

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

AOKAUTERE BASINS: A STUDY IN MORPHOMETRY

A thesis presented in partial fulfilment
of the requirements for the Degree of
Master of Arts in Geography at
Massey University

by

NANYANG LEE

1973

ACKNOWLEDGMENTS

I gratefully acknowledge the following individuals and organisations : Dr. J.L. McArthur who supervised and offered valuable advice and criticism throughout the study; Geography Department of Massey University for providing a field work vehicle and equipment; farm owners of the study area for giving permission to carry out field work on their farmlands; Aerial Mapping Ltd. of Hastings, City Council of Palmerston North and the Manawatu Catchment Board for supplying information and topographic maps; Wellington Meteorological Office for providing the required climatic data; Messrs. C.T. Liew and A. Fleming for assistance in field work; and all the people who have assisted in the course of study.

	page
III.4 Frequency Distributions Of Lengths And Areas	23
III.5 Relation Between Area And Length	26
III.6 Drainage Density And Constant Of Channel Maintenance	
III.7 Basin Shapes	29
III.8 Summary	32
CHAPTER IV BASIN CHARACTERISTICS - RELIEF	36
IV.1 Drainage Basin Relief	36
IV.2 Erosional Surfaces	38
IV.3 Total Relief	39
IV.4 Relief Ratio	40
IV.5 Relation Between Drainage Density And Relief Ratio	42
IV.6 Channel Gradient	45
IV.7 Maximum Slope Angle	46
IV.8 Hypsometric Integral	47
IV.9 Correlation Of Relief Variables	52
IV.10 Summary	55
CHAPTER V CONCLUSIONS	58
REFERENCES	61

LIST OF TABLES

		page
Table 1	Mean And Extreme Temperatures	8
2	Earth Temperatures At Four Inches And Three Feet	8
3	Number Of Days Of Ground Frost	8
4	Rainfall In Inches	9
5	Wind Force	9
6	Wind Frequency And Force	9
7	Drainage Density (Mi/Mi ²)	28
8	Constant Of Channel Maintenance (Mi ² /Mi)	29
9	Elongation Ratio	31
10	Average Total Relief (Feet)	40
11	Relief Ratio	41
12	Observed Average Values Of Relief Ratio, Drainage Density And Length Of Overland Flow	44
13	Expected Average Values Of Drainage Density And Length Of Overland Flow Derived From The Observed Relief Ratio	44
14	Average Channel Gradient	45
15	Percentage Frequency Distributions Of Hypsometric Integral Of First And Second Order Basins, Alton And Bolton Creeks	48
16	Average Hypsometric Integrals	49
17	Table Of Correlation Coefficients	53

LIST OF FIGURES

	following page
Figure 1 Location Of The Study Area	1
2 Topographic Map of Alton And Bolton Basins	1
3 Mean Temperatures (^o F)	7
4 Monthly Rainfall (Inches)	7
5 Mean Annual Percentage Frequency And Force Of Wind Directions	7
6 Palmerston North Area : Geology	10
7 Northwest-Southeast Cross Section Of The Tiritea Formation	14
8 Cross Profile Of The Cliff Stream Terraces	15
9 Relation Of Stream Order And Number	18
10 Relation Of Stream Order And Average Length	21
11 Relation Of Stream Order And Average Area	22
12 Histograms Showing Log Distributions Of Channel Lengths	23
13 Histograms Showing Log Distributions Of Basin Areas	24
14 Relation Of Channel Length To Basin Area, Alton First Order	26
15 Relation Of Channel Length To Basin Area, Alton Second Order	26
16 Relation Of Channel Length To Basin Area, Bolton First Order	26
17 Relation Of Channel Length To Basin Area, Bolton Second Order	26
18 Frequency Distribution Histograms Of Elongation Ratio	31

		following page
Figure 19	Relation Of Basin Order And Average Total Relief	40
20	Relation Of Basin Order And Relief Ratio	41
21	Relation Of Drainage Density To Relief Ratio, Alton Creek, First Order	43
22	Relation Of Drainage Density To Relief Ratio, Alton Creek, Second Order	43
23	Relation Of Drainage Density To Relief Ratio, Bolton Creek, First Order	43
24	Relation Of Drainage Density To Relief Ratio, Bolton Creek, Second Order	43
25	Relation Of Basin Order And Channel Gradient	45
26	Frequency Distribution Histograms Of Channel Gradient	45
27	Frequency Distribution Histograms Of Maximum Slope Angle	47
28	Selected First-Order Hypsometric Curves	49