

ACCIDENTAL ERROR

Measured Parameter	Error
Fan Slope	Verification of each measurement value has effectively eliminated all accidental error from the study.
Basin Area	
Basin Height	
Basin Length	
Basin Slope	
Relative Relief Ratio	

TABLE 6

OBSERVER BIAS

Measured Parameter	Error
Fan Slope	Since all measurements were derived by the same observer, the observer bias in the study is considered relatively constant and insignificant.
Basin Area	
Basin Height	
Basin Length	
Basin Slope	Dependent on observer bias occurring in other Basin Parameters.
Relative Relief Ratio	

TABLE 7

INSTRUMENT ERROR

Fan Slope - instrument; GK 1 Small Engineers Level.

Height - absolute threshold 0.02 feet.

- rounded-off threshold 0.01 feet.
- maximum relative error recorded in the study was 1.4%
- minimum relative error recorded in the study was 0.2%

Length - absolute threshold 4.0 feet.

- rounded-off threshold 2.0 feet.
- most probable error 2.83 feet.
- maximum relative error recorded in the study was 1.7%
- minimum relative error recorded in the study was 0.4%

Basin Area - instrument; Koizumi Compensating Planimeter Type KP-23.

- absolute threshold 0.01 square centimeters.
- map scale 1:50,000.
- actual error 0.0025 square kilometers.

Basin Height - contour interval on 1:50,000 topographic map is 25.0 feet.

- absolute threshold 25.0 feet.
- rounded-off threshold 12.5 feet.

TABLE 7 (cont'd)

Basin Length	- instrument; rule.
	- absolute threshold 0.1 centimeters.
	- rounded-off threshold 0.05 centimeters.
	- map scale 1:50,000.
	- actual error 2.5 meters.
Basin Slope	- mathematically defined as basin height divided by basin length; therefore, no direct instrument measurement.
Relative Relief Ratio	- mathematically defined as the basin height divided by the square root of the basin area; therefore, no direct instrument measurement.

TABLE 8

METHOD ERROR

Fan Slope	- the ratio of rise over run of two points lying on the surface of the alluvial fan in the upper one fourth of the medial radial line.
	- mathematical operation - rise divided by run.
	- error - relative error in the rise estimate minus the relative error in the run estimate.
Basin Area	- total (plane) area of the basin upstream from the fan apex.
Basin Height	- the difference between the elevation of the fan apex and the elevation of the highest point on the basin perimeter.
	- mathematical operation - elevation at the divide minus the elevation at the fan apex.
	- error - absolute threshold - 25 feet. - rounded-off threshold - 12.5 feet. - most probable error - 17.68 feet.
Basin Length	- the straight line distance from the fan apex to the most extreme point on the perimeter.
Basin Slope	- basin height divided by basin length.
	- error - relative error in basin height estimate minus the relative error in the basin length estimate.
Relative Relief Ratio	- the basin height divided by the square root of the basin area.
	- error - the relative error in the basin height estimate minus one half of the relative error in the basin area estimate.

TABLE 9

RANDOM ERROR

Fan Slope	
Basin Area	Random error is assumed to obey the Normal Law of Error for all measured parameters.
Basin Height	
Basin Length	
Basin Slope	
Relative Relief Ratio	

TABLE 10

MAXIMUM RELATIVE ERROR OCCURRING IN EACH MEASURED PARAMETER

Parameter	Max. Relative Error
Fan Slope	1.5%
Basin Area	0.1%
Basin Height	2.8%
Basin Length	0.1%
Basin Slope	2.8% approximately
Relative Relief Ratio	2.8% approximately

TABLE 11

MORPHOMETRIC DATA SUMMARY

	λ	A	Ht	L	Ht/L	$Ht/\sqrt{A}$
Mean	1.13	8.14	0.18	5.94	0.0432	0.0927
Median	1.06	4.17	0.18	4.08	0.0448	0.0862
Var	0.14	72.25	0.00	18.66	0.0001	0.0014
St Dev	0.38	8.50	0.03	4.32	0.0141	0.0387
SK	0.05	1.40	0.00	1.38	-0.1300	0.5000
Coef Var	0.34	1.04	0.17	0.73	0.3300	0.4200
Max	1.82	27.72	0.26	9.72	0.0705	0.1538
Min	0.63	1.00	0.12	2.25	0.0185	0.0361
R	1.19	26.72	0.14	9.47	0.0520	0.1177

Mean $\bar{X} = \sum_{i=1}^{N} Xi/N$

Median $Md = (X_{10} + X_{11})/2$

Variance $Var = \sum_{i=1}^{N} \frac{(Xi - \bar{X})^2}{N}$

Standard Deviation $s = \sqrt{Var}$

Skewness $SK = \frac{3(\bar{X} - Md)}{s}$ (Blaylock, 1960, 74)

Coefficient of Variability $Coef\ Var = s/\bar{X}$

Maximum Max

Minimum Min

Range $R = Max - Min$

The normally distributed data and relatively small coefficient of variability (0.34) are very important when considering an equilibrium model in a general systems framework. This model implies that the complex geometric element (landform) is in a steady state or equilibrium and therefore the parameters representing the landform are virtually constant. Probability theory interprets "virtually constant" as normally distributed about a mean value with a relatively small variance. In view of this interpretation it is assumed that the alluvial fans located in the study area are in a steady state.

3:8:2 Basin Area (A)

The sample basin areas range from 1 sq. mi. to 27.72 sq. mi. and have a mean value of 8.14 sq. mi. The median basin area however, is 4.17 sq. mi. and this suggests that the sample population is highly skewed (SK = 1.40) toward the relatively small basins. The sample basin areas have a large variance (72.25) and standard deviation (8.5). A high degree of variation in sample basin areas is desirable in this study since it indicates that the study does not concentrate on a particular basin size but is concerned with the large range of basins located in the study area.

3:8:3 Basin Length (L)

Basin length is directly related to basin area and therefore it can be expected to have a relatively large range (maximum 9.72 mi., minimum 2.25 mi.) and high degree of variation (variance 18.66, standard deviation 4.32). The sample basin lengths are also positively skewed (SK = 1.38) and therefore log-normally distributed about their mean value (5.94 mi.).

3:8:4 Basin Height (Ht)

Sample basin heights appear to be normally distributed (SK = 0.00) about their equivalent mean and median values of 0.18 mi., with a variance of 0.00 and standard deviation of 0.03 mi. This is to be expected since the sample basins are included in a relatively small segment of the Manitoba Excarpment which exhibits only minor variations in relative relief in the study area. However it would be inappropriate to assume normality for the sample basin height data, since it has previously been demonstrated that the Manitoba Escarpment increases in relative relief in a northward direction (p. 9).

3:8:5 Basin Slope and Relative Relief Ratio

Both, sample basin slope (Ht/L) and relative relief ratios ($Ht/\sqrt{A}$) are functions of previously described morphometric parameters and reflect the variability and non-normality of their components.

In summary, the sample basin parameters have relatively high coefficients of skewness and variability and are, therefore, characterized by log-normal sampling distributions with high degrees of variation. The log-normal distributions pose a minor problem in that logarithmic transformations of data are required for further statistical analysis. However, the relatively large variances are desirable in this type of study as they indicate an objective systematic sampling of the total basin population.

3:9:0 The Fan/Basin Morphometric Relationships in the Study Area

If the hydrologic variables, illustrated in the partial synthetic systems model (Figure 9) are placed in a 'black box' situation, the partial synthetic systems model becomes a simplified morphometric system (Figure 11). The nature and strength of the linkages in this system may be investigated by applying simple linear regression and correlation analysis.

SIMPLIFIED MORPHOMETRIC SYSTEMS MODEL

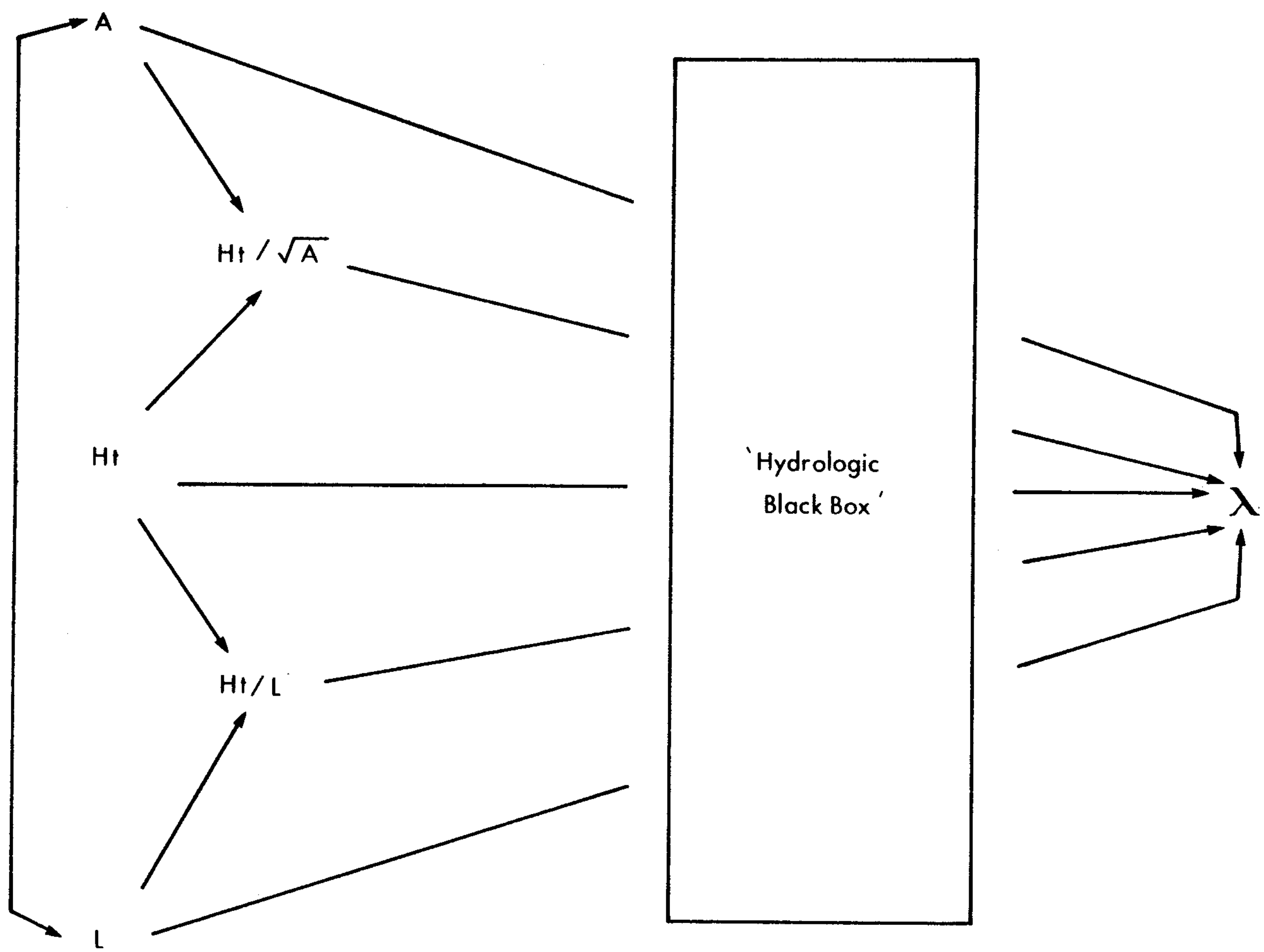


Figure 11

The simple linear regression model assumes that the values of the independent variable (X) and the dependent variable (Y) are observed without measurement error (Poole and O'Farrell,1971, 148). The less than 3% relative error in all measurement is significantly small to fulfill the first assumption. The second assumption of the linear model is that the relationship between Y and X is linear. In a correlation-regression analysis the coefficient of determination (r^2) is a measure of the strength of this assumption. The third, fourth, and fifth assumptions involve the nature of the error term; namely, that the distribution of errors about any measured parameter is a standard normal with a mean value of zero, variance of one, and that they are not serially auto-correlated.

The sixth and last assumption of the correlation-regression model is that the variables themselves are normally distributed. In this study it has been demonstrated that the measured morphometric parameters are not normally distributed but positively skewed, which suggests that the sampling distributions of these parameters are log-normal. Therefore, in order to maintain the last assumption of normality, the data must be converted to logarithms (Table 4).

Plots, or scatter diagrams, of fan slope versus the five selected basin parameters are illustrated in Figures 12-16, (Appendix IV). Clearly, no linear trends are discernable. Figures 17-21 (Appendix IV) represent the scatter diagrams of the same data plotted on logarithmic paper and linear trends are suggested in these plots.

The least squares regression analysis is summarized in Table 12 and the t values for the five analyses indicate that there is a 99% probability that the established correlations exist. Relatively high r

TABLE 12

CORRELATION - REGRESSION ANALYSIS

SUMMARY TABLE

Variables	r	r^2	F Significant at	c	n	Sn	t Significant at
λ and A	-0.84	0.71	0.01	1.61	-0.27	0.08	0.01
λ and Ht	-0.46	0.21	0.05	0.23	-0.90	0.14	0.01
λ and L	-0.77	0.59	0.01	2.57	-0.58	0.10	0.01
λ and Ht/L	+0.70	0.49	0.01	7.43	0.60	0.11	0.01
λ and Ht/$\sqrt{A}$	+0.80	0.64	0.01	4.66	0.60	0.10	0.01

values are obtained for fan slope and basin area (-0.84) basin length (-0.77), basin slope (0.70), and basin relief ratio (0.80). In view of the very high correlation coefficient (r = -0.84) for fan slope vs basin area and the obvious interdependence of the other three basin parameters with basin area, these high r values are expected. The five correlation coefficients (r) are significant at the 5% probability level, and four of the five are significant at the 1% probability level (λ vs Ht being the exception).

The coefficient of determination (r^2) is a measure of the variance explained by the calculated regression line $Y = cX^n$ and the F test statistic establishes the probability level of significance.

3:9:1 Fan Slope, Basin Area, and Relief Ratios

Clearly the fan slope-basin area relationship $\lambda = 1.61\ A^{-0.27}$ accounts for the greatest amount of variation in fan slope. The fan slope-basin height relationship $\lambda = 0.23\ Ht^{-0.9}$ appears relatively insignificant in explaining this variation ($r^2 = 0.21$).

Melton (1965) arrived at similar results, yet further analysis employing a multiple regression model revealed a 15% increase in r^2 values when basin area and basin height were employed as independent variables. This led Melton to postulate that the basin relief ratio ($Ht/\sqrt{A}$) would be a useful measure in evaluating fan slopes.

Ryder (1971a) supported Melton's findings. In three of the five regions studied the $\lambda = cHt/\sqrt{A}^{\,n}$ relationship accounted for more fan slope variance than the $\lambda = cA^n$ function.

However, in the Manitoba Escarpment study the $\lambda = cHt/\sqrt{A}^{\,n}$ equation accounts for 64% of the fan slope variance which is 7% less than the variance explained by the $\lambda = cA^n$ function.

A brief discussion of the relevant basin parameters and their respective variances in each of the three study areas may account for the discrepancies.

Ryder (1971a) has studied paraglacial alluvial fans located in five different river valleys in British Columbia. An examination of the study area characteristics (Ryder 1971a, 1255) indicates that there are significant differences in the respective basin height values (Ht). This allows Ryder's sub-regions to be categorized as areas of large or small basin height. The large basin height category includes alluvial fan systems with basin height values which range from 5000 to 8000 feet. The small basin height category varies in height from 2000 to 3500 feet. Ryder found that the $\lambda = c(Ht/\sqrt{A})^n$ function accounted for more variance in fan slope than the $\lambda = cA^n$ equation only in those study areas displaying large basin height values. In those areas with a small basin height value, the $\lambda = cA^n$ function explained more variance in fan slope.

The fan systems located in Melton's study region range in basin heights from 1300 to 9180 feet, but are generally in the large basin height category. The alluvial fan systems studied in the Manitoba Escarpment area have a basin height of 600 feet and definitely lie in the small basin height category. It is concluded that in areas where the basin height values vary greatly (display a large range), the $Ht/\sqrt{A}$ variable assumes more significance in explaining fan slope variance. In areas where the basin height values do not vary greatly, drainage basin area accounts for a significant amount of fan slope variation.

This empirical finding is theoretically predictable when the nature of the independent variables is closely examined. Given that basin area (A) has a large coefficient of variability; the $\sqrt{A}$ will have a significantly smaller coefficient of variability. If basin height (Ht) varies over a large range it is possible that the independent variable $Ht/\sqrt{A}$ may account for greater variance in fan slope than basin area (A). However, if basin height (Ht) has a relatively small coefficient of variability (in effect Ht is a constant), then it becomes mathematically impossible for the $Ht/\sqrt{A}$ variable to account for more variation in fan slope than the basin area (A) variable.

3:9:2 Fan Slope and Drainage Basin Area

The application of the least squares regression model to the selected pairings of morphometric variables indicates that the drainage area is the most significant basin parameter contributing to alluvial sedimentation along the Manitoba Escarpment. Furthermore, the relationship $\lambda = 1.61A^{-0.27}$ accounts for 71% of the variation occurring in fan slope. These results are not unexpected.

Drew (1873), Eckis (1928), and Blackwelder (1931), observed that small fans have steep slopes while large fans are characterized by low gradients. Bull (1962), Melton (1965), Ryder (1971a) and Beaumont (1972) have empirically substantiated these early observations. Bull, Melton, Ryder and Beaumont have also derived fan slope - basin area functions similar to the $\lambda = 1.61A^{-0.27}$ equation calculated in the Manitoba Escarpment area. Table 13 summarizes the empirical relationships found in the five studies.

Several similarities and differences are apparent.

1. All five researchers have employed the power function $\lambda = cA^n$ as a model. This suggests that preliminary scattergrams have indicated

TABLE 13

MORPHOMETRIC FUNCTIONS (Comparison Chart)

Author Date	Location	Regression Equation	r	c	Sc	n	Sn
		$\lambda = cA^{n}$					
Bull 1962	California	$\lambda = 1.33A^{-0.16}$	-	1.33	-	-0.16	-
	"	$\lambda = 1.25A^{-0.32}$	-	1.25	-	-0.32	-
Melton 1965	Arizona	$\lambda = 4.11A^{-0.39}$	-0.86	4.11	-	-0.39	-
Ryder 1971[a]	Fraser	$\lambda = 8.86A^{-0.22}$	-0.85	8.86	1.83	-0.22	0.10
	Thompson	$\lambda = 7.28A^{-0.14}$	-0.73	7.28	1.07	-0.14	0.10
	Bonaparte	$\lambda = 6.95A^{-0.18}$	-0.66	6.95	1.43	-0.18	0.13
	Similkameen	$\lambda = 8.95A^{-0.39}$	-0.92	8.95	1.17	-0.39	0.11
	Kamloops	$\lambda = 0.07A^{-0.54}$	-0.56	0.07	-	-0.54	-
Beaumont 1972	Iran	$\lambda = 42.27A^{-0.13}$	-	42.27	-	-0.13	-
McGinn 1979	Manitoba Escarpment	$\lambda = 1.61A^{-0.27}$	-0.84	1.61	0.38	-0.27	0.08

that the variables are log-normal and that the mathematical relationship is log-linear.

2. The sign of the exponent is negative. This indicates that fan slope decreases with increasing drainage basin area. Hooke (1967) suggests that this empirical law is due to the larger discharges associated with larger drainage basin areas. The larger discharges are capable of transporting the sediment load a greater distance down the fan slope, therefore building larger fans with gentler gradients. A corollary to this hypothesis is that the larger basins supply less sediment per unit area than the smaller basins (Hooke, 1968).

3. Although not all the studies employ the same operational definitions and some do not include the standard error of the slope coefficient, it appears that n is generally restricted in its range. The regional variations occurring in n may be due to factors affecting the hydrological variables - stream discharge and sediment yield.

The tenet that larger discharges are associated with large drainage basin areas does not apply if a precipitation event does not occur over the total catchment area. The probability of maximum storm coverage, for a given storm, decreases as the basin area increases and the frequency of total basin area storm coverage also decreases as basin areas increase. Snow accumulation over extended time periods is the natural exception to these postulates. However, for precipitation events, the percentage of the basin area covered and the frequency of maximum coverage may be significant in determining the exponent n in the fan slope - basin area function.

The sediment yield of a given basin is dependent on the amount of potential sediment produced on the respective valley slopes. Hence different types of mechanical and chemical weathering and their accompanying different rates of sediment production are also thought to influence the value of the exponent (Hooke, 1968).

Another factor affecting sediment yield and related to stream discharge and drainage basin area, is the basin sediment storage potential. Weathered material may be stored on the valley slopes and in the stream channels until a major precipitation event essentially 'flushes out' the basin. Hooke (1968) postulates that the magnitude and frequency of these events is significant in determining the value of n.

4. The intercept values c display a large coefficient of variability. Again several factors may account for the large variance.

Bull (1962) suggests that c may fluctuate in response to differing basin lithologies and consequently varying weathering rates. Bull's fan slope - basin area functions for "sandstone and shale fans" have a small c value indicating relatively small sediment yields. The fan slope - basin area functions derived for Ryder's "paraglacial (till) fans" have relatively high c values and therefore, indicate larger sediment yields (Ryder, 1971a).

Tectonic activity would definitely alter c values and both Bull (1962) and Beaumont (1972) have indicated that there is evidence that this has occurred in their study areas.

Hooke (1968) postulates that c values are a measure of the depositional area/erosional area ratio. Differing c values are a result of factors which restrict the development of either area. The glacial lake beaches, located along the base of the Manitoba Escarpment, have restricted fan development in the depositional area and a smaller ratio (c) value can be expected.

Hooke (1968) also suggests that a downstream shift in the locus of deposition results in fan head entrenchment and the abandoning of the upper depositional area. This affects the depositional area/erosional area ratio and therefore affects the c value.

3:10 Summary Statement

Figure 22 implies that the partial synthetic systems model representing the alluvial fan geomorphic system (Figure 9) is subdivided into two fan generating subsystems; the drainage basin morphology and the stream hydrology. These two fan generating subsystems give rise to the resultant alluvial fan physiography.

Fan slope has been selected as the composite morphometric parameter which best reflects the basin morphometry - stream hydrology - fan physiography relationship (p. 51). Furthermore, an analysis of the fan slope distribution in the study area indicates that this alluvial fan geomorphic system can be considered to be in a state of equilibrium (p. 58).

The three dimensions fundamental to basin morphology (height, length, and width) have been incorporated into several key components; namely, basin area, slope and relative relief ratio. The linear regression model has been employed to evaluate the nature of the relationships between the fundamental basin morphometric parameters, the composite basin morphometric components and the alluvial fan slope. The results (Figure 22, and Table 12) indicate that the empirical function $\lambda = 1.61\ A^{-0.27}$ represents the strongest ($r = -0.84$) morphometric linkage evident in the alluvial fan geomorphic system operating in the Manitoba Escarpment study area. Figure 22 also illustrates and summarizes the nature and strength of the other morphometric linkages

REFINED MORPHOMETRIC SYSTEMS MODEL
(The Riding Mountain Area)

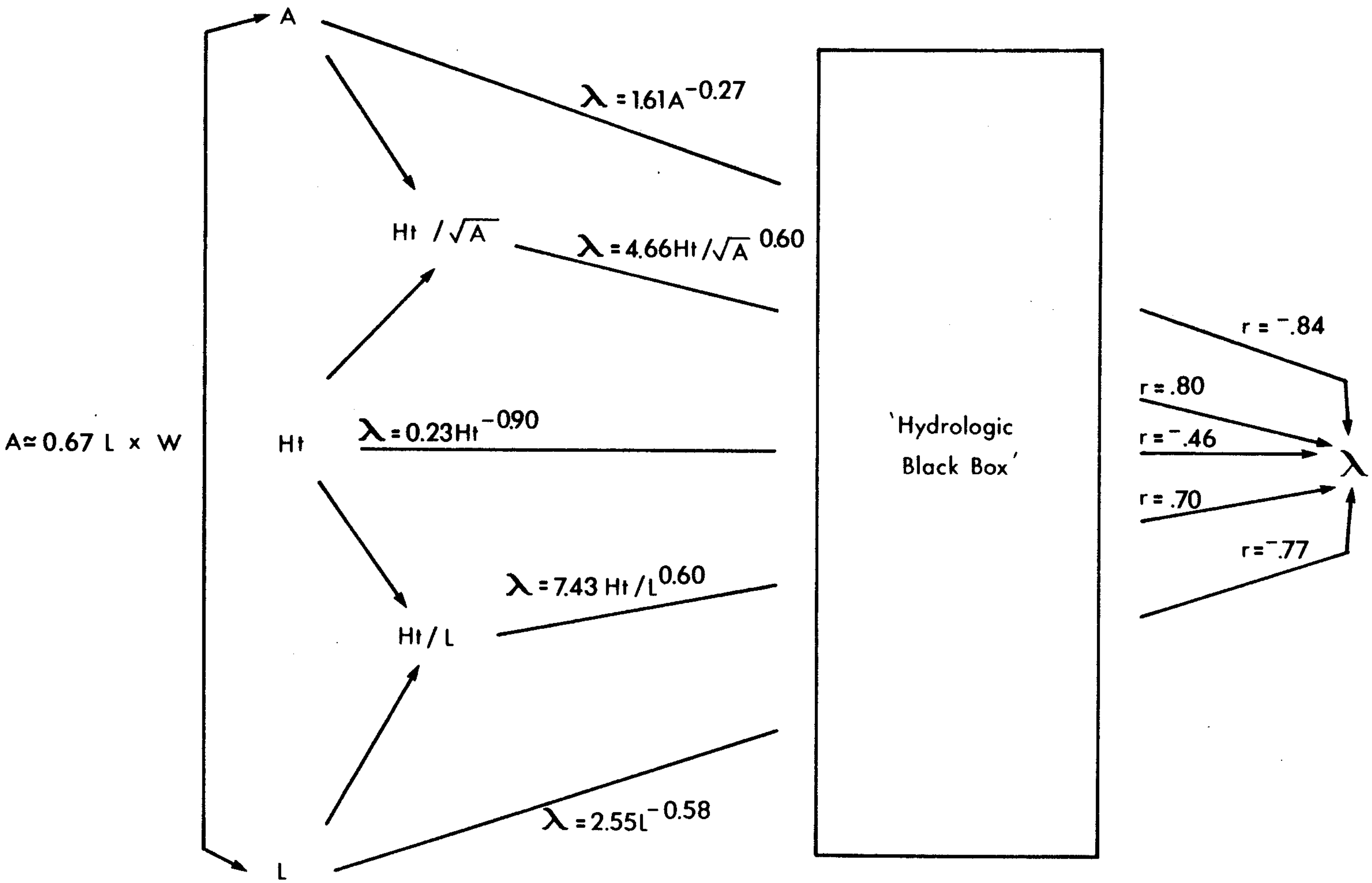


Figure 22

studied in the partial synthetic system model (Figure 9). Of particular interest is the relative relief - fan slope relationship. Contrary to the published results (Melton, 1965 and Ryder, 1971a), the relative relief ratio $Ht/\sqrt{A}$ does not add significantly to the explained fan slope variance in the study area. It is believed that the virtually uniform height of the Manitoba Escarpment in the study region accounts for these results.

The initial assumption of the model was that the hydrological variables illustrated in Figure 9 were placed in a "black box situation" and essentially treated as constants. The investigation of the fan slope - basin area function indicates that the intercept value c and the slope coefficient n are significantly related to several of these hydrological variables, namely; discharge, sediment yield, sediment size and channel storage potential. Clearly an understanding of the alluvial fan geomorphic system requires a detailed investigation of this 'Hydrological Black Box'.

CHAPTER IV

GENERAL HYDROCLIMATOLOGY AND HYDROLOGY OF THE STUDY AREA

4:1 Introduction

In the alluvial fan geomorphic system the drainage basin area parameter represents a surface upon which a weathering subsystem and a climatic-meteorologic subsystem are operating. These two subsystems are considered to be generators of the principal material inputs in the alluvial fan system. The weathering subsystem provides the sediment composing the alluvial fan; the climatic-meteorologic subsystem provides the transport medium, water. The slope of the drainage basin - alluvial fan complex represents the energy gradient of the system. Therefore, the accumulation of alluvial fan deposits along the Manitoba Escarpment is a function of the interaction of the weathering subsystem and the climatic-meteorologic subsystem operating on a drainage basin area. The resulting material inputs are transfered along an energy gradient via the stream hydrology subsystem to the alluvial fan. Furthermore, the material transfers takes place through a narrow interface termed the fan apex or drainage basin mouth. (Figure 23).

The fluvial transport of solid debris is generally considered to be a function of the ratio between shear stress at the boundary and the critical shear stress of the material (Henderson, 1966). Often this is considered in terms of size of material and stream discharge (Gilbert, 1914; Shields, 1936;). Hooke (1968,623) suggests that

ALLUVIAL FAN

GEOMORPHIC SYSTEM MODEL

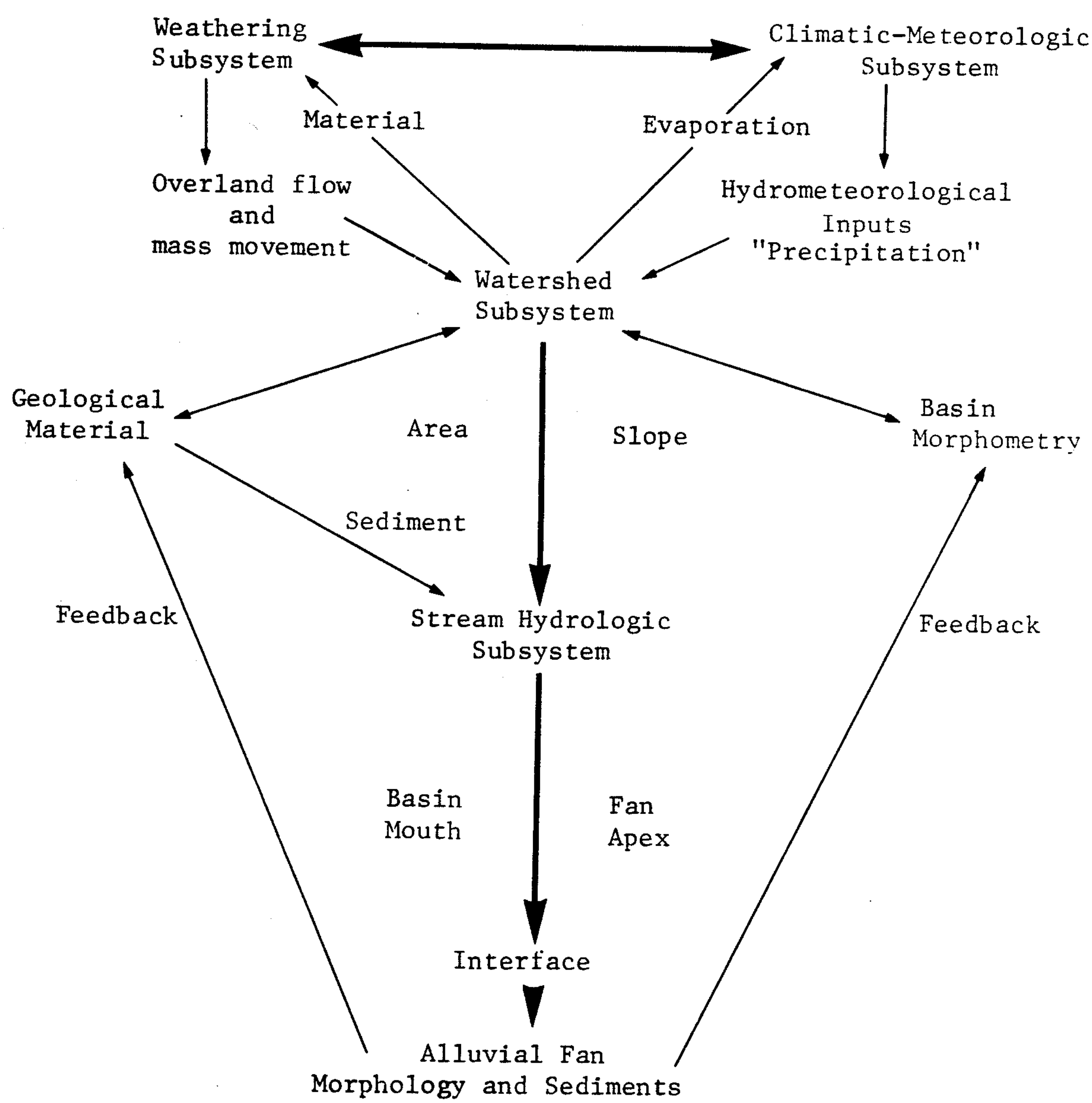


Figure 23

the slope of an alluvial fan is produced by a series of discharges which deposit associated sizes of material at various points on the fan surface and he introduces the concept of a "dominant" fan building discharge, defined as the discharge which would result in a fan of a given slope if only that discharge occurred (Hooke, 1968, 625). This operational definition and the significance of a dominant fan building discharge will be discussed later. At this time the major consideration is that a term can be defined which will relate the magnitude and frequency of material inputs to the fan form.

4:2 Hydrological Models of Drainage Basins

The ancient concept of a hydrological cycle considers the transport, loss and recharge of the earth's waters. This continuum has been traditionally divided into three principal phases: runoff (surface and ground water), evaporation and precipitation (Gray, 1970). Each phase usually includes mass transfer, temporary storage, and a change in state. Considering these assumptions, the quantity or volume of water passing through each phase may be evaluated in terms of a general input-output model, i.e., input minus output equals changes in storage.

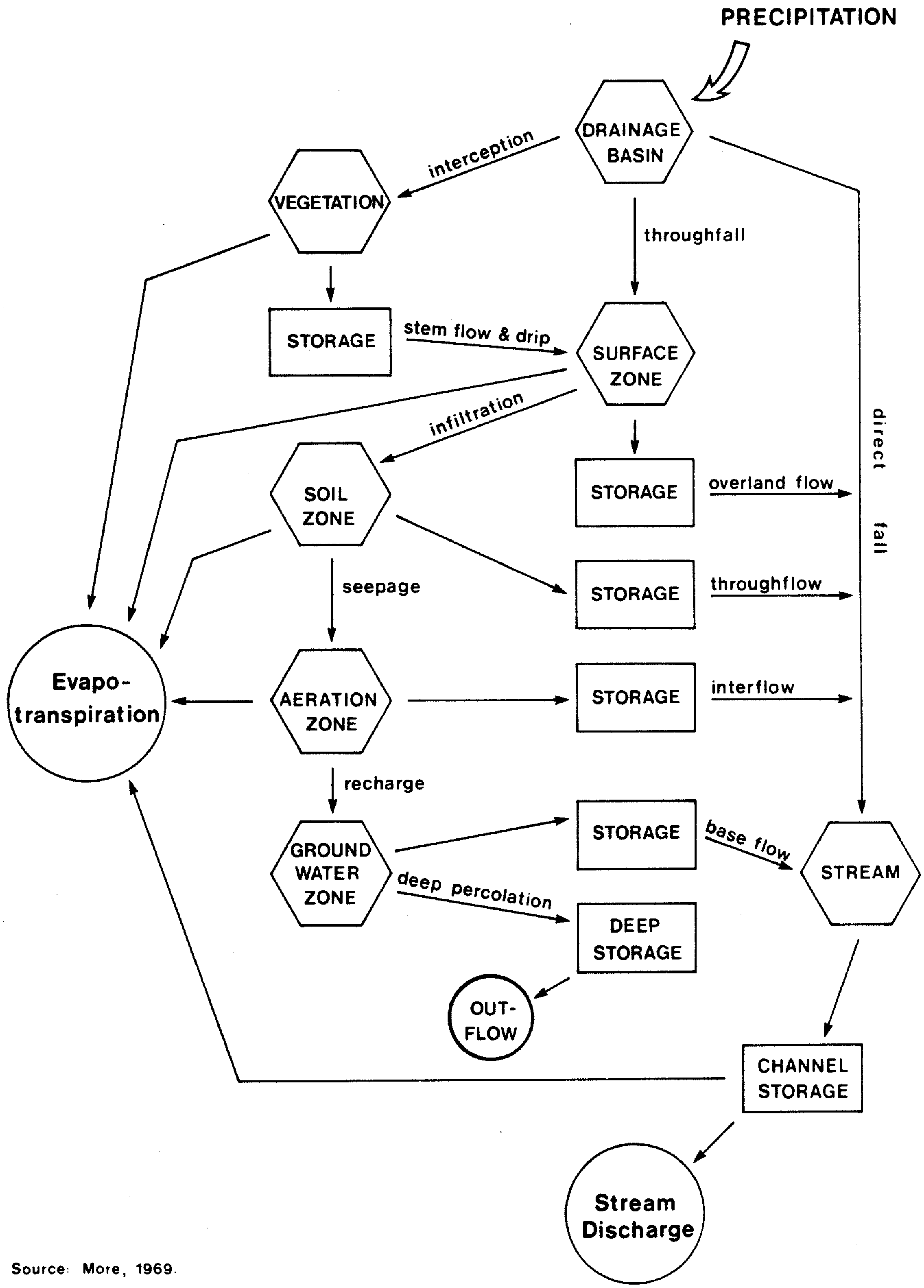
Meinzer (1942) has examined the historical investigations of the hydrological cycle and subdivided this continuum into eight categories for study: precipitation, infiltration, percolation, storage, evaporation, transpiration, ground water flow, and surface runoff. Present day researchers have accepted the concept of a global hydrological cycle and the representative input-output models.

Recent studies frequently apply the theory of a hydrological cycle input-output model to Meinzer's specific categories of study for a given drainage basin system. This methodology constitutes what Chorley and Haggett (1969) define as a natural analogue model and is based on the assumption that the individual drainage basin is a representative sample of all drainage basins within a specified area. The natural analogue model is particularly useful in that it permits intensive data collection and subsequent data analysis on a relatively small scale. Meinzer's eight components of the hydrological cycle of a given drainage basin may be systematically analyzed and modelled; often employing submodels of structure, function, and explanation. Minshull (1975) points out that each submodel lends itself to further investigation; employing various iconic, hardware, mathematical, analogue, and symbolic models.

The 1948 Thornthwaite model has been a useful input-output model employed by applied hydrologists. Essentially the model equates water inputs (precipitation and irrigation) to water outputs (evaporation, transpiration and stream discharge). Since the model is primarily a 'black box' input-output model, it cannot account for feedback relationships and transfer lags. Consequently, apparent water losses which occur within the system due to feedback and transfer lags are assigned to the particular parameter estimated by the input-output equation (usually evapotranspiration).

More (1969)has symbolically modelled the hydrology of a drainage basin system, subdividing inputs, storages, transfers, and outputs (Figure 24). Several researchers have attempted to evaluate the

PARTIAL SYSTEMS MODEL
Hydrological Cycle of a Drainage Basin



Source: More, 1969.

Figure 24

components of this or similar systems models (e.g. Chorley, 1969, ed. and Gray, 1970, ed.). The major problems confronting this approach were equipment limitation, the need for long term data collection, and the difficulty in approximating various non-linear gradients (e.g. vapour pressure and percolation rates).

For these reasons, it is often as valid and generally more convenient to modify More's synthetic systems model by combining it with a generalized hydrological input-output model (Figure 25). Certain components of this drainage basin input-output model are estimated by employing empirical functions derived from natural analogue models. The specific components under investigation are then considered within the conceptual framework of a partial synthetic systems model. The key input, storage, and output components are operationally defined and the nature of the transfer and feedback linkages modelled (usually mathematically modelled). The newly established models are then empirically tested, revised and retested.

4:3 Alluvial Sedimentation and the Hydrological Input-Output Systems Model

As stated previously the accumulation of alluvial deposits in the Riding Mountain area is a function of the interaction of a weathering subsystem and a climatic-meterologic subsystem operating on a drainage basin. The material inputs are transported via the stream system to the basin mouth-fan apex.

Hooke (1968) and Ryder (1971a) point to a need for investigations into the nature and strength of the key hydrological variables present in the alluvial fan geomorphic system and both authors suggest that

A MODIFIED INPUT/OUTPUT MODEL

THE WATERSHED HYDROLOGICAL CYCLE

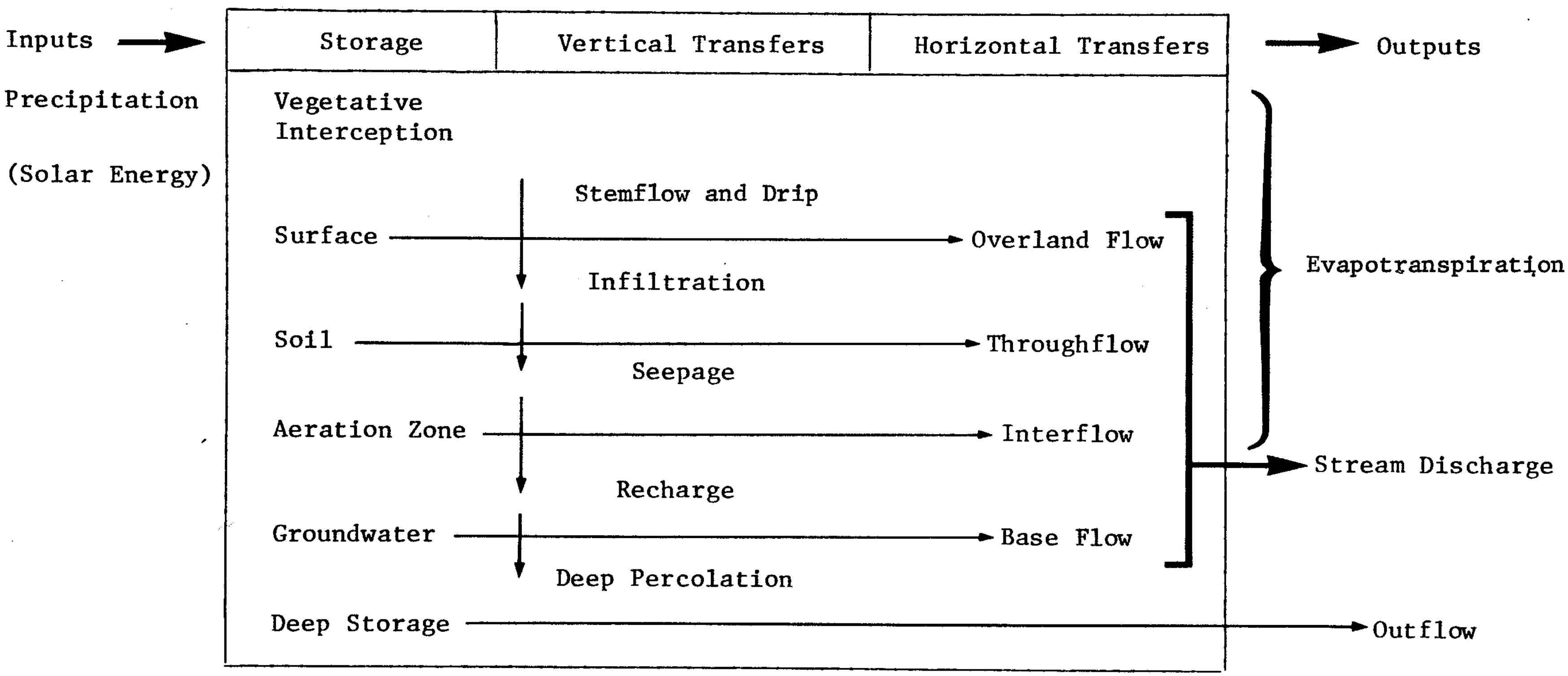


Figure 25

stream discharge and sediment load, measured at the fan apex, are obvious fundamental hydrometric parameters.

A government monitored hydrometric data collection programme has been in operation for approximately 18 years in the study area. This programme focuses on five drainage basins (Figure 10) and the resulting concentration of data encourages the use of these watersheds as natural analogue models. However, the conclusions derived from this proposed analogue approach depend on the basic assumption, that the selected drainage basins are characteristic of all drainage basins in the study area.

The important environmental characteristics of the drainage basins with respect to this study include physiography, geology, vegetation, climate and hydrology. The previously discussed physical description of the study area and the discussion of basin morphometry would tend to support the assumption of similitude with respect to physiography and geology. Furthermore, the presence of Riding Mountain National Park has successfully maintained the natural vegetation cover in 85% of the study basins and all the proposed analogue basins exhibit the characteristic natural vegetation patterns outlined in the Introduction to the Study Area (p. 18). It is also reasonable to assume that uniform climatic conditions exist and have existed over the 1000 km^2 study area, despite significant changes in the continental climate during the last 10,000 years. Durrant and Blackwell (1959) have suggested that the drainage basins located on the east slope of the Manitoba Escarpment north of Neepawa comprise a distinctive mean annual flood region and a specific flood frequency division. Their empirical evidence may be interpreted as demonstrating hydrologic similitude. It can be concluded that the general natural analogue model assumption of physiographic, geologic, vegetal, climatic and hydrologic similarity in the sample watersheds has been adequately fulfilled.

4:4:0 Hydrological Data Sources

4:4:1 Climatic-Meteorologic Data Sources

Four meteorological data collection stations are located within or adjacent to the study area, at Dauphin Airport, Wilson Creek, Riding Mountain, and Neepawa. Figure 1 indicates their respective locations.

4:4:2 Hydrometric Data Sources

Five of the six continuous flowing streams located in the study area are monitored by the Water Survey of Canada. The location of these monitored streams and the period of record for the daily discharge data are indicated in Figure 10. Additional information regarding flood frequency, sediment loads, and ground water flow can be derived from the published reports on the Edwards Creek and Ochre River Watersheds situated immediately north of the study area.

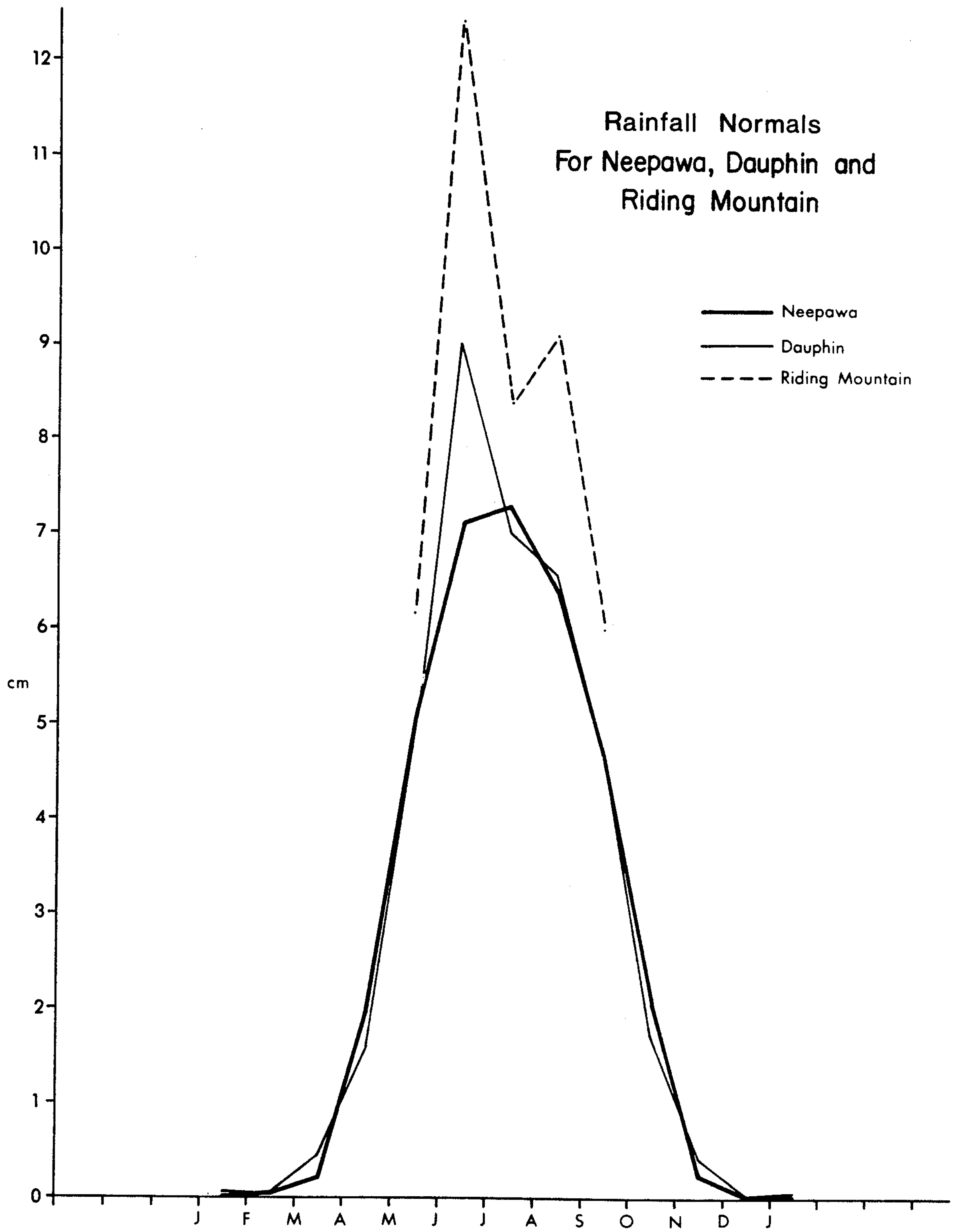
The implied hydrological similarity of these six drainage basins and all other basins comprising the study area must be examined in more detail. The Wilson Creek I.H.D. research watershed is the smallest of the monitored drainage basins ($A = 22.6\ km^2$). While this area is only slightly larger than the mean drainage basin area of the sample basins, it must be noted that drainage basin areas of this study are highly skewed toward the smaller watersheds (Table 3). One must conclude that while these data are significantly representative of discharge and sediment yield for the larger drainage basins, the intermittant flows of the smaller watersheds have not been adequately sampled. For this reason, the cross sections of nine intermittant streams were surveyed at sites located near the fan apex. Channel slope and the size distribution of bed material were also evaluated, and discharge measurements were taken whenever significant flows occurred.

4:5:0 General Hydroclimatology of the Study Area

4:5:1 Precipitation

The most significant material input constituting the hydrological cycle of a drainage basin is termed precipitation. Precipitation may be discussed with respect to type, amount, intensity, frequency, seasonal distribution and areal extent. Table V:1 and Figures 26, 27, 28, 29 illustrate precipitation amounts occurring in the study area.

Total annual precipitation amounts recorded at Dauphin Airport and Neepawa do not appear to vary significantly although the Dauphin area receives approximately 5% more precipitation annually. However, comparisons of the monthly precipitation data collected at the Riding Mountain and Wilson Creek meteorologic stations indicate that approximately 25 percent or 84 millimetres more precipitation falls on the escarpment plateau than on the alluvial fan apex. Figures 28 and 29 substantiate this observation and clearly illustrate that the annual, and perhaps individual storm, precipitation is concentrated on the escarpment plateau.


Rainfall Normals
For Neepawa, Dauphin and
Riding Mountain
Neepawa
Dauphin
Riding Mountain
cm
0
1
2
3
4
5
6
7
8
9
10
11
12
J
F
M
A
M
J
J
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S
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Figure 26

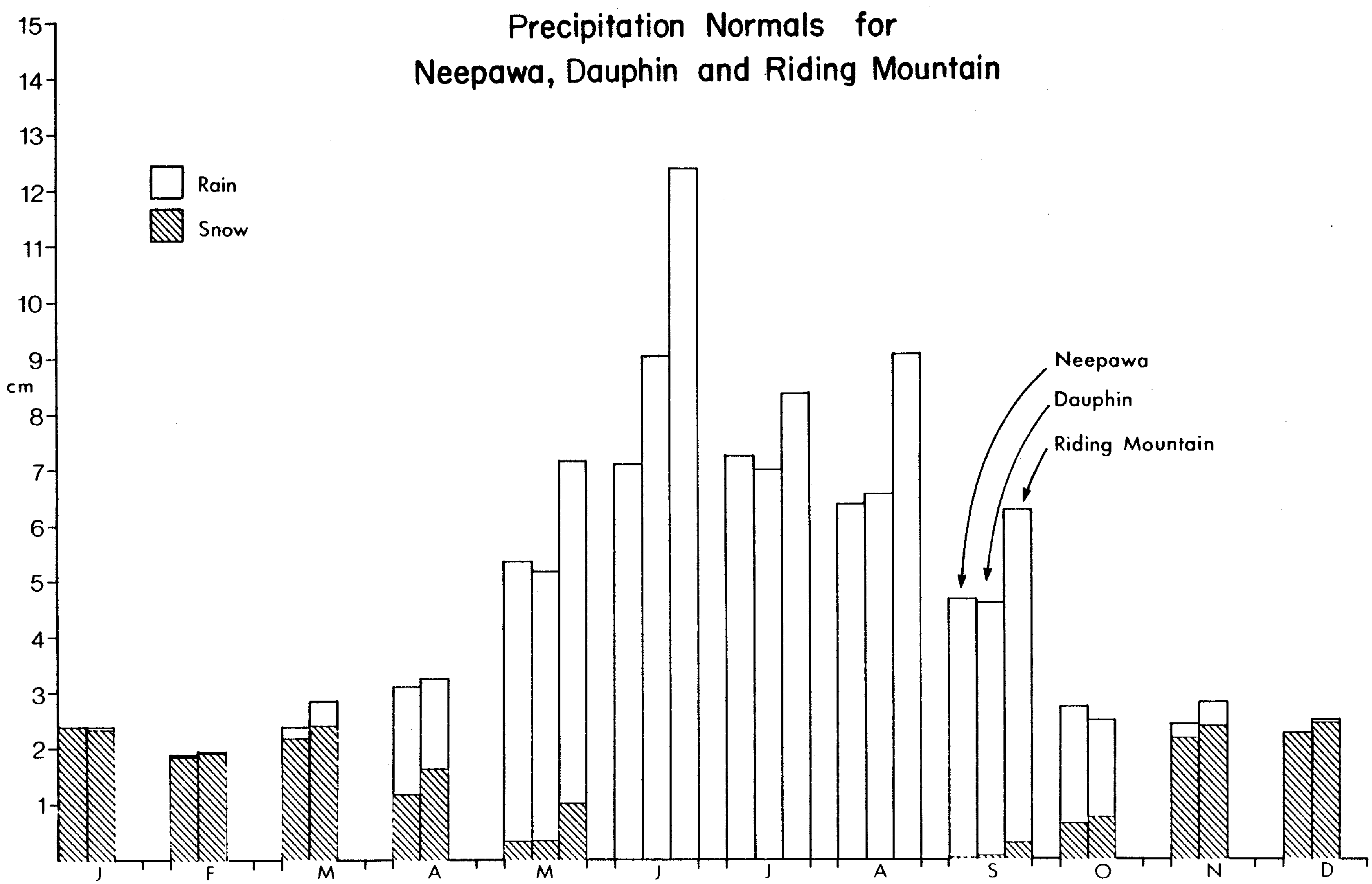
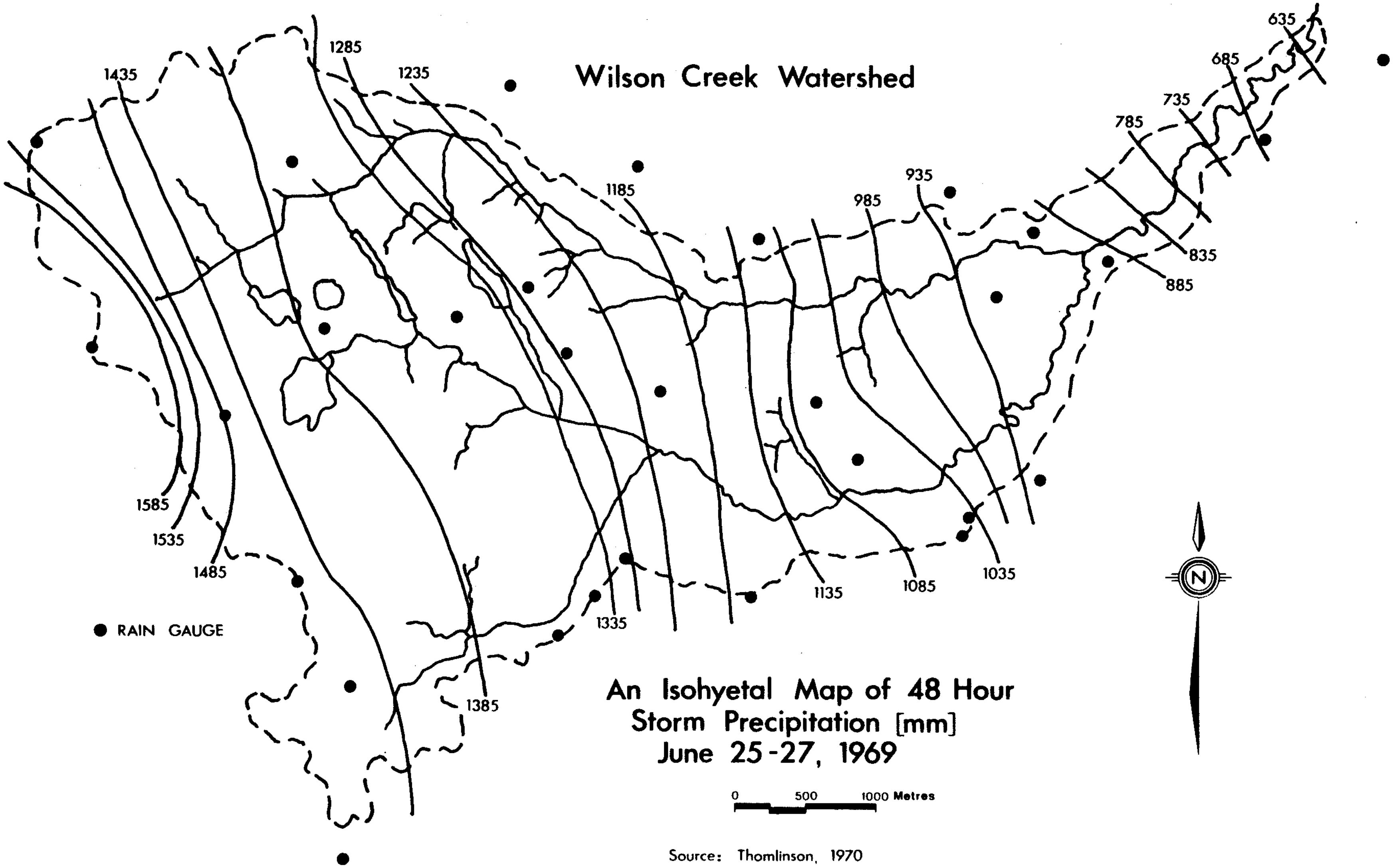

Precipitation Normals for
Neepawa, Dauphin and Riding Mountain
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
cm
Rain
Snow
Neepawa
Dauphin
Riding Mountain
J
F
M
A
M
J
J
A
S
O
N
D

Figure 27

Wilson Creek Watershed



An Isohyetal Map of 48 Hour Storm Precipitation [mm] June 25-27, 1969

Source: Thomlinson, 1970

Figure 28

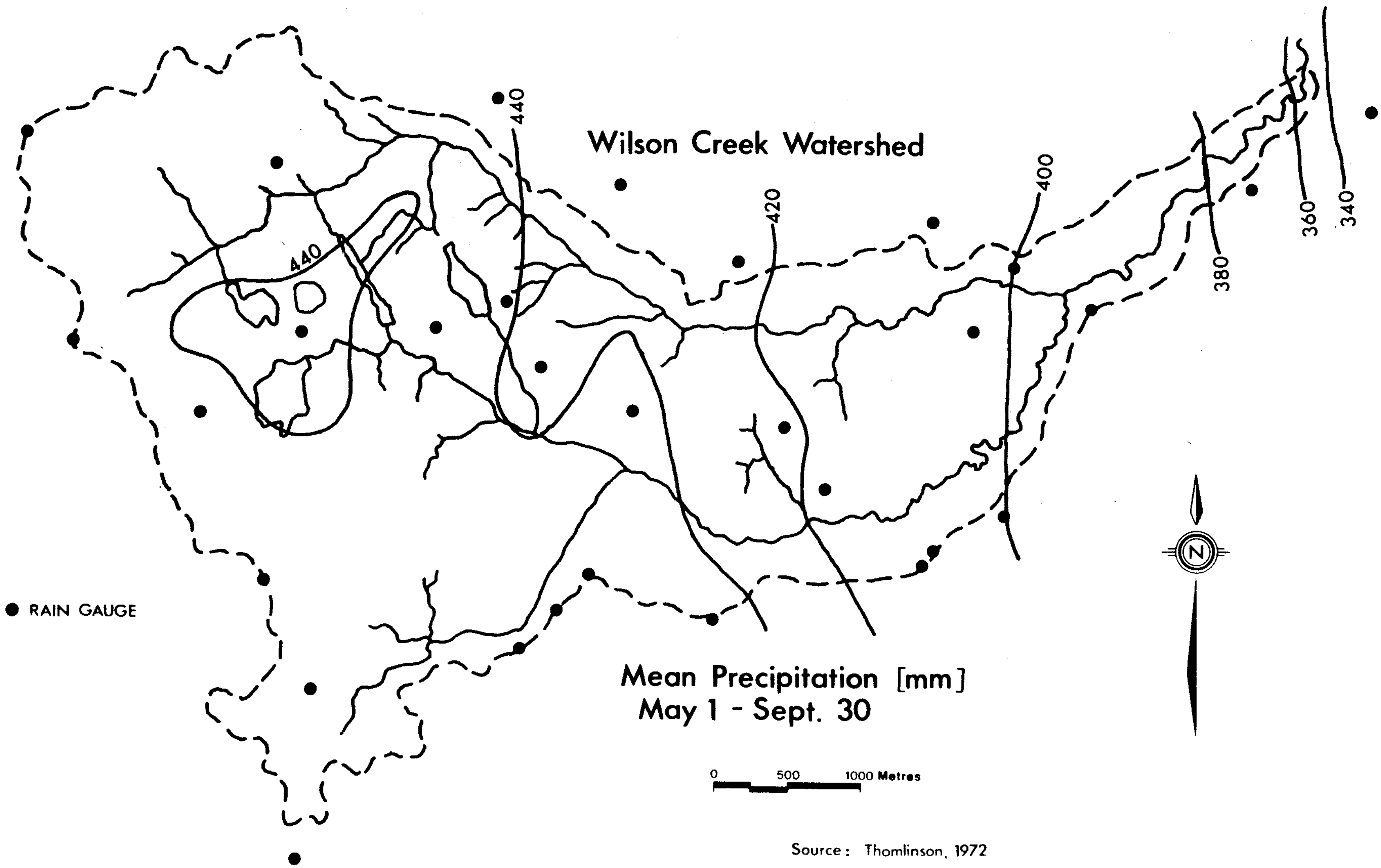

Wilson Creek Watershed
440
440
420
400
380
360
340
RAIN GAUGE
N
Mean Precipitation [mm]
May 1 - Sept. 30
0 500 1000 Metres
Source: Thomlinson, 1972

Figure 29

Such large variations in total precipitation amounts over a relatively small area are frequently related to orography. The orographic factor affecting local precipitation patterns may be of several types: mechanical lifting, enhanced convection, spillover, and direct deposition (Reinelt, 1970). The low absolute relief of the Manitoba Escarpment (approximately 700 m) effectively eliminates any possibility of orographic precipitation by direct deposition and since the orographic barrier is an escarpment, spillover cannot occur except in unusual local situations.

Measurable orographic intensification of precipitation associated with mechanical lift occurs as a result of several factors; the physiographic characteristics of the orographic barrier (mean slope and relative relief), the physical characteristics of the air mass, and the lifting rate.

The Manitoba Escarpment in the vicinity of Neepawa has a mean slope and relative relief of 2.2° and 230 m, respectively. Any orographic influence on precipitation in this region is restricted to southeasterly circulation flow components of humid air masses. The normal frequency of these winds (ESE, SE, SSE) is estimated at 15%, as presented in the Portage la Prairie meteorological record. Such meteorological conditions in association with the escarpment plateau region can result in orographic intensification of precipitation.

The Neepawa meteorological station, located 20 km southeast of the escarpment, is most likely in a marginal zone of orographic influence and thus, the Neepawa precipitation record is assumed to represent precipitation amounts unaffected by orography.

Dauphin Airport is located 25 km north and 400 m below the Manitoba Escarpment. Favourable wind directions for orographic precipitation (N, NNE, NE, ENE) occur 30% of the year but once again the distance from the meteorological station to the escarpment appears to restrict measurable orographic intensification of normal precipitation amounts.

Two meteorologic stations which demonstrate the orographic intensification of precipitation are located in Riding Mountain National Park. The Riding Mountain station is located on the escarpment plateau at an elevation of 725.5 m,whereas the Wilson Creek station lies 4 km to the east and 361 m below on the alluvial fan surface. Strong easterly circulation flow components associated with cold lows (Reinelt, 1970) force humid air to rise rapidly over the Riding Mountain escarpment. This enhanced orographic influence probably explains why the Riding Mountain station receives 37% greater precipitation than the Wilson Creek station. This figure is also in agreement with a 39% precipitation intensification estimate for western Alberta during similar cold low conditions (Reinelt, 1970, 58).

The development of these cold lows is particularily common in late spring (May and June) and they occasionally occur in late summer - early fall. The intense storm precipitation recorded in September 1975 is definitely associated with a cold low system (Strilaeff, 1976) and clearly illustrates the orographic intensification of precipitation in the study area; the Riding Mountain station having received 34% more precipitation than the Wilson Creek station.

TABLE 14: ANALYSIS OF WILSON CREEK PRECIPITATION DATA

TABLE 14a OPERATIONAL DEFINITIONS

Summer Precipitation: (May 1 - Sept. 30)	1965-1971 average precipitation
Winter Precipitation: (Oct. 1 - March 30)	12 year average of the "March Snowpack Survey" (Thomlinson, 1972).
The April Precipitation Estimate: (April 1 - April 30)	Calculated from the Neepawa and Dauphin Airport Records (see Table 1b)

TABLE 14b THE APRIL PRECIPITATION ESTIMATE

i. Mean summer precipitation: mm, (in)

a. $\frac{\text{Neepawa + Dauphin}}{2} = 320.3 \quad (12.61)$

b. Wilson Cr. Fan = 359.2 (14.14)

c. Wilson Cr. Plateau = 443.5 (17.46)

ii. Fan Correction Factor:

$$\frac{\text{Wilson Cr. Fan - Nee-Dauph Mean}}{\text{Nee-Dauph Mean}} = 0.121$$

iii. Plateau Correction Factor:

$$\frac{\text{Wilson Cr. Plateau - Nee-Dauph Mean}}{\text{Nee-Dauph Mean}} = 0.385$$

iv. April Precipitation: mm, (in)

a. $\frac{\text{Neepawa + Dauphin}}{2} = 31.8 \ (1.25)$

b. Wilson Cr. Fan
(31.8 x 0.121) + 31.8 = 35.6 (1.40)

c. Wilson Cr. Plateau
(31.8 x 0.384) + 31.8 = 44.0 (1.73)

.../cont'd

Table 14 Analysis of Wilson Creek Precipitation Data - Cont'd

TABLE 14c: A REGIONAL ANALYSIS OF THE ANNUAL PRECIPITATION FOR WILSON CREEK WATERSHED

Precipitation Catagory	Physiographic Region Fan	 Escarpment Slope	 Escarpment Plateau	$\frac{\text{Plateau - Fan}}{\text{Fan}} \times 100$
Summer Precipitation mm, (in.)	359.2 (14.14)	418.1 (16.46)	443.5 (17.46)	23.5
*Mid-March Snowpack Water Equivalent	49.5 (1.95)	109.2 (4.30)	125.2 (4.93)	152.9
April Estimate	35.6 (1.40)	38.1 (1.50	44.0 (1.73)	23.6
Total Annual	444.3 (17.49)	565.4 (22.26)	612.7 (24.12)	37.9

* Thomlinson (1972) employs Mid-March snowpack water equivalent values as an estimate of the total winter precipitation.

Orographic intensification of summer precipitation (June, July and August) appears to be the result of enhanced convection. Numerous and sometimes extensive areas of unvegetated shale outcroppings (Plate III) common to the higher elevations of the escarpment slope region may generate intense convectional uplift. The eastern and southeastern aspect and normally dry nature of these steep sloping shale banks can induce high surface temperatures and consequently lead to the development of autoconvective lapse rates (Lowry, 1969) in the late morning and early afternoon.

In this account of the regional distribution of annual precipitation, the meteorologic records of Neepawa and Dauphin Airport have been examined as well as the data obtained from the partial records of the Riding Mountain and Wilson Creek stations (Appendix V). Clearly the more relevant findings are associated with the partial records of the latter two stations and since the summer precipitation record at the Wilson Creek station is in general agreement with the Dauphin and Neepawa records the remainder of the discussion on general hydroclimatology will focus on the Riding Mountain and Wilson Creek data. The Dauphin Airport and Neepawa records will be employed in a supportative role when appropriate.

When discussing the annual precipitation recorded in the study area it is useful to employ several subjectively defined precipitation categories (Table 15).

The total annual precipitation falling on the Wilson Creek watershed is estimated to be 602 mm (Thomlinson, 1972). Thomlinson (1972) also presents a second estimate based on total summer precipitation and the water equivalent of the mid-March snow pack.

TABLE 15

A SUBJECTIVE CLASSIFICATION OF PRECIPITATION

Rain	Precipitation deposited in the liquid state.
Snow	Precipitation deposited in the solid state.
Normal Rainfall	Rainfall with intensities amounting to less than 1.0 mm/hr.
Storm Precipitation	At least 25.0 mm of rain deposited within a 24 hour period (intensities assumed to be at least 1.0 mm/hr.
Summer Precipitation	Rain or snow deposited between May 1 and September 30 inclusive.
Winter Precipitation	Rain or snow deposited between October 1 and April 30 inclusive, and measured as water equivalent for a mid-March snowpack.

This estimate is significantly smaller; 487 mm. However, neither estimate attempts to separate precipitation occurring on the escarpment plateau, escarpment slope and alluvial fan. Table 14 estimates total precipitation for the three physiographic segments of the Wilson Creek watershed. Thirty-nine percent more annual precipitation is recorded on the escarpment plateau than on the alluvial apron. This figure agrees with the previous estimate attributed to orographic intensification and amounts to a difference of 171 mm. A brief examination of this difference (Table 14) indicates that winter snowfalls account for 87 mm and summer precipitation the remaining 84 mm. The amount of precipitation resulting from orographic intensification is apparently evenly divided between summer and winter precipitation. Furthermore, the Dauphin Airport and Neepawa winter records (Table V:1 Appendix V) indicate that an average 182 mm of winter precipitation is evenly distributed over the seven month winter period with a mean of 26.0 mm and standard deviation equal to 3.8. Assuming that this winter snowfall distribution pattern applies throughout the study area, it must be concluded that orographic intensification of precipitation is even more common than first predicted. If this is the case, an investigation of winter precipitation should demonstrate the orographic influence of the Manitoba Escarpment on snowfall accumulations and an association with easterly flow components of the more frequent but less humid low pressure systems.

The total summer precipitation (May-September) may be divided into storm precipitation and normal rainfall (Table 15). Wilson Creek data indicate that from one to ten summer storms (approximately 25 mm of precipitation in 24 hours) occur annually with an average of 5 (plus or minus 2) storms. On the basis of a twelve year record, these storms account for one quarter to one-half of the total summer precipitation. The greater amount of summer precipitation occurring in late May and June helps to substantiate the hypothesis that a significant portion of summer precipitation is associated with easterly flow components of late spring cold low systems.

4:5:2 Temperature

Air temperature is directly related to solar radiation inputs and thus theoretically related to evapotranspiration (Gray, 1970, 3.46). The summer temperatures of the study area range from a mean daily maximum of 27°C. to a mean daily minimum of 2°C. The mean daily temperature for the May - September period is 14°C. The Neepawa, Dauphin Airport and Riding Mountain temperature records indicate little temperature variation between sites (Figure 30) and on this basis, evapotranspiration rates are considered to be uniform throughout the study region (Weir, 1960, 19). This estimate (550.0 mm) compares favourably with the 11 year average free water surface evaporation values measured on the escarpment plateau at the Wilson Creek station number 32. Measured evaporation is 522.7 mm (Thomlinson, 1972) for the May through October period but does not include early spring values or any transpiration estimate.

The magnitude and sequence of mean daily temperatures in the month of March, April and May are significant for snowpack ripening and subsequent snowmelt peak flows.

PLATE IV

A Summer Storm Over Riding Mountain

On the basis of a twelve year record, these summer storms account for 25% to 50% of the "summer precipitation" received in the study area. The orographic influence of Riding Mountain (background) probably explains why the plateau region receives 37% more precipitation than the alluvial apron (foreground).

Mean Daily Temperature Normals for Neepawa, Dauphin and Riding Mountain

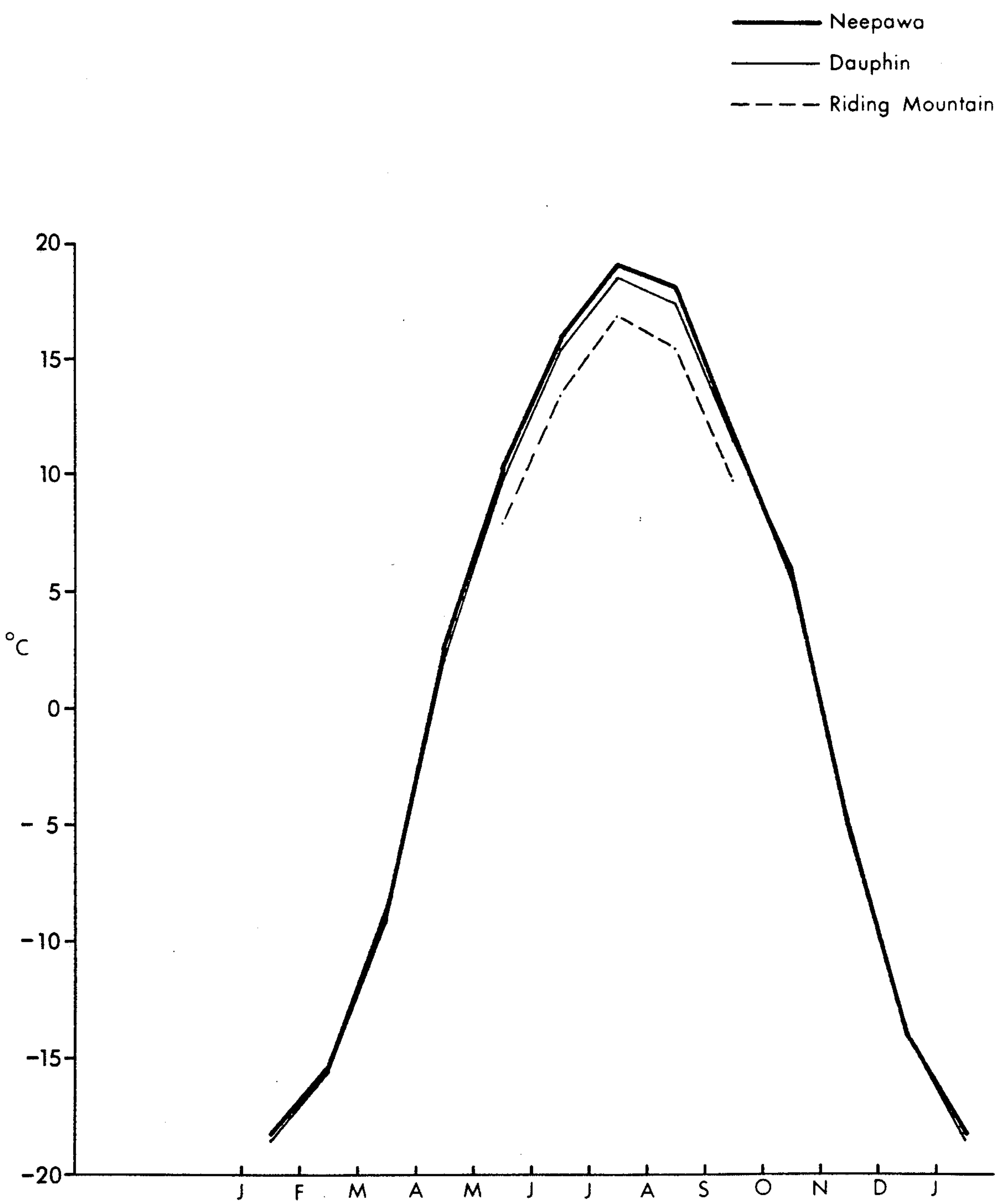


Figure 30

4:5:3 Summary of Hydroclimatology

The general input-output model of the hydrological cycle acting on a watershed integrates the basin climatology and hydrology. Hydroclimatology deals with the principal input - precipitation - and a potentially major output - evapotranspiration. Net storage is theoretically neutral over a long term in a steady state watershed (i.e. assumed to be zero) and given this assumption, runoff must be considered as a positive imbalance in the precipitation - evapotranspiration equality. In the Wilson Creek watershed, estimated summer precipitation is approximately 432 mm (Table 14) and free water surface evaporation approximately 523 mm (Thomlinson, 1972). A soil moisture deficit as defined by Thornthwaite (1931) is expected during the summer period and Weir (1960, 19) indicates an average annual moisture deficit of 75-100 mm. During this same period average annual summer runoff is estimated from the Wilson Creek record to be 133 mm.

Figure 31 graphically demonstrates the general correlation between storm precipitation and peak flow events and indicates that a large proportion of this annual summer runoff accompanies these peak flows. Since large discharges are capable of transporting large sediment loads it can be hypothesized that storm peak flow events are responsible for major flooding and subsequent fan aggradation.

4:6 General Hydrology

More (1969) suggests that drainage basin discharge is the result of a combination of various vertical and horizontal water transfers taking place through several hydrologic sub-systems or

PRECIPITATION AND STREAM DISCHARGE

WILSON CREEK WATERSHED, 1971

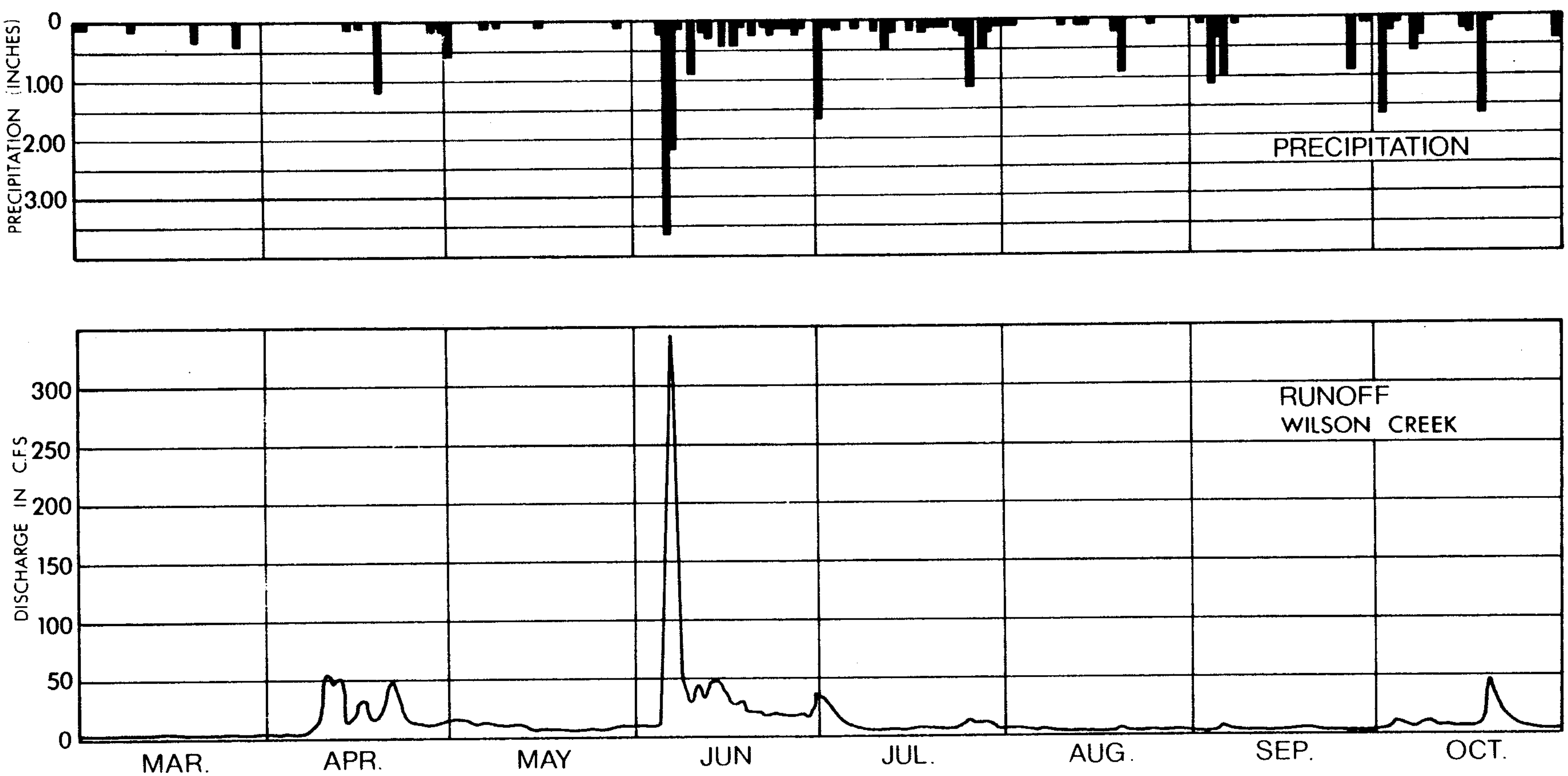


Figure 31

Thomlinson, 1972.

drainage basin zones. The two generalized types of mass transfer may be further subdivided into surface zone and subsurface zone water transfers. These mass transfers are not mutually exclusive. Vertical subsurface transfers involve infiltration and percolation processes, and rates depend on several interrelated variables (Gray, 1970), but are primarily influenced by soil porosity and permeability. Subsurface horizontal mass transfers (throughflow, interflow, and base flow) are also generally related to permeability as well as distance from stream channel and hydraulic head.

Hydrological processes which occur in the vegetation subsystem (interception, storage, stemflow and drip) often delay hydrograph response times by increasing the drainage basin lag times. Since 85% of the watersheds located in the study area are heavily vegetated in the plateau region, these basin lag times might be considered to be at a maximum. However, numerous unvegetated shale banks in the escarpment slope region are believed to contribute significantly to shorter lag times, greater peak discharge magnitudes, and excessive sediment loads (Thomlinson, 1969). Efforts to revegetate these steep sloping shale banks have generally met with difficulty both in the establishment and maintenance of the vegetative growth. Some attempts have also been made to assess the effects or potential effects of revegetation on the magnitude of the peak flow hydrograph and basin lag times (Thomlinson, 1969).

Precipitation falling directly on the stream channel will generally shorten hydrograph response times. However, since stream channels in the study watersheds have small surface areas, direct channel precipitation is considered to be an insignificant factor with respect to discharge.

The horizontal free water transfer component of stream discharge (overland flow) is believed to be the primary contributor to storm runoff in small (250 km^2) watersheds (Gray, 1970, 8.2). By definition this overland flow occurs when rainfall intensity is greater than the infiltration rate (Horton, 1945). Therefore, the overland flow component of a storm discharge hydrograph is related to the mean infiltration rate and those factors which control infiltration. The combined effects of these physical factors results in a general infiltration rate curve which demonstrates relatively high infiltration rates at the beginning of the storm and decreasing to a constant rate as the storm continues (Kirkby, 1969). The base rate or transmission constant is usually employed as the mean infiltration rate. The variety of physiographic, vegetative, and geologic conditions common to the study area have generated a relatively wide range of transmission constant estimates. Young (1975) suggests values as high as 12.5 mm/hr., whereas storm intensity versus stream discharge data (Figure 31) indicates a base infiltration rate of approximately 1.0 mm/hr. Ayers (1959; In; Gray, 1970, 5:5) suggests that a value of 0.5 mm/hr. is common for shallow soils over bedrock and his estimate is employed in this study.

4.7 The Storm Hydrograph Analogue

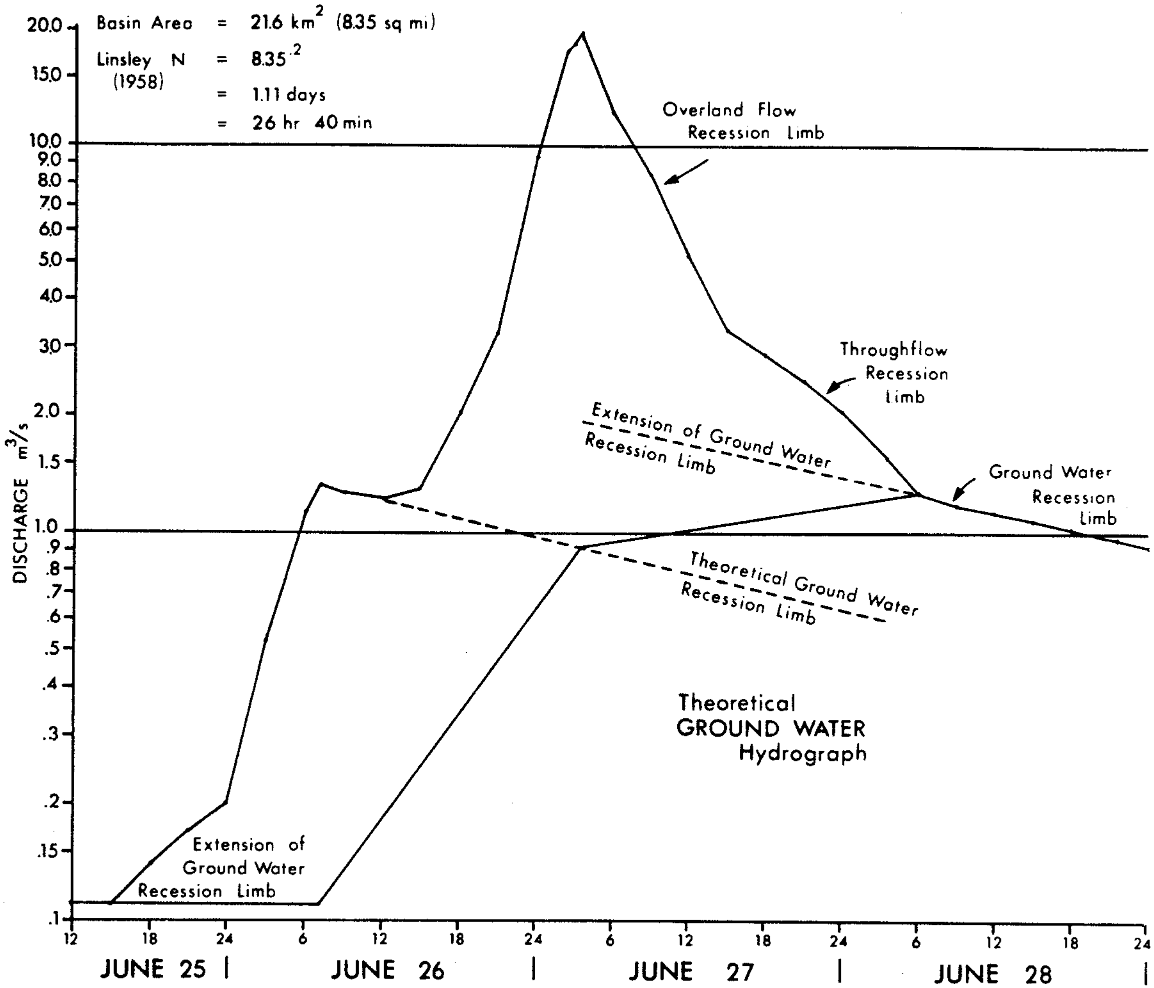
The storm hydrograph illustrates the temporal responses of a stream channel discharge to precipitation inputs and the various mass transfer processes, antecedent soil moisture conditions and storage potential of a given watershed. As such, storm hydrograph analysis may be employed to evaluate the relative significance of the natural linkages between the various components of a drainage basin hydrological system.

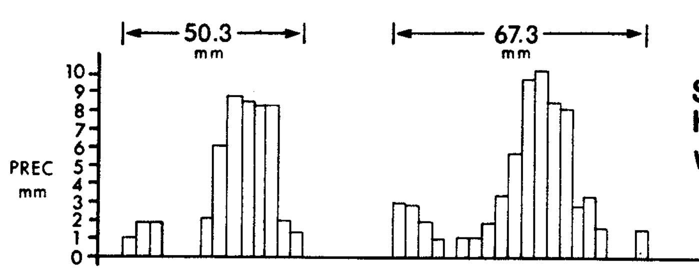
Figure 32 represents a natural analogue model for a major storm hydrograph analysis in the study area. Frequency analysis of the precipitation intensity and duration values based on Bruce's maps (Gray, 1970,2:82-84) suggest that the 48 hour storm of June 25-27, 1969 has a recurrence interval of 25 years. The storm hydrograph has been subdivided into base flow and runoff components and the methodology employed is outlined in Gray (1970).

The initial peak response of the storm hydrograph to the June 25-26 precipitation occurred 3 hours after the rainfall had stopped. The relative small magnitude of this peak (1.33 m^3/s) suggests that a large part of the 45.5 mm precipitation had infiltrated and recharged previously depleted groundwater storage. In view of this premise, it was expected that the theoretical groundwater contribution to stream discharge generated by the initial (June 25) rainfall, would rise rapidly following the surface runoff peak (Figure 32).

Linsley (1958; In: Gray, 1970) has demonstrated that the groundwater basin lag time (N) may be calculated as a function of basin area ($N = A^{0.2}$) and according to this estimate the groundwater peak discharge from the June 25 storm should have occurred approximately 27 hours after the surface runoff peak. However, the precipitation of June 26-27, coming only 7 hours after the June 25, storm, maintained the rising limb of the June 25 groundwater hydrograph and produced a theoretical groundwater peak discharge of 1.28 m^3/s,

STORM HYDROGRAPH ANALOGUE
June 25-27, 1969 Wilson Creek Watershed





STORM HYETOGRAPH June 25-27 1969
Wilson Creek Watershed

Source. Thomlinson, 1971

Figure 32

occurring approximately 25 hours after all rainfall had ceased.

Since the 67.3 mm of precipitation recorded for this June 26-27 storm fell on saturated ground, the initial infiltration rates were rapidly reduced to the transmission constant (approximately 0.5 mm/hr.) and overland flow was initiated. The peak discharge of 19.94 m^3/s occurred immediately after the rainfall had stopped, and the relative large magnitude of this peak accompanied by the steep sloping throughflow recession limb suggests that most of the June 26-27 precipitation had runoff.

Clearly, the response of the Wilson Creek hydrograph to the June 25-27 storm illustrates the relative significance of overland flow to the peak flow events recorded in the study area. The storm hydrograph analysis also points out the importance of antecedent soil moisture conditions and basin storage potential to the magnitude of this overland flow component. It follows that studies of the peak flow events which occur in the study area, not only must consider the magnitude of the storm events, but also the frequency and sequence of storms.

4:8 Flood Frequency Analysis

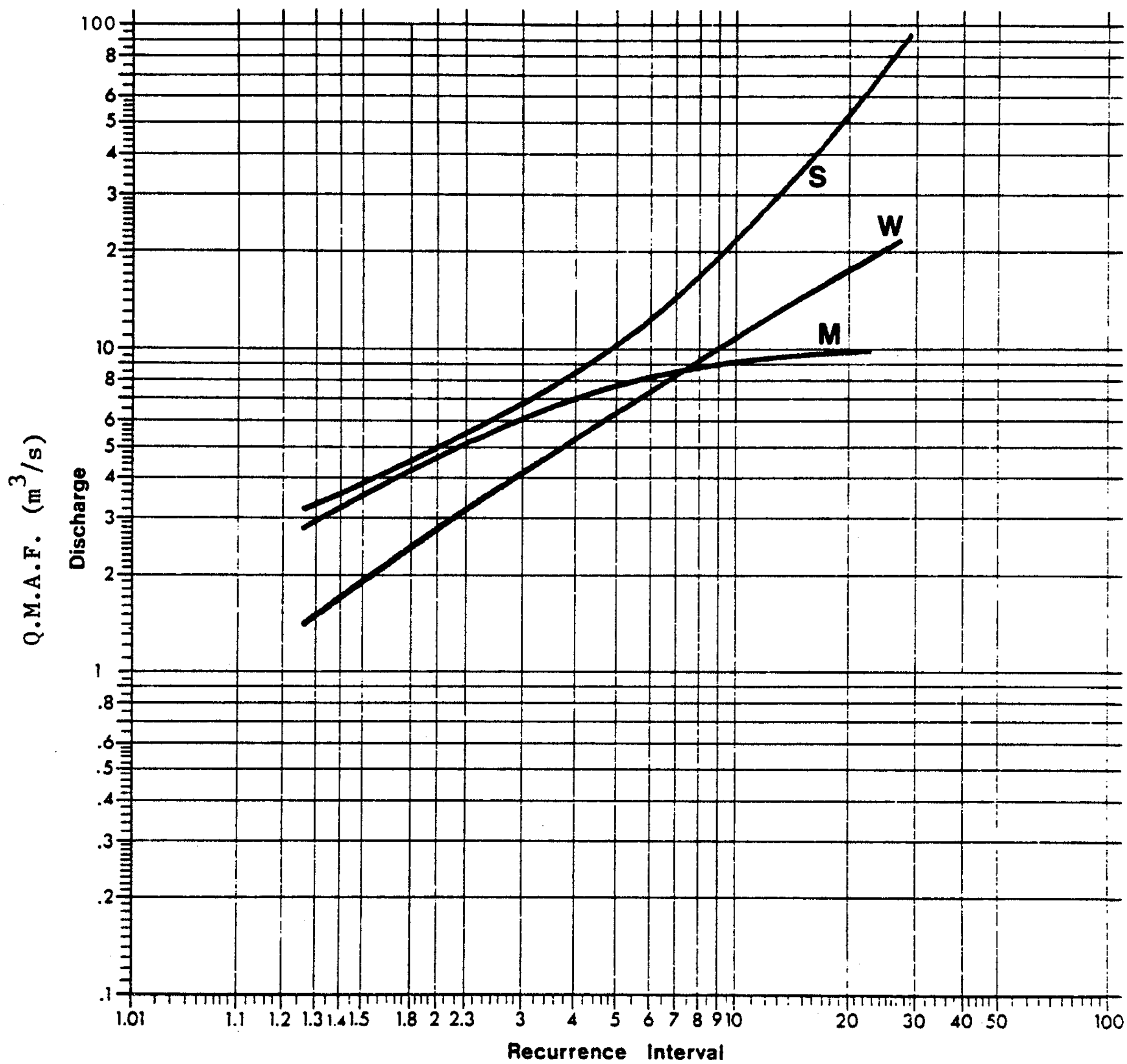
The previous discussions, the literature (Thomlinson, 1969, 1970, 1971, 1972; Durrant and Blackwell, 1959; and MacKay and Stanton, 1964) and the hydrologic history of the Riding Mountain area (pgs. 1 and 2) suggest that the effective fan building discharges are directly related to peak flow flooding. A peak flow event is usually described in terms of its magnitude (discharge or stage) and the recurrence interval. These peak flow magnitudes and recurrence intervals are useful for purposes of modelling stream hydrology and drainage design programmes.

Flood frequency analysis provides a means of evaluating peak flow magnitudes and frequencies. Dalrymple (1960) presents a particularly thorough review of the various methodologies employed in flood frequency analysis. Generally, the magnitudes of the annual flood peak discharges are assigned a ranking (R) for the number of years of record (n). The largest flood discharge receives a ranking of R = 1. A recurrence interval based on the relationship RI = n+1/R or a probabilistic adaptation of this formula (Dalrymple, 1960), can be calculated for each annual flood. The relationship between the magnitude of the flood discharge and the associated recurrence interval can then be plotted on appropriate graph paper. Since a linear plot is most desirable for predictive and long term planning purposes, a variety of recurrence interval scales have been used. Hence, appropriate graph paper may be, for example; arithmetic, logarithmic, semi-logarithmic, probability, cube root, or "Gumbel" (Powell, 1943).

An annual flood frequency analysis was performed on the 19 years of flood data for three of the five monitored streams in the study area. Pelican Creek and Birnie Creek do not have sufficient years of record for flood frequency analysis. Figure 33 illustrates the flood frequency recurrence interval curves for McKinnon Creek, Scott Creek and Wilson Creek.

Any attempt at averaging or regionalizing these curves must consider the well documented positive correlation between catchment

MEAN ANNUAL FLOOD FREQUENCY PLOTS



McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**

Figure 33

area (A) and mean annual flood discharge (M.A.F.) (Gray, 1970; Wilson, 1969). Durrant and Blackwell (1959) have demonstrated that for the Manitoba Escarpment area (division 7) this relationship can be expressed as mean annual flood (cfs) = 45 $A^{0.7}$. However, they caution its use with drainage basins smaller than 30 $mi.^2$ (75 km^2). The three study basins are among the largest in the study area, yet according to Durrant and Blackwell (1959) they must be categorized as small. Since this is the case, the methodology proposed by Durrant and Blackwell (1959) is considered to be inappropriate for calculating the regional mean annual flood frequencies for the watersheds comprising the study area. Furthermore, since these small watersheds exhibit a large variation (Table 3 and 11) in basin area (A) and are positively skewed (SK = +1.4), a standardized or unit basin area regional flood frequency is more desirable.

Standardization was accomplished by converting the flood discharge magnitudes to unit area discharge magnitudes (flood discharge divided by drainage basin area, Q/A). This methodology presents an immediate problem of whether A is a contributing or effective drainage basin area (Durrant and Blackwell, 1959) or merely a gross topographic basin area. All the drainage basins which comprise the study area are less than 80 km^2 and defined as small. Since definition and subsequent measurement of the non-contributing areas of these small basins is difficult, if not impossible, only the gross basin areas were estimated. This procedure implies an assumption that gross basin area is not significantly different from effective basin area. The empirical evidence (Figure 33) suggests that this is not the case with respect to certain basins within the study area.

The McKinnon Creek watershed (77.7 km^2) is significantly larger than both the Scott Creek and Wilson Creek watersheds. The flood frequency plot (Figure 33) places the McKinnon Creek frequency curve between the Scott Creek and Wilson Creek curve, whereas the expected position of the larger McKinnon Creek basin should be located at higher flood discharges for any given recurrence interval. The relative positions of the three flood frequency plots suggests that the effective drainage basin area of McKinnon Creek is significantly smaller than the total basin area.

The McKinnon Creek gauging station is located approximately 10.5 km downstream from the fan apex. This necessitates the inclusion of six tributary basins in the operational definition of basin area above the gauge site. In fact, five of these tributary basins are at best periodic contributors to the McKinnon Creek flows, yet they effectively double the gross basin area.

An examination of the genesis of peak flow events may provide support for this hypothesis. Since all of the analogue basins are considered small, storm precipitation and snowfall accumulations are assumed to occur over the total watershed area. If this is the case, tributary flows which do not contribute to all recorded McKinnon Creek discharges are probably infiltrating and recharging ground water stored in the alluvial apron.

Direct evidence of fan groundwater storage is available for the comparatively small Eden Creek fan; where relatively large storm discharges (Q = 25 cfs or 0.7 m^3/s), measured at the fan apex, experience a 2-4% infiltration in the first three kilometers downstream and the daily discharges of 1 cfs totally infiltrate. The small storm discharges of the McKinnon Creek tributaries, in comparison with those of Eden Creek, must traverse 10.5 km over a very large alluvial apron and in all probability experience greater infiltration. Indirect evidence of substantial groundwater storage is represented by the numerous wells tapping the fan aquifer in the McCreary-Laurier area.

Storm runoff measured at a stream gauge is a combination of overland flow and subsurface inflows, and is, therefore, a function of rainfall intensity, infiltration and percolation rates. Snowmelt runoff represents a release of surface accumulations of stored moisture and since snowmelt runoff generally occurs over frozen ground, infiltration, percolation and ground water flows are minimized. One might suggest that in theoretical watersheds, where the effective drainage basin area and the gross basin area are similar, both storm runoff and snowmelt determine the mean annual flood = cA^n function. (M.A.F. in cfs; A in sq. mi.). Since the regression coefficient c in this equality represents a unit drainage area flood discharge it is assumed also to represent the average of a mean unit area storm discharge (c') and a mean unit area snowmelt discharge (c"); that is, $c = \frac{c' + c''}{2}$. However, if in the theoretical watershed the effective drainage area/gross drainage area ratio is not close to unity, the c" value for snowmelt peak flow will assume a greater significance than the c' value in the determination of the overall c regression coefficient. This is necessarily true since the storm runoff is derived from the smaller effective drainage basin area but evaluated in terms of unit gross basin, while the snowmelt runoff is derived from the entire watershed and likewise evaluated in terms of unit gross basin area. As a result, c" is more representative of the c regression constant than the storm discharge, i.e. coefficient c'; and if this were the case, the M.A.F. = cA^n relationship would be dominated by snowmelt flooding since unit area storm discharges are mathematically depressed.

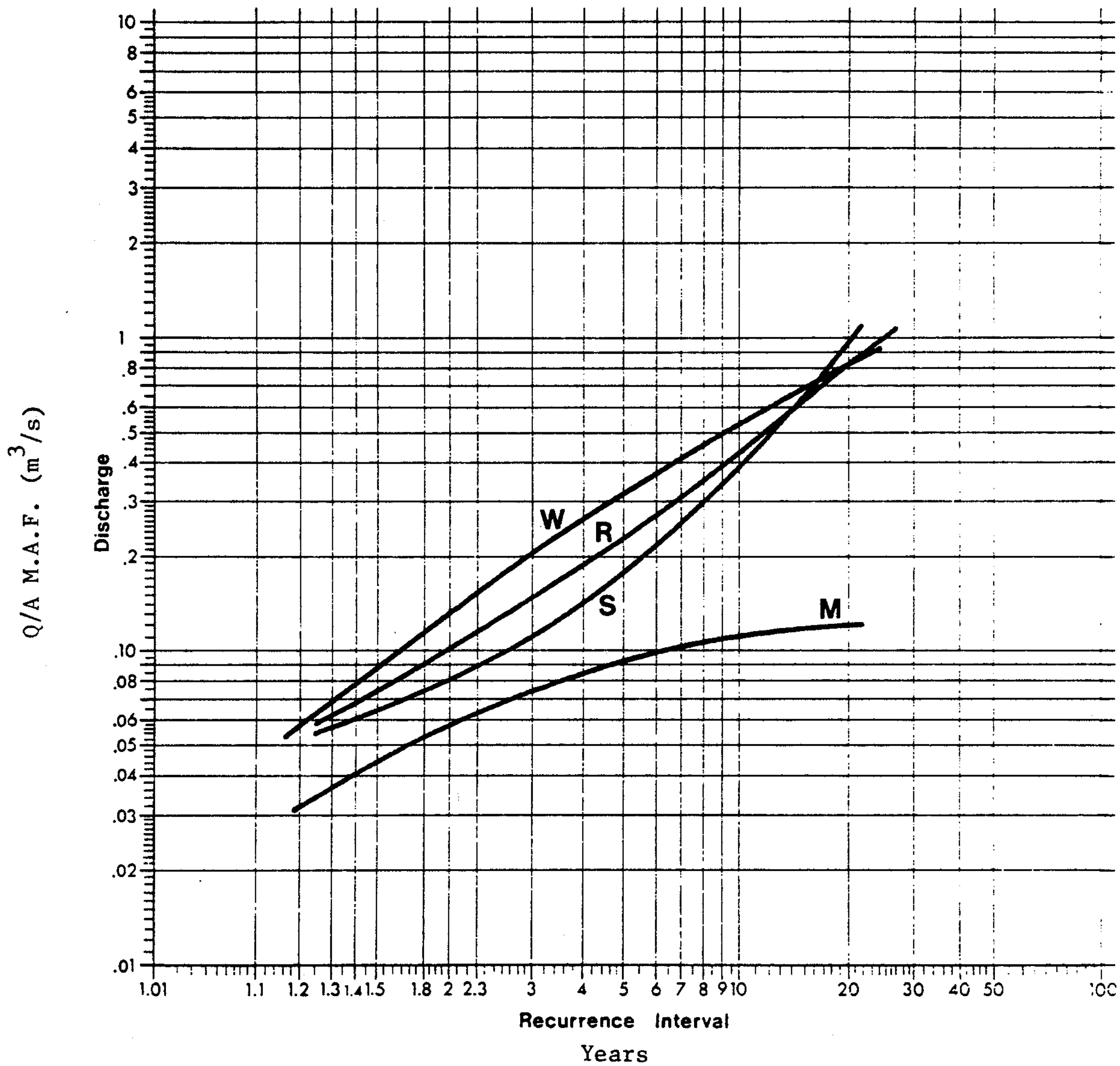
Thirty-five percent of the annual floods on Scott Creek and Wilson Creek are the result of snowmelt runoff, whereas 65% of the annual flood discharges recorded on McKinnon Creek are attributed to snowmelt. This supports the hypothesis that the effective drainage basin area is not equal to the gross basin area, and also clearly indicates that the peak flow events recorded for the Scott Creek and Wilson Creek watersheds are not always the same flood events registered on McKinnon Creek.

The annual flood frequency plot (Figure 33) and the replotted unit area flood frequency curves (Figure 34) indicate that the McKinnon Creek curve deviates significantly from the theoretical linear plot when the recurrence interval is greater than four years. The specific location of the McKinnon Creek stream gauge may help explain this deviation. The gauge is located 10.5 km downstream from the fan apex. Therefore, fan building discharges can reach bankfull stages upstream of the stage recorder and large volumes of floodwaters could bypass the gauge and not be recorded. Figure 35, a map of breakout points (zones of overbank flooding) observed during the 1975 flooding of McKinnon Creek, supports this viewpoint, indicating at least four major breakouts upstream of the gauge. The flattening out of the annual flood frequency plot at maximum discharges of 250-350 cfs (7-10 m^3/s) also supports this hypothesis by suggesting that bankfull stage on McKinnon Creek is reached within this discharge range.

Several arguments have been presented which suggest that the McKinnon Creek watershed data are unrepresentative of the study basins. These arguments may be summarized as follows:

i. Approximately one-half of the McKinnon Creek watershed is a non-contributing drainage area.

ANNUAL SERIES UNIT AREA FLOOD FREQUENCY PLOTS



McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**
Regional **R**

Figure 34

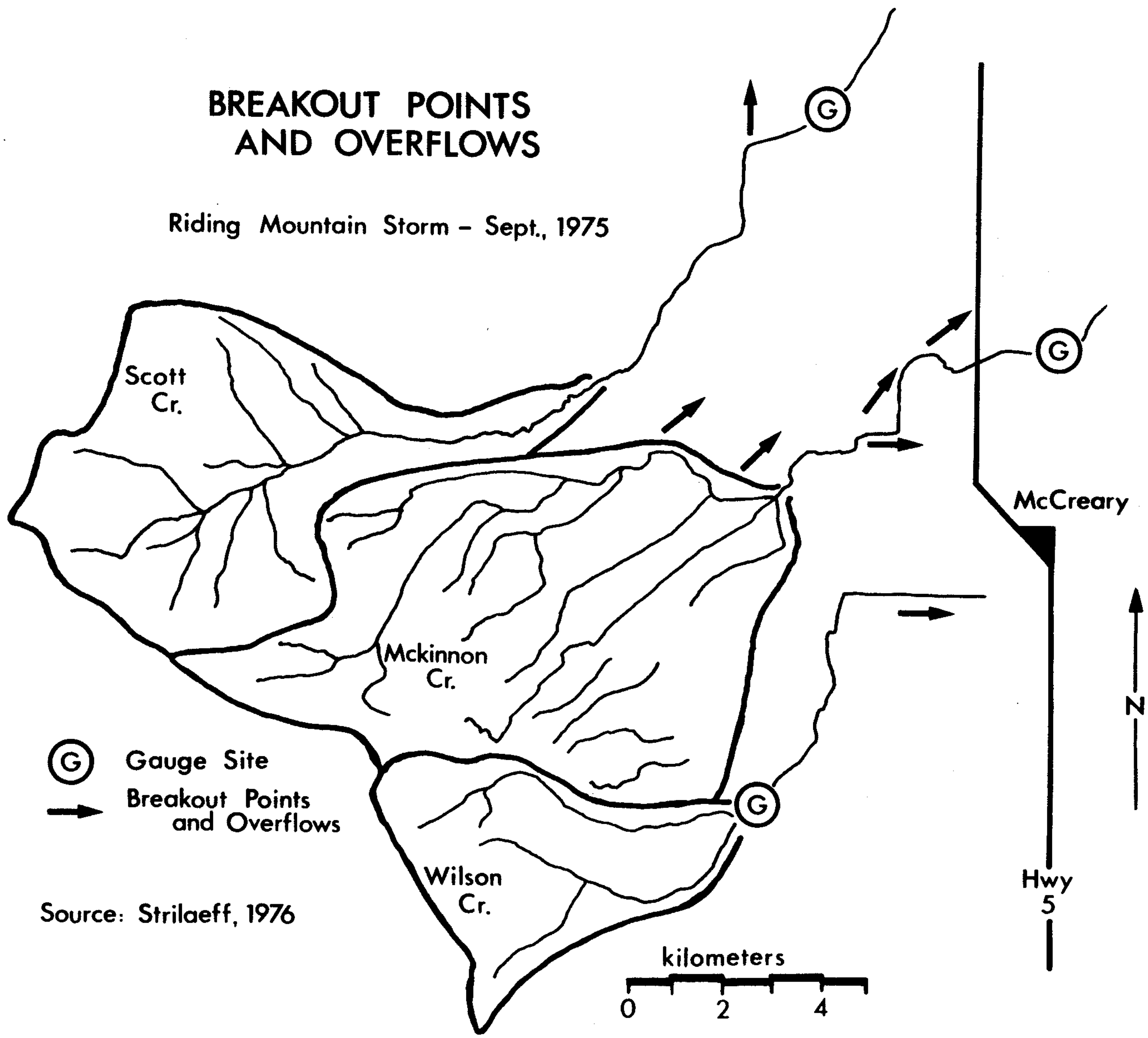

BREAKOUT POINTS
AND OVERFLOWS
Riding Mountain Storm – Sept., 1975
Scott
Cr.
Mckinnon
Cr.
Wilson
Cr.
McCreary
Hwy
5
N
G
Gauge Site
Breakout Points
and Overflows
Source: Strilaeff, 1976
kilometers
0
2
4

Figure 35

ii. Bankfull discharges are not usually recorded at the gauge site since peak discharge 'breakouts' occur upstream.

iii. The annual flood recorded on McKinnon Creek may not be the same peak flow event as those measured on Scott and Wilson Creeks.

Therefore, the McKinnon Creek flood data should not be used for the development of a regional flood frequency plot. Furthermore, it is suggested that the stream gauge be relocated upstream of the present site or totally abandoned as any engineering design based on the McKinnon Creek flood discharge data is likely to be in error.

Wilson (1974) suggests that a full series of flood events may be more valuable in situations where the frequency of the peak flows is more significant than the actual magnitudes. For the alluvial fan geomorphic system this appears to be the case.

The Riding Mountain alluvial apron is constructed by specific fan building discharges which are not necessarily restricted to the annual flood but may occur several times each year, and consequently several significant fan building discharges may pass unrecorded. For example, while spring melt discharges usually carry significant sediment loads, they will not be recorded in an annual flood frequency analysis if a larger storm discharge occurs later in the year. Similarly only the largest storm discharges could be employed in an annual series flood frequency analysis.

Figure 36 indicates the relationship between peak flows and suspended sediment loads for Edwards Creek. A general agreement between the two curves is evident and clearly demonstrates that both the annual spring melt and significant storm discharges must be considered as potential fan building discharges.

A full series or partial flood frequency analysis requires the selection of a base discharge which is the smallest peak discharge to be considered in the analysis (Wilson, 1969). The previous discussion would suggest that this base discharge value must be representative of both spring snowmelt and storm discharges.

Since the peak discharges of each analogue watershed are a function of the effective drainage basin area, several base discharge values may be considered. The selection of an arbitrary and universal base discharge value may result in either the exclusion of some significant peak flows or the inclusion of several non-significant fan building discharges. Clearly, it is more appropriate to employ a flexible base discharge value associated with the annual snowmelt peak discharge and the peak flows produced by significant storm precipitation.

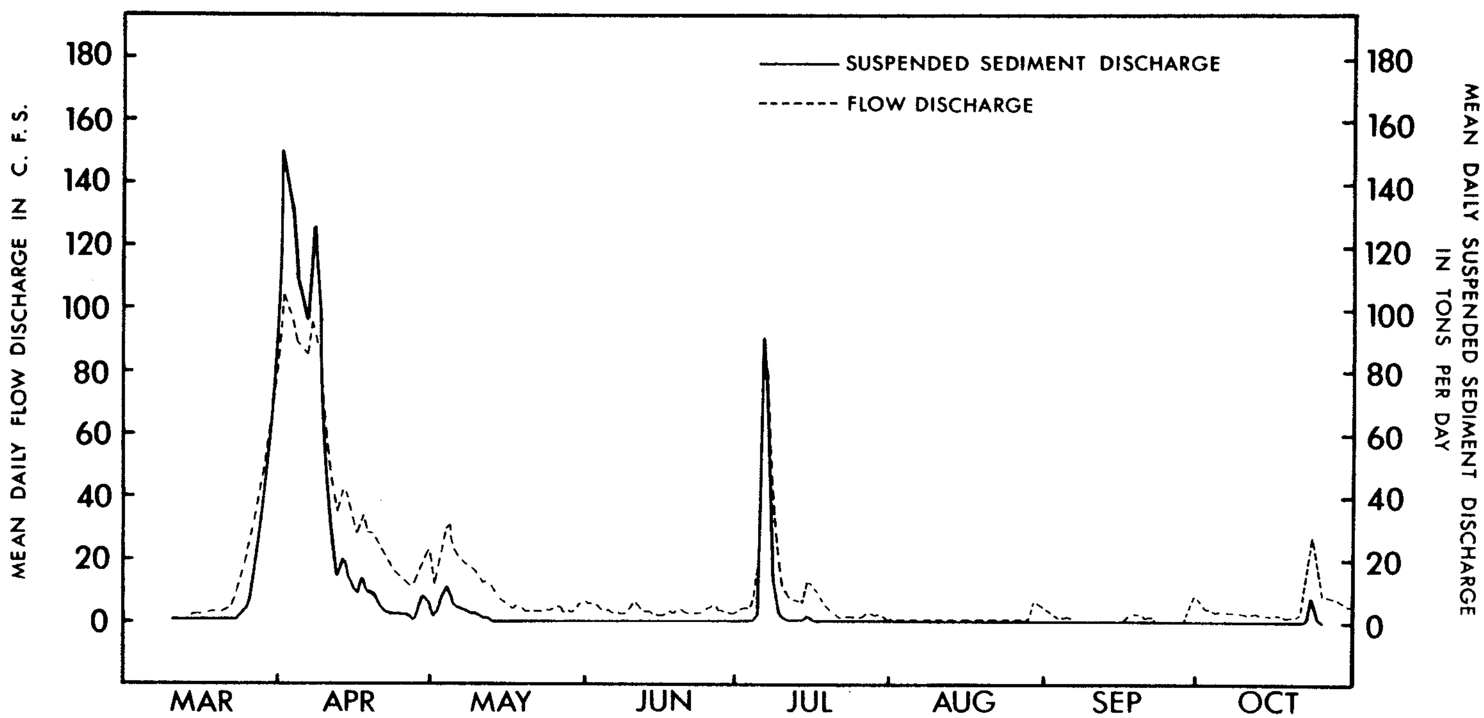
Previous discussions; an investigation of Gray's Prairie Storm Data (2.68-2.85); duration, recurrence intervals, and total precipitation; and a brief graphic comparison between precipitation events and hydrograph response for Wilson Creek (Figure 31), suggest that a storm which deposits approximately 25 mm of precipitation in 24 hours produces a peak flow event. This genetic definition of 'base discharge' has been selected since it roughly corresponds with the previously defined storm precipitation and allows antecedent ground moisture conditions to assume a more or less significant role in determining peak flow discharges. The base discharge employed in this study also assumes that spring snowmelt discharges annually achieve this base discharge value.

The full series discharge data are presented for Scott Creek, McKinnon Creek, Wilson Creek and Birnie Creek records (Appendix VI). These values are standardized into unit area discharges and a unit area frequency curve has been plotted on Gumbel paper (Figure 38).

EDWARDS CREEK

FLOW AND SUSPENDED SEDIMENT DISCHARGE HYDROGRAPHS

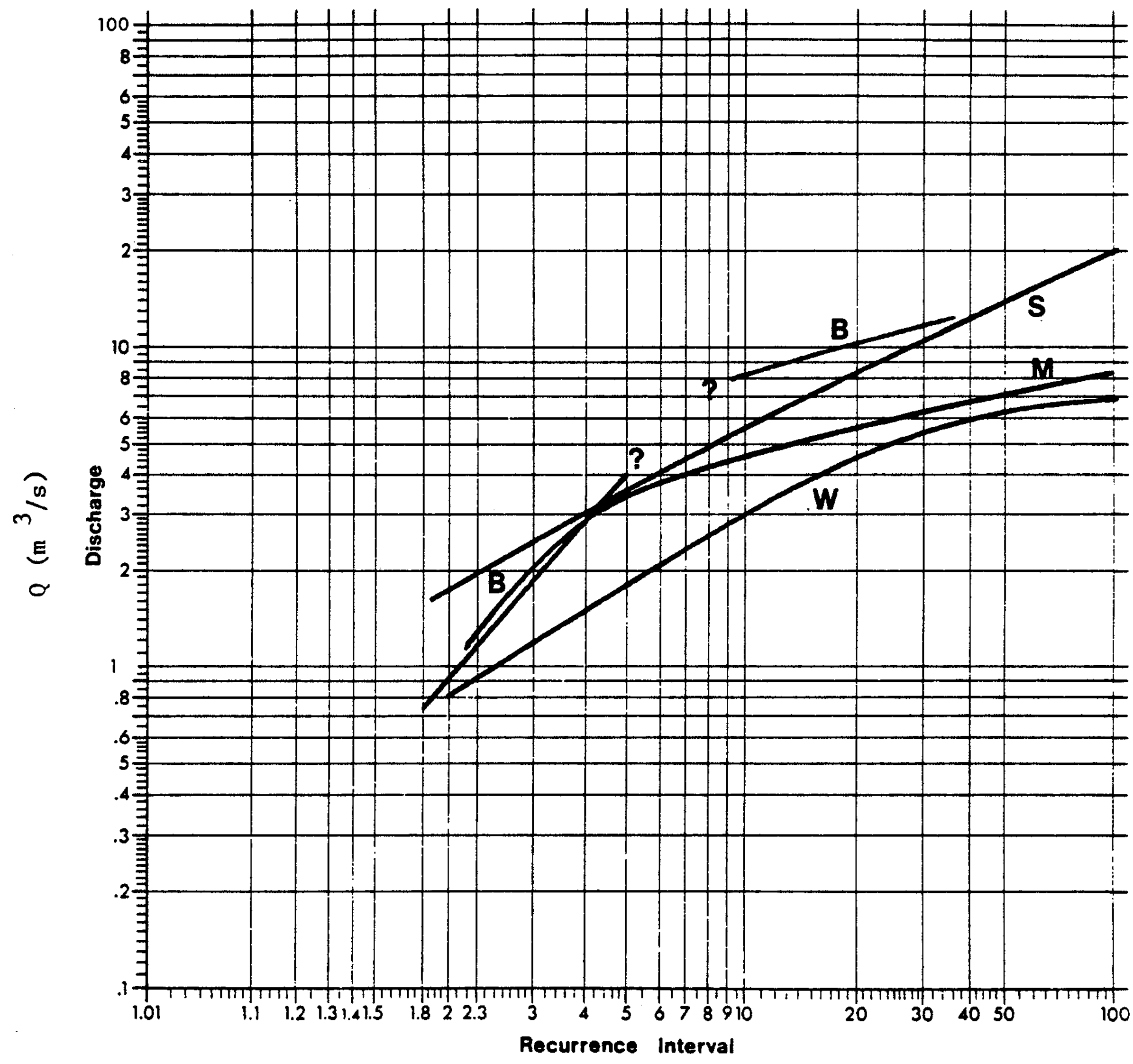
1958



Canada, Water Survey of Canada, 1971.

Figure 36

FULL SERIES FLOOD FREQUENCY PLOTS



Birnie Creek **B**
McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**

Figure 37

FULL SERIES UNIT AREA FLOOD FREQUENCY PLOTS

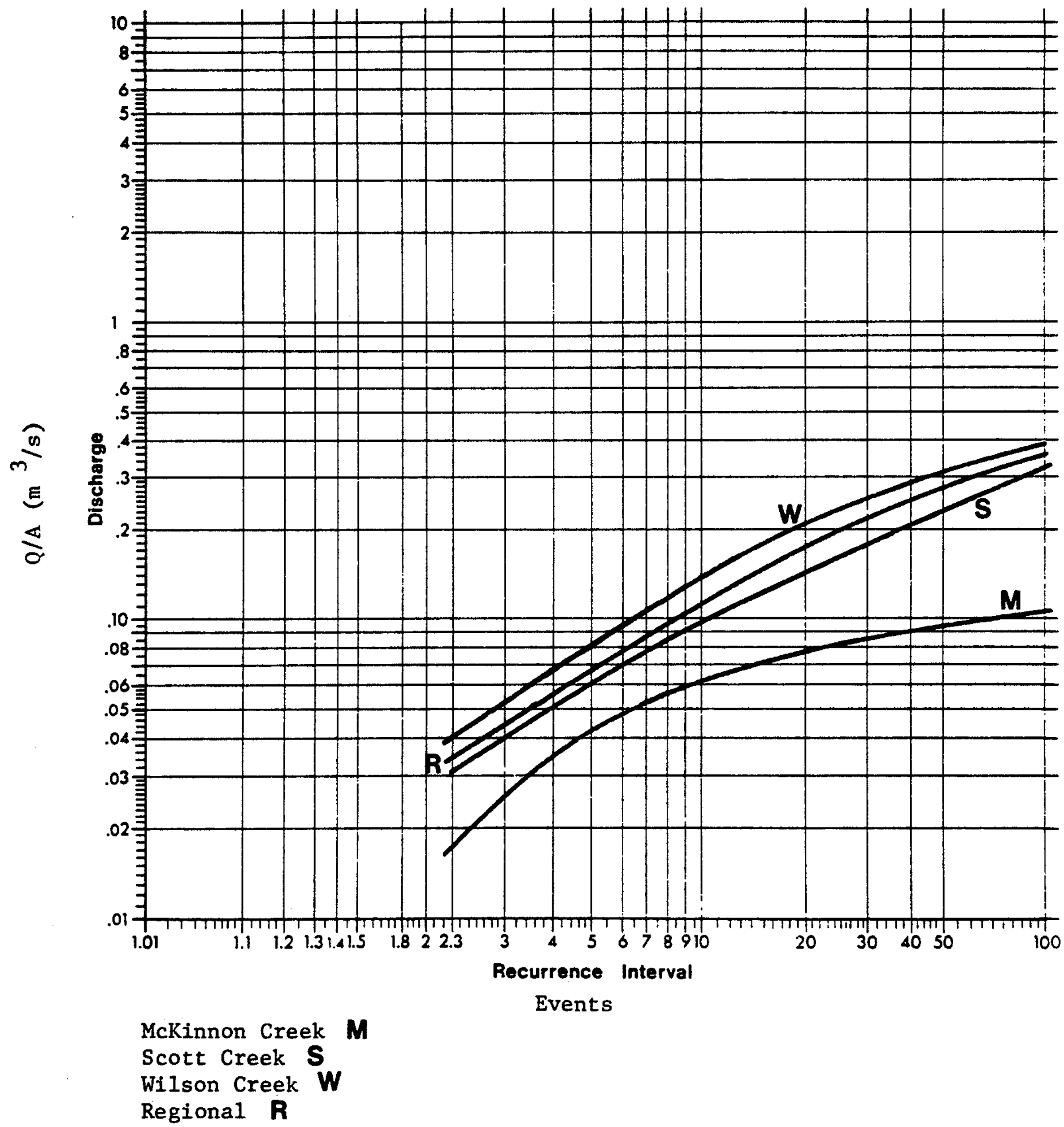


Figure 38

Contrary to Gray's suggestion (Gray, 1970, 2.66) Gumbel paper is employed for the full series frequency plot since both the Scott Creek and Wilson Creek data plot as linear functions on this graph paper.

The Scott Creek and Wilson Creek data were used to construct a regional full series unit flood frequency plot. McKinnon Creek data were not included for reasons previously stated. Birnie Creek data were also not included as an examination of the Birnie Creek plot reveals some irregularities which are possibly due to the short term nature of the data and/or anomalies in the stage/discharge relationship.

This regional frequency curve provides an interesting overview of peak flow events occurring in the study area and some specific interpretations are presented in Table 16.

TABLE 16a

FLOOD FREQUENCY DATA AND ANALYSIS SUMMARY

ANNUAL SERIES

Recurrence Interval (Years)	McKinnon Creek		Scott Creek		Wilson Creek		Region Scott + Wilson / 2	
	Q	Q/A	Q	Q/A	Q	Q/A	Q	Q/A
2.3	180.0	6.0	195.9	8.5	116.5	13.5	156.2	11.0
Mean Annual Flood	(5.10)	(0.066)	(5.55)	(0.093)	(3.30)	(0.148)	(4.43)	(0.121)
5.0	267.6	8.9	397.5	17.3	239.7	27.8	318.8	22.5
	(7.58)	(0.098)	(11.26)	(0.189)	(6.79)	(0.304)	(9.03)	(0.246)
10.0	301.8	10.1	759.3	33.0	340.6	39.6	550.0	36.3
	(8.55)	(0.110)	(21.51)	(0.361)	(9.65)	(0.433)	(15.58)	(0.397)
20.0	1008.9	33.6	2077.8	90.3	639.2	74.3	1358.7	82.3
	(28.58)	(0.368)	(58.86)	(0.988)	(18.11)	(0.812)	(38.49)	(0.900)

Q = cfs or (m^3/s)

Q/A = cfs/1.0 mi^2 or (m^3/1.0 km^2)

* Note: mean QD_{90}/A = 9.5 cfs/1.0 mi^2 or 0.103 $m^3/s/1.0\ km^2$ Regional RI = 2.0 years

mean QD_{75}/A = 6.0 cfs/1.0 mi^2 or 0.066 $m^3/s/1.0\ km^2$ Regional RI = 1.3 years

* QD_{90}/A and QD_{75}/A are defined on text page 124.

TABLE 16b

FLOOD FREQUENCY DATA AND ANALYSIS SUMMARY

PARTIAL OR FULL SERIES

Recurrence Interval (Events)*	Birnie Creek		McKinnon Creek		Scott Creek		Wilson Creek		Region Scott + Wilson / 2	
	Q	Q/A	Q	Q/A	Q	Q/A	Q	Q/A	Q	Q/A
2.3	43.4 (1.23)	1.7 (0.019)	48.0 (1.36)	1.6 (0.018)	62.8 (1.78)	2.7 (0.030)	32.8 (0.93)	3.8 (0.042)	48.0 (1.36)	3.3 (0.036)
6.0	145.8 (4.13)	5.8 (0.064)	142.6 (4.04)	4.8 (0.052)	156.7 (4.44)	6.8 (0.075)	73.4 (2.08)	8.5 (0.093)	115.1 (3.26)	7.7 (0.084)
9.0	176.5 (5.00)	7.1 (0.077)	156.7 (4.44)	5.2 (0.057)	167.7 (4.75)	7.3 (0.080)	103.8 (2.94)	12.1 (0.132)	135.9 (3.85)	9.7 (0.106)
15.0	335.4 (9.50)	13.4 (0.147)	194.9 (5.52)	6.5 (0.071)	208.6 (6.76)	9.1 (0.113)	139.8 (3.96)	16.3 (0.178)	189.2 (5.36)	12.7 (0.145)
22.5	406.0 (11.50)	16.2 (0.177)	224.5 (6.36)	7.5 (0.082)	387.6 (10.98)	16.9 (0.184)	191.7 (5.43)	22.3 (0.243)	289.6 (8.21)	19.6 (0.214)

* Events

2.3 = average event

6.0 = average annual flooding event, i.e. the largest peak flow of the annual storm events or the spring snowmelt (five storms + snowmelt = 6.0)

9.0
15.0
22.5

An estimated range for the occurrence of the mean annual flood. This estimate is based on the following assumptions;

i. the mean annual flood recurrence interval on Gumbel paper = 2.3 years, and
ii. there is an average of 4-9 peak flow events, annually.

CHAPTER V

THE DEVELOPMENT OF THE ALLUVIAL FAN GEOMORPHIC SYSTEMS MODEL

5:1 Introduction

Throughout the text there have been numerous references to fan building discharge, a term implying that discharge capable of providing material for alluvial fan aggradation. Hooke (1968) employs a somewhat similar term, dominant discharge, and there is an immediate temptation to add one more dominant discharge definition to the growing list. However, the term dominant discharge has often been employed in the literature and a continuing series of various engineering and geomorphologic definitions will only serve to contradict and confuse. It can be stated that the principal fan building discharges are associated with peak flow events of sufficient discharge magnitudes to transport a significant proportion of bed material. Figure 36 tentatively supports this generalized definition by graphically associating suspended sediment load and peak flow discharge data for the Edwards Creek watershed. Furthermore, Thomlinson (1970) also indicates a high correlation between periods of sediment trap accumulation (bed load transport) and these same peak flow events for the Wilson Creek watershed. Clearly the fan building discharges, like many of the defined dominant discharges, are related to sediment transport.

Regime theory states that:

"regime channels tend to adjust themselves to average breadths,

> depths, slopes and meander sizes that depend on: (i) the sequence of water discharges imposed on them; (ii) the sequence of sediment discharges acquired by them from catchment erosion, erosion of their own boundaries or other sources; and (iii) the liability of their cohesive banks to erosion and deposition"(Blench, 1969, 1).

The partial systems model (Figure 9) of the alluvial fan geomorphic system and Blench's revised concept of stream regime are closely related with respect to sequences of discharge, sediment load and sediment size. As such, both models are also associated with sediment transport theory.

5:2 Incipient Particle Motion and Sediment Transport Theory

Since the late 1700s the problems of evaluating fluvial sediment transport have focused on the concept of initial or incipient particle motion. Incipient particle motion occurs when the shear stress associated with stream flow over the bed attains or exceeds a critical value (Simons and Şentürk, 1976, 399). Simply stated, a threshold exists for each particle where the forces promoting movement overcome the specific particle's resistance to movement. Researchers in fluvial hydraulics prefer to use the term critical tractive force as a measure of this threshold (e.g., Shields, 1936; White, 1940; Vanoni et al., 1966), whereas geomorphologists have employed the various critical erosion velocity terms (Hjulström, 1935, 1939; Rubey, 1937; Bagnold, 1954; Novak, 1973).

White (1940) presents a simplified model which theoretically analyzes the fluid forces acting on a spherical particle lying on a horizontal stream bed. This model equates the resistance to movement (the moment of weight, Mw) to the forces required for movement (the critical tractive force or the moment of drag, Md) and may be summarized as Mw = Md. While this and similar critical tractive force models

(Shields, 1936; Gessler, 1971) are supported by numerous laboratory experiments, application to stream channels has not been that successful (Lane and Carlson, 1953; Baker and Ritter, 1975). Carson (1971) suggests that a weakness in the theoretical models is that they assume average conditions. The flume studies which support these models employ average velocity terms, uniform grain size and spherical shaped particles; conditions not normally found in the natural environment. It is believed that this assumption of average conditions accounts for the variation between the natural observations and experimental results. Carson (1971) also points out that some tractive force models assume the lift component of critical tractive force to be very small (White, 1940), whereas Chepil (1961) has demonstrated that lift and drag forces may be of equal magnitudes.

Hjulström (1935, 1939) produced an empirically derived diagram which relates particle size to critical erosion velocity, or as Morisawa (1968) suggests, a velocity at which a critical tractive force operates on a given particle on a given slope. This geomorphological concept has also been investigated by several researchers (Rubey, 1937; Bagnold, 1954; Sundborg, 1956; Galay, 1971;and Novak, 1973). However, once again the results of empirical studies involving natural channels (Galay, 1971; Novak, 1973) deviate from those predicted by controlled flume modelling (Hjulström, 1935; Hallmark and Smith, 1965). Novak (1973) suggests that these discrepancies may be due to several factors:

i) various operational definitions of erosion velocity terms, e.g., the bottom erosion velocity (Bogardi and Yen, 1938), and the mean cross sectional erosion velocity (Hjulström, 1935);

ii) the effect of depth of flow on velocity gradients and associated shear stresses;

iii) the effects of suspended sediment load, channel pavements, and various bedforms; and

iv) the use of uniform size spheroid bed material in the flume studies.

In addition, Novak (1973) proposes that the difference between naturally observed erosion velocities and comparable critical erosion velocities measured in flume experiments is even more significant when gravel size material is being considered.

Galay (1971 and 1972) has compared the experimental results of several researchers (Izbash, 1936; Hallmark and Smith, 1965; and Bhowmik and Simons, 1970) with respect to critical mean cross sectional erosion velocities (V_{mc}) and particle size (D), and derived the empirical relationship $V_{mc} = cD^{0.5}$, where D usually represents the median of uniform size gravels. He pointed out that the above studies employed both uniform grain sizes and uniform material in the flume experiments and predicted that natural stream conditions would result in significantly different constants. Galay (1971) directed his research toward deriving an empirical function for North American gravel bed rivers. His results may be summarized as $V_{mc} = 8.0\ D^{0.33}$, where D, measured in feet, represents the size of a rock exposed on the river bed which is larger than 90% of the total size population.

Research involving an evaluation of either critical tractive forces or critical erosion velocities in natural channels requires some measurement of the size of the bed material. Galay (1971) and Novak (1973) suggest that the estimated particle size value D must be representative of the full size distribution of the river bed material and both authors point out that this D value may not be compatible with D values employed in simulation model studies. Consequently, the derived theoretical functions are often not useful for the natural river situation. Since the parameter D must be representative of the entire grain size distribution, the statistically logical choice for a D value would appear to be the arithmetic mean or more practically the sample arithmetic mean. Krumbein and Graybill (1965, 110) indicate that naturally occurring grain size distributions are generally log-normal and suggest the use of the less biased median value. The median (D_{50}) grain size value is frequently employed by fluvial researchers investigating river regimes and sediment characteristics of stable alluvial channels (e.g., Lacey, 1929; Lane, 1955; and Blench, 1969). As such, the D_{50} value is generally assumed to be associated with average flows and channel equilibrium situations. However, it has been suggested that the effective fan building discharges are associated with peak flow events and therefore represent above average flows and, consequently, channel modification. It follows that a coarser D value must be employed for estimating the critical erosion velocity required for the significant bed load transport associated with these peak flows. Kellerhals (1967), Neill (1968), Galay (1971), and Kellerhals, Neill and Bray (1972) employ the D_{90} value in their respective studies of coarse gravel bedded streams in which significant bedload sediment transport takes place when 90 percent of the bed material is capable of being eroded. It is similarly assumed that the principal fan building discharges occurring in the Riding Mountain study area are capable of eroding and transporting 90% of the bed material. These effective fan building discharges are denoted as QD_{90} where Q represents discharge and D represents the size of a specific rock and the subscript (90) indicates that D is larger than 90% of the bed material size distribution.

5:3:0 <u>The Operational Definition and Estimation of Effective Fan Building Discharge in the Study Area</u>

Ryder's (1971a) partial synthetic systems model (Figure 9) implies a correlation between fan slope (λ) and stream discharge (Q), sediment yield (G) and sediment size (D). Galay (1971) has established an empirical relationship between sediment size (D) and critical erosion velocity (V_{mc} or V_*). Since major alluvial fan aggradation in the study area is related to significant bedload transport; stream discharge, sediment yield, and sediment size may be combined to create effective fan building discharge parameters (QD), where Q represents the specific stream discharges passing through a segment of channel which will transport specified size (D) rocks. A subscript on the D value, say, for example, 70, would indicate that D refers to the size of rock larger than 70% of the bed material size distribution.

5:3:1 <u>Site Selection</u>

In order to investigate the nature of the proposed fan slope versus QD relationship, it was necessary to provide a rational estimate of the various effective fan building discharges which occur in the study watersheds. Since five of the larger watersheds are monitored by Water Survey of Canada and the mean daily discharge recorded, it was decided to focus the hydrometric data collection programme on a sample of the ungauged drainage basins. The selection of the sample watersheds was based on the criteria outlined below:

i. Spatial Accessibility:

Since the hydrometric data collection programme was designed to provide estimates of peak flows discharged from a drainage basin onto an alluvial apron, the basin mouth-fan apex is the preferred data collection site. Spatial accessibility refers to both the ability to operationally define the data collection site and the physical accessibility of this locale.

ii. Temporal Accessibility:

Due to the relatively short basin response times demonstrated by the Wilson Creek watershed, it was considered advisable that all sample sites be accessible within a short interval of time. Temporal accessibility then, refers to the ability to visit and conduct hydrometric measurements at all sample sites within one day.

iii. The Sensitivity of the Hydrometric Sample Site:

Before selecting each hydrometric site, some evidence of measurable discharge response to the variety of precipitation and snowmelt events was required. A short term monitoring of staff gauges located at each potential site was considered to be an effective means of evaluating this discharge sensitivity.

All spatially accessible ungauged streams were observed for a short period (one full field season) and seven relatively sensitive and temporally accessible sample sites were selected for study. These sites and the associated drainage basins (Figure 10) constitute a 44% sampling of the ungauged watersheds and this sample size can be increased to 55% of the study area by including four of the government monitored drainage basins.

The exact location of gauge sites and hydrometric survey sites were subjectively chosen with the prerequisite that the sediment transporting flows must pass the fan apex but not the loci of deposition. This permitted an estimation of the effective fan building discharge which transported material from the basin to the fan. The staff gauges were monitored for two seasons and all measurable peak flow discharges recorded. Abnormally dry conditions during the two year observation period resulted in only six peak flow events, and, as a result, the assumption of regime or stream equilibrium could not be established with any degree of confidence. However, annual trips to the gauge sites indicated no apparent net erosion or deposition and the presence of established short term rating curves for the four gauged streams lends support to the short term stable channel regime assumption.

5:3:2 Methodology

A stepwise summary of the procedures used to estimate the effective fan building discharge parameter (QD) is presented in section 5:4, p. 131. Further discussion of the methodologies, assumptions and requirements involved in these operational procedures follows.

The channel and floodplain of the seven sample sites were surveyed for cross sectional form and the channel slope established over a 100 metre reach. Since most of the study sections occur in entrenched channels or modified drainage ditches, the stream channels are usually sub-rectangular in cross sectional form and of uniform slope through the study reach (Table 17 and Plate V).

Bed material was sampled at each site. Kellerhals and Bray

PLATE V

The Hydrometric Sample Site 191510

An example of a peak flow event ($Q = 4.3$ $ft.^3/s$; $V_{mc} = 2.6$ ft./s). Since most of the hydrometric sample sites occur in entrenched channels or modified drainage ditches,the stream channels are usually sub-rectangular in cross sectional form and of uniform slope through the study reach.

(1971) review sampling procedures for coarse river bed gravels and present an interesting discussion regarding the measurement procedure and the equivalence of the varying sampling methods. McGinn (1972) statistically supports Kellerhals and Bray's (1971) general conclusion that different sampling procedures produce different grain size distributions and reiterates their warning that derived size distributions be comparable with the early research data of fluvial hydraulics and sediment transport theory.

The Wolman (1954) grid sampling method was employed and the b or intermediate axis of each pebble was measured with calipers (threshold of sensitivity = 0.01 ft). The arithmetic triaxial mean, or perhaps the more appropriate geometric triaxial mean, were not determined, since McGinn (1972) demonstrated that there was no significant difference between these complex parameters and the b axial value for the individual rocks or resulting grain size distributions.

Volumetric or bulk sample sieve analysis was not considered due to the problems associated with armoured river beds (Plate VI). Kellerhals and Bray (1971) indicate that armoured riverbeds consist of two sediment size populations, the surface armour and the subsurface fines. Volumetric sampling mixes these two sediment populations and thus presents a statistically unnatural grain size distribution. An additional reason for rejecting the sieving methodology concerns the lithology and associated shape of the stream bed material. Over 90 percent of the material is shale and essentially disc shaped. Since square hole sieves sort sediment by shape as well as by size (Sahu, 1964), the grain size distribution curve may be significantly shifted toward the finer sizes (Van der Plas, 1962). Leopold (1970, pers. comm.)

PLATE VI

A Shale Armoured Streambed (191514a)

Armoured riverbeds consist of two sediment populations, the surface armour and the subsurface fines. The shale armour protects the finer subsurface sediment from stream scour, and probably reduces the effects of particle impact, and water-sediment density and viscosity fluctuations, on the initiation of particle motion.

suggests that this effect could be significant for plate or disc shaped gravel, and McGinn (1972) provides additional statistical support for this hypothesis.

Once a grain size frequency distribution curve had been derived (Folk, 1965) the specific D_{90}, D_{75} and D_{50} values were determined (Table 17). D_{90} values were substituted in Galay's (1971) mean critical erosion velocity equation ($V_{mc} = 8.0\ D^{0.33}$) for North American rivers and the critical erosion velocities for each sample stream were calculated (Table 17). Manning "n" roughness values were also estimated by substituting D_{90} and D_{75} values into the Strickler (1923) equation ($n = 0.0342\ D_{50}^{0.17}$). The calculated n values (Table 17) compare favourably with Gray's (1970) tabled values for dredged channels with gravel beds or straight clean natural streams, conditions approximating those of the study streams.

The estimated critical erosion velocity (V_*), the Manning roughness coefficient (n), and the measured channel slope (S) permit the calculation of a mean depth for each stream, by substituting the above values into the Manning equation

$$V_* = \frac{1.49}{n} R^{0.67} S^{0.5},$$

and assuming that the hydraulic radius (R) of sub-rectangular channels is approximately equal to mean flow depth (Leopold, Wolman and Miller, 1964, 157). The estimated mean flow depth ($\bar{d}$), associated with a specific critical erosion velocity (e.g., V_{*90}), may be used in conjunction with the surveyed channel and floodplain cross sections to estimate the channel cross sectional area (AX). Since the channel form is sub-rectangular, cross sectional area equals the product of mean depth of flow and stream width; i.e., $AX = \overline{d} \cdot w$ (Gregory and Walling, 1973, 132). The estimated flow depths and stream widths associated with specific threshold fan building discharges are presented in Table 18. The product of the calculated cross sectional areas (AX_{90} and AX_{75}) and the calculated critical erosion velocities (V_{*90} and V_{*75}, respectively) represent the lower boundary or threshold effective fan building discharge (QD_{90} and QD_{75}, respectively). Hence, the threshold effective fan building discharge estimates (QD) represent a composite hydrometric parameter which employs established principles of stream regime and sediment transport, and can now be correlated with the alluvial fan composite morphometric parameter, fan slope (λ).

5:4 A Stepwise Summary of the Operational Definition of Effective Fan Building Discharge (QD_{90})

i. Effective fan building discharge (QD_{90}) equals the cross sectional area at the site (AX_{90}) times the critical erosion velocity for the D_{90} particle size (V_{*90}),

i.e., $QD_{90} = AX_{90} \cdot V_{*90}$

ii. Calculate V_{*90}:

$$V_{*90} = 8.0\ D_{90}^{0.33} \qquad \text{(Galay equation, 1971)}$$

iii. Calculate AX_{90}:

a. The cross sectional area of stream flow (AX_{90}) required to pass the effective fan building discharge (QD_{90}) equals the stream width (w_{90}) times the mean critical depth of flow for QD_{90},

i.e., $\overline{d}_{90}$.

AX_{90} also equals the wetted perimeter (P_{90}) times the hydraulic radius R_{90}.

b. In rectangular form channel cross sections, where the stream width is very much greater than depth, the following relationships are assumed:

$\bar{d} = R$ (Leopold, Wolman and Miller, 1964, 157)

$w \simeq \bar{w}$ (Simons and Albertson, 1963, 82)

$P = w$

c. Calculation of R_{90}:

$$V_{*90} = \frac{1.49}{n} R_{90}^{0.67} S^{0.5} \quad \text{(Manning equation)}$$

$$n = 0.0342\ D^{0.17} \quad \text{(Strickler equation)}$$

$$S = Sw = Sb \quad \text{(Henderson, 1966, 71)}$$

Sb is the surveyed bed slope for the sample reach.

$$R_{90} = \left(\frac{n}{1.49} \cdot \frac{V_{*90}}{\sqrt{S}}\right)^{1.5}$$

d. Combine the calculated value for $R_{90} = \bar{d}_{90}$ with the surveyed cross section to calculate AX_{90} (sectional method; Gregory and Walling, 1973, 132).

iv. Calculate QD_{90}:

$$QD_{90} = AX_{90} \cdot V_{*90}$$

5:5 Problems Involving the Operational Definition of Effective Fan Building Discharge

The previously outlined operational procedure for estimating the threshold effective fan building discharges has several unavoidable

TABLE 17

DATA SUMMARY FOR THE CALCULATION OF V_*, n, and R PARAMETERS

FAN NO.	BED SEDIMENT SIZE (ft)			MANNING $n=0.0342D^{0.17}$			Vmc (ft/sec) $V_*=8.0D^{0.33}$		CHANNEL SLOPE	HYDRAULIC RADIUS (ft) $R=\left(\frac{V_*}{S^{0.5}} \cdot \frac{nD50}{1.49}\right)^{1.5}$	
	D90	D75	D50	D90	D75	D50	V_*90	V_*75	TAN	R90	R75
1a	0.180	0.135	0.050	0.025	0.024	0.020	4.55	4.25	0.0088	0.6	0.5
1b	0.215	0.165	0.160	0.026	0.025	0.025	5.00	4.45	0.0081	0.9	0.9
2a	0.185	0.120	0.045	0.026	0.024	0.020	4.65	3.95	0.0108	0.4	0.3
2b	0.115	0.080	0.045	0.024	0.022	0.020	3.90	3.45	0.0163	0.2	0.2
8	0.235	0.125	0.080	0.027	0.024	0.050*	4.93	4.00	0.0166	0.9	0.7
10	0.185	0.130	0.050	0.026	0.024	0.020	4.63	4.15	0.0132	0.3	0.3
12	0.180	0.135	0.050	0.025	0.024	0.020	4.60	4.20	0.0105	0.5	0.4
13	0.090	0.075	0.045	0.023	0.022	0.020	3.65	3.35	0.0101	0.3	0.3
14a	0.200	0.135	0.050	0.026	0.024	0.020	4.75	4.20	0.0102	0.5	0.4

0.050* - Includes a vegetation encroachment and unusually large boulders estimate

TABLE 18

SUMMARY OF DATA FOR CALCULATION OF QD PARAMETERS

FAN NO.	SIZE (ft) D90	D75	AX (ft²) # AX_{90}	AX_{75}	Vmc (ft/sec) V_{*90}	V_{*75}	R = d (ft) 90	75	width (ft) 90	75	QD (cfs) QD_{90}	QD_{75}
1a	0.180	0.130	11.36	5.74	4.55	4.25	0.6	0.5	19.3	11.5	51.7	24.4
1b	0.215	0.165	7.52	6.45	5.00	4.45	0.9	0.9	8.0	7.3	37.6	28.7
2a	0.185	0.120	3.53	1.70	4.65	3.95	0.4	0.3	8.0	5.0	16.4	6.7
2b	0.115	0.080	1.13	0.46	3.90	3.45	0.2	0.2	6.3	3.0	4.4	1.6
8	0.235	0.125	8.70	5.40	4.93	4.00	0.9	0.7	10.0	7.5	42.9	21.6
10	0.185	0.130	2.41	1.69	4.65	4.15	0.3	0.3	7.5	6.3	11.2	7.0
12	0.180	0.135	3.61	2.40	4.60	4.20	0.5	0.4	8.0	6.0	16.6	10.1
13	0.090	0.075	3.04	2.60	3.65	3.35	0.3	0.3	9.3	9.0	11.1	8.7
14a	0.200	0.135	5.64	4.40	4.75	4.20	0.5	0.4	11.5	10.8	26.8	18.5
$\bar{X}$	0.176	0.122			4.52	4.00	0.5	0.4				
SD	0.046	0.022			0.45	0.37	-	-				

AX # Calculated using the sectional method; Gregory and Walling, 1973, 132.

shortcomings. The technique assumes that the trunk streams associated with the seven sample watersheds are at equilibrium or in regime. Regime theory and sediment transport theory assume a uniform flow permitting the application of established formulae, yet in the study area there is little empirical evidence supporting both the assumption of regime and uniform flow. It may be argued that if a small segment of the channel (between the fan apex and the loci of deposition) exhibits the assumed uniform flow characteristics (i.e., gradually varying flow, Simons and Şentürk, 1976) and stable bed elevations, the application of erosion velocity equations, the Strickler equation, the Manning equation and the equations of regime theory may be justified (Blench, 1969).

Sediment transport theory also assumes that the sediment particles are spherical or almost spherical in shape. The shale sediment occurring in the study area is plate-like or disc shaped and these shapes generally require higher erosion velocities but lesser velocities for transport (Lane and Carlson, 1954). Clearly, a considerable amount of empirical research is required in the study region regarding stream regime and shale sediment transport. The present monitoring system and the available sediment data are insufficient for testing and evaluating the accepted theoretical models.

The well documented concept of the mobile or erodible stream bed (Blench, 1969) may also significantly influence the calculation of effective fan building discharge. Saltating particles and contact bed material transport can generate an "impact mechanism" (Bagnold, 1954, 102) and this phenomenon significantly reduces erosion velocity thresholds (Bagnold, 1954, 88). Large quantities of suspended material are known to affect water-sediment specific gravity, apparent viscosity, and turbulence (Simons and Şentürk, 1976, 77). These fluid parameters influence particle impacts, the magnitude of tractive forces, and erosion velocity thresholds, but their effects have not been well documented in previous research.

In the study area, wide spread channel armouring probably limits the effect of particle impact, and water-sediment density and viscosity fluctuations on initiation of particle motion. However, in view of the complexity of the positive and negative effects of these flow parameters on erosion velocity thresholds, a second effective fan building discharge (QD_{75}) was also considered as a parameter for the proposed multiple regression model.

5:6 The Effective Fan Building Discharges in the Study Area

Table 18 summarizes the data required for derivation of the threshold effective fan building discharge. The mean D_{90} for the sample basins is 0.176 ft ± 0.046 (53.6 mm ± 14 mm) requiring an average D_{90} threshold erosion velocity of 4.5 ± 0.5 ft/sec. Stream velocities of this magnitude are frequently encountered during storm runoff peak flow events. Values of greater than 15 ft/sec have been observed on Wilson Creek (Galay, 1971; and Thomlinson, 1977, pers. comm.) and consistent recession limb velocities of between 3 and 4 ft/sec have been frequently recorded on all seven of the sample basins. Substantial sediment transport has also been observed and recorded during the measurement of these flow velocities.

A theoretical velocity value based on an application of the Manning equation (slope = 0.013, average n = 0.03, and a depth of flow = 0.8 ft) results in a calculated average cross sectional velocity of

4.87 ft/sec. This value appears consistent with the empirically derived critical erosion velocity values (Table 17) and observed flow depths. The theoretical and empirical observations suggest that stream bed erosion and sediment transport occur as a result of storm event stream flows.

As previously indicated, the dependent variable, mean annual flood discharge (Q M.A.F.) is exponentially related to the size of the effective drainage basin area (Q M.A.F. = cA^n). Durrant and Blackwell (1959) suggest that the exponent n equals 0.7 for the study area and that the regional unit basin area constant (c) is approximately equal to 45. Forsaith (1949) established n equal to 0.5 and an annual unit basin area constant equal to the product k • 32.3 where k in the study area would range from 1.0 to 2.0, but is likely 1.5 (Gray, 1970, 8.7 and 8.15). Although both models produce similar unit basin area discharge coefficients, the values of the exponent are not the same. This difference may be attributed to differences in the operational definition of the basin area variable. Durrant and Blackwell (1959) employ an effective basin area, whereas Forsaith (1949) utilizes the more common gross basin area.

A similar empirical study was conducted for the Riding Mountain area and generally supports both the Durrant and Blackwell (1959) and Forsaith (1949) models. The Riding Mountain study employs the previously outlined power function model and considers the relationship between the independent variable, gross basin area, and the dependent variable, effective fan building discharge. In this study of relatively small watersheds (gross basin area less than 25 mi^2.), the exponent n equals 0.5 and the unit area discharge coefficient (c) equals 13.2.

The calculated exponent (n = 0.5) is the same as Forsaith's (1949) value for the Prairie Provinces and is in general agreement with world regional values (Gray, 1970, Table VIII:3). However, the unit area discharge coefficient (13.2) is considerably smaller than either of the two previously discussed models. This difference is probably due to the variation in the operational definitions of the dependent variable, (discharge). The mean annual flood discharge estimated by the Durrant and Blackwell (1959) and Forsaith (1949) models has a Gumbel plot recurrence interval of 2.33 years, whereas the effective fan building discharge (QD_{90}) employed in the Riding Mountain study is estimated to occur every 2.00 years. Considering Gumbel's (1954) extreme value theory, QD_{90} must be relatively smaller discharge than Q M.A.F. It follows that the associated unit area discharge coefficients will also reflect this difference.

5:7 Fan Slope, Basin Area, and Effective Fan Building Discharge Relationships

Table 19a presents a zero order correlation matrix of basin area, fan slope and various discharge parameters (QD_{90} and QD_{75}). The correlation coefficient value (r) for QD_{90} versus A has a relatively high positive value of 0.80, suggesting that 64 percent of the variation in effective fan building discharge may be explained by a corresponding variation in drainage basin area. The high negative correlation between fan slope (λ) and basin area (-0.89) has been previously discussed. Fan slope is also negatively correlated with effective fan building discharges (e.g. r = -0.81 for QD_{90}). This negative correlation reflects the capability of high discharges to transport sediment farther down the slope of the alluvial fan.

TABLE 19a

ZERO ORDER CORRELATION MATRICES

Small basin sample (n = 7)

VARIABLE	AREA	SLOPE	DISCHARGE QD_{90}	QD_{90}/A	QD_{75}/A
AREA	1.0	-0.89	0.80	-0.80	-0.84
SLOPE		1.0	-0.81	0.61	0.70
DISCHARGE QD_{90}			1.0	-0.28	-0.37
QD_{90}/A				1.0	0.98
QD_{75}/A					1.0

TABLE 19b

Large basin sample (n = 11)

VARIABLE	AREA	SLOPE	DISCHARGE QD_{90}	QD_{90}/A
AREA	1.0	-0.93	0.89	-0.50
SLOPE		1.0	-0.88	0.37
DISCHARGE QD_{90}			1.0	-0.06
QD_{90}/A				1.0

5:8 Unit Area Effective Fan Building Discharge

Since fan slope (λ) is highly correlated with both the drainage basin area and effective fan building discharges and since A and QD_{90} are also highly correlated, there is an obvious need for standardization of the sample discharges. This standardization is achieved by deriving a unit area effective fan building discharge QD_{90}/A and QD_{75}/A. QD_{90}/A and QD_{75}/A remain highly correlated with drainage basin area (r = -0.80 and -0.84, respectively). However, the standardization of effective fan building discharge results in a negative correlation indicating that threshold effective fan building discharges increase in magnitude as the drainage basin area decreases. This serves to reiterate the hydrologic significance of peak flow events occurring in the smaller watersheds, and emphasizes the need for detailed hydrological investigations of these relatively unmonitored drainage basins.

Table 20 presents the fan morphometric parameter slope (λ), the representative watershed parameter drainage basin area (A) and the unit area effective building discharges (QD_{90}/A and QD_{75}/A). The mean QD_{90}/A equals 9.51 cfs with a standard deviation of 6.48 and the average QD_{75}/A is 6.05 cfs with a standard deviation of 4.95 cfs. The associated relatively high coefficients of variation (0.68 and 0.82, respectively) probably reflect the relatively large variance in drainage basin area as well as the variation in stream discharges.

5:9 Fan Slope/Unit Area Effective Fan Building Discharge Relationship

In view of the earlier correlation-regression analysis (p. 62) and the statistically established dependence of the effective fan building discharge on the log-normally distributed drainage basin area

TABLE 20

CORRELATION - REGRESSION DATA SUMMARY

Fan No.	$A(mi^2)$	λ(degrees)	QD_{90}/A (cfs)	QD_{75}/A (cfs)
1	11.40	1.03	4.53	2.23
2	4.95	1.03	4.19	1.67
3	23.45	0.63	6.09	-
8	5.63	1.10	7.62	3.84
10	1.00	1.73	11.16	7.00
12	3.06	1.38	5.41	3.29
13	1.01	1.47	11.02	8.65
14a	1.18	1.35	22.69	15.69
16	8.35	1.05	17.13	-
17	26.20	0.63	5.46	-
18	15.34	0.65	9.32	-
$\overline{X}$		1.10	9.51	6.05
SD			6.48	4.95

parameter, a logarithmic transformation of the basic data (Table 20) is appropriate. The simple regression least squares solution and associated coefficients were calculated for both QD_{90}/A and QD_{75}/A versus the fan slope. Table 21 summarizes the results. The various regression equations, their constants, exponents and associated correlation coefficients permit some theorizing regarding the nature of the components and linkages in the alluvial fan partial system model (Figure 9).

In the fan slope versus unit area effective fan building discharge relationship the values of the dependent variable (fan slope) increase exponentially as the unit area effective fan building discharge increases. This appears contrary to Bull's (1964b) observation that large discharges result in gentle fan gradients, but it must be recalled that the unit area discharges are negatively correlated with basin area ($r = -0.80$ for QD_{90}) and consequently decrease in absolute value as basin area increases.

The regression constant (c) in the mathematical model, $\lambda = c\ (QD/A)^n$, represents the mean fan slope for a unit discharge (1 cfs) from a unit drainage basin area (1 sq. mi.). As the D value decreases (e.g., $QD_{90} \rightarrow QD_{75}$), c approaches the sample mean fan slope of 1.10 degrees. This trend suggests that the regression constant is predominantly dependent on the grain size parameter D, and supports Hooke's (1968) postulate that the fan slope is primarily a function of sediment size.

The exponent, n, in the function $\lambda = c\ (QD/A)^n$, indicates the rate of fan slope variation as a consequence of variation in unit area effective fan building discharges. The low exponent values (0.201 for

TABLE 21

SUMMARY OF SIMPLE REGRESSION AND CORRELATION ANALYSIS

Model $\lambda = 0.83\ (QD_{90}/A)^{0.201}$

$c = 0.83$

$n = 0.201 \pm 0.116$

$r = 0.615$

$r^2 = 0.378$

Standard error of the estimate = 0.074

$F = 3.034$ Deg. F = 1/5

F significant at < 90%

Model $\lambda = 0.98\ (QD_{75}/A)^{0.175}$

$c = 0.98$

$n = 0.175 \pm 0.08$

$r = 0.698$

$r^2 = 0.488$

Standard error of the estimate = 0.068

$F = 4.76$ Deg. F = 1/5

F significant at 90%

QD_{90}/A and 0.17 for QD_{75}/A) suggest only a moderate positive increase in fan slope as the unit area discharge increases. This is not unexpected, as the unit area discharges are negatively correlated with drainage basin area and, therefore, a high QD/A as produced by small watersheds generally results in low absolute discharges and relatively steep fan gradients. Similarly, low QD/A values are generated by large drainage basin areas yielding higher absolute discharges and gentle fan slopes.

The correlation coefficient, r, associated with these equations ($r = 0.615$ for QD_{90}/A, and $r = 0.698$ for QD_{75}/A) supports the postulate that unit area effective fan building discharges are moderately correlated with alluvial fan slopes. The coefficient of determination (r^2) indicates that 37.8% of the variance in the fan slope is explained by the QD_{90}/A variable while 48.8% variance is accounted for by the QD_{75}/A value. These results somewhat contradict the established concept (p. 123) that it is the peak flow discharges (QD_{90}) which are fundamental for alluvial fan construction.

5:10 The Dominant Discharge vs the Distribution of Discharges in Alluvial Fan Construction

Hooke (1968) empirically demonstrates that actual fan slopes are created by a distribution of discharges, and he inferred that the smaller discharges deposit material near the loci of deposition or intersection point, while larger discharges winnow these sediments and deposit near the fan toe (Hooke, 1968, 623). These observations suggested the possibility of defining a "dominant discharge" as "that discharge which, if it alone occurred, would produce a fan having the same slope as a fan built with a distribution of discharges" (Hooke, 1968, 625). Further empirical investigations revealed that this dominant discharge was "equaled or exceeded 35% of the total time during which flow occurred" (Hooke, 1968, 625). However it should be noted that this is not equivalent to; "equaled or exceeded by 35% of the peak flow discharges." Hooke (1968, 625) concludes that it is not known whether the dominant discharge has a similar frequency of occurrence on natural alluvial fans.

Hooke's (1968) observations are particularly useful in that they empirically establish the role of the range of discharges and associated sediment yields in the alluvial fan geomorphic system. This role may be summarized as:

i. small discharges and associated small sediment loads are deposited near the intersection point and result in steep fan gradients;

ii. large discharges are capable of transporting their relatively large sediment loads far down the fan slope, depositing near the fan toe and producing relatively low fan gradients; and

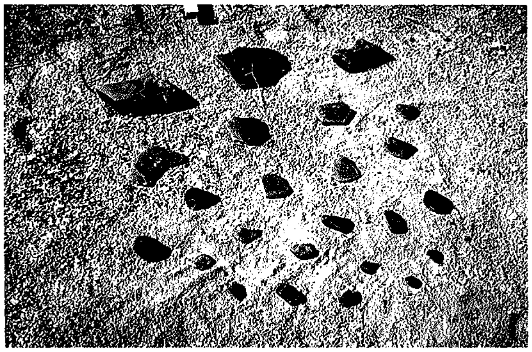
iii. that the distribution of both large and small discharges results in the equilibrium fan slope.

In the study area the distribution of discharges also assumes a significant role in alluvial fan construction. The high peak flow discharges associated with intense summer storms (e.g., September, 1975) tend to deposit sediment far down the fan slope while the mean annual flood and less significant storm discharges usually result in channel aggradation near the fan apex. These shale sediment loads, deposited in the channel, undergo rapid physical disintegration during low water periods. Substantial size reduction has been observed for shale particles exposed for two wet-dry cycles over a six week period (Plate VII). This rapid weathering of channel stored sediment permits discharges of similar magnitudes to move the sediment through the channel system by first depositing shale near the apex and then, after weathering, transporting the smaller particles further along the channel. This process effectively charges the stream channel system with large volumes of stored sediment. The less frequent, but more significant effective fan building discharges (e.g., QD_{90}) periodically flush the alluvial fan hydrological system and produce measurable fan aggradation. Thus, for the Riding Mountain area, it is the distribution of discharges, the frequency of peak flow events, and the sequence of flood discharges which determine both the rate and magnitude of alluvial fan construction.

5:11 Fan Slope, Basin Area, and Unit Area Effective Fan Building Discharge Relationships

Ryder's (1971a) partial synthetic systems model (Figure 9) implies that the relationships among fan slope, basin area and stream discharge (effective fan building discharge) are linear or log-linear. This suggests that a multiple regression equation may provide a statistically satisfactory mathematical model accounting for variation in fan slope.

The assumptions employed in multiple regression analysis are similar to those used in simple regression (Poole and O'Farrell, 1971, 148) with the additional assumption that the explanatory variables can not be "perfectly linearly related" (Mather, 1976, 44). The problem of linear relationships among the explanatory variables (independent variables) is termed multicollinearity (Mather, 1976, 45). Mather states that if multicollinearity exists in a given multiple regression



June 13

June 29

July 10

July 31

PLATE VII

A Weathering Study of the Riding Mountain Shales

Substantial size reduction has been observed for various sizes of shale particles which have been exposed for two naturally occurring wet-dry cycles over a six week period.

PLATE VIII

Wilson Creek Channel During a Period of Low Flow

The shale sediments, previously deposited in the channel, undergo rapid physical disintegration during these low water periods. Small peak flow discharges winnow the weathered sediments and redeposit the fines downstream. This process effectively charges the stream channel with large volumes of stored sediment.

model, it often becomes difficult to sort out the separate contributions of the explanatory variables to the variance of the dependent variable (Mather, 1976, 73). The high correlations between unit area effective fan building discharges and drainage basin area ($r = -0.80$ for QD_{90}/A; $r = -0.84$ for QD_{75}/A), suggest the possibility of a multicollinearity problem in the proposed multiple regression model (Hauser, 1974, 152). However, by applying stepwise multiple regression procedures to the two independent variables, basin area (A) and unit area effective fan building discharge (QD/A), and the dependent variable, fan slope (λ), some control over the suspected collinearity between the two independent variables may be achieved (Mather, 1976, 174; and Hauser, 1974, 156). Since drainage basin area is clearly the dominant independent variable considered in the multiple regression model ($r = -0.89$), this variable (A) is forced to enter the equation in the initial step (Hauser, 1974, 156). This permits the calculation of the partial correlation coefficient (r_*) at step one. The associated partial coefficient of determination (r_*^2) is indicative of the relative explanatory power of the second variable QD/A.

The logarithmic transformation of the sample data results in a complementary transformation of the general multiple regression model to the form

$$\lambda = cA^n \cdot (QD/A)^m.$$

Both unit area effective fan building discharges (QD_{90}/A and QD_{75}/A) are investigated as independent variables and Table 22 summarizes the results of both regression solutions.

Generally there is no unexpected variation in either the multiple regression constant (c) or the basin area exponent (n) from those calculated for the simple regression models (Table 21). However,

TABLE 22

SUMMARY OF MULTIPLE REGRESSION AND CORRELATION ANALYSIS

Model $\lambda = 1.9\ A^{-0.225} \cdot (QD_{90}/A)^{-0.085}$

c = 1.9

n for (A) = -0.225 ± 0.073

m for (QD_{90}/A) = -0.085 ± 0.116

r = 0.904

r^2 = 0.817

Standard error of the estimate = 0.045

r* = -0.345

$r*^2$ = 0.119

F = 8.916 Deg. F = 2/4

F significant at 95%

Model $\lambda = 1.69\ A^{-0.212} \cdot (QD_{75}/A)^{-0.044}$

c = 1.69

n for (A) = -0.212 ± 0.085

m for (QD_{75}/A) = -0.044 ± 0.103

r = 0.895

r^2 = 0.801

r* = -0.209

$r*^2$ = 0.044

Standard error of the estimate = 0.047

F = 8.06 Deg. F = 2/4

F significant at 95%

---

large differences occur between the exponent values derived from the multiple regression independent variables (QD/A) and the exponent of the simple regression solutions, $\lambda = c(QD/A)^n$.

The regression constant, c, in the multiple regression model $\lambda = cA^n \cdot (QD/A)^m$ represents the fan slope produced by a unit area effective fan building discharge of 1 cfs from a one square mile drainage basin. Since none of the study watersheds is less than one square mile in size, the regression constant also represents a practical upper bound for the fan slopes generated by the specified effective fan building discharge. A comparison of the regression constants calculated for the QD_{90}/A and QD_{75}/A multiple regression equations illustrated that steep alluvial fan slopes are associated with the large unit area effective fan building discharges (QD_{90}/A), and gentler fan gradients were associated with the small unit area effective fan building discharge (QD_{75}/A). These observations support the previous discussion (5:9, p. 140).

The exponent n in the derived multiple regression functions

$$\lambda = cA^n \cdot (QD_{90}/A)^m \quad \text{and} \quad \lambda = cA^n \cdot (QD_{75}/A)^m$$

does not exhibit significant variation (-0.225 for QD_{90} and -0.212 for QD_{75}). However, these values are less than the exponent calculated for the simple regression model $\lambda = cA^n$, (n = -0.27). The difference is possibly related to sample size and general location within the study area. The lower exponent values of the multiple regression equations are derived from a sample of seven relatively small (less than 10 mi^2.) and predominantly southern drainage basins. The larger n value calculated for the simple regression equation involves the same seven basins plus thirteen other basins located primarily north of Norgate and generally larger in gross basin area. Although the recorded difference in these exponent values is not significant, it does imply two possible hypotheses:

i. that the rate of change in fan slope, due to variation in drainage basin area, is different for small watersheds ($A < 10$ mi.^{2}) versus the larger watersheds; and

ii. that the watershed-fan systems located north of Norgate behave differently than those located farther south.

A second multiple regression analysis, involving a larger sample number and consisting of specifically selected watershed-fan systems, may provide some insight into these hypotheses.

The exponent m in the multiple regression models, $\lambda = cA^n \cdot (QD_{90}/A)^m$ and $\lambda = cA^n \cdot (QD_{75}/A)^m$, differs significantly from the exponent n in comparable simple regression models, $\lambda = c(QD_{90}/A)^n$ and $\lambda = c(QD_{75}/A)^n$; i.e., $m = -0.085$ versus $n = 0.201$ for the QD_{90}/A equations, and $m = -0.044$ versus $n = 0.175$ for QD_{75}/A mmodels.

A comparison of the standard errors in the exponents n and m and their effect on the F values and associated significance levels may be of further interest. Both the simple regression solution ($\lambda = cA^n$) and the first step of the multiple regression equations model the dependency of fan slope on basin area as a power function, and these equations are significant at the 99% level. The standard errors in the exponent, n, in these functions are essentially uniform for both solutions and furthermore, the variability (SE/n x 100) does not change significantly. The variability is 30% in the simple regression equation, and 33% and 40% for the QD_{90}/A and QD_{75}/A multiple regression equations, respectively.

The standard errors of the exponent, n, for the simple regression model, $\lambda = c\ (QD/A)^n$, are 0.116 and 0.08 for QD_{90}/A and QD_{75}/A, respectively. These standard errors represent a variability of 58% and 46%. In the second step of the multiple regression solution, the standard errors in the exponent m are similar in magnitude to those of the simple regression model, 0.116 for QD_{90}/A and 0.102 for QD_{75}/A. However, these standard errors represent corresponding variabilities of 136% and 234%, respectively. The dramatic increase in variability of the exponents between the two models is not because of data variance, but results from the designed removal of the dominant independent variable, basin area, in step one of the stepwise multiple regression technique.

The calculated F values for the simple regression models, $\lambda = c\ (QD/A)^n$, indicate a slightly less than 90% significance level for the QD_{90}/A function, and a slightly greater than 90% significance level for the QD_{75}/A equation. Control of the independent, but highly correlated, basin area parameter in the stepwise multiple regression solution results in a 10% rise in the significance level for the QD_{90}/A equation to a value greater than 99%. The significance level of the corresponding QD_{75}/A equation also rises to slightly greater than 95%. The difference in the change in significance (10% versus 5%) is probably due to the difference in the simple correlations between QD_{90} and QD_{75} with basin area, the extreme event (QD_{90}) being less dependent on basin area ($r = 0.80$) than the more frequent QD_{75} ($r = 0.84$).

5:12 Evaluation of the Proposed Multiple Regression Models

The inductive value of the stepwise multiple regression technique lies in the interpretation of the correlation coefficients (r), and the partial correlation coefficients (r_*). Table 23 summarizes the correlation coefficients and coefficients of determination calculated for the multiple regression models,

$$\lambda = cA^n \cdot (QD_{90}/A)^m \quad \text{and} \quad \lambda = cA^n \cdot (QD_{75}/A)^m.$$

Table 24 provides additional information regarding the simple correlation coefficients derived for the simple regression models,

$$\lambda = cA^n \text{ (7 basin sample, and 20 basin sample),}$$

$$\lambda = c\ (QD_{90}/A)^n \quad \text{and} \quad \lambda = c\ (QD_{75}/A)^n.$$

Table 24 indicates a high negative correlation between fan slope and gross basin area for both the regional (twenty basin) sample and the selected small basin sample ($r = -0.84$ and $r = -0.89$, respectively). The lower r value associated with the regional study is probably due to the inclusion of several poorly defined watershed-fan complexes, while the higher correlation coefficient calculated for the small basin study (7 basin sample) may be attributed to the careful selection of precisely defined watershed-fan systems. This hypothesis leads to the possibility of improving the alluvial fan systems model with respect to multiple correlation coefficients and significance levels by including several well defined large area watershed-fan systems (p. 160 and Table 25).

Table 24 also indicates a moderate degree of correlation between fan slope and unit area effective fan building discharge ($r = .615$) for QD_{90}/A and $r = .698$ for QD_{75}/A). However, the significance levels for these correlations are relatively unacceptable and as previously suggested (p. 146) may be influenced by the established high correlations between unit area effective fan building discharge (QD) and drainage basin area (A).

TABLE 23

CORRELATION COEFFICIENTS (SIMPLE, MULTIPLE, AND PARTIAL)

AND COEFFICIENTS OF DETERMINATION

Fan Slope versus Basin Area and Unit Area Effective Fan Building Discharge (QD_{90}/A)

Model $\lambda = cA^n \cdot (QD_{90}/A)^m$

Sample Size n = 7

Step One (A is forced into the equation)

multiple r = 0.890

multiple r^2 = 0.792

F significant at 99%

simple r = -0.890

simple r^2 = 0.792

F significant at 99%

partial r* for (QD_{90}/A) = -0.345

partial r^{*2} = 0.119

Step Two (enter QD_{90}/A variable)

multiple r = 0.904

multiple r^2 = 0.817

F significant at 95%

change in r^2 = 0.025

simple r for (A) = -0.890

simple r^2 = 0.792

F significant at 95%

cont'd ..../2

.../2 of Table

TABLE 23

Fan Slope versus Basin Area and Unit Area Effective Fan Building Discharge (QD_{90}/A)

simple r for (QD_{90}/A) = 0.615

simple r^2 = 0.378

F significant at 95%

Variance unexplained by the model = 18.3%

<u>Model</u> $\lambda = cA^n \cdot (QD_{75}/A)^m$

<u>Sample Size</u> n = 7

<u>Step One</u> (A is forced into the equation)

multiple r = 0.890

multiple r^2 = 0.792

F significant at 99%

simple r = -0.890

simple r^2 = 0.792

F significant at 99%

partial r* for (QD_{75}/A) = -0.209

partial r^{*2} = 0.044

<u>Step Two</u> (enter QD_{75}/A)

multiple r = 0.895

multiple r^2 = 0.801

F significant at 95%

Change in r^2 = 0.009

cont'd ..../3

.../3 of Table

TABLE 23

Fan Slope versus Basin Area and Unit Area Effective Fan Building Discharge (QD_{75}/A)

simple r for (A) = −0.890

simple r^2 = 0.792

F significant at 95%

simple r for (QD_{75}/A) = 0.698

simple r^2 = 0.488

F significant at 95%

Variance unexplained by the model = 19.9%

TABLE 24

SUMMARY OF SIMPLE CORRELATION COEFFICIENTS AND COEFFICIENTS OF DETERMINATION

Fan Slope versus Basin Area

r_{20} = -0.840 [twenty basin sample]

r_{20}^2 = 0.706

F significant at 99%

r_7 = -0.890 [seven basin sample]

r_7^2 = 0.792

F significant at 99%

Fan Slope versus Unit Area Effective Fan Building Discharge (QD_{90}/A)

r = 0.615

r^2 = 0.378

F significant at 90%

Fan Slope versus Unit Area Effective Fan Building Discharge (QD_{75}/A)

r = 0.698

r^2 = 0.488

F significant at 90%

By forcing basin area (A) into the multiple regression solution in step one, the multiple correlation coefficient equals 0.890 and demonstrates that variation in basin area accounts for 79.2% of the variance in fan slope. The partial correlation coefficient associated with the variables not included in the step one solution, i.e., QD_{90}/A, equals -0.345 and represents a variable accounting for 11.9% of the 20.8% variance unexplained by drainage basin area (A).

Step two in the stepwise multiple regression solution enters the unit area effective fan building discharge independent variable (QD_{90}/A) and results in a rise in the multiple correlation coefficient to 0.904. The coefficient of determination consequently rises to 0.817 or 81.7%, indicating the additional 2.5% variance explained by the second variable, (QD_{90}/A). This is significantly less than the anticipated value suggested by the simple regression model, $\lambda = c\ (QD_{90}/A)^n$, where $r^2 = 0.378$ (Table 24) or 37.8%. However, considering that 80% of the variance in fan slope is attributed to the variation in drainage basin area and only 20% remains unexplained, a parameter which can account for 11% of the unexplained variance is significant and worthy of consideration in a general model.

Similar results are achieved by employing QD_{75}/A as the second independent variable in the proposed multiple regression model. The multiple correlation coefficient calculated in step one remains at 0.890 and rises to 0.895 on entry of the second independent variable in step two. The partial correlation coefficient ($r_*^2 = 0.044$) demonstrates that the variation in QD_{75}/A accounts for 4.4% of the variance unexplained by the basin area variable, and this value translates into 0.9% of the variance in fan slope.

Both multiple regression models support the theoretical power function relationship between fan slope and drainage basin area and generally establish a similar relationship between fan slope and unit area effective fan building discharge. However, the extreme event model, $\lambda = cA^n \cdot (QD_{90}/A)^m$, leaves 18.3% of fan slope variance unexplained, while the second multiple regression model, $\lambda = cA^n \cdot (QD_{75}/A)^m$, has 19.9% unexplained variance in fan slope. For these reasons it is concluded that the $\lambda = cA^n \cdot (QD_{90}/A)^m$ multiple regression model is a slightly better predictor of alluvial fan slopes. Therefore, the $\lambda = cA^n \cdot (QD_{75}/A)^m$ model is now abandoned in favour of the extreme event model, $\lambda = cA^n \cdot (QD_{90}/A)^m$. This decision is also supported by the following previously stated conclusions:

i. that peak flow discharges are fundamental to alluvial fan construction (p. 119 and p. 123);

ii. that the rate of fan slope variation as a consequence of variation in unit area effective fan building discharge is greater for QD_{90}/A than QD_{75}/A (p. 160); and

iii. that the less frequent but more significant effective fan building discharge QD_{90} is capable of flushing the fully charged alluvial fan hydrological system and producing measurable fan aggradation (p. 146).

5:13 Improvement of the Model

On several occasions it has been suggested that the sample size be increased to include the large watersheds in the study area. This should improve the proposed multiple regression model statistically by increasing the sample size and consequently the model's statistical validity (Blalock, 1960, 10). The inferential reliability (Blalock, 1960, 11) is also improved since the scope of the model assumes regional proportions. However, the inclusion of additional fan-watershed systems may significantly alter the equation constants, correlation coefficients and levels of significance.

The four watersheds, gauged by Water Survey of Canada (Figure 10), were selected in order to increase the sample number from seven to eleven watershed-fan systems. The published watershed drainage areas were used as estimates of the independent variable (A).

A flood discharge of 143 cfs (4.0 m^3/s) was selected as an average regional effective fan building discharge (QD_{90}). This was based on a brief examination of the annual series flood frequency plots which suggest that a QD_{90} event occurs once every 7 storm events or approximately annually (RI = 2.00 years) in the study region (Appendix VI, Figures 33 and 37). The unit area effective fan building discharges (QD_{90}/A) were then calculated and the data for the two independent variables, basin area (A) and unit area effective fan building discharge (QD_{90}/A), were added to the original seven basin sample data deck. The stepwise multiple regression technique, as previously described, was employed and Table 25 presents the results.

Generally, there were no unexpected changes in the regression constant, the exponents, the correlation coefficients or the significant levels.

The regression constant, c, increased slightly in absolute value from 1.9 to 2.01, extending the theoretical upper bound for the alluvial fan slopes to about two degrees. No alluvial fan in the study area has an operationally defined fan slope of greater than 1.83 degrees, thus empirically supporting the model's theoretical upper bound.

TABLE 25

SUMMARY OF CORRELATION COEFFICIENTS (SIMPLE, MULTIPLE, AND PARTIAL)

AND COEFFICIENTS OF DETERMINATION

Fan Slope versus Basin Area and Unit Area Effective Fan Building Discharge (QD_{90}/A)

Regression model $\lambda = c\ A^n \cdot (QD_{90}/A)^m$

Sample size n = 11

Step one (A is forced into the equation)

multiple r = 0.933

multiple r^2 = 0.870

F significant at 99%

partial r* for (QD_{90}/A) = -0.315

partial $r*^2$ = 0.099

Step two (enter QD_{90}/A)

multiple r = 0.939

multiple r^2 = 0.883

F significant at 99%

change in r^2 = +0.013

simple r for (A) -0.933

simple r^2 = 0.870

F significant at 99%

simple r for (QD_{90}/A) = 0.368

simple r^2 = 0.135

F significant at 99%

Variance unexplained by the model = 11.7%

The basin area exponent, n, for the regional model (11 basin sample) is greater than the same exponent derived for the small basin model (7 basin sample), (n = -0.291 versus n = -0.225 respectively). However, in the regional model, n closely approximates the exponent, n, calculated for the simple regression model, $\lambda = cA^n$, (20 basin sample; n = -0.27). This generally supports the previously suggested postulate (p. 152) that "the rate of change in fan slope, due to variation in drainage basin area, is different for small watersheds ($A < 10\ mi^2$) versus the larger watersheds." It follows that the expansion of the sample size to include large watersheds increases the inferential reliability of the multiple regression model.

The exponent m remained at -0.085 indicating that there is no significant change in the rate of fan slope variation as a response to variation in unit area effective fan building discharge.

The multiple correlation coefficient improved from 0.89 to 0.933 in the initial step and to 0.939 with the inclusion of the second independent variable (QD_{90}/A) in step two. This suggests that the regional model provides a better data fit than the small basin multiple regression model. The corresponding increase in the multiple coefficient of determination, from 81.7% to 88.3%, illustrates the greater amount of variance explained by the regional multiple regression model, i.e., 6.6%.

The partial correlation coefficient ($r_* = -0.315$) closely approximates the previously calculated small basin model partial correlation coefficient, ($r_* = -0.345$). However, the corresponding drop in r_*^2, from 11.9% to 9.9%, represents a 1.3% decrease in variance explained by the QD_{90}/A variable in the regional model. Despite this decrease in explained variance, the overall amount of fan slope variation left unexplained is significantly reduced from 18.3% to 11.7% by expanding the sample size to include the predominantly larger watershed-fan systems. The unexplained variance must be attributed to additional parameters, associated with the weathering system and the sediment transport system, and their interrelationships with the watershed morphometry and hydrology.

The better data fit, reduction in unexplained variance and a higher significance level (99%) generally improves the reliability and validity (Blalock, 1960) of the multiple regression model and leads to the acceptance of

$$\lambda = 2.01\ A^{-0.291} \cdot (QD_{90}/A)^{-0.085}$$

as the regional watershed-fan system model.

CHAPTER VI

SUMMARY AND CONCLUSIONS

6:1 Introduction

"An alluvial fan is a body of stream deposits whose surface approximates a segment of a cone that radiates down slope from a point where the stream leaves the mountainous [highland] area" (Bull; In: Fairbridge, 1968). Bull's definition implies that the physiography of an alluvial fan represents sediment deposition in response to stream flow from a highland watershed. Chorley and Haggett (1969) would, perhaps, suggest that the alluvial fan landform represents the product of an integrated complex operating so that energy and material inputs produce predictable responses in terms of internal organization and energy and material outputs. In other words, there is an alluvial fan geomorphic system.

6:2 The Objective of this Study

The purpose of this dissertation has been to investigate the alluvial fan geomorphic system which has developed along the Manitoba Escarpment. The study has attempted to outline the relationships between the key components defining the watershed morphology and stream hydrology and the parameters representing the alluvial fan landform. The ultimate objective has been to establish an empirical model representative of the alluvial fan geomorphic system operating within the Manitoba Escarpment region.

6:3 Modelling the Alluvial Fan Geomorphic System

Figure 23 presented an annotated synthetic systems model of the alluvial fan geomorphic system. The system is divided into three subsystems: the alluvial fan physiographic subsystem; and the two fan generating subsystems — the watershed morphology and the stream hydrology. The drainage basin area represents the watershed subsystem, a surface upon which rock weathering and climate operate. Weathering provides the sediment comprising the alluvial fan and climate provides the sediment transport medium, water. The relative relief of the watershed combined with the stream channel length establishes the energy gradient of the alluvial fan system. Therefore, the accumulation of alluvial fan deposits is a function of the interaction between rock weathering and climate as they operate on a watershed. The resulting material inputs are transferred along the energy gradient via the stream hydrology subsystem to the alluvial fan.

Ryder (1971a) presented a partial synthetic systems model (Figure 9) of the alluvial fan geomorphic system which outlined empirically established key components of the watershed morphology. In this model, Ryder proposes several representative hydrologic and alluvial fan physiographic parameters. Ryder's (1971a) model implies that the linkages between these various parameters are linearly or log-linearly related and that a multiple regression or series of simple regression equations may produce a statistically satisfactory mathematical model accounting for variations in fan physiography.

6:4 The Study Area

The Riding Mountain segment of the Manitoba Escarpment was selected as the study area. Since natural analogue models were to be employed in this research, it proved necessary to establish environmental homogeneity among the study region watersheds (Chorley and Haggett, 1969, 60). Although there is some variation in the physiography, geology, soils and natural vegetation within the study region, each watershed displays the same physical environmental patterns, thus providing a degree of physical homogeneity. The hydrologic homogeneity of the Riding Mountain Escarpment region has been previously established (e.g., Durrant and Blackwell, 1959; Weir, 1960). Climatologic homogeneity could only be established over a 65 km latitudinal zone due to the systematic increase in orographic precipitation northwards. This constraint has limited the potential number of watershed-fan systems available for study. Difficulties encountered in applying the selected operational definitions of basin area and fan slope further reduced the sample number to twenty watershed-fan systems. The geographic location of each watershed is illustrated in Figure 10 and the relevant morphometric parameters are displayed in Tables 1 and 2.

6:5 Watershed-Fan Morphology and Morphometric Relationships

Fan slope was selected as the composite morphometric parameter which best reflects the basin morphometry-stream hydrology-fan physiography relationship. A simple statistical evaluation of the distribution of fan slopes (Table 3) in the study area indicates that the alluvial fan morphology can be considered to be in a state of equilibrium, resulting in mean fan slopes of 1.13 degrees and a variance of 0.14.

The three linear dimensions fundamental to basin morphometry (height, length, and width) were incorporated in several key components: namely basin area (A), basin slope (Ht/L) and basin relative relief ratio ($Ht/\sqrt{A}$). The linear regression model was then employed to evaluate the nature of the relationships between these basin morphometric parameters and the alluvial fan slope (λ). The results (Figure 22 and Table 12) indicate that the empirical function, $\lambda = 1.61\ A^{-0.27}$, represents the strongest ($r = -0.84$) morphometric linkage evident in the alluvial fan geomorphic system operating in the Riding Mountain study area. Figure 22 also illustrates and summarizes the nature and strength of the other morphometric linkages studied in the partial synthetic systems model.

Of particular interest is the relative relief ratio-fan slope relationship. Contrary to the published results (Melton, 1967 and Ryder, 1971a) the relative relief ratio ($Ht/\sqrt{A}$) does not add significantly to the explained variance in fan slope. It is suggested that the relatively uniform height of the Manitoba Escarpment in the study region accounts for these results.

The investigation of the fan slope vs basin area function suggests that the intercept value (c) and the slope coefficient (n) are related to several hydrological variables, namely, discharge, sediment yield, sediment size and channel storage potential.

These observations and conclusions imply that the simple morphometric regression model $\lambda = cA^n$ can be expanded to include several of the proposed hydrological parameters; namely discharge (Q) and sediment yield (G). The expanded theoretical model takes the form,

$$\lambda = cA^n \cdot Q^m \cdot G^p.$$

6:6:0 The Development of the Composite Morphometric/Hydrometric Systems Model

Several problems immediately arose regarding the empirical testing of the theoretical model and the derivation of the regression constant and respective exponents. The problems, in order of treatment, were:

i. measurement of the independent variables Q and G;

ii. variability in the magnitudes of discharge;

iii. frequency of recurrence of the magnitudes of Q; and

iv. multicollinearity in the multiple regression model.

6:6:1 Measurement of the Independent Variables

The sediment yield parameter G could not be satisfactorily estimated for the watershed-fan systems in the study area. This was due to the lack of reliable data and difficulties involved in measurement of the various components of total sediment load.

Although the trunk streams of five watershed-fan systems are gauged (Figure 10), there is a scarcity of reliable discharge data. Two of the gauged watersheds do not have sufficient length of record, and a third has proven to be unreliable with respect to flood discharge data and flood frequency analysis. However, the two remaining watershed-fan systems provide excellent long term discharge data and these data were employed for the development of natural analogue models and subsequent regional models (Figures 34 and 38).

6:6:2 Variation in Stream Discharge

Hooke (1968) empirically demonstrated that alluvial fans are constructed by a sequence of variable discharges and associated erosion and sedimentation processes. This appears to be the situation in the Riding Mountain area. Flood discharges transport predominantly shale detritus to the fan apex region, depositing the coarse fraction on the fan surface or in the stream channel. These shale sediments undergo rapid physical disintegration (Plate VIII) and substantial size reduction during low water periods. Smaller, but more frequent discharges winnow the weathered fluvial sediments and redeposit the fines downstream. This process effectively charges the stream channel with large volumes of stored sediment. Subsequently, high discharges, associated with intense summer storms, flush the alluvial fan hydrological system and produce measurable downslope fan aggradation.

This sequence of discharge magnitudes results in an overall concave fan slope which may be subdivided into two component slopes, a steep concave slope associated with the fan apex, and a gentle concavo-convex slope along the main body of the fan to the fan edge.

These observations also support Hooke's (1968) conclusion that alluvial fan slopes are primarily a function of sediment size. In particular the steep concave slopes are associated with coarse sediments and the gentle fan gradients reflect the finer material.

Since fan slope is operationally defined as the upstream or fan apex slope, it follows that this component of total fan slope reflects the flood discharges which transport coarse material and, consequently, is less significantly related to the winnowing discharges. In view of these observations and conclusions a hydrological parameter employed to describe the nature of stream flow on alluvial fans should incorporate both peak flow discharge magnitudes and associated stream competence. The term "effective fan building discharge" (QD) was used to describe this parameter and an associated numerical subscript (e.g., QD_{50}) indicates the percentage of the sediment finer than the critical grain size (D) that is transported by such discharges.

Traditionally the median grain size value (D_{50}) is employed by fluvial geomorphologists when investigating river regimes and sediment transport capabilities. However, median size sediment is generally associated with average flows and channel equilibrium situations. It has been demonstrated that the effective fan building discharges are, in fact, associated with peak flow events and, as such, represent above average flows and greater stream competence. Consequently the QD_{90} effective fan building discharge was employed as an independent variable representing the hydrological subsystem in the theoretical multiple regression-correlation model.

Problems associated with the estimation of QD_{90} suggest that a QD_{75} effective fan building discharge is also a valid hydrological parameter.

6:6:3 Discharge Frequency and Recurrence Intervals

An argument has been put forward suggesting that the primary fan building discharges are directly related to peak flow events. Furthermore, it is not only the magnitude of such events which is significant to fan aggradation but also the frequency of these floodings. This postulated flood magnitude, frequency and fan aggradation relationship is particularly important for drainage ditch design and drainage ditch maintenance programmes.

Since the discharges of most watersheds comprising the study area are not monitored and since the standard methodology for determining regional flood frequency curves (i.e., Durrant and Blackwell, 1959) is not advisable for small watersheds, a different methodology was used. This methodology employed the natural analogue model, the available daily discharge data for the five monitored watersheds, and the concept of a unit area flood discharge. Unit area annual flood frequency curves were plotted and examined. Birnie Creek and Pelican

Creek data were not considered in this model as the period of record is less than ten years. McKinnon Creek data were also rejected for the following reasons:

i. approximately one half the drainage basin is non-contributing drainage area;

ii. bankfull discharges are not usually recorded at the gauging station due to overtopping upstream; and

iii. the annual floods recorded are not the same peak flow events measured on the other creeks.

A regional (mean) unit area annual flood frequency curve was then derived for the small watersheds comprising the Riding Mountain study area (Figure 34).

The Riding Mountain alluvial apron is constructed by specific fan building discharges which are not necessarily restricted to the annual recorded flood. In fact, the effective fan building discharges often occur several times each year. For this reason a full series flood frequency analysis of the Scott, McKinnon, Wilson and Birnie Creek records was undertaken. The peak discharges were standardized into unit area discharges, and unit area flood frequency curves were derived (Figure 37). Scott Creek and Wilson Creek data were also employed to derive a regional full series unit area flood frequency curve (Figure 38).

6:6:4 Multicollinearity in the Multiple Regression Model

Table 19 presented a zero order correlation matrix of basin area, fan slope and various discharge parameters. Since fan slope is highly correlated with both drainage basin area (r = -0.89) and effective fan building discharge (for QD_{90}, r = -0.81), and since basin area and effective fan building discharge are also highly correlated (for QD_{90},

$r = 0.80$) an obvious problem of multicollinearity exists in the proposed multiple regression model,

$$\lambda = cA^{n} \cdot QD^{m}.$$

The effective fan building discharges were standardized to unit area effective fan building discharges (QD/A) so as to reduce their dependency on basin area. Since the simple correlation coefficients remained high (for QD_{90}/A vs A, $r = -0.80$), further control over the independent variable (basin area) was required. This was achieved by employing stepwise multiple regression procedures.

6:7 Simple Hydrometric/Fan Slope Relationships

The fan slope-unit area effective fan building discharge relationship is mathematically modelled as the power function, $\lambda = c(QD/A)^{n}$, where the fan slope increases exponentially as QD/A increases in magnitude.

A comparative evaluation of the regression constants (c) for the QD_{90}/A and QD_{75}/A models indicates that the fan slope decreases as the D value (grain size) decreases and this suggests that fan slope is very much dependent on the size of the sediment transported by the hydrological system.

The relatively low values derived for the exponent (n) imply that there is a moderate positive increase in fan slope as the unit area effective fan building discharge increases. This was not unexpected however, as the unit area effective fan building discharge is negatively correlated with drainage basin area. Therefore, a low absolute discharge (Q) derived from a small drainage basin area becomes a high QD/A and is associated with steep alluvial fan gradients. Conversely, low unit area effective fan building discharges (QD/A) are generated by large watersheds and result in high absolute discharges (Q) and consequently gentle fan slopes.

The correlation coefficients associated with these equations also support the hypothesis that unit area effective fan building discharges are in fact moderately correlated with alluvial fan slopes ($r = 0.61$ for QD_{90}/A). Furthermore, the coefficients of determination imply that variation in unit area effective fan building discharges may explain 37%-50% of the variation in the alluvial fan slopes on the Riding Mountain alluvial apron.

6:8:0 Composite Morphometric and Hydrometric Relationships

By applying stepwise multiple regression procedures to the two independent variables, basin area (A) and unit area effective fan building discharge (QD/A), and the dependent variable, fan slope (λ), one can produce the multiple regression model,

$$\lambda = cA^{n} \cdot (QD/A)^{m}.$$

The QD_{90}/A (extreme event) and the QD_{75}/A (peak flow) models were derived and examined individually. Both multiple regression models support the theoretical power function relationship between fan slope and drainage basin area, and generally establish a similar relationship between fan slope and unit area effective fan building discharge. However, the extreme event model leaves 18.3% of fan slope variance unexplained while the peak flow model has 19.9% unexplained variance in fan slope. For this reason the extreme event model,

$$\lambda = cA^{n} \cdot (QD_{90}/A)^{m},$$

is considered to be a slightly better predictor of alluvial fan slopes in the Riding Mountain area.

6:8:0 Extension of the Small Sample Model

The inferential reliability and statistical validity of this extreme event model was improved by increasing the sample size to include several larger and well defined watershed-fan systems in the study area. The stepwise multiple regression procedure was again employed. By forcing the independent variable, basin area, into the multiple regression equation in step one and standardizing the effective fan building discharge variable in terms of unit area, the collinearity between the variables may be controlled (Hauser, 1974, 156).

The resulting function,

$$\lambda = 2.01A^{-0.291} \cdot (QD_{90}/A)^{-0.085},$$

represents a negatively sloping plane and is described as the Riding Mountain Regional Model.

The resulting regression constant, c = 2.01, represents the fan slope produced by a unit area effective fan building discharge of 1 cfs derived from a 1 square mile drainage basin and may be considered as a practical upper bound for the fan slopes generated by QD_{90}/A discharges in the Riding Mountain area. Since no alluvial fan in the study region has an operationally defined fan slope of greater than 1.83 degrees, the empirical evidence supports the regional model's theoretical upper bound.

The exponents, n = -0.291 and m = -0.085, derived for the two independent variables, are indicative of the rate of alluvial fan slope variation as a response to increases in both basin area and unit area effective fan building discharge. These negative exponents imply the following geomorphic relationships:

i. large discharges associated with large watersheds are capable of transporting sediment loads farther down the fan slope, consequently building expansive alluvial fans with gentle gradients; and

ii. large watersheds supply less sediment per unit area than smaller watersheds. Hooke (1968) suggests that a geomorphic relationship of this type would result in a reduction of the depositional area/erosion area ratio, generally restricting the maximum possible fan slope and, in effect, producing gentle fan gradients.

By forcing basin area (A) into the multiple regression in step one, the multiple correlation coefficient (r) equals 0.933 and demonstrates that variation in basin area accounts for 87.0% of the variance in fan slope. Step two entered the unit area effective fan building discharge independent variable (QD_{90}/A) and increased the multiple correlation coefficient to 0.939. The coefficient of determination consequently rose to 0.883 or 88.3%, indicating that an additional 1.3% variance was explained by this second independent variable.

The remaining 11.7% variance in fan slope which is unexplained by the regional model must be attributed to additional parameters within the weathering system (sediment production per unit area), the sediment transport system (channel sediment storage potential) and their interrelationships with the watershed morphology and hydrology.

6:9 Conclusions

This investigation of the various morphometric and hydrometric components and their respective systematic linkages, considered to be representative of the alluvial fan geomorphic system in the Riding Mountain study area, has produced several significant academic and socio-economic conclusions:

1. The watershed-fan geomorphic systems in the Riding Mountain area are considered to be in a state of geomorphic equilibrium.

This conclusion has several socio-economic implications with respect to the municipal drainage projects associated with these geomorphic systems. The drainage ditch projects permit significant downstream migration of the loci of deposition resulting in fan head channel entrenchment and increased channel sediment storage potential. These primary responses to the imposed short term geomorphic disequilibrium result in several secondary responses:

i. downslope extension of fan sedimentation and a general shift in the flood hazard areas from the escarpment face-fan apex region to the edge of the alluvial apron;

ii. an over all reduction in the frequency of flooding; and

iii. a significant increase in the magnitudes of sediment yield associated with the high discharge floods having a recurrence interval greater than 10 years.

These secondary responses result in periodic flooding and alluvial fan aggradation in areas previously unaccustomed to such economically severe hazards.

2. The alluvial fan aggradation is a systematic response to a sequence of various discharge magnitudes and their associated frequency of occurrence.

The socio-economic implication of this conclusion focuses on the uncertainty involved in drainage ditch design and channel maintenance schemes. Until further research into the frequencies and sequences of the various effective fan building discharges is undertaken, drainage channel design and maintenance must remain conservative.

3. The alluvial fan geomorphic system operating in the Riding Mountain region may be mathematically modelled as $\lambda = 2.01\ A^{-0.291} \cdot (QD_{90}/A)^{-0.085}$. This empirical model attempts to incorporate Ryder's (1971a) partial synthetic systems model by collapsing the basin morphology and stream hydrology variables into two independent variables A and QD_{90}/A and then establishing an empirical relationship with the fan physiographic parameter, slope (λ). In effect this approach expands Ryder's systems concept by incorporating several highly correlated variables which were not previously considered in the systems model. This revised theoretical partial synthetic systems model is presented in Figure 39.

The derivation of the Riding Mountain regional model,

$$\lambda = 2.01\ A^{-0.291} \cdot (QD_{90}/A)^{-0.085},$$

has established several geomorphic certainties:

i. The specific alluvial fans and the composite alluvial apron of the Riding Mountain region are in a state of dynamic equilibrium.

ii. The basin area appears to be the dominant independent variable comprising the alluvial fan geomorphic system and accounts for 87.0% of the variation in fan physiography.

iii. The effective fan building discharge associated with the fluvial transport of 90% of the channel sediment (the extreme event discharge) is less significant for fan aggradation than expected.

iv. The various effective fan building discharges are highly correlated with basin area.

If this basin area-effective fan building discharge

A REFINED PARTIAL SYNTHETIC SYSTEM MODEL OF THE ALLUVIAL FAN GEOMORPHIC SYSTEM

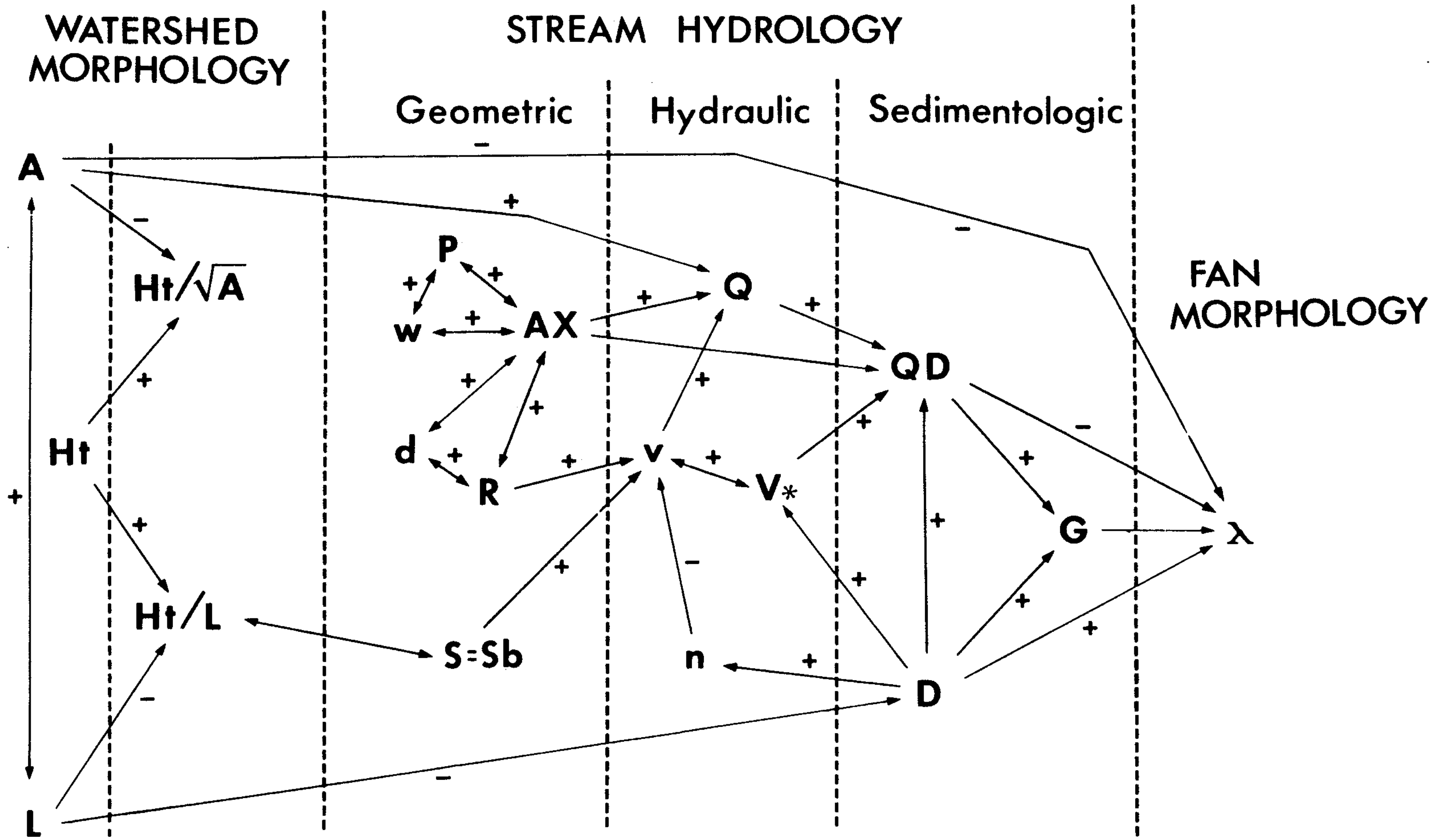


Figure 39

correlation is considered jointly with the previous conclusion, that alluvial fan aggradation is a systematic response to a sequence of various discharges, the relatively low explanatory power attributed to the extreme event discharge variable is not unexpected. In other words, the extreme event discharge (QD_{90}) represents one of several discharges comprising the critical sequence of fan building discharges and consequently accounts for only a part of the total explanatory power attributed to the effective fan building discharge variables.

v. The empirical model derived for the Riding Mountain study area,

$$\lambda = 2.01\ A^{-0.291} \cdot (QD_{90}/A)^{-0.085},$$

is statistically reliable, valid and considered significant at the 99% confidence level.

6:10 Concluding Statement

The accumulation of alluvial fan deposits is a function of the interaction among the components of a weathering subsystem and a climatic-meteorologic subsystem as they operate on a watershed morphometry. The resulting material inputs are transferred along the geomorphic energy gradient via the stream hydrology subsystem to the alluvial fan.

This dissertation has investigated the empirical relationships between key components defining this watershed morphometry and stream hydrology, and the parameters representing the alluvial fan. However, the partial synthetic systems procedures employed in this work necessitate the exclusion of several subsystems and numerous components.

Consequently this dissertation emphasizes several areas for further research:

i. studies are needed to investigate the interrelationships between the climatic-meteorologic subsystem and the geologic-topographic subsystem with respect to the weathering of shale and production of sediment;

ii. further research is required into the sediment transport capabilities of overland flow and its significance to channel sediment storage;

iii. additional information is required regarding the interrelationships between stream flow, channel bed morphology and the shale sediment transport subsystem;

iv. a statistical analysis is also needed in order to determine the critical sequences and frequencies of effective fan building discharges for fan aggradation; and

v. additional work is also required regarding the characteristics of alluvial fan sediments and the stratigraphic implications of these Holocene deposits.

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APPENDIX I

SOME PHYSICAL CHARACTERISTICS

OF THE GEOLOGICAL MEMBERS

FOUND IN THE RIDING MOUNTAIN AREA

SOME PHYSICAL CHARACTERISTICS OF THE GEOLOGICAL MEMBERS FOUND IN THE RIDING MOUNTAIN AREA

<u>Lower Ashville Member</u>

dark grey shale
clayey texture
breaks into chunks

<u>Upper Ashville Member</u>

greasy black shale
weathers to a brownish colour
breaks into flat chips

<u>Keld beds</u>

dark grey speckled shale
slightly calcareous
minor amounts of bentonite
upper foot is grey limestone with fossils

<u>Assiniboine beds</u>

dark grey speckled shale
calcareous
minor amounts of bentonite
contains numerous limestone beds with fossils
thin
weathers buff

<u>Morden Member</u>

dark grey to black carbonaceous shale
calcareous concretions up to 6 feet in diameter
yellow coating on exposures

<u>Boyne Member</u>

upper part of this member is missing in Riding Mountain area
lower part is a dark grey carbonaceous shale
calcareous
some white specks
numerous thin bentonite bands

<u>Gammon Ferruginous Member</u>

this member is speculative in the Riding Mountain area

Pembina Member

lower - interbedded yellow non-swelling bentonite and black carbonaceous shale

upper - brown wavy carbonaceous shale

Millwood Member

greenish-brown bentonitic shale
"popcorn" weathered surface
ironstone and calcite concretions occurs in layers
thin bands of olive green bentonite near upper contact

Odanah Member

variations in clay content create a hard and soft Odanah shale. The Riding Mountain Odanah shale is described here.
grey siliceous shale
greenish grey when moist
jointed - joints stained reddish to purplish brown
ironstone concretions are common
thin beds of bentonite in lower part
Riding Mountain Odanah Shales have higher absorption rates and air dry shrinkage rates 4% - 8%

APPENDIX II

ELSON'S (1967) SUMMARY

OF THE HISTORY OF GLACIAL LAKE AGASSIZ

ELSON'S (1967) SUMMARY OF THE HISTORY OF GLACIAL LAKE AGASSIZ

Elson (1967) summarizes the history of glacial Lake Agassiz as follows:

1. As the ice melted and retreated, the Herman phase of Lake Agassiz rapidly expanded northward until the ice paused at, or readvanced to the Darlingford-Edinburg-Erskine morainic positions. Stabilization of the southern Lake Traverse outlet coupled with differential glacio-istatic uplift resulted in a series of Herman strandlines along the Manitoba Escarpment. Increased discharge gradually eroded the Lake Traverse outlet and consequently, lake levels lowered to the Norcross level.
2. Further glacial retreat opened the Dog River Spillway in North-western Ontario dropping lake levels to about the Tintah stage.
3. A readvance to the Dog Lake morainic position blocked the Dog River Spillway and again brought lake levels to the Norcross stage.
4. Erosion of the Lake Traverse outlet continued until stabilized by a boulder pavement resulting in the Tintah stage strandline.
5. Accelerated melting increased the discharge through the Lake Traverse outlet. The spillway eroded to a bedrock sill which maintained Lake Agassiz water levels at the Campbell stage.
6. As glacial recession continued and the Northwestern Ontario outlets opened the lake levels dropped in a series of steps to about the Burnside level.

7. A major readvance closed the eastern outlets north of the Kaiashk Spillway and briefly brought lake levels up to the McCalleyville level.

8. Continued readvance to the Hartman-Kaiashk and Marks morainic position accounts for the closing of the Kaiashk outlet and raising lake levels to the lower Campbell stage. This phase of Lake Agassiz history is believed to have lasted between 200 and 500 years.

9. Northward retreat of the ice margin reopened the eastern outlets and consequently, lake levels dropped in a steplike series to the Pipun stage.

10,11
& 12. Cochrane readvance accounts for a brief rise in Lake Agassiz levels as the ice sheet disintegrated in Hudson Bay.

APPENDIX III

A REVIEW OF ERROR THEORY AND THE CLASSIFICATION OF ERROR

Error Theory and the Classification of Error

Introduction:

Measurement, as defined by Stevens (1946), is the process of assigning a numerical value (an estimate) to some quality of an object (a parameter) in accordance with definite rules (the operational definition). This definition of measurement - an estimate or assigned numerical value - implies that a true or target value exists. The difference between the true value Xo and the estimate Xi is defined as the exact error ei (Shchigolev, 1960).

A. Classification of Error

Invariably, each scientific discipline has attempted to classify or group the types of measurement error occurring in its respective research field. Although minor differences are found in these classifications (see for example Topping, 1972; Krumbein and Graybill, 1965) it is generally accepted that four factors account for most measurement error.

1. Errors Associated with the Observer.

Observer error is often subdivided into accidental or gross error (Krumbein *et al.*, 1965) and operator bias. Accidental error is the result of an incorrect measurement due to the carelessness or inattentiveness of the observer. It may occur during the initial adjustment of the measuring instrument, during the measuring process, or during the reading and recording of the measurement. Accidental error seldom occurs and varies randomly in magnitude (Krumbein *et al.*, 1965). Verification (where possible) of each measurement by a second measurement effectively eliminates accidental error.

Operator bias is consistant in that it exists to some degree in each measurement; however, it cannot be considered a constant. Like accidental error, operator bias may and usually occurs in the three steps of the measurement procedure. Consider, for example, the measuring of a drainage basin area. Operator bias may occur in the initial setting of the planimeter wheel at zero. The operator may be viewing the scale at an angle and therefore, slightly over-estimate or under-estimate the initial setting. Secondly, variation will result if the operator traces the basin perimeter in a "jerky" fashion as opposed to a smooth continuous motion. Lastly, operator bias may result if, on reading the final setting of the planimeter wheel, the operator again views the scale at an angle.

Although it may be argued that individual operator bias can be considered a constant for any specific measurement procedure and therefore, relatively insignificant in magnitude; when more than one operator is employed, individual measurements of identical parameters may reveal significant variation.

Operator bias may be minimized by employing only one operator and instructing him thoroughly in the measurement procedure. If several operators are required, the measurement procedure must demonstrate that no significant difference in operator bias exists. This method has in fact been tested by Griffiths and Rosenfeld (1954), Chorley (1958), and Thornes and Hewitt(1967). All three studies indicated favourable minimization of operator bias.

2. Error Associated with the Instrument

The utilization of an instrument for assigning a numerical value to a given parameter is fundamental to all objective measurement. Each instrument, no matter how finely calibrated, has a physical limitation for measurement known as the threshold of sensitivity.

The absolute threshold of sensitivity is defined as the smallest change which can be registered by the instrument (Shchigolev, 1960). Consider, for example, the determination of the straight line distance between two points A-B. The instrument of measurement is a rule calibrated in centimeters. The absolute threshold of sensitivity is therefore, one centimeter. If each centimeter is subdivided into millimeters, the absolute threshold of sensitivity becomes 0.1 centimeters.

Often, observers are able to extend the absolute threshold of sensitivity by "rounding off" the measured value. The result is known as the rounded off threshold of sensitivity and is defined as one half the absolute threshold of sensitivity (Shchigolev, 1960). Consider the aforementioned example: a rule subdivided into centimeters which are subdivided into millimeters; the absolute threshold of sensitivity is 0.1 cm. the rounded off threshold of sensitivity is therefore $1/2 \cdot 0.1$ cm. or 0.05 cm.

In geomorphology, as well as other disciplines, measurements are often made on a 'hardware model' (Chorley and Haggett, 1969) of the real parameter. If this is the case, the threshold of sensitivity is subject to alteration depending on the scale of the model. The previous mentioned points A and B are found on a map at a scale 1:50,000. The rounded off threshold of sensitivity on the rule is 0.05 cm. Therefore, the true rounded off threshold of sensitivity for the measure of length is 0.05 x 50,000 or 2.5 meters. A calculation of this type assumes no external error, i.e. error in the scale of the model and observer error.

Alteration of the instrument calibration due to mechanical fatigue will produce systematic instrument error. Depending on the mechanism of the measuring instrument, these systematic errors may be increasing, decreasing, or constant. Repetitive measurement of a standard known parameter at various time periods during the study acts as a control on this type of instrument error.

3. Error of Method.

Methodological error is primarily associated with subjective interpretations of the operational definition. This may take place during the formulation of the operational definition. As an example, consider fan slope. An operational definition of fan slope may be the rise divided by the run where this ratio is the differences in height/length at the fan apex and the edge of the fan(Bull,1962). A second operational definition might consider a part of this gradient as representative of the fan slope (eg. Melton,1965 and Ryder,1971a). Both operational definitions are believed functional, yet they cannot be expected to yield identical estimates of the fan slope.

Subjective interpretations of the operational definition may also occur during the measurement procedure. For example, the measuring of an A axis of a rock (operationally defined as the length of the longest axis of the rock in any plane) involves more than the simple application of a rule. The operational definition leaves little doubt as to what an A axis is; however, strict adherence to this operational definition during the measurement procedure is often difficult due to the numerous variations in rock shape. Thus, a subjective interpretation of the operational definition is required for each measurement. This may result in considerable method error.

4. Random Error

If all sources of error are absent or controlled, fluxuations in repeatedly measured values will still occur (Krumbein et al., 1965). This unpredictable error, described as random or stocastic error, is believed to be the result of a large number of relatively small deviations caused by independent variables (Laplace). As a result, attempts to control random error are futile. However, a body of knowledge and theory has evolved since the early studies of Laplace and Gauss which enables researchers to deal statistically with this type of error (see error theory).

Grouping of Error

A. Compensating Error

Compensating error may be defined as error which, in the long run, tends to balance out. That is to say, the positive deviations from the true value equal the negative deviations (Wilson, 1952). Gross observer error and random error are believed to fall into this grouping.

B. Non-compensating Error

Errors which continually over-estimate or under-estimate the true or "target" (Krumbein et al., 1965) value are grouped as non-compensating error (Wilson, 1952). Operator bias, instrument error, and method error are generally considered to be in this group.

Error Theory

Introduction

As indicated above, strict controls on the operational definition, the observer, and the instrument will effectively reduce most non-compensating error to a significantly small amount - often infinitesimal.

However, random error cannot be avoided.

As early as 1783, mathematicians began investigating random error. Laplace theoretically deduced the normal law of error stating that the deviations of any set of measurements from the mean of that set is the result of a large number of small deviations due to independent causes, and in addition, these positive and negative deviations are equally probable. Gauss proposed a proof based on the assumption that the arithmetic mean is the most probable value of any one set of measurements. However, Pearson, in 1901, demonstrated that some sets of measurements deviated from this normal law. Jefferies (1938) has substantiated Pearson's findings. As a result, today it is generally agreed that not all sets of observations satisfy the normal law of error.

A large body of statistical methods has been built around the assumption of a normal distribution of error. Since error distribution in many types of observation is closely approximated by the normal distribution function, this function is widely used unless there is evidence to show that a different probability distribution function applies. The Chi Square test may be employed to establish whether the probability distribution of a given set of observations is normal or non-normal.

<u>Relative and Absolute Error</u>

If a true quantity Xo units is measured and recorded to be Xi units, the difference Xo - Xi is called the <u>error in Xo</u> (usually denoted as ei). The error, ei, is more commonly called the <u>exact</u> or <u>absolute error</u> (Topping, 1972).

Assuming the absolute value of ei is very much smaller than the absolute value of Xo, that is $|ei| \ll |Xo|$ one may write;

$$Xi = Xo + ei$$

or

$$Xi = Xo(1 + fi)$$

where

$$fi = ei/Xo$$

fi is known as the fractional error (Topping,1972) or the relative error (Baird,1962). The more commonly quoted percentage error is simply the relative error, fi or ei/Xo, times one hundred.

When a measurement, Xi, is made on a specific parameter, the absolute error, ei in Xo, cannot usually be determined. As a result, the relative error, fi, and the percentage error are also unknown.

Generally, all that is known about ei is that it may have any value between -Ei and +Ei, where Ei is the limiting absolute error. (Shchigolev, 1960). The limiting absolute error, Ei, represents the outer limits of confidence of measurement. That is to say, the observer is almost certain (say 99% sure) that the measurement's target value Xo lies between Xi - Ei and Xi + Ei. Occasionally, the standard deviation of a sample of n measurements $\sqrt{\frac{\sum_{i=1}^{n} (Xi - \bar{X})^2}{n-1}}$ denoted as s is employed as the limits of confidence in the mean value ($\bar{X}$) and referred to as the standard error of the estimate.

The development of the above terminology leads to the distinction between accuracy and precision. Accuracy describes the closeness of Xi to the "actual" or target value of the measured parameter (Topping, 1972). Therefore, ei is a measure of accuracy. Precision indicates a measure of the closeness of a set of measurements X1, X2, ..., Xn to one another regardless of the true value of the measured parameter (Topping,1972). Relative errors fi or s are measures of precision.

The Normal Law of Error.

The deviations r1, r2, ..., rn of any finite set of measurements X1, X2, ..., Xn from the mean of the set $\bar{X}$ are the result of a large number of small deviations due to independent causes. Furthermore, it has been demonstrated that the distribution function of ri is normal (Gauss).

That is; $Fr^{(t)} \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}\sigma} e^{-(X-u)^2/2\sigma^2} dX$

or the distribution function of r for any given value t is the integral between $-\infty$ and t of $\frac{1}{\sqrt{2\pi}\sigma} e^{-(X-u)^2/2\sigma^2}$

where; π and e are constants approximately equal to 3.14 and 2.27 respectively

X is a given deviation ri

u is the mean $\bar{r}$

and σ is the standard deviation $\sqrt{\frac{\sum_{i=1}^{n} (ri - \bar{r})^2}{n}}$

The set of random errors ri, bounded by $-E$ and $+E$ are normally distributed about the mean of the errors $\frac{\sum_{i=1}^{n} ri}{n} = \bar{r}$ which is zero and has a standard deviation equal to one. The distribution function can now be simplified to;

$$Fr^{(t)} \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}} e^{-1/2\, X^2}$$

This standard normal distribution of error is a fundamental assumption for many of the more widely used statistical methods; for example, correlation, regression, and analysis of variance.

Propagation of Error

Even in the most elementary research, the required values are often computed from several different values, each independently measured and subject to random error. The arithmetic operations employed to calculate the required values also effect the limiting absolute error of these values. Unfortunately, in most geographical research, the effects of arithmetic operations on limiting absolute error are completely overlooked. A summary of the treatment of error in arithmetic compounds follows. For a better understanding and more thorough explanation of this aspect of error theory see Shchigolev 1960, Baird 1962, and Topping 1972.

Addition.

Assume X1 and X2 are measured values with limiting absolute error E1 and E2 respectively.

Consider $X1 + X2 = Z$

The error in Z can be obtained from

$$(X1 \pm E1) + (X2 \pm E2)$$

that is $X1 + X2 \pm (E1 + E2)$

Simply, the limiting absolute error of a sum is the sum of the limiting absolute errors.

The relative error will be;

$$\frac{E1 + E2}{X1 + X2}$$

Subtraction.

Consider $X1 - X2 = Z$

As in addition, the limiting absolute error of a difference is the sum of the limiting absolute errors.

That is $(X1 \pm E1) - (X2 \pm E2)$

or $X1 - X2 \pm (E1 + E2)$

However, the relative error will be;

$$\frac{E1 + E2}{X1 - X2}$$

The possibility of X1 - X2 being equal to or less than E1 + E2 and therefore resulting in a large relative error, may destroy the value of the measurement. This is an important and often unrecognized property of measurement.

Multiplication.

Suppose that X1X2 = Z

where X1 and X2 are measured values with limiting absolute errors E1 and E2 respectively. The limiting absolute error in Z is the result of

$$(X1 \pm E1)\ (X2 \pm E2)$$

taking the absolute values of the error

$$Z = X1X2 + E1X2 + E2X1 + E1E2$$

E1E2 is a second order infinitesimal and as such may be considered approximately equal to zero. Therefore the limiting absolute error of a product is;

$$X1E2 + X2E1$$

The relative error is;

$$\frac{X1E2 + X2E1}{X1X2}$$

which may be simplified to;

$$\frac{E1}{X1} + \frac{E2}{X2}$$

That is, the relative error of a product approximately equals the sum of the relative errors.

Division.

By employing slightly more complex terminology, the limiting absolute error of Z for Z = X1/X2

equals $$\frac{X2E1 - X1E2}{X2^2}$$

The relative error in Z is therefore;

$$\frac{\frac{X2E1 - X1E2}{X2^2}}{X1/X2}$$

which can be simplified to;

$$\frac{X2E1 - X1E2}{X1X2}$$

or $$\frac{E1}{X1} - \frac{E2}{X2}$$

Therefore, the relative error of a quotient approximately equals the difference of the relative errors.

Powers and Roots

Powers may be considered as a special case in multiplication. It has been demonstrated that the relative error of a product is equal to the sum of the relative errors. This implies that the relative error in a value X1 raised to the power n is equal to n times the relative error of X1. That is to say, the relative error in $Z = X1^n$

is; $$n \frac{E1}{X1}$$

Logarithmic Transformations.

The logarithmic transformation of values is a common practice in many morphometric studies (Maxwell,1960). Such transformations have interesting effects on the error associated with the values transformed.

Consider $$Z = \log X1$$

$$\frac{dZ}{dX} = \frac{1}{X1}$$

Therefore, the limiting absolute error in Z is;

$$\frac{1}{X1} \; E1$$

This is recognized to be the relative error in X1.

The relative error in Z is calculated to be;

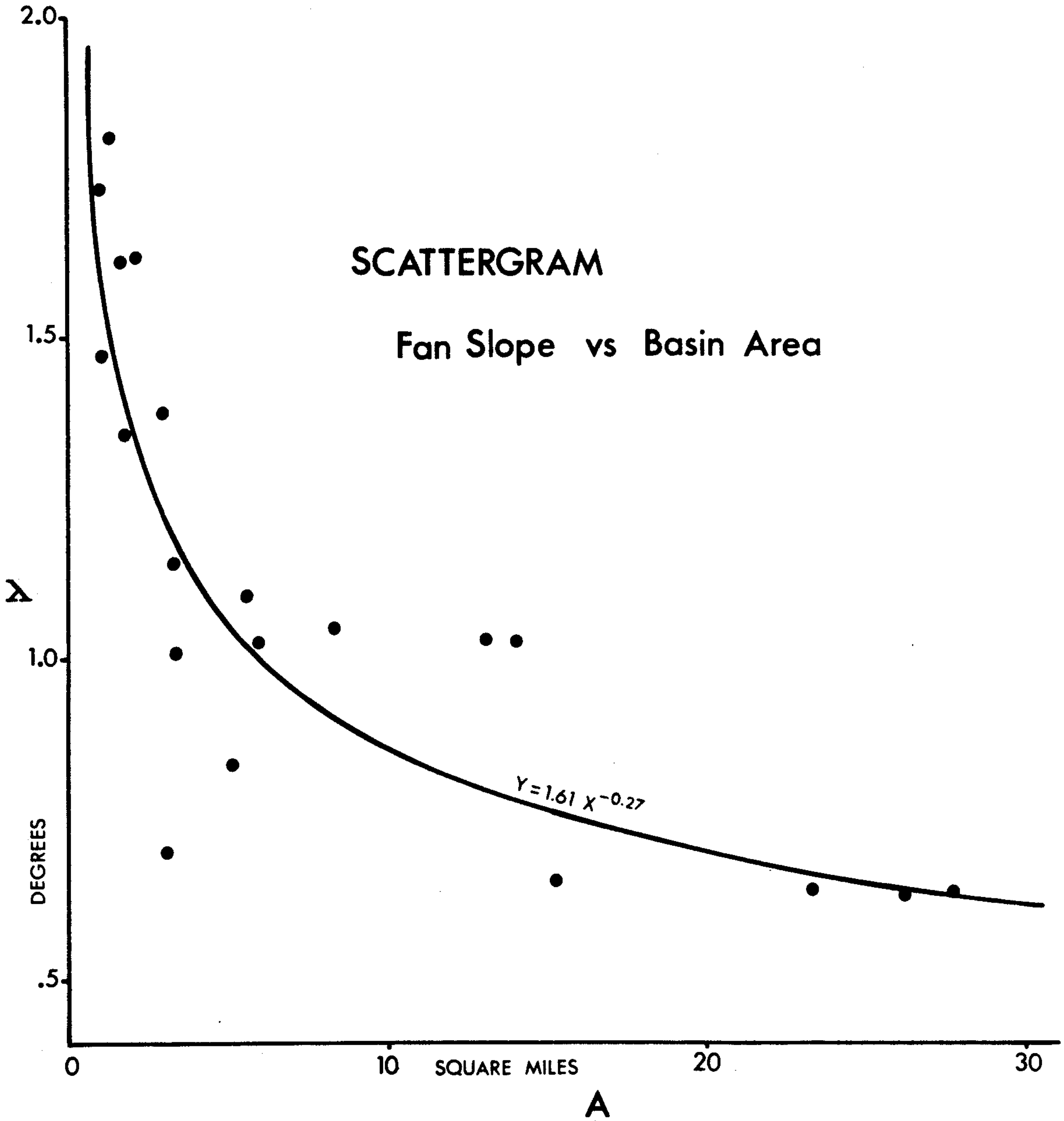
$$\frac{\frac{E1}{X1}}{\log X1} \quad \text{or} \quad \frac{E1}{X1 \log X1}$$

APPENDIX IV

MORPHOMETRIC RELATIONSHIPS

Scattergrams and Logarithmic Regression Plots.

(Text Figures 12-21)



SCATTERGRAM
Fan Slope vs Basin Area
2.0
1.5
1.0
.5
λ
DEGREES
Y=1.61 X^-0.27
0
10
SQUARE MILES
20
30
A

Figure 12

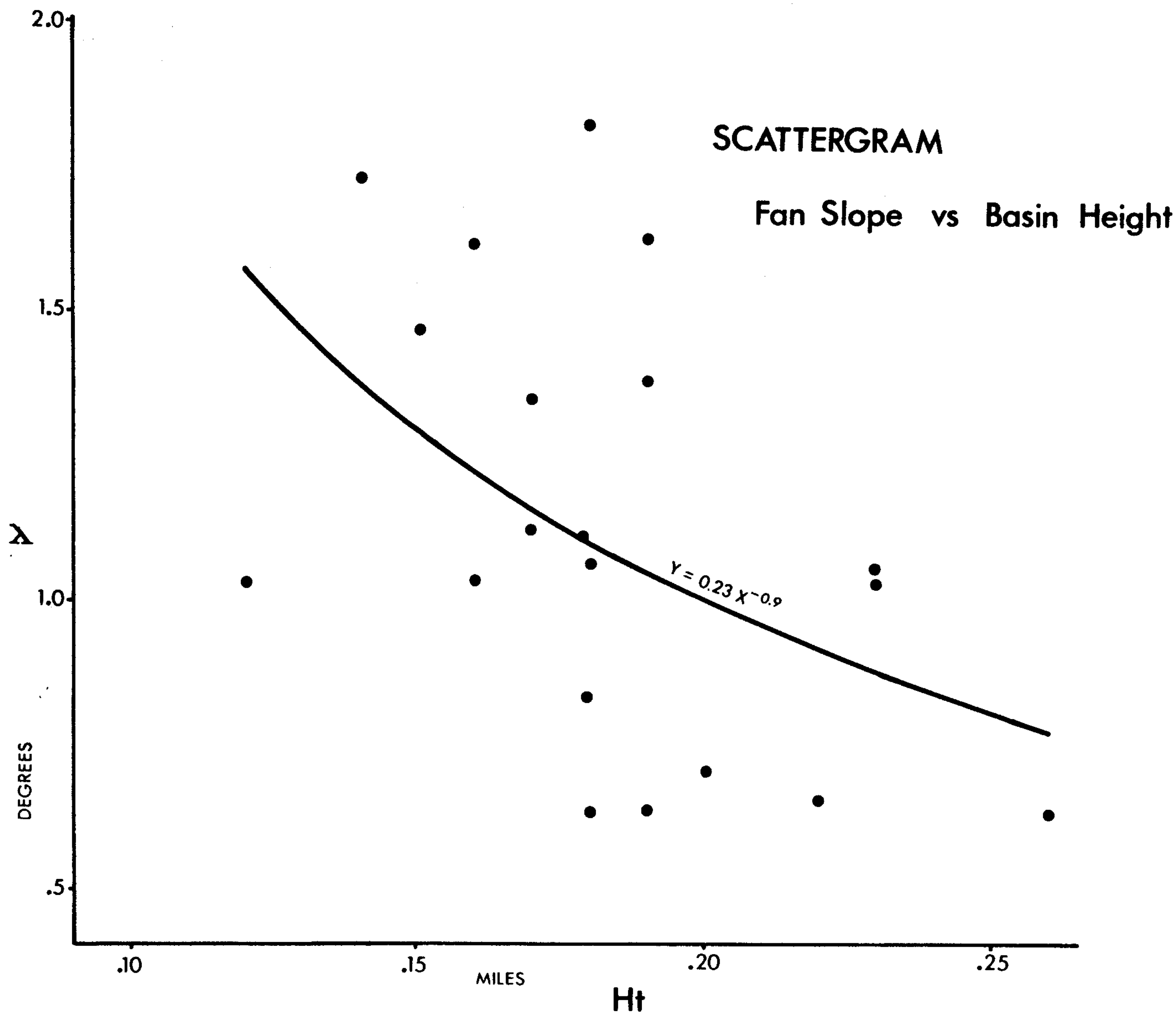

SCATTERGRAM
Fan Slope vs Basin Height
2.0
1.5
1.0
.5
λ
DEGREES
Y = 0.23 X^-0.9
.10
.15
.20
.25
MILES
Ht

Figure 13

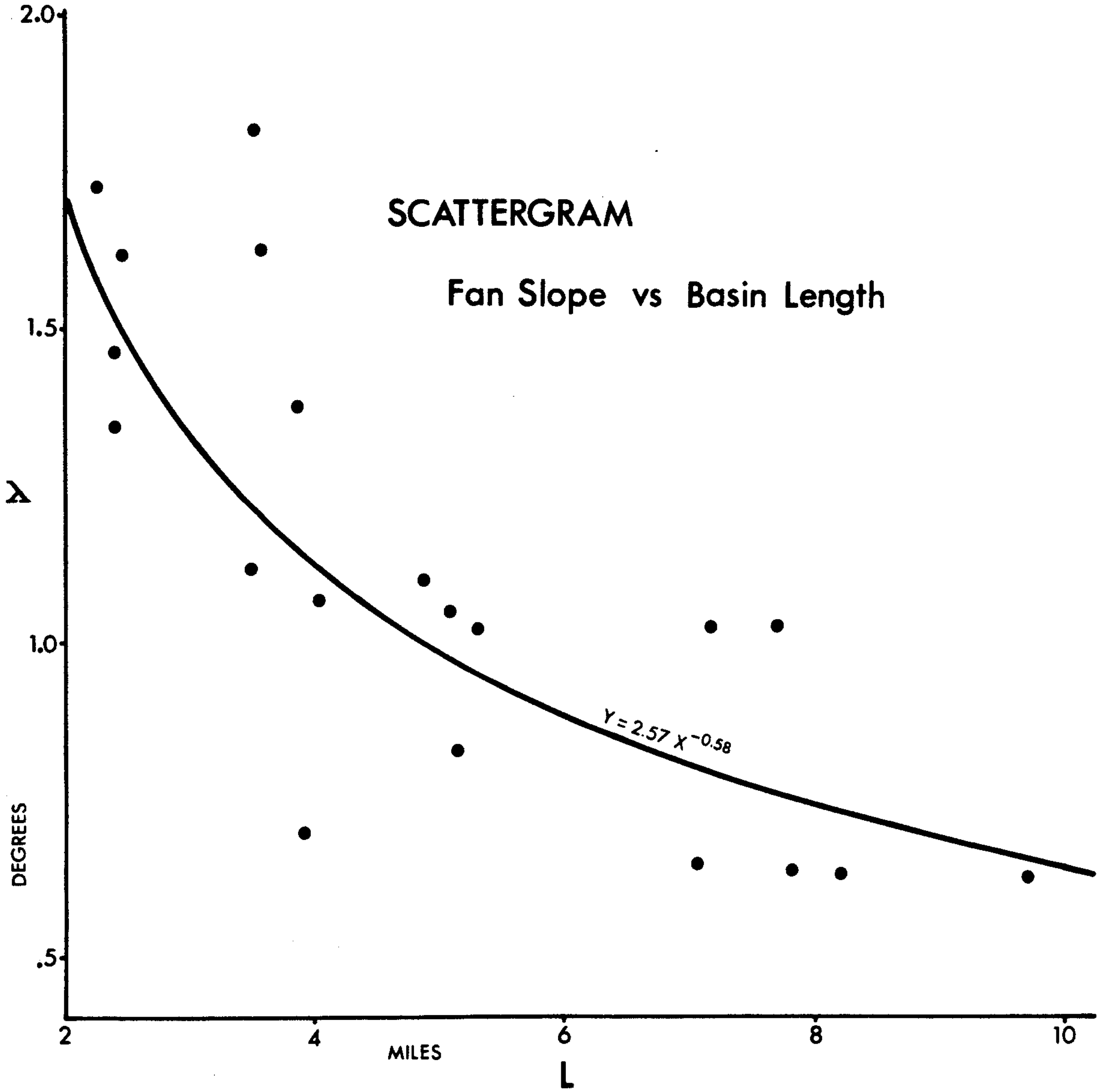

2.0
1.5
1.0
.5
λ
DEGREES
SCATTERGRAM
Fan Slope vs Basin Length
Y = 2.57 X^-0.58
2
4
6
8
10
MILES
L

Figure 14

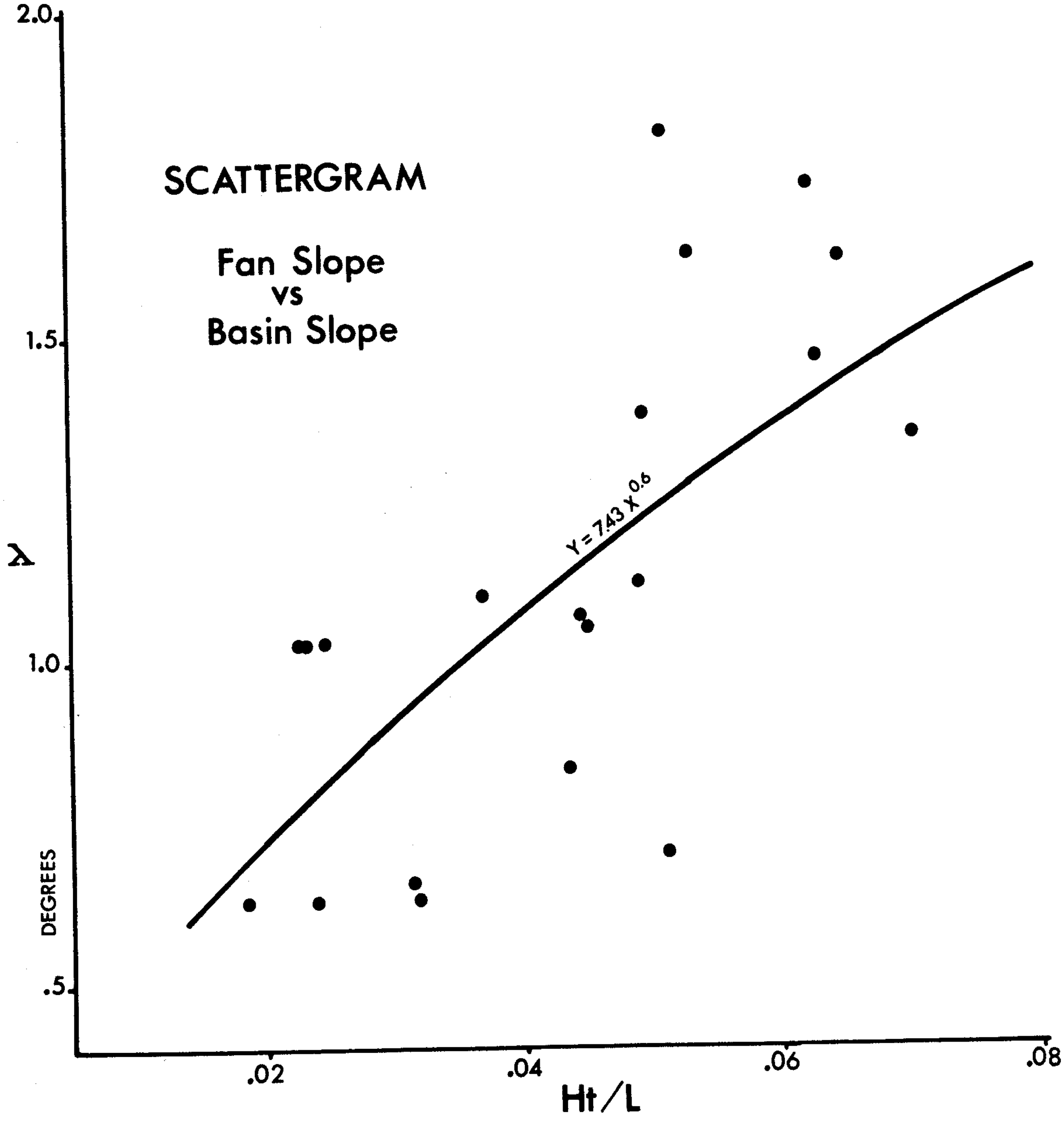
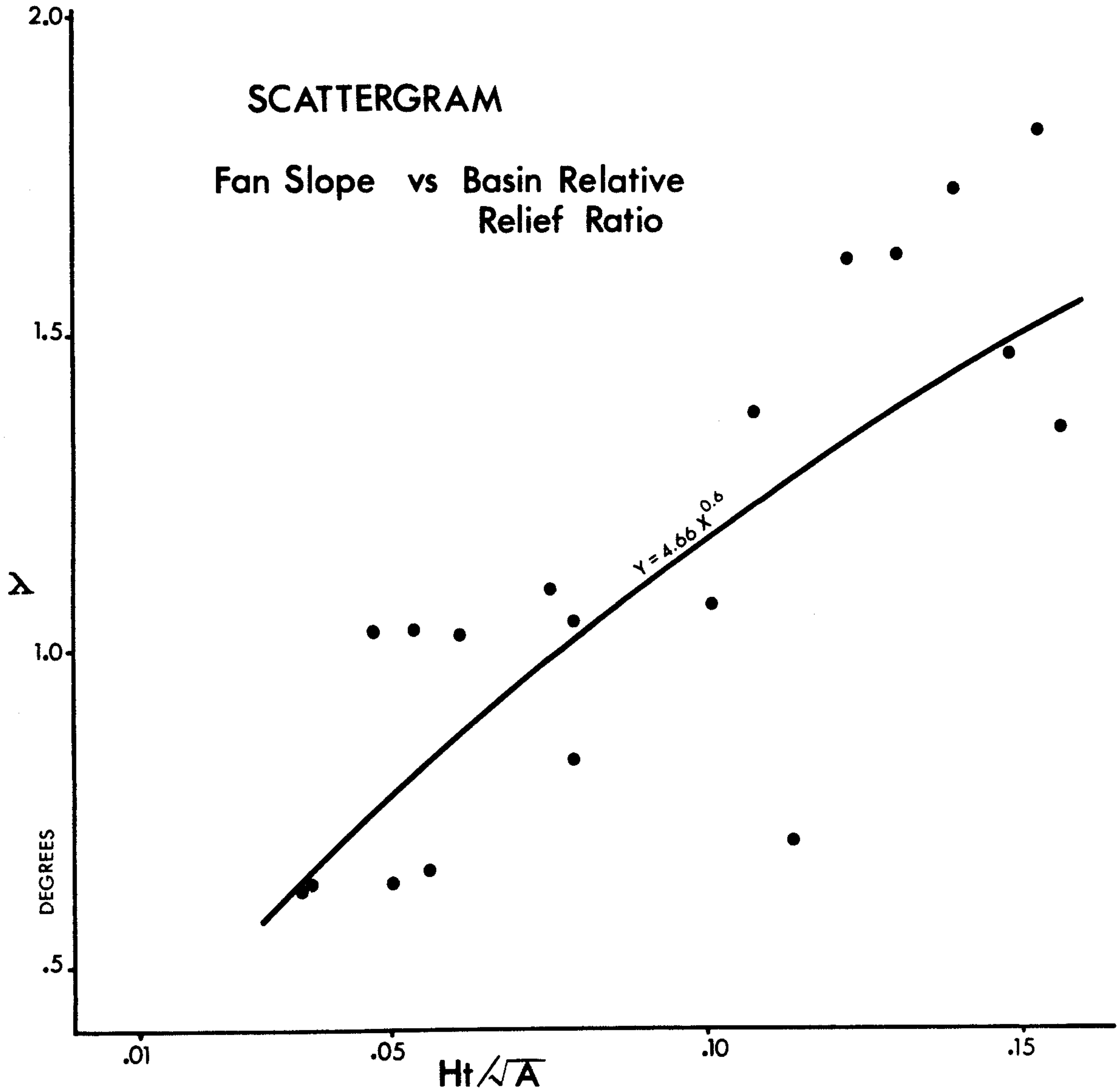

SCATTERGRAM
Fan Slope
vs
Basin Slope
2.0
1.5
1.0
.5
λ
DEGREES
Y = 7.43 X 0.6
.02
.04
.06
.08
Ht/L

Figure 15



SCATTERGRAM
Fan Slope vs Basin Relative Relief Ratio
Y = 4.66 X0.6
λ
DEGREES
2.0
1.5
1.0
.5
.01
.05
.10
.15
Ht/√A

Figure 16

LOGARITHMIC REGRESSION PLOT

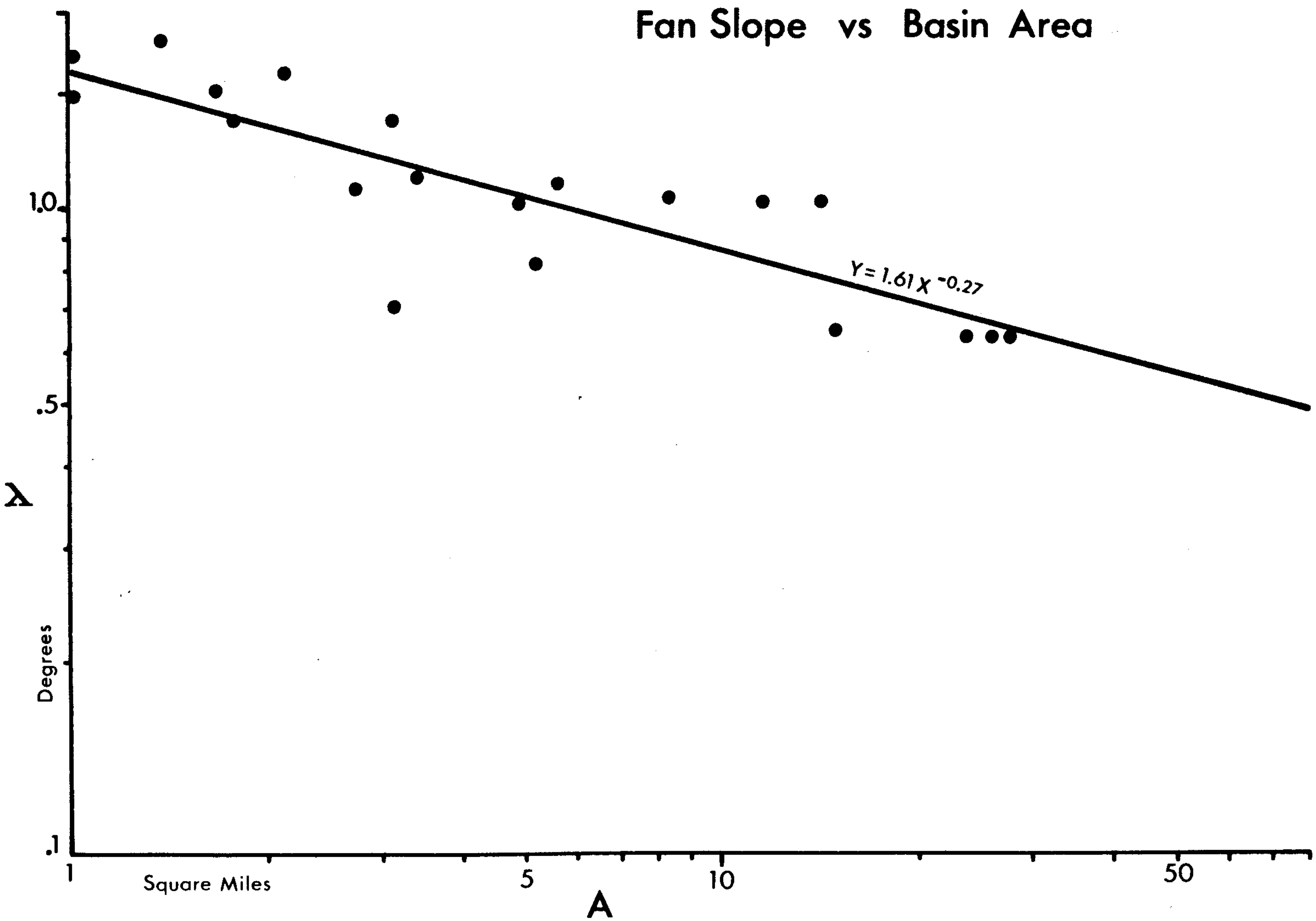
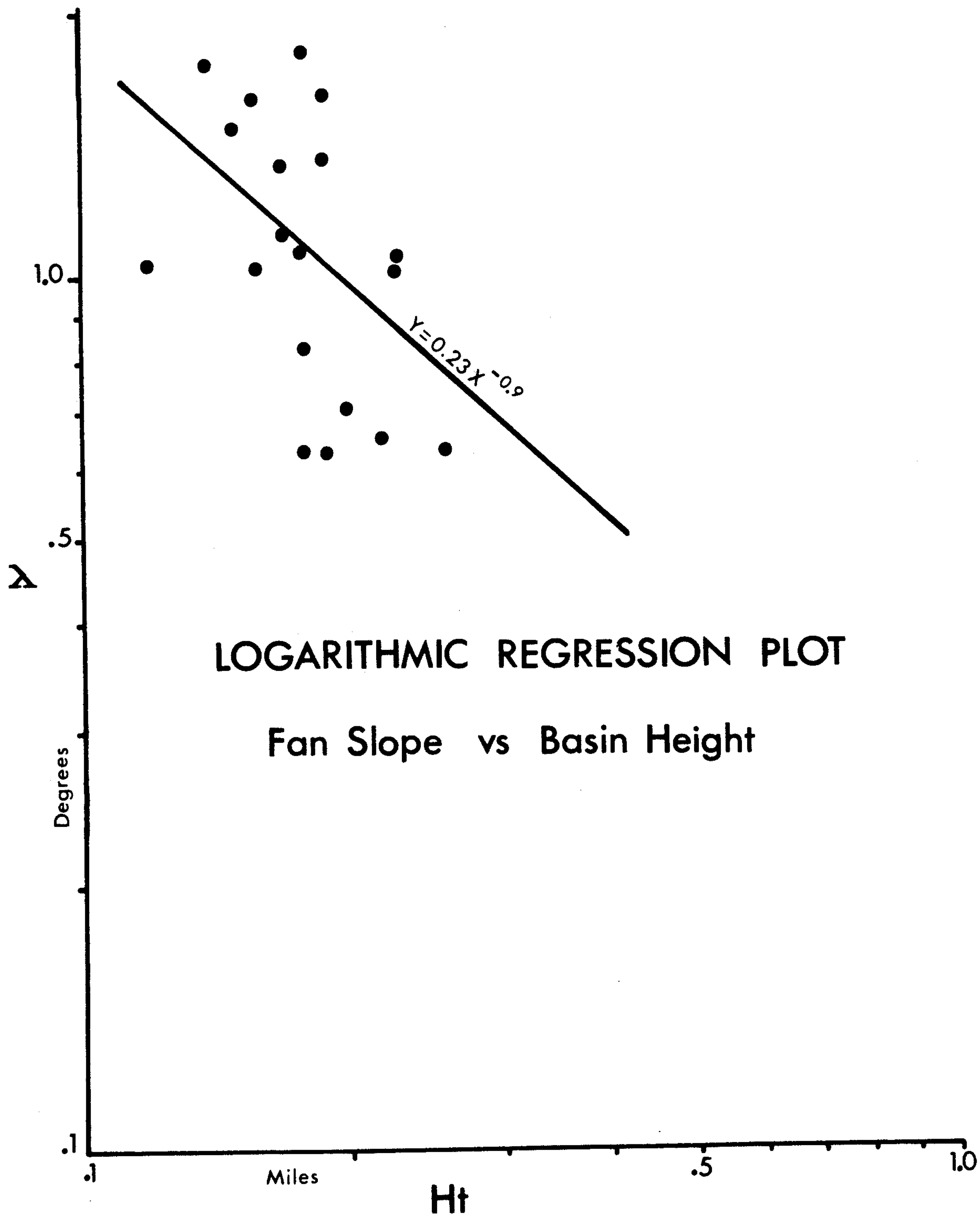


Figure 17



1.0
.5
.1
λ
Degrees
Y=0.23X^-0.9
LOGARITHMIC REGRESSION PLOT
Fan Slope vs Basin Height
.1
Miles
.5
1.0
Ht

Figure 18

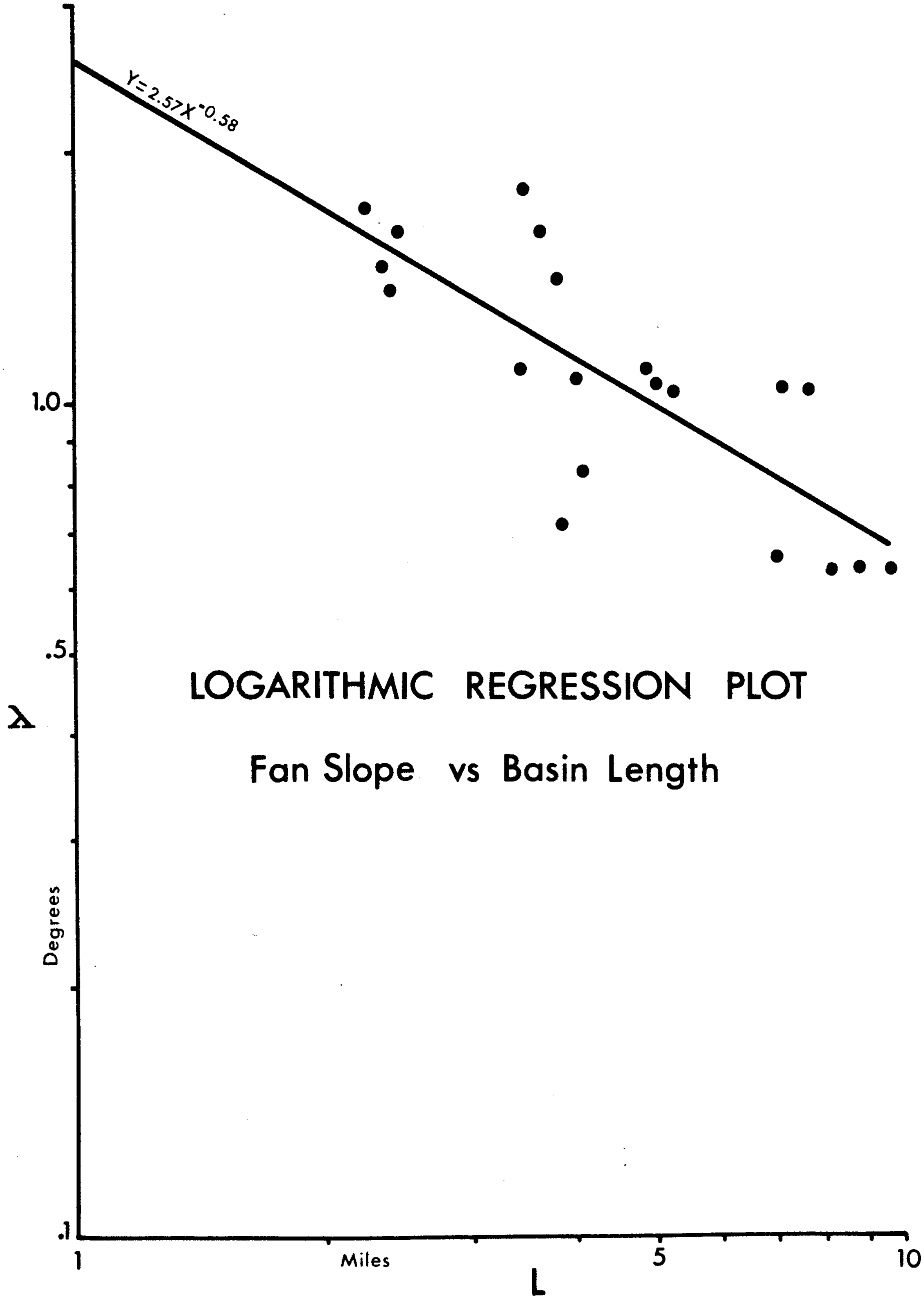

$Y = 2.57X^{-0.58}$
1.0
.5
λ
Degrees
.1
LOGARITHMIC REGRESSION PLOT
Fan Slope vs Basin Length
1
Miles
5
10
L

Figure 19

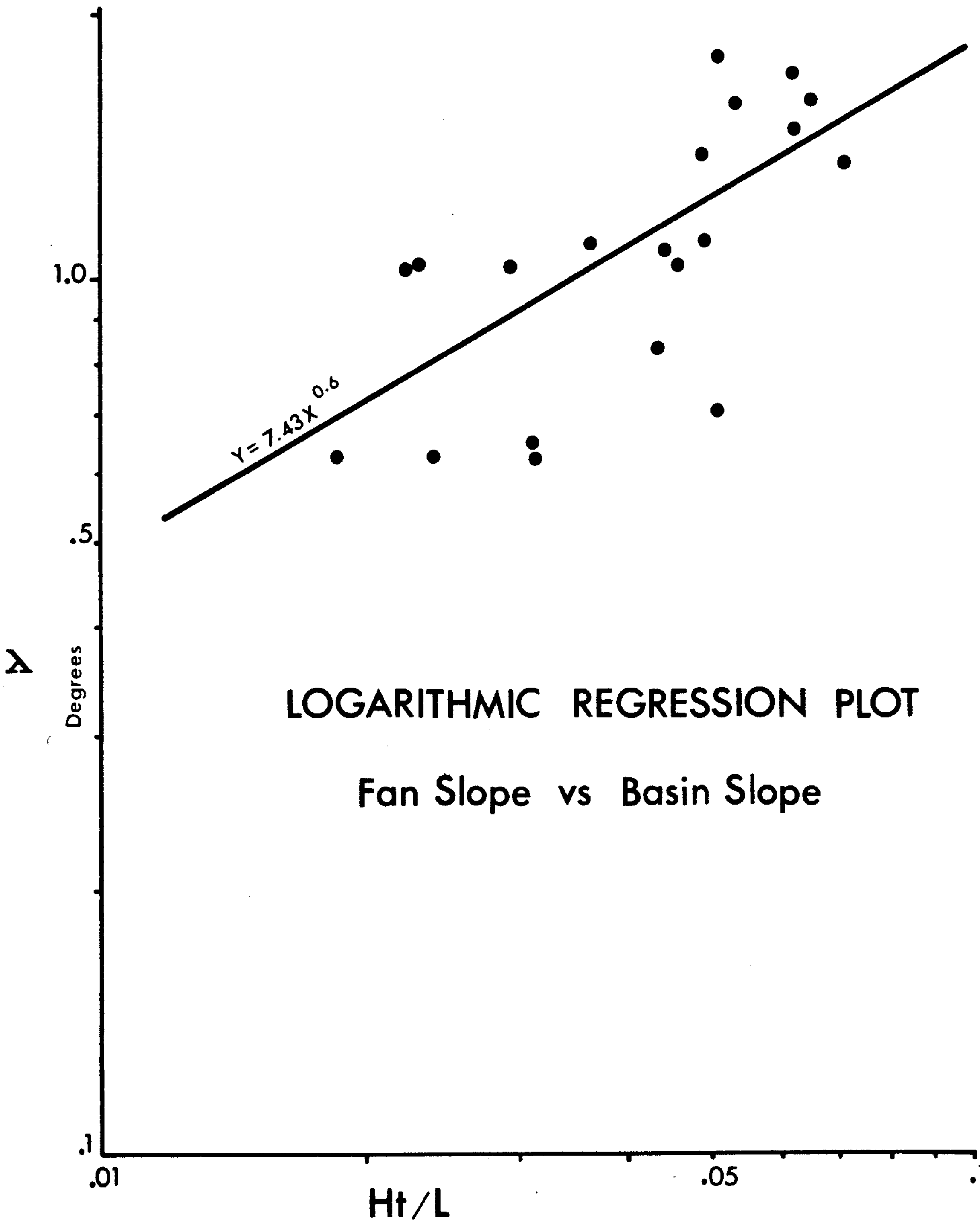

1.0
.5
.1
λ Degrees
Y = 7.43X 0.6
LOGARITHMIC REGRESSION PLOT
Fan Slope vs Basin Slope
.01
.05
.1
Ht/L

Figure 20

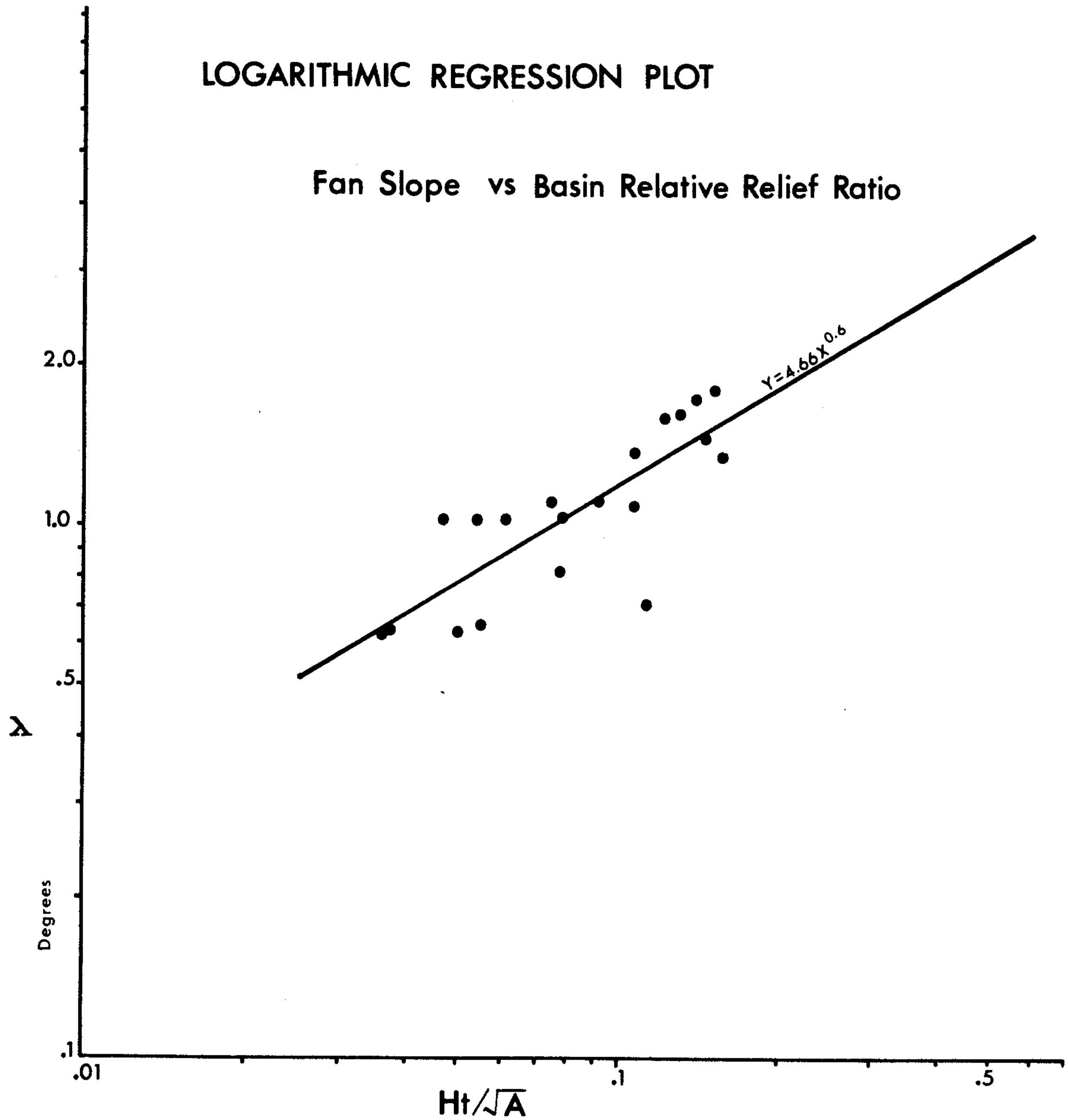

LOGARITHMIC REGRESSION PLOT
Fan Slope vs Basin Relative Relief Ratio
Y=4.66X^0.6
2.0
1.0
.5
λ
Degrees
.1
.01
.1
.5
Ht/√A

Figure 21

APPENDIX V

TEMPERATURE AND PRECIPITATION NORMALS FOR DAUPHIN AIRPORT, NEEPAWA AND RIDING MOUNTAIN METEOROLOGIC STATIONS

(Table V: 1 and Text Figures 26, 27 and 30)

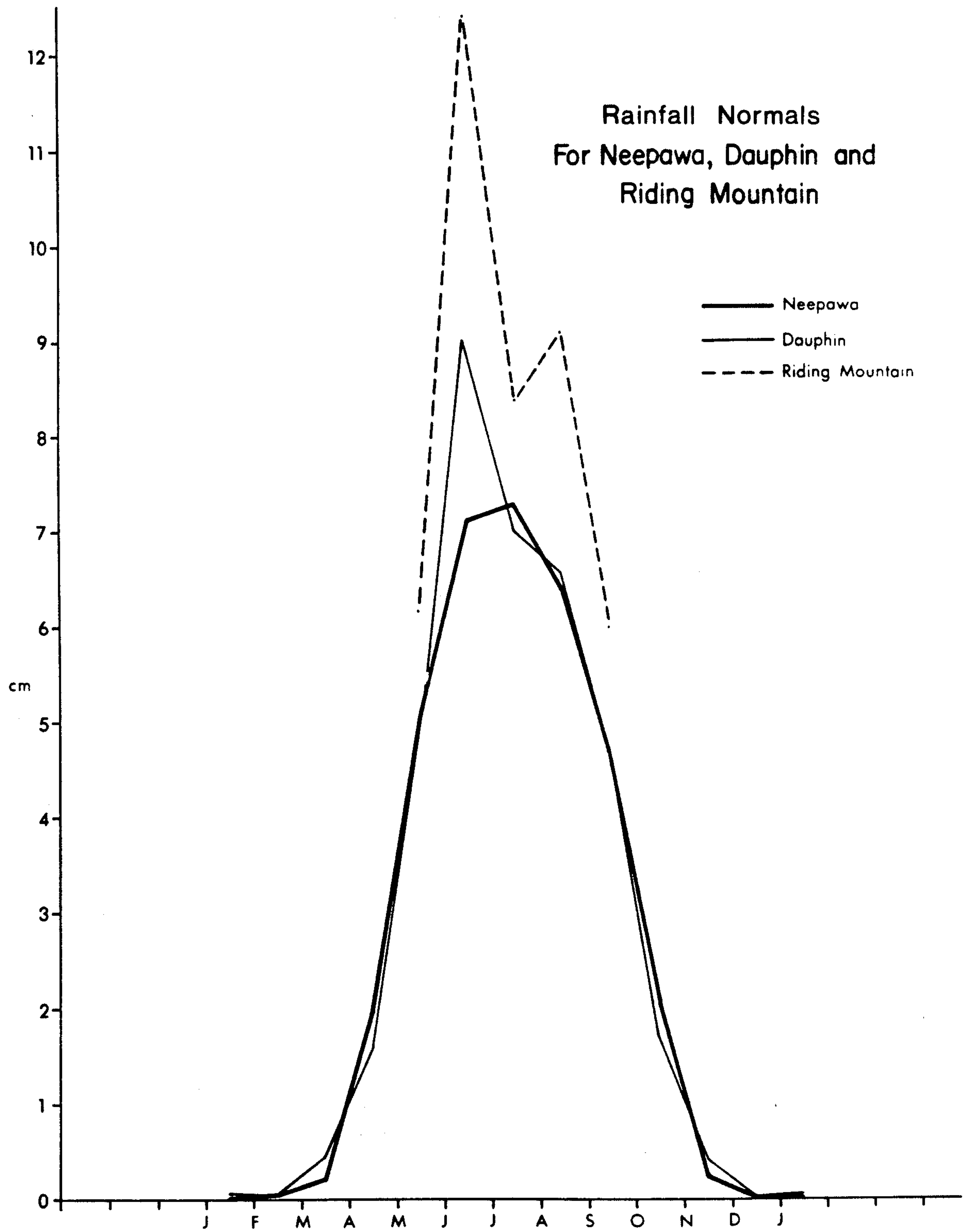
TABLE V : 1

TEMPERATURE AND PRECIPITATION NORMALS

NEEPAWA, DAUPHIN, AND RIDING MOUNTAIN

	JAN.	FEB.	MAR.	APRL.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
NEEPAWA													
MDT	-18.3	-15.3	- 8.6	2.4	10.2	15.8	19.1	18.1	11.7	5.6	-5.3	-13.9	1.8
MAX	-13.2	- 9.8	- 3.3	7.9	16.7	21.9	25.5	24.7	17.8	11.3	-0.9	- 9.1	7.5
MIN	-23.4	-20.7	-13.8	-3.1	3.6	9.6	12.7	11.6	5.5	-0.3	-9.7	-18.7	-3.9
RAIN	0.0	0.3	2.0	19.3	50.3	70.9	72.6	63.8	46.5	20.6	2.5	0.0	348.8
SNOW	23.9	18.8	21.9	11.7	3.3	0.0	0.0	0.0	0.2	6.6	21.6	22.4	130.4
PREC	23.9	19.1	23.9	31.0	53.6	70.9	72.6	63.8	46.7	27.2	24.1	22.4	479.2
DAUPHIN													
MDT	-18.6	-15.5	- 9.2	2.3	9.8	15.4	18.6	17.4	11.6	6.1	-5.1	-13.9	1.6
MAX	-13.5	- 9.6	- 3.4	7.9	16.5	21.8	25.1	24.1	17.7	11.9	-0.6	- 8.9	7.4
MIN	-23.7	-21.4	-14.9	-3.4	3.0	8.9	12.2	10.7	5.3	0.3	-9.6	-18.9	-4.3
RAIN	0.5	0.3	4.3	15.7	48.3	90.4	70.1	65.5	45.2	17.3	4.1	0.3	362.0
SNOW	23.4	19.3	24.1	16.6	3.5	0.0	0.0	0.0	0.8	7.6	23.8	24.6	143.7
PREC	23.9	19.6	28.4	32.3	51.8	90.4	70.1	65.5	46.0	24.9	27.9	24.9	505.7
RIDING MOUNTAIN													
MDT					7.9	13.4	16.9	15.5	9.7				
MAX					13.4	18.4	22.3	20.6	14.4				
MIN					2.4	8.3	11.5	10.4	4.9				
RAIN					61.5	124.0	83.8	90.9	59.7				
SNOW					10.1	0.0	0.0	0.0	3.0				
PREC					71.6	124.0	83.8	90.9	62.7				

TEMP. - °C
Prec. - mm.



Rainfall Normals
For Neepawa, Dauphin and
Riding Mountain
Neepawa
Dauphin
Riding Mountain
cm
12
11
10
9
8
7
6
5
4
3
2
1
0
J
F
M
A
M
J
J
A
S
O
N
D
J

Figure 26

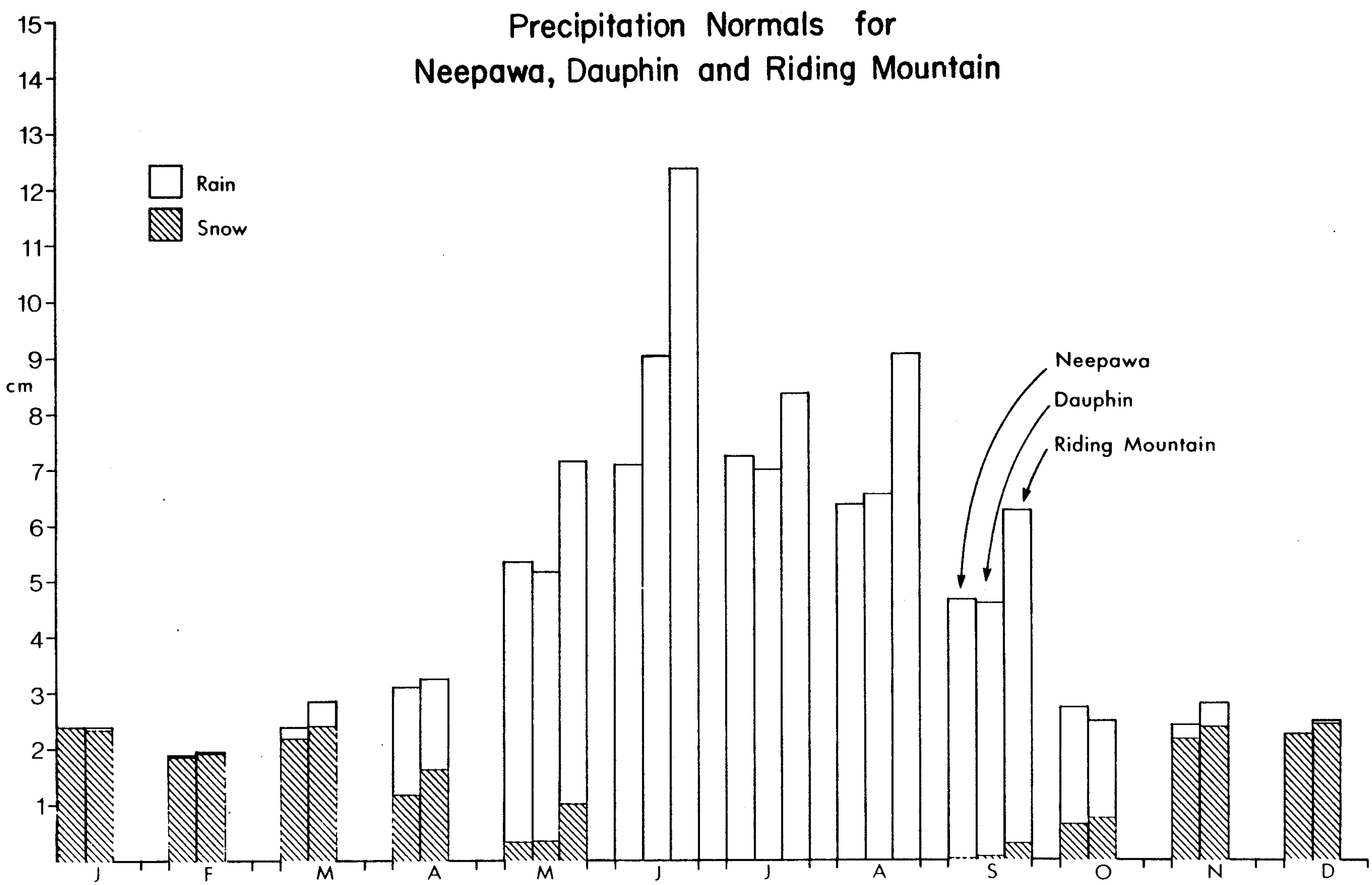

Precipitation Normals for
Neepawa, Dauphin and Riding Mountain
Rain
Snow
cm
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Neepawa
Dauphin
Riding Mountain
J
F
M
A
M
J
J
A
S
O
N
D

Figure 27

Mean Daily Temperature Normals for Neepawa, Dauphin and Riding Mountain

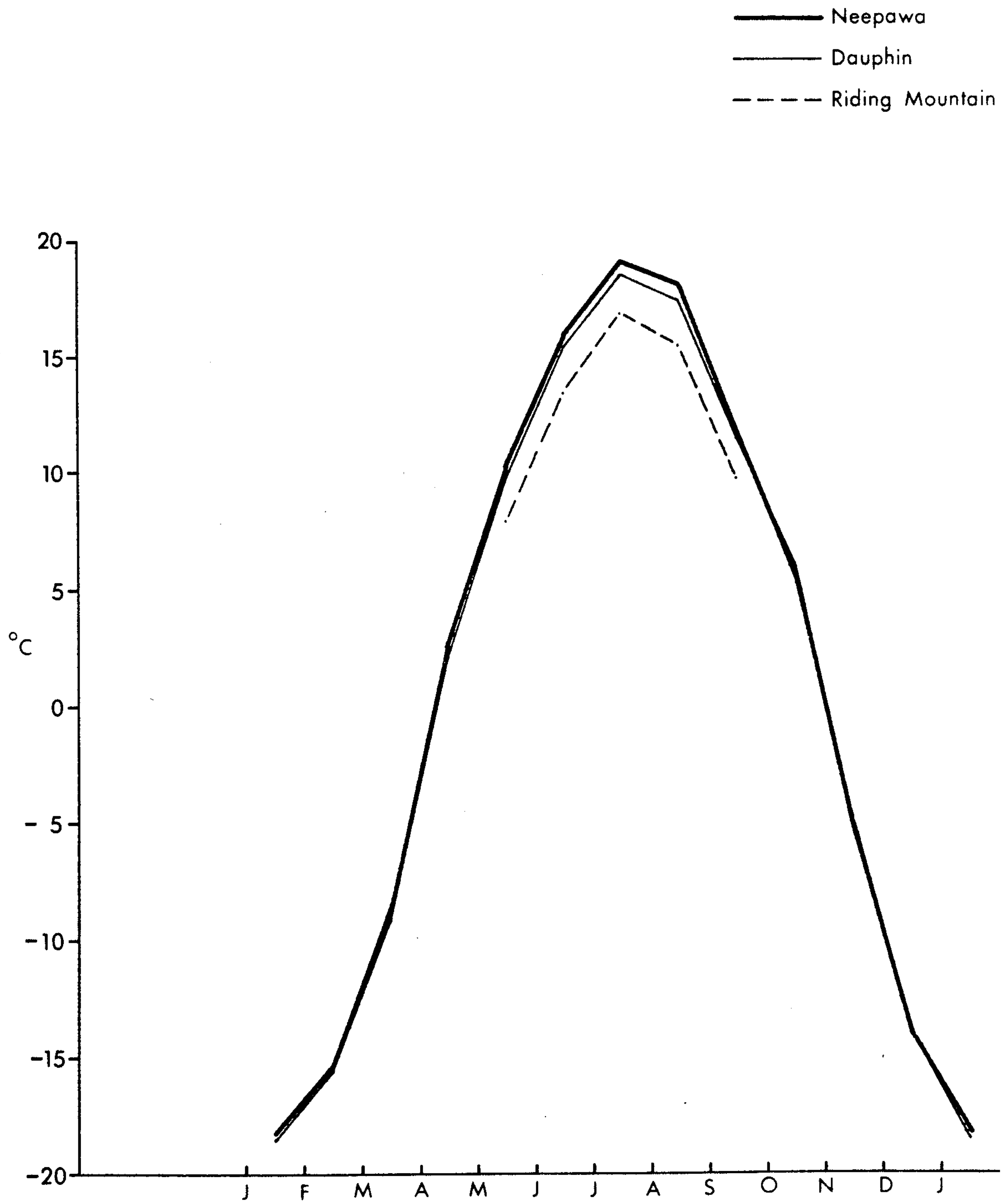


Figure 30

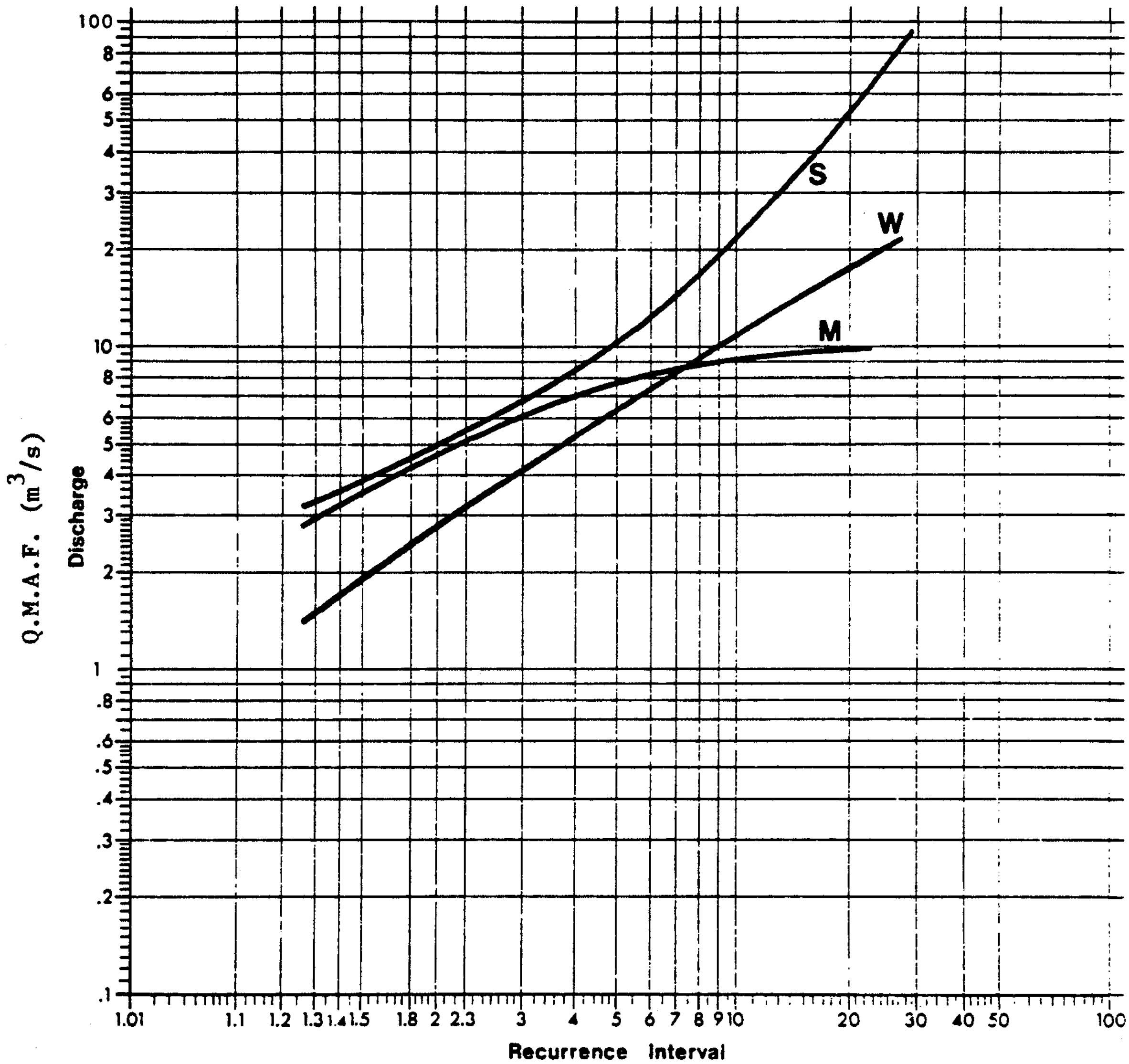
APPENDIX VI

PEAK FLOW DISCHARGE DATA IN ORDER OF MAGNITUDE AND FREQUENCY PLOTTING POSITION AND INDIVIDUAL FLOOD FREQUENCY PLOTS FOR BIRNIE CREEK; McKINNON CREEK; SCOTT CREEK; AND WILSON CREEK

(Text Figures 33, 34, 37 and 38;

Tables VI: 1-13 and Figures VI: 1-16)

MEAN ANNUAL FLOOD FREQUENCY PLOTS



Years

McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**

Figure 33

ANNUAL SERIES UNIT AREA FLOOD FREQUENCY PLOTS

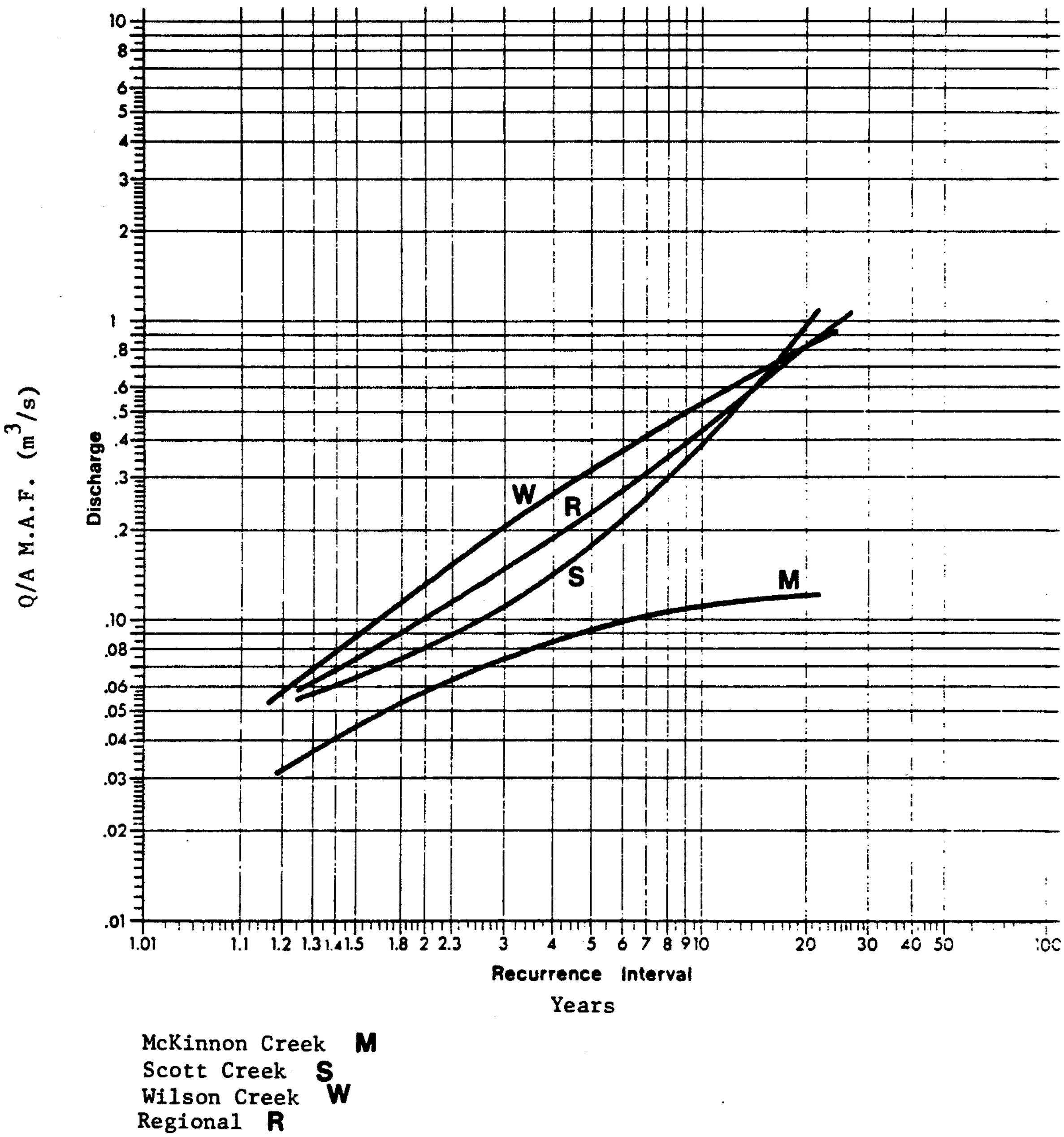
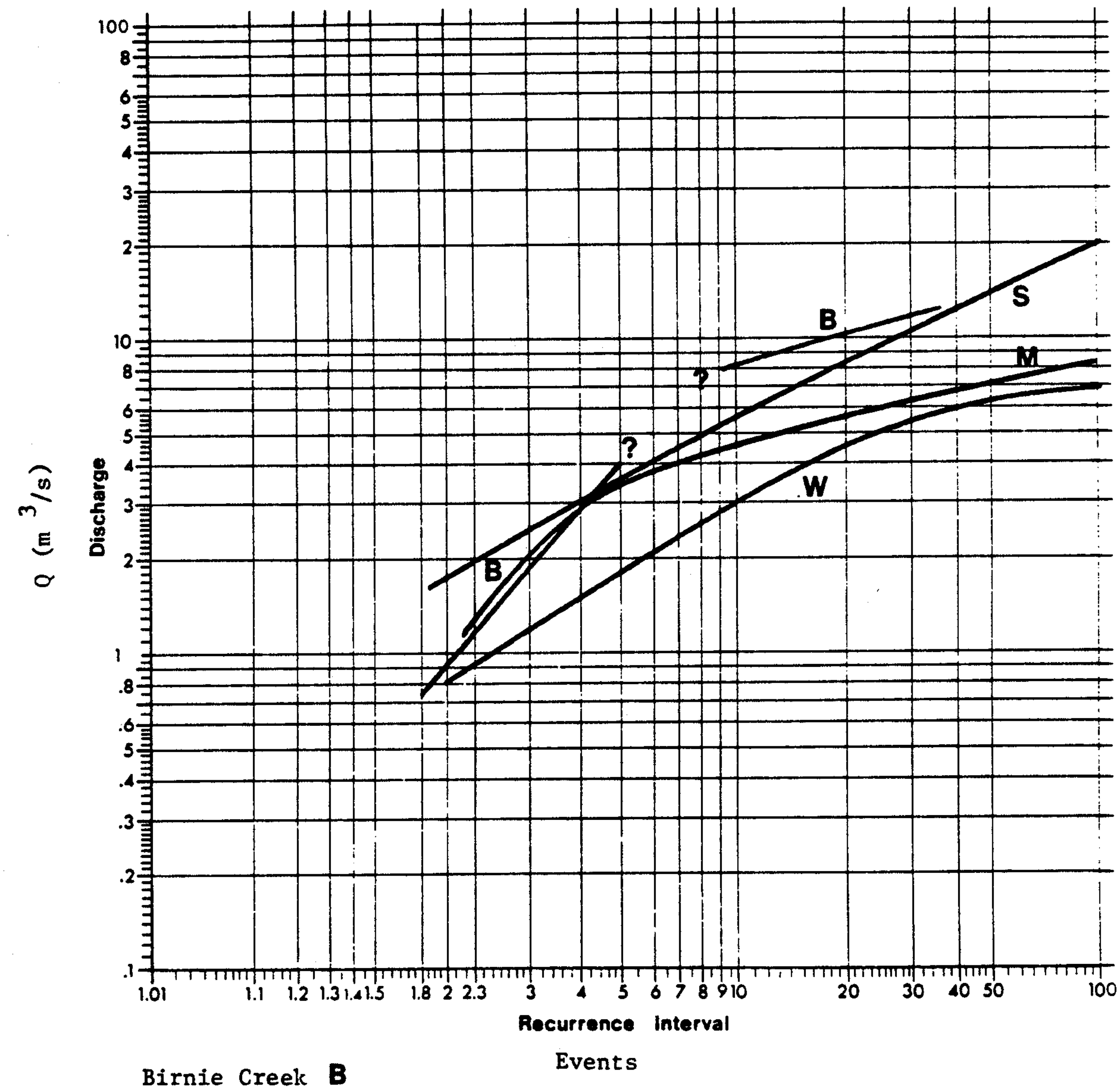


Figure 34

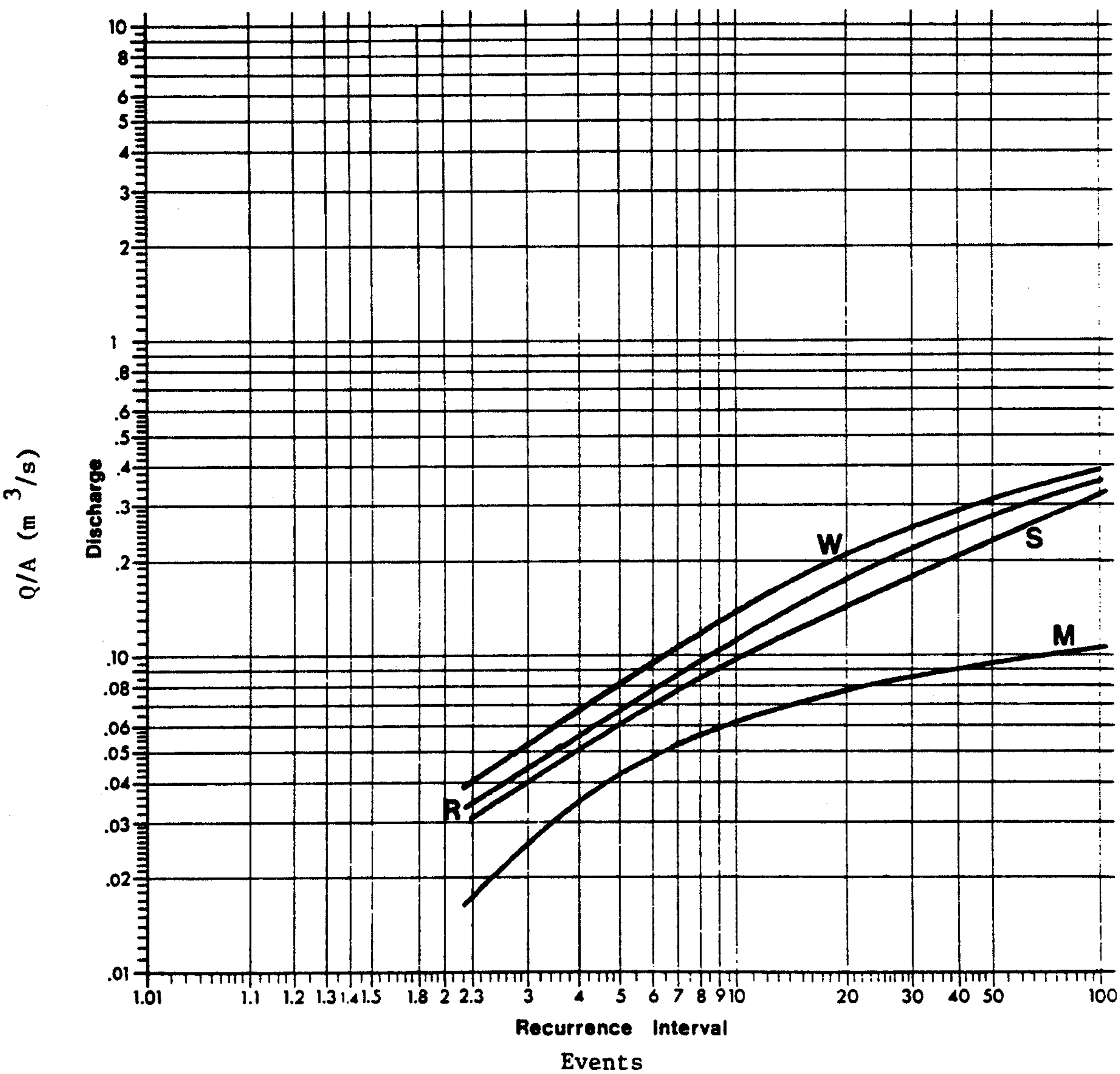
FULL SERIES FLOOD FREQUENCY PLOTS



Birnie Creek **B**
McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**

Figure 37

FULL SERIES UNIT AREA FLOOD FREQUENCY PLOTS



McKinnon Creek **M**
Scott Creek **S**
Wilson Creek **W**
Regional **R**

Figure 38

TABLE VI : 1

BIRNIE CREEK BASIN AREA - 64.8 SQUARE KILOMETERS

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE		MAXIMUM DAILY DISCHARGE		MAXIMUM DAILY DISCHARGE SNOWMELT EVENT		MAXIMUM DAILY DISCHARGE RAINFALL EVENT	
	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE
1969			10.73	June 27	0.93	April 15	10.73	June 27
70	15.31	May 7	12.93	May 7	12.93	May 7	2.56	May 15
71	6.42	June 6	4.92	April 20	4.92	April 20	4.22	June 6
72			4.13	April 22	4.13	April 22	1.25	May 13
73	1.51	Oct. 4	0.83	May 7	0.52	April 21	0.83	May 7
74	8.24	May 12	6.76	May 12	5.01	April 27	6.76	May 12
75	14.80	Sept. 19	10.78	Sept. 19	5.91	April 29	10.78	Sept. 19
76			5.32	April 10	5.32	April 10	4.73	April 17
77	1.42	Sept. 26	1.27	Sept. 26	0.21	April 15	1.27	Sept. 26

TABLE VI : 2

McKINNON CREEK BASIN AREA - 77.7 SQUARE KILOMETERS

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE		MAXIMUM DAILY DISCHARGE		MAXIMUM DAILY DISCHARGE SNOWMELT EVENT		MAXIMUM DAILY DISCHARGE RAINFALL EVENT	
	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE
1959	5.38	May 3	2.6	May 4	0.91	April 28	2.60	May 4
60	5.18	May 26	3.74	April 21	3.74	April 21	2.83	May 27
61	2.14	May 3	1.24	April 30	0.76	April 23	1.24	April 30
62	4.02	May 30	2.82	May 30	1.09	April 21	2.82	May 30
63	11.29	April 16	6.37	June 10	5.52	April 8	6.37	June 10
64	5.69	April 25	4.36	April 25	4.36	April 25	1.60	May 4
65	8.01	April 30	5.07	April 30	5.07	April 30	4.33	May 6
66			5.27	April 20	5.27	April 20	3.88	May 5
67			3.03	May 7	3.03	May 7	0.50	June 20
68	3.31	April 21	2.13	April 21	2.13	April 21	1.69	July 1
69	9.82	June 27	7.58	April 13	7.58	April 13	6.57	June 27
70	8.60	May 8	6.42	May 7	6.42	May 7	4.44	May 17
71	10.30	June 6	8.55	June 6	3.40	April 21	8.55	June 6
72			3.85	April 25	3.85	April 25	1.30	May 7
73	6.23	June 20	3.54	June 20	0.91	March 26,27,28	3.54	June 20
74	8.52	May 12	6.71	April 27	6.71	April 27	6.57	May 12
75	29.72	Sept. 19	28.58	Sept. 19	3.51	April 29	28.58	Sept. 19
76			8.38	April 6	8.38	April 6	8.26	April 17
77	10.53	July 12	4.81	July 12	0.58	April 15	4.81	July 12

TABLE VI : 3

SCOTT CREEK BASIN AREA 59.6 SQUARE KILOMETERS

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE		MAXIMUM DAILY DISCHARGE		MAXIMUM DAILY DISCHARGE SNOWMELT EVENT		MAXIMUM DAILY DISCHARGE RAINFALL EVENT	
	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE
1959	7.36	May 3	4.25	May 8	3.68	April 15	4.25	May 8
60	7.47	May 26	4.64	April 20	4.64	April 20	4.44	May 26
61	1.84	May 7	1.48	May 7	1.32	April 22	1.48	May 7
62			4.47	May 30	0.97	April 27	4.47	May 30
63	10.41	April 16	5.52	June 10	3.34	April 8	5.52	June 10
64	10.44	April 24	3.11	April 24	3.11	April 24	2.72	May 4
65			12.03	April 29	12.03	April 29	4.75	May 6
66	10.53	May 4	4.70	May 5	1.70	April 24	4.70	May 5
67	5.07	May 15	3.57	May 15	3.57	May 15	0.54	June 20
68	3.31	July 1	2.00	July 1	0.63	April 12	2.00	July 1
69	22.19	June 27	10.98	June 27	7.58	April 14	10.98	June 27
70			11.26	May 7	11.26	May 7	6.76	May 17
71	26.32	June 6	21.51	June 6	3.82	April 21	21.51	June 6
72	8.66	April 26	5.58	April 25	5.58	April 25	1.77	May 25
73	6.25	June 20	3.96	June 20	0.65	May 8	3.96	June 20
74	12.03	May 11	6.57	April 27	6.57	April 27	6.08	May 12
75			58.86	Sept. 19	4.58	May 7	58.86	Sept. 19
76	11.32	April 19	7.13	April 9	7.13	April 9	6.14	April 17
77			1.42	May 20	0.63	April 13	1.42	May 20

TABLE VI : 4

WILSON CREEK BASIN AREA - 22.3 SQUARE KILOMETERS

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE		MAXIMUM DAILY DISCHARGE		MAXIMUM DAILY DISCHARGE SNOWMELT EVENT		MAXIMUM DAILY DISCHARGE RAINFALL EVENT	
	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE	DISCHARGE m^3/s	DATE
1959	0.93	Sept. 26	0.79	Sept. 26	Not Available		0.79	*Sept. 26
60	3.25	May 26	2.23	May 9	"			
61	1.16	May 5	1.09	May 5	"		1.12	*May 5
62	4.53	May 30	3.25	May 30	"		3.25	*May 30
63	7.16	June 10	4.47	June 10	"		4.47	*June 10
64	1.78	May4,6,7,9&10	1.78	May4,6,7,9&10	"		1.78	*May4,6,7,9&10
65	6.59	April 29	3.96	April 29	3.96	April 29	3.14	May 6
66	3.34	May 4	1.70	May 5	0.57	April 16,17,23	1.70	May 4
67	2.00	May 15	1.65	May 14	1.65	May 14	0.20	June 20
68	4.70	Aug. 16	1.16	July 1	1.00	April 21	1.16	July 1
69	19.81	June 27	7.30	June 27	5.43	April 14	7.30	June 27
70	10.19	May 17	6.11	May 8	6.11	May 8	5.91	May 17
71			9.65	June 6	1.48	April 10	9.65	June 6
72			2.68	April 26	2.68	April 26	0.65	May 8
73	1.78	June 20	1.27	June 20	0.44	April 20	1.27	June 20
74	8.15	May 11	3.51	May 11	3.31	April 26	3.51	May 11
75	44.70	Sept. 18	18.11	Sept. 19	5.15	April 14	18.11	Sept. 19
76	4.22	April 13	2.75	April 14	2.75	April 14	1.41	April 22
77			6.79	July 11	0.09	April 12	6.79	July 11

* as the records are incomplete these are assumed storm peaks

TABLE VI : 5

McKINNON CREEK 77.7 km^2

Maximum Daily Discharge

Year	Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
1975	28.58	.368	1	20.0
1971	8.55	.110	2	10.0
1976	8.38	.108	3	6.7
1969	7.58	.098	4	5.0
1974	6.71	.086	5	4.0
1970	6.42	.083	6	3.3
1963	6.37	.082	7	2.9
1966	5.27	.068	8	2.5
1965	5.07	.065	9	2.2
1977	4.81	.062	10	2.0
1964	4.36	.056	11	1.8
1972	3.85	.050	12	1.6
1960	3.74	.048	13	1.5
1973	3.54	.046	14	1.4
1967	3.03	.039	15	1.3
1962	2.82	.036	16	1.25
1959	2.60	.033	17	1.17
1968	2.13	.027	18	1.11
1961	1.24	.016	19	1.05

TABLE VI : 6

SCOTT CREEK 59.6 km^2

Maximum Daily Discharge

Year	Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
1975	58.86	.988	1	20.0
1971	21.51	.361	2	10.0
1965	12.03	.202	3	6.7
1970	11.26	.189	4	5.0
1969	10.98	.184	5	4.0
1976	7.13	.120	6	3.3
1974	6.57	.110	7	2.9
1972	5.58	.094	8	2.5
1963	5.52	.093	9	2.2
1966	4.70	.079	10	2.0
1960	4.64	.078	11	1.8
1962	4.47	.075	12	1.6
1959	4.25	.071	13	1.5
1973	3.96	.066	14	1.4
1967	3.57	.060	15	1.3
1964	3.11	.052	16	1.25
1968	2.00	.033	17	1.17
1961	1.48	.025	18	1.11
1977	1.42	.024	19	1.05

TABLE VI : 7

WILSON CREEK 22.3 km^2

Maximum Daily Discharge

Year	Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
1975	18.11	.812	1	20.0
1971	9.65	.433	2	10.0
1969	7.30	.327	3	6.7
1977	6.79	.304	4	5.0
1970	6.11	.274	5	4.0
1963	4.47	.200	6	3.3
1965	3.96	.178	7	2.9
1974	3.51	.157	8	2.5
1962	3.25	.146	9	2.2
1976	2.75	.123	10	2.0
1972	2.68	.120	11	1.8
1960	2.23	.100	12	1.6
1964	1.78	.080	13	1.5
1966	1.70	.076	14	1.4
1967	1.65	.074	15	1.3
1973	1.27	.057	16	1.25
1968	1.16	.052	17	1.17
1961	1.09	.049	18	1.11
1959	0.79	.035	19	1.05

TABLE VI : 8

REGIONAL (Wilson Cr. + Scott Cr.)

Annual Series Unit Area Flood Frequencies

Q/A	Rank R	Plotting Position T = (n+1)/R
.900	1	20.0
.397	2	10.0
.264	3	6.7
.246	4	5.0
.229	5	4.0
.160	6	3.3
.144	7	2.9
.126	8	2.5
.120	9	2.2
.101	10	2.0
.099	11	1.8
.088	12	1.6
.076	13	1.5
.071	14	1.4
.067	15	1.3
.055	16	1.25
.043	17	1.17
.037	18	1.11
.030	19	1.05

FIGURE VI : 1

McKINNON CREEK

Mean Annual Flood Frequency Plot

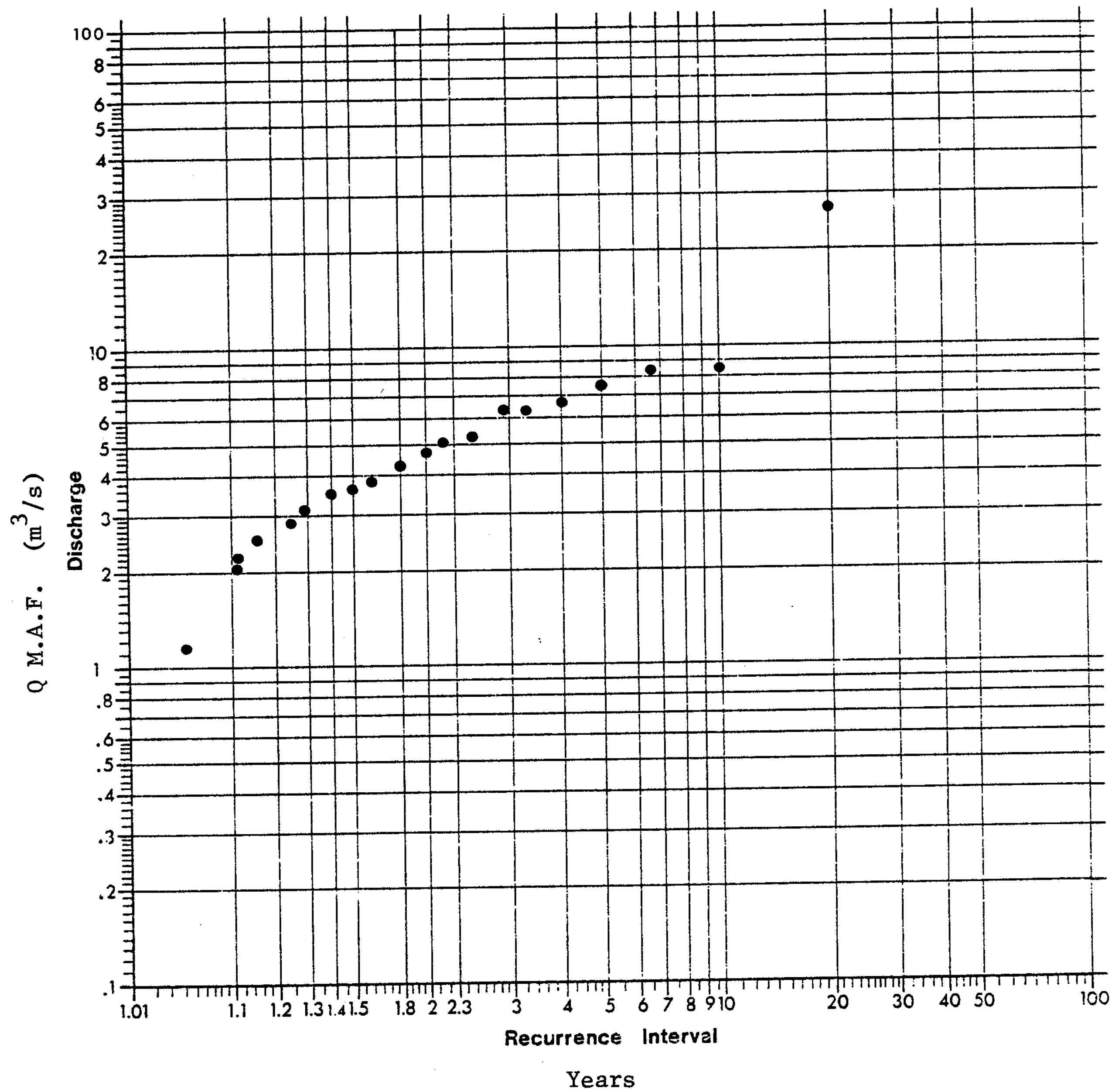


FIGURE VI : 2

SCOTT CREEK

Mean Annual Flood Frequency Plot

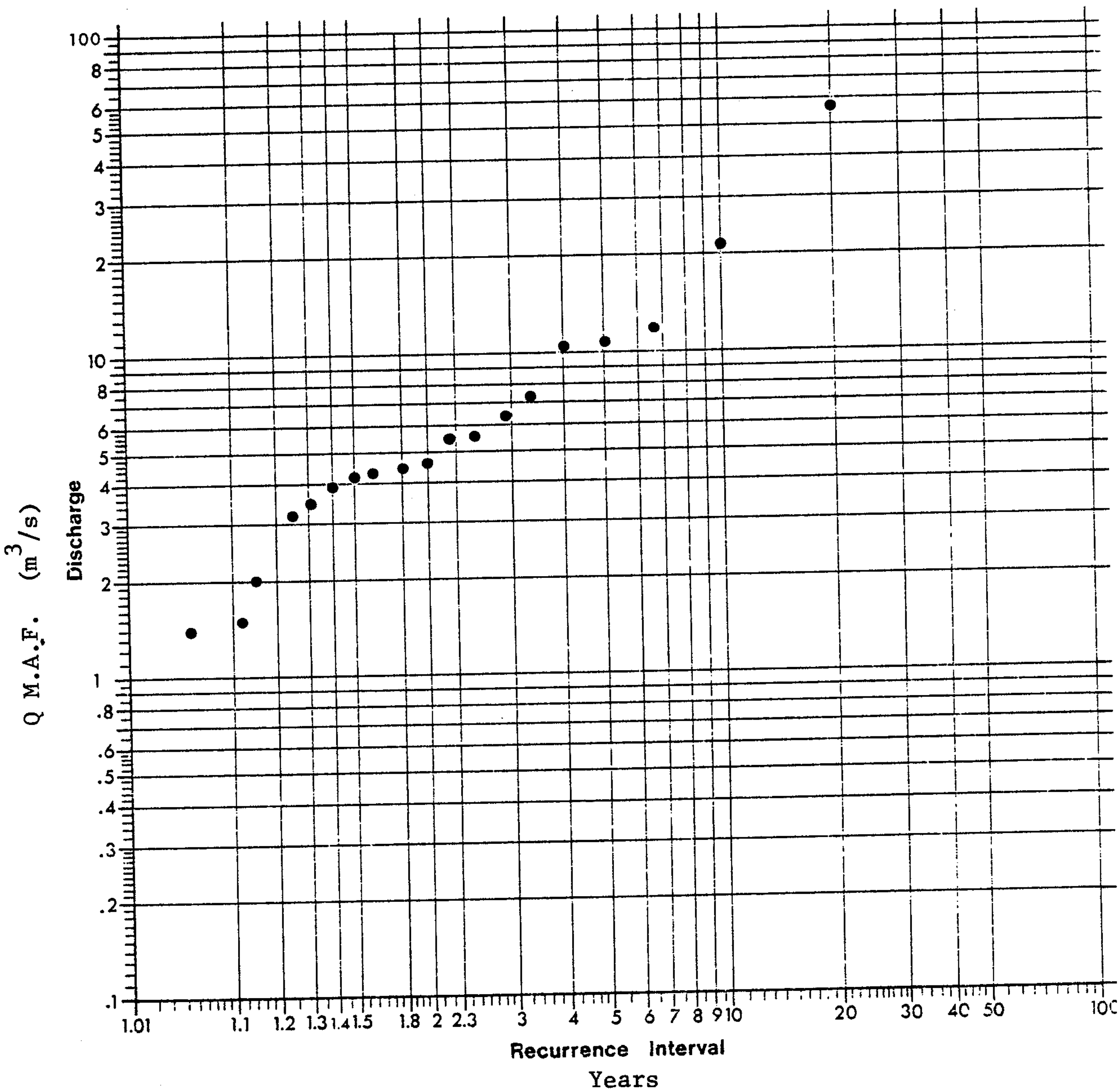


FIGURE VI : 3

WILSON CREEK

Mean Annual Flood Frequency Plot

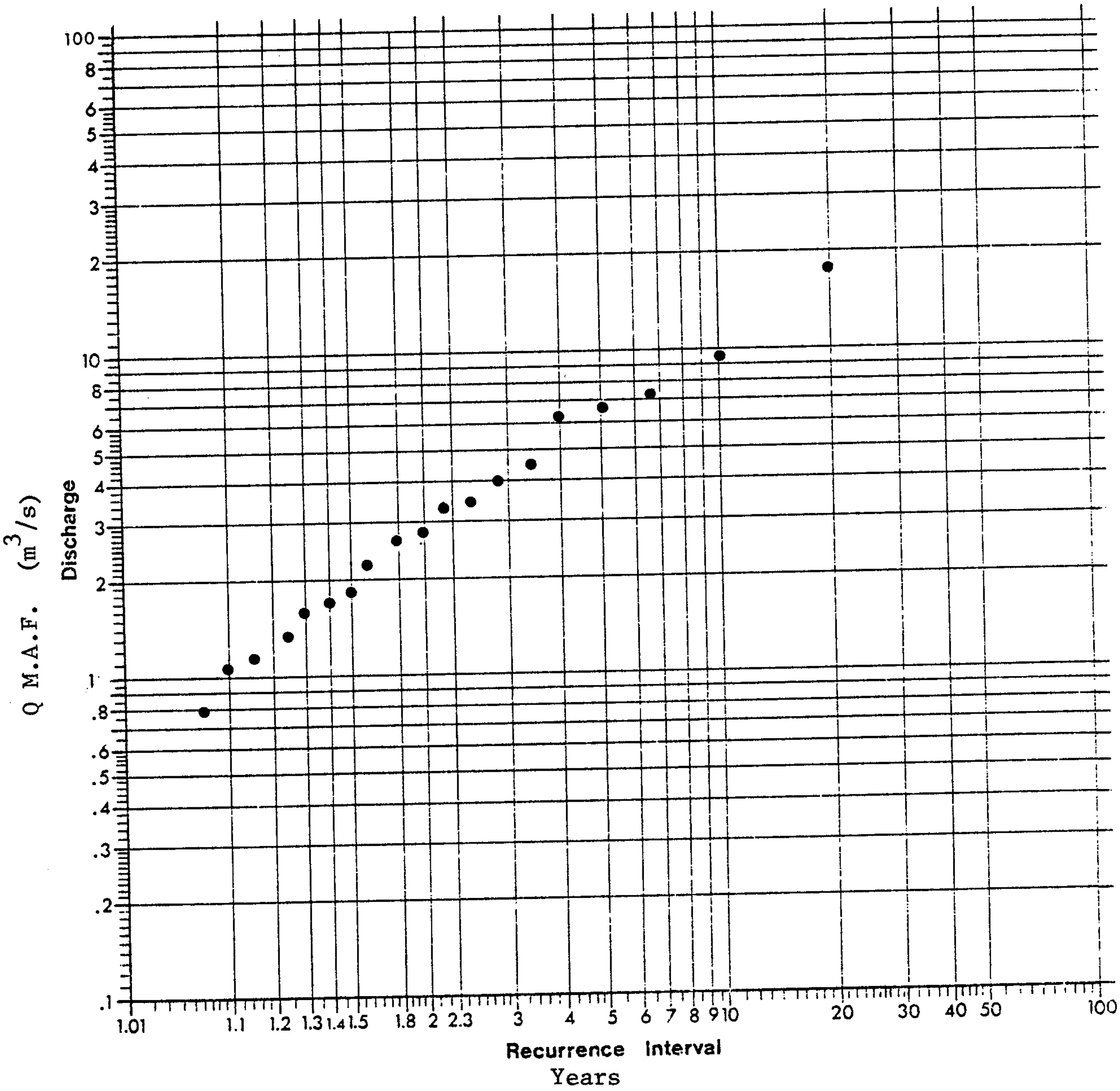


FIGURE VI : 4

McKINNON CREEK

Unit Area Mean Annual Flood Frequency Plot

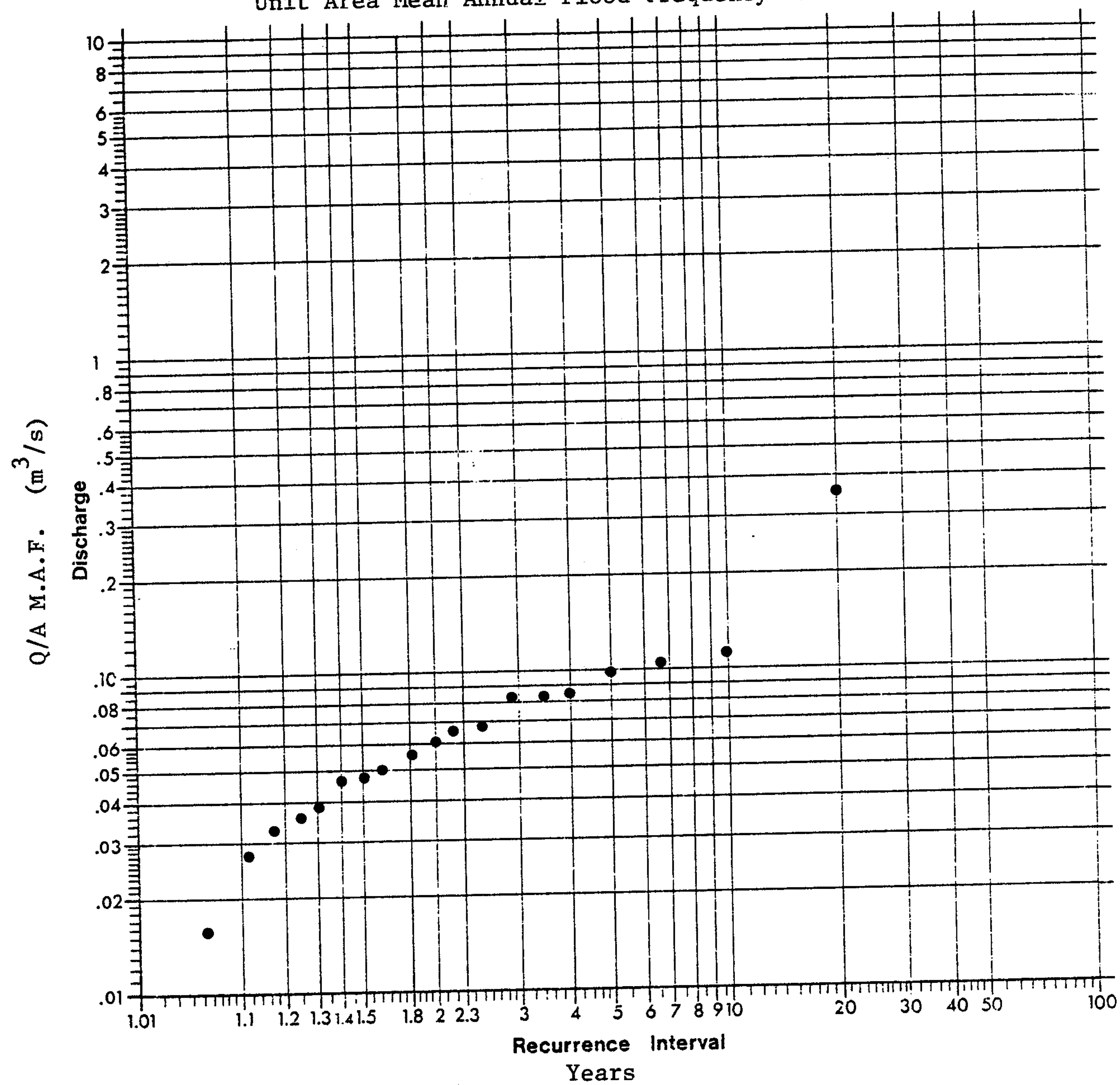


FIGURE VI : 5

SCOTT CREEK

Unit Area Mean Annual Flood Frequency Plot

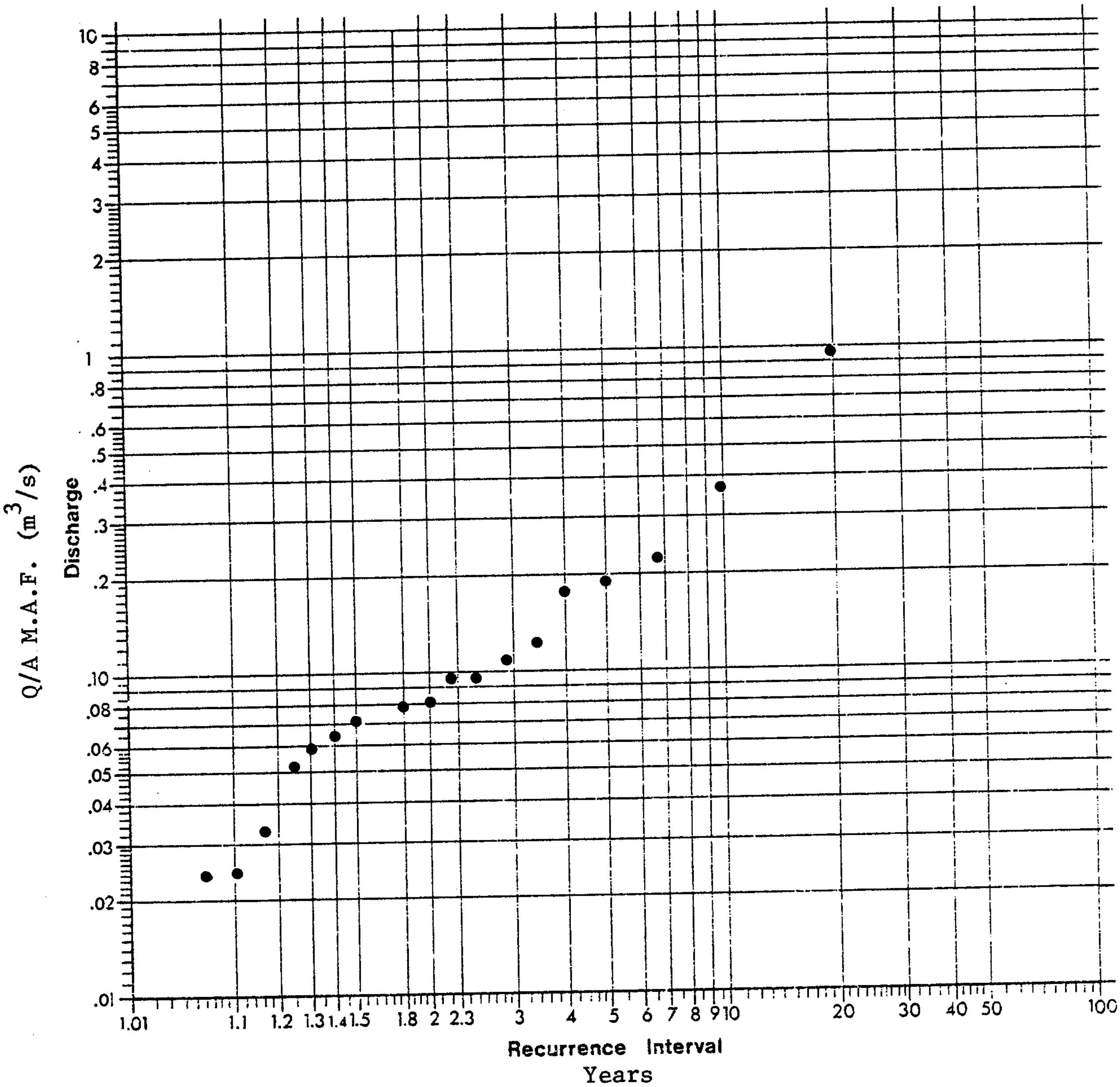


FIGURE VI : 6

WILSON CREEK

Unit Area Mean Annual Flood Frequency Plot

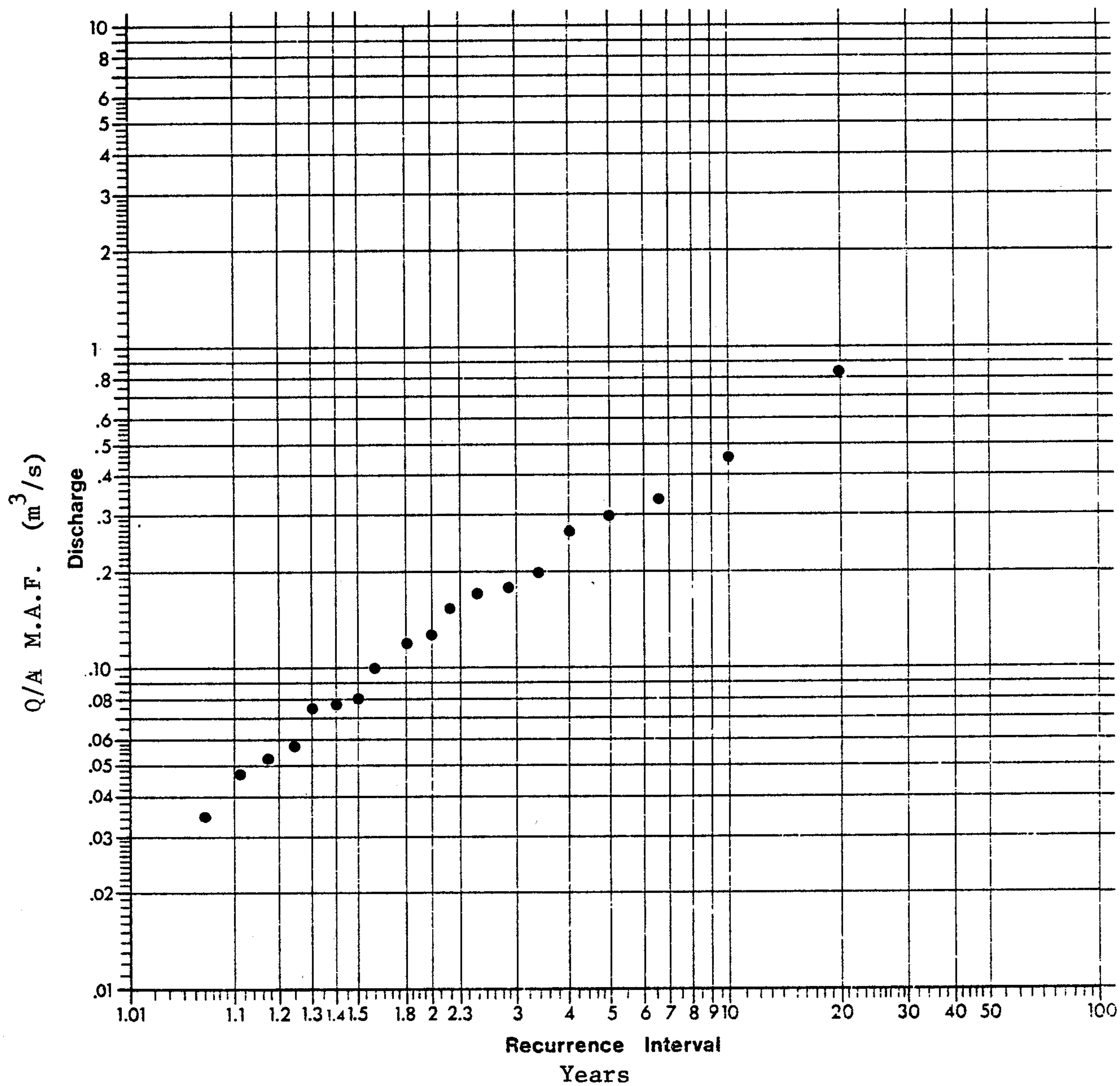


FIGURE VI : 7

REGIONAL (Wilson Cr. + Scott Cr.)

Annual Series Unit Area Flood Frequency Plot

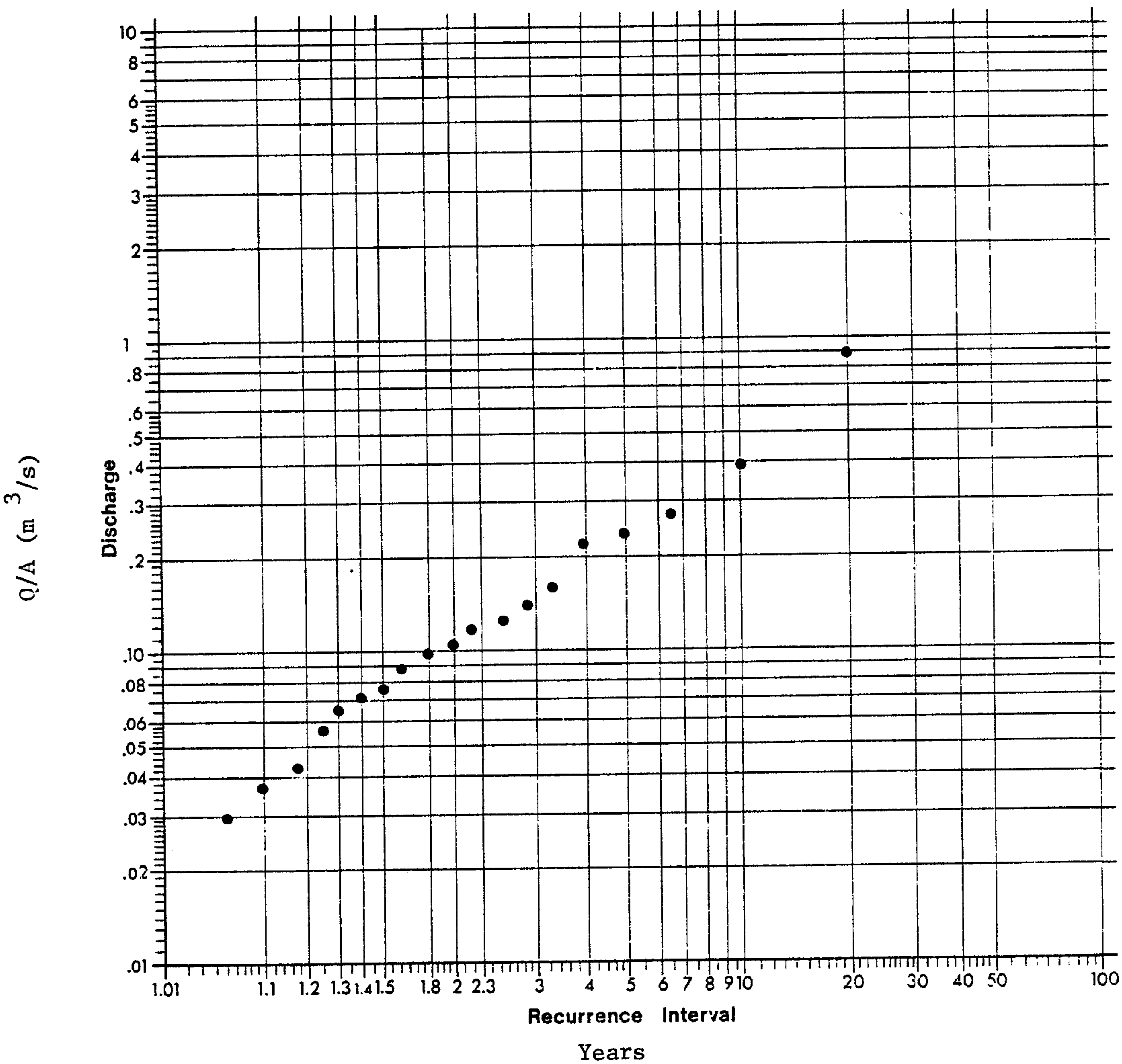


TABLE VI : 9

BIRNIE CREEK 64.8 km^2

Spring Melts and Storm Precipitation Discharges
(Full Series Flood Frequencies (1969-1973)

Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
*12.93	.200	1	35.0
10.72	.165	2	17.5
* 9.25	.150	3	11.7
* 4.92	.076	4	8.8
4.21	.065	5	7.0
* 4.13	.064	6	5.9
4.10	.063	7	5.0
3.79	.058	8	4.4
3.41	.053	9	3.9
2.55	.039	10	3.5
2.14	.033	11	3.1
1.77	.027	12	3.0
1.61	.025	13	2.7
1.25	.019	14	2.5
1.23	.019	15	2.3
1.02	.016	16	
.94	.015	17	
.83	.013	18	
.80	.012	19	
* .52	.008	20	
.48	.007	21	
.47	.007	22	
.46	.007	23	
.42	.006	24	
.40	.006	25	
.38	.006	26	
.35	.005	27	
.35	.005	28	
.23	.004	29	
.23	.004	30	
.16	.002	31	
.06	.001	32	
.04	-	33	
.03	-	34	

* - Snowmelt

n = 34

TABLE VI : 10

McKINNON CREEK 77.7 km^2

Spring Melts and Storm Precipitation Discharges
(Full Series Flood Frequencies 1960-1973)

Q m^3/s	Q/A	Rank R	Plotting Position T - (n+1)/R
8.54	.110	1	90.0
*7.58	.098	2	45.0
6.56	.084	3	30.0
6.36	.082	4	22.5
*6.33	.081	5	18.0
*5.52	.071	6	15.0
*5.29	.068	7	12.9
5.06	.065	8	11.3
4.90	.063	9	10.0
4.44	.057	10	9.0
*4.35	.056	11	8.2
4.32	.056	12	7.5
4.16	.054	13	6.9
4.13	.053	14	6.4
4.04	.052	15	6.0
4.01	.052	16	5.6
3.87	.050	17	5.3
*3.85	.050	18	5.0
*3.73	.048	19	4.7
3.54	.046	20	4.5
*3.40	.044	21	4.3
3.03	.039	22	4.1
2.97	.038	23	3.9
2.88	.037	24	3.8
2.82	.036	25	3.6
2.73	.035	26	3.5
2.62	.034	27	3.3
2.17	.030	28	3.2
*2.13	.027	29	3.1
2.00	.026	30	3.0
1.96	.025	31	2.9
1.95	.025	32	2.8
1.83	.024	33	2.7
1.74	.022	34	2.6
1.68	.022	35	2.6
1.60	.021	36	2.5
1.43	.018	37	2.4
1.36	.018	38	2.3
1.30	.017	39	2.3

* - Snowmelt

n = 89

TABLE VI : 11

SCOTT CREEK 59.6 km^2

Spring Melts and Storm Precipitation Discharges
(Full Series Flood Frequencies (1960-1973)

Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
21.51	.361	1	90.0
*12.05	.202	2	45.0
*11.26	.189	3	30.0
10.98	.184	4	22.5
* 7.58	.127	5	18.0
6.76	.113	6	15.0
6.00	.101	7	12.9
* 5.57	.093	8	11.3
5.52	.093	9	10.0
4.75	.080	10	9.0
4.70	.079	11	8.2
4.64	.078	12	7.5
* 4.64	.078	13	6.9
4.47	.075	14	6.4
4.44	.075	15	6.0
4.41	.074	16	5.6
3.96	.066	17	5.3
* 3.82	.064	18	5.0
3.76	.063	19	4.7
3.56	.060	20	4.5
3.56	.060	21	4.3
* 3.53	.059	22	4.1
* 3.34	.056	23	3.9
* 3.11	.052	24	3.8
3.08	.052	25	3.6
3.06	.051	26	3.5
3.03	.051	27	3.3
* 3.00	.050	28	3.2
3.00	.050	29	3.1
2.83	.047	30	3.0
2.72	.046	31	2.9
2.54	.043	32	2.8
2.23	.037	33	2.7
2.00	.034	34	2.6
1.97	.033	35	2.6
1.87	.031	36	2.5
1.85	.031	37	2.4
1.78	.030	38	2.3
1.77	.029	39	2.3

* - Snowmelt

n = 89

TABLE VI : 12

WILSON CREEK 22.3 km^2

Spring Melts and Storm Precipitation Discharges
(Full series Flood Frequencies 1960-1973)

Q m^3/s	Q/A	Rank R	Plotting Position T = (n+1)/R
7.30	.327	1	90.0
*6.11	.274	2	45.0
5.83	.261	3	30.0
5.43	.243	4	22.5
5.31	.238	5	18.0
*3.96	.178	6	15.0
3.73	.167	7	12.9
3.25	.146	8	11.3
3.14	.141	9	10.0
2.94	.132	10	9.0
*2.67	.120	11	8.2
2.35	.105	12	7.5
2.23	.100	13	6.9
2.12	.095	14	6.4
2.08	.093	15	6.0
*1.86	.083	16	5.6
*1.79	.080	17	5.3
1.78	.080	18	5.0
1.70	.076	19	4.7
1.70	.076	20	4.5
1.65	.074	21	4.3
*1.54	.070	22	4.1
1.48	.066	23	3.9
1.47	.066	24	3.8
1.38	.062	25	3.6
1.35	.061	26	3.5
1.35	.061	27	3.3
*1.33	.060	28	3.2
1.26	.057	29	3.1
1.21	.054	30	3.0
1.16	.052	31	2.9
1.11	.050	32	2.8
1.04	.047	33	2.7
1.00	.045	34	2.6
*1.00	.045	35	2.6
* .95	.043	36	2.5
.94	.042	37	2.4
.93	.042	38	2.3
.89	.040	39	2.3

* – Snowmelt

n = 89

TABLE VI : 13

REGIONAL (Wilson Cr. + Scott Cr.)

Full Series Unit Area Flood Frequencies

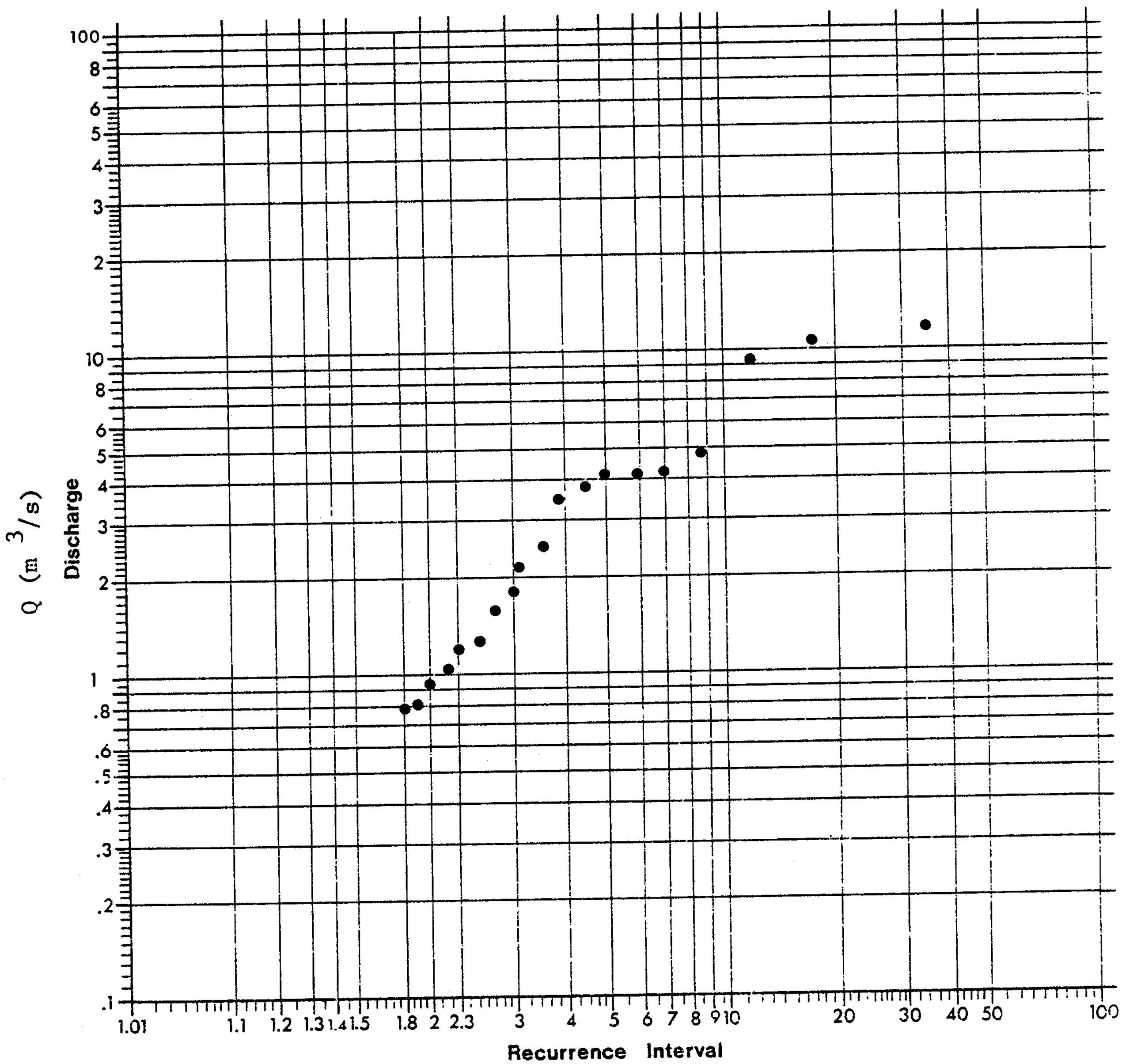
Q/A	Rank R	Plotting Position T = (n+1)/R
.344	1	90.0
.238	2	45.0
.225	3	30.0
.214	4	22.5
.183	5	18.0
.146	6	15.0
.134	7	12.9
.120	8	11.3
.117	9	10.0
.106	10	9.0
.100	11	8.2
.092	12	7.5
.089	13	6.9
.085	14	6.4
.084	15	6.0
.079	16	5.6
.073	17	5.3
.072	18	5.0
.070	19	4.7
.068	20	4.5
.067	21	4.3
.065	22	4.1
.061	23	3.9
.059	24	3.8
.057	25	3.6
.056	26	3.5
.056	27	3.3
.055	28	3.2
.054	29	3.1
.051	30	3.0
.049	31	2.9
.047	32	2.8
.042	33	2.7
.040	34	2,6
.039	35	2.6
.037	36	2.5
.037	37	2.4
.036	38	2.3
.035	39	2.3

n = 89

FIGURE VI : 8

BIRNIE CREEK

Full Series Flood Frequency Plot

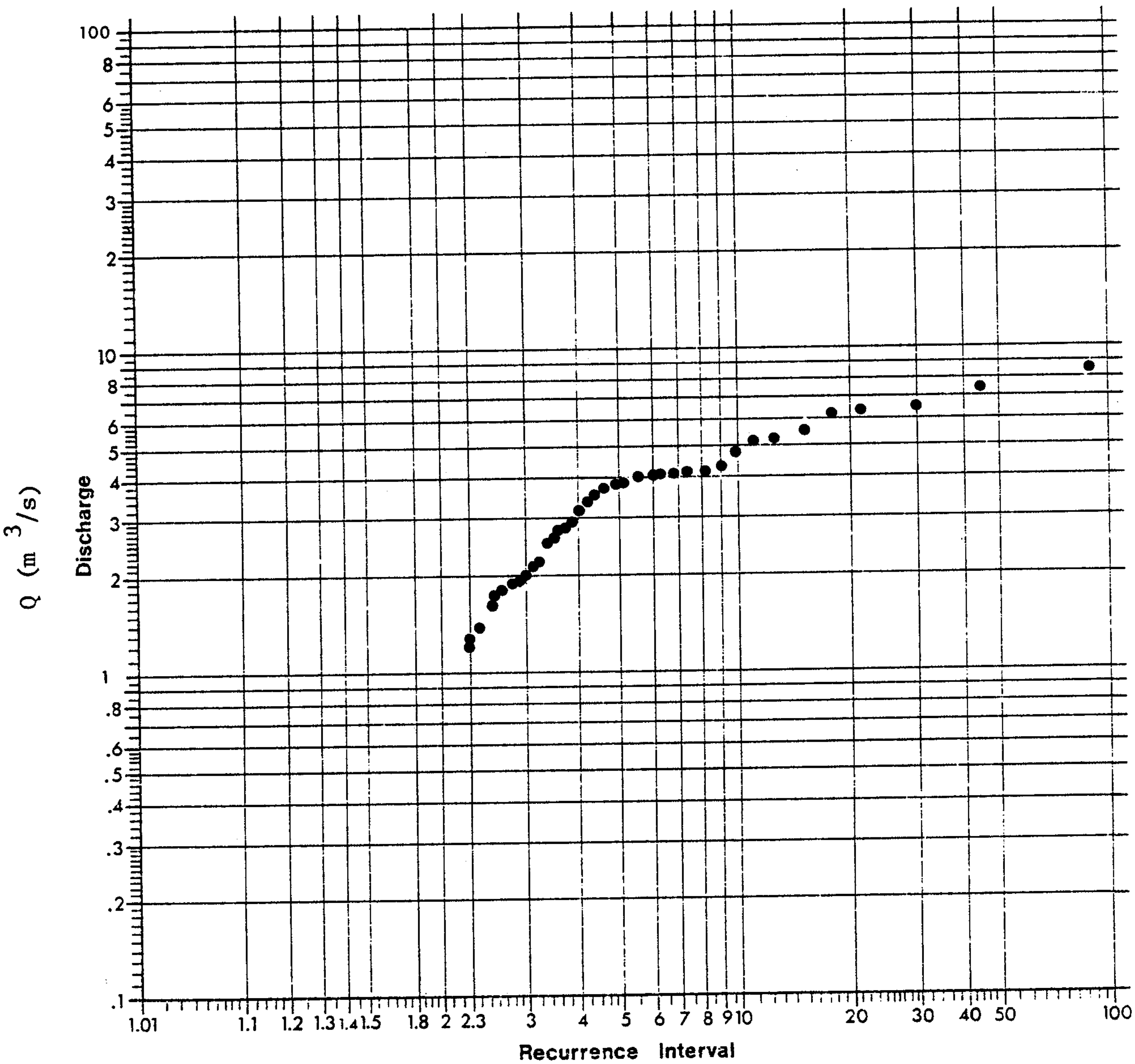


Events

FIGURE VI : 9

McKINNON CREEK

Full Series Flood Frequency Plot



Events

FIGURE VI : 10

SCOTT CREEK

Full Series Flood Frequency Plot

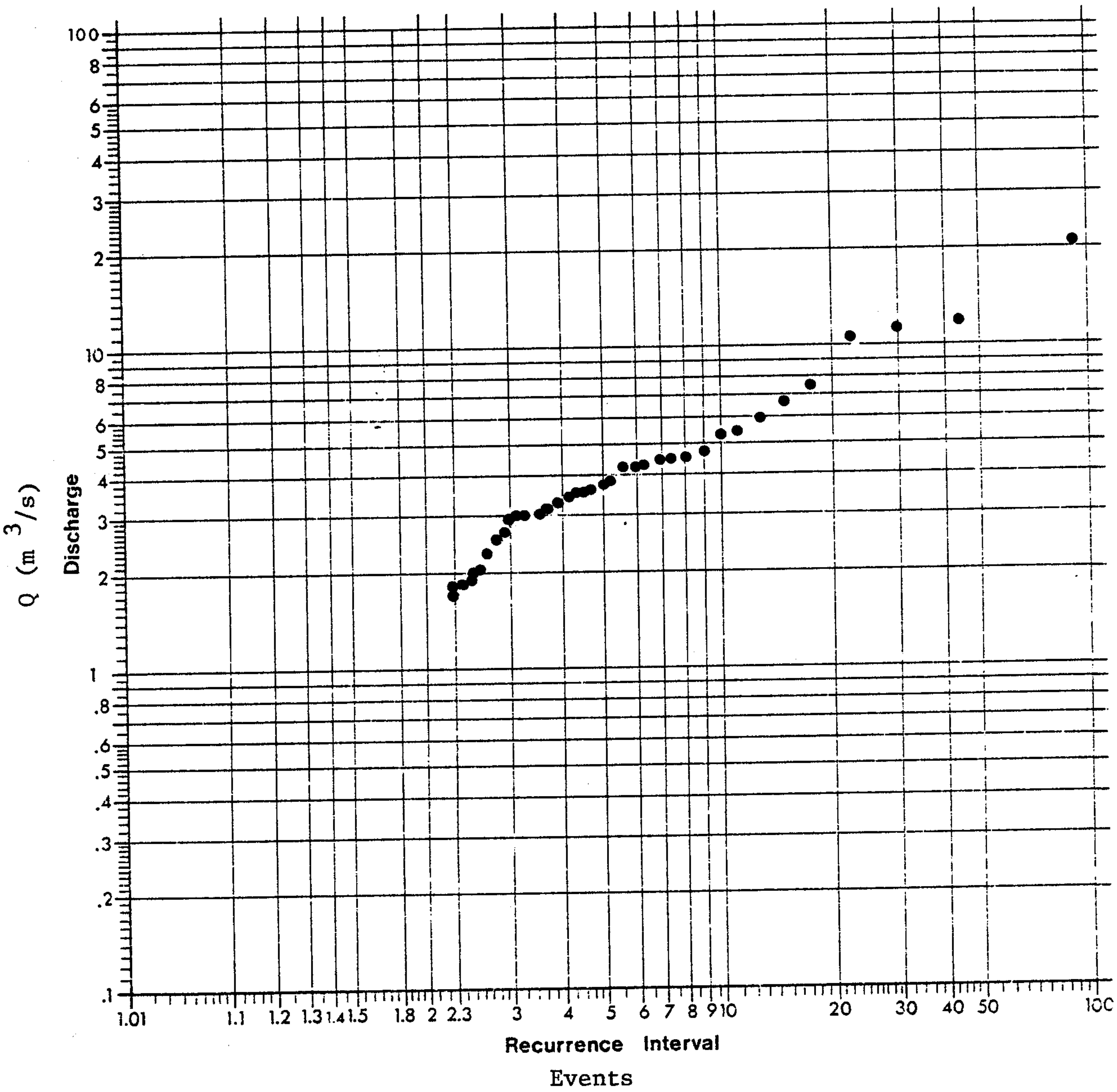


FIGURE VI : 11

WILSON CREEK

Full Series Flood Frequency Plot

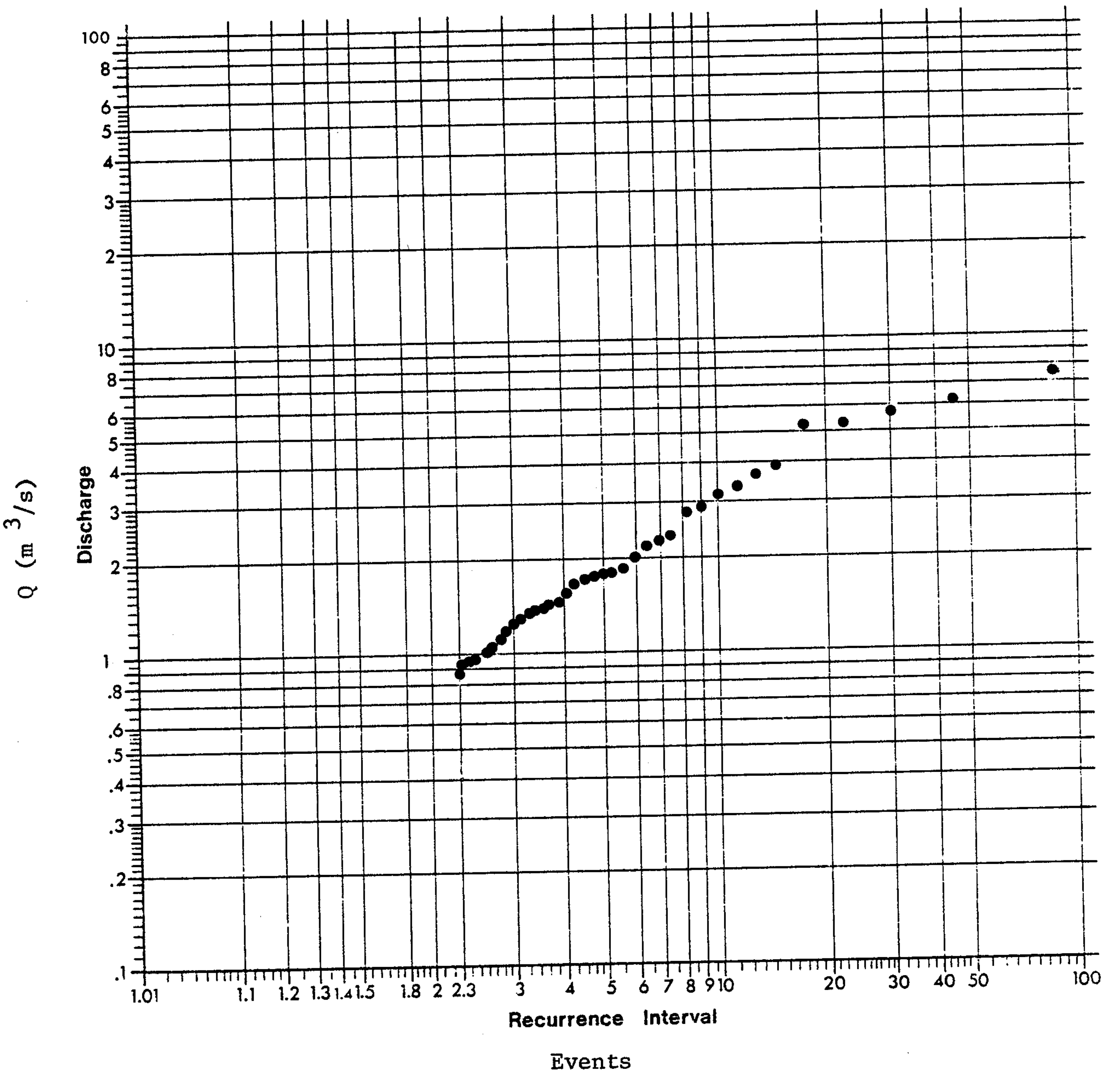
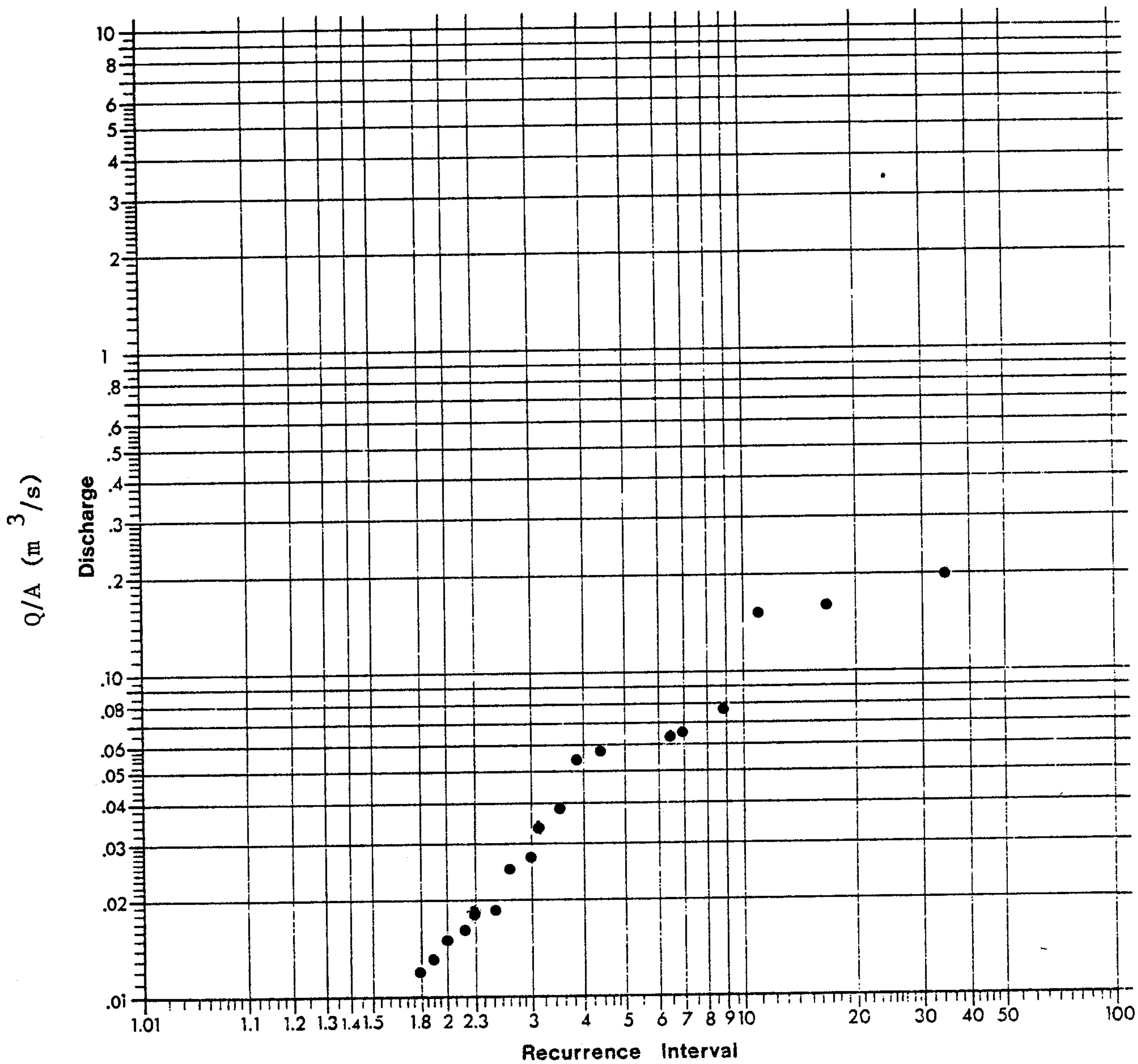


FIGURE VI : 12

BIRNIE CREEK

Full Series Unit Area Flood Frequency Plot

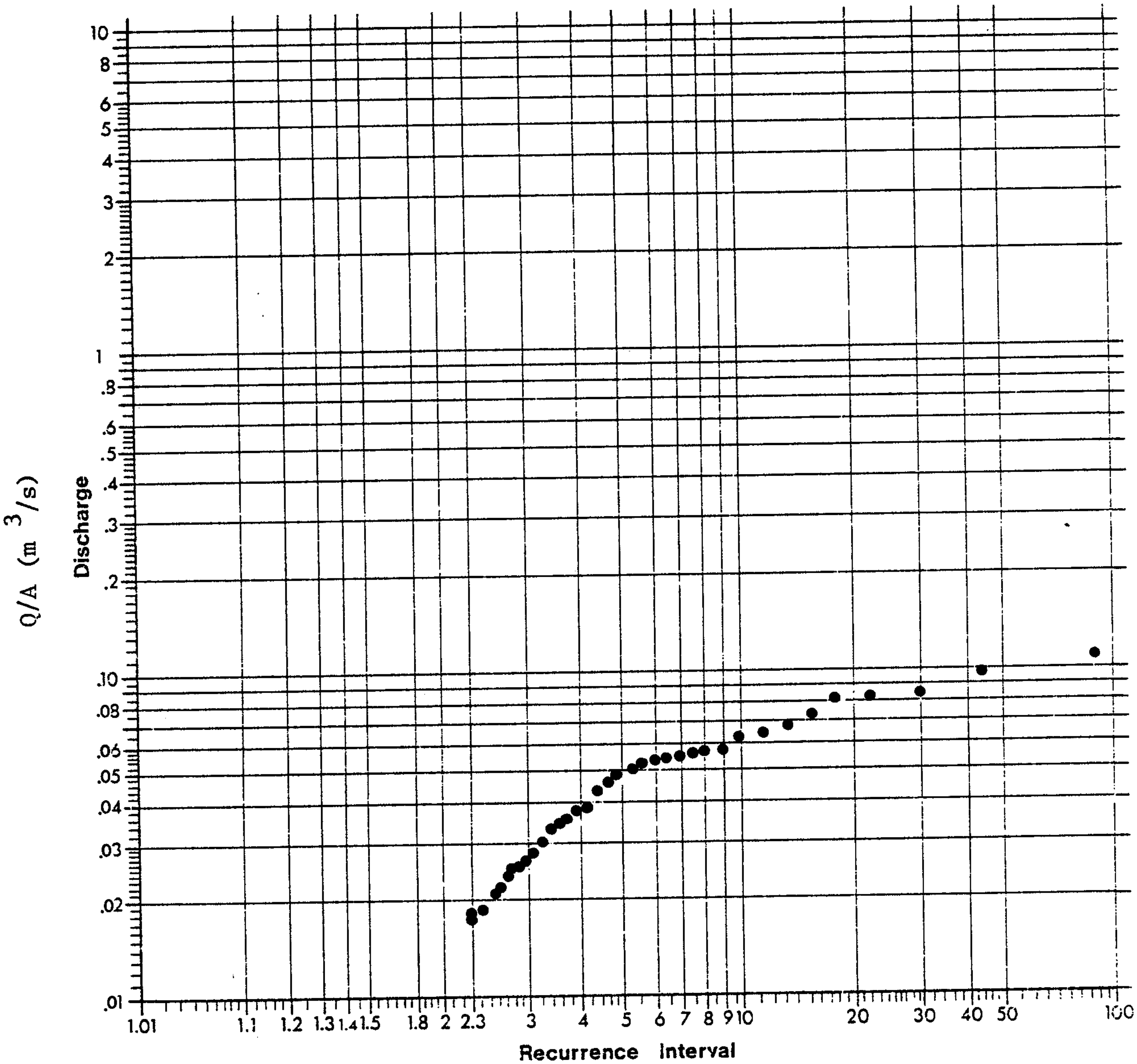


Events

FIGURE VI : 13

McKINNON CREEK

Full Series Unit Area Flood Frequency Plot

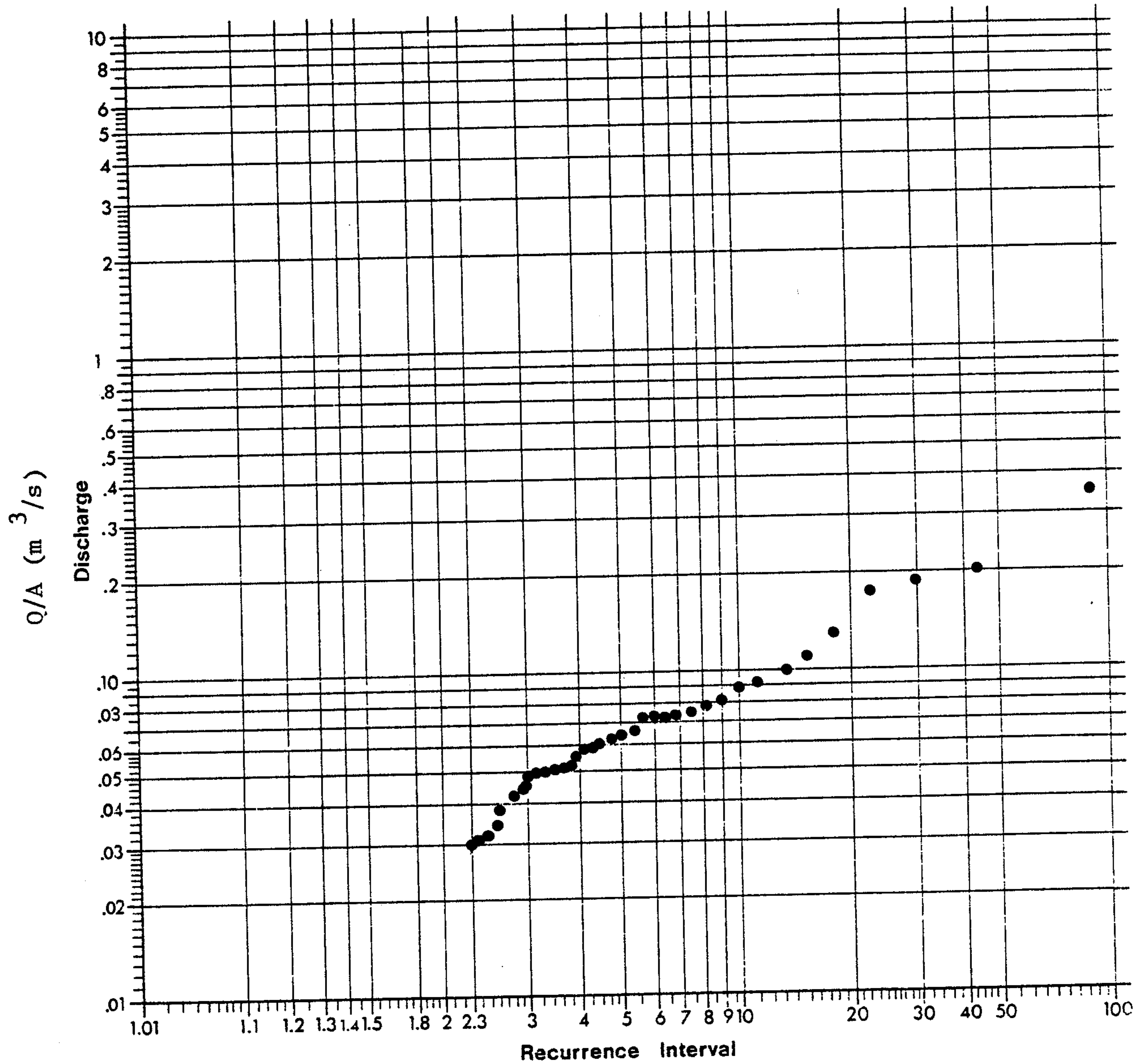


Events

FIGURE VI : 14

SCOTT CREEK

Full Series Unit Area Flood Frequency Plot



Events

FIGURE VI : 15

WILSON CREEK

Full Series Unit Area Flood Frequency Plot

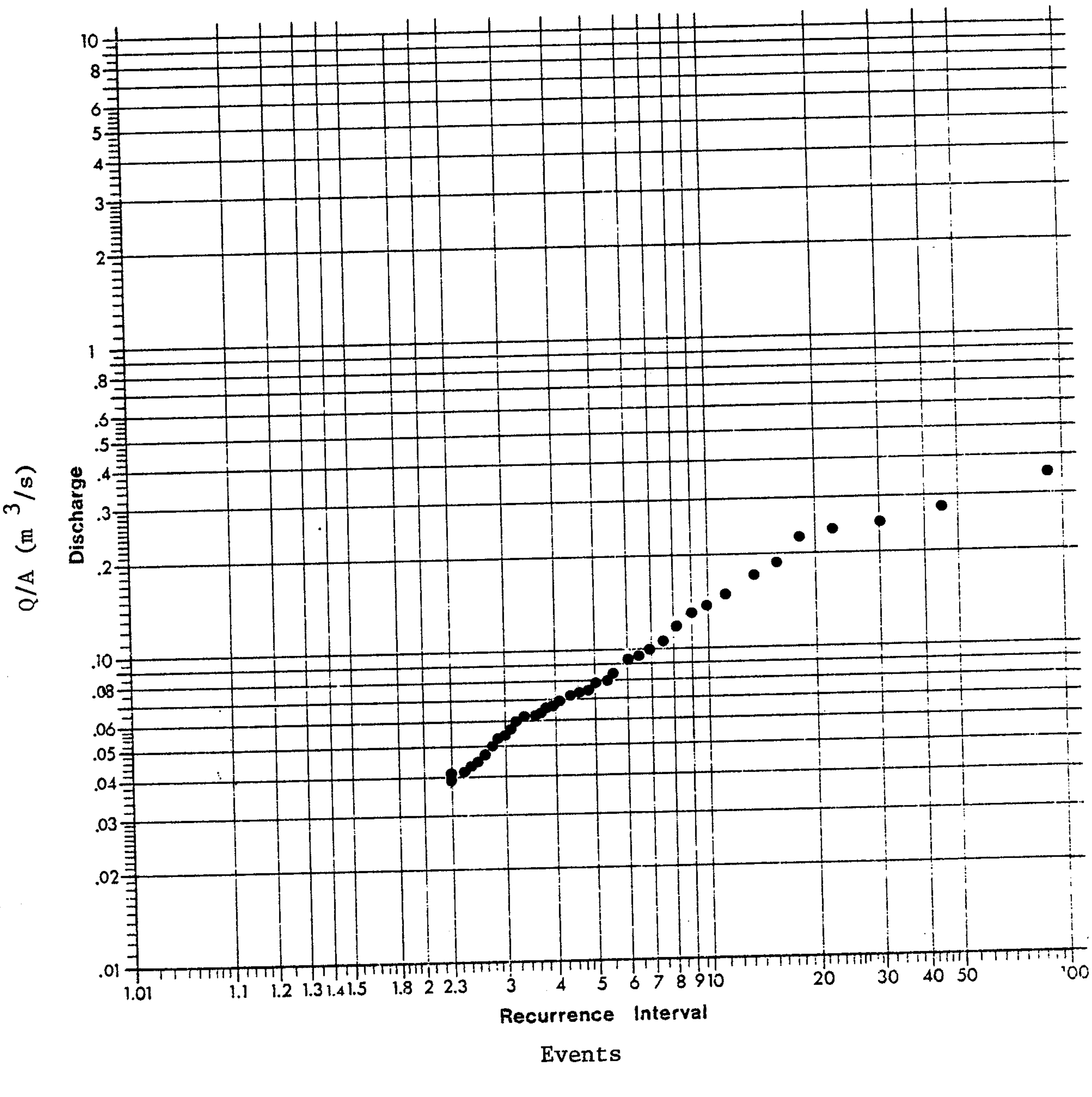


FIGURE VI : 16

REGIONAL (Wilson Cr. + Scott Cr.)

Full Series Unit Area Flood Frequency Plot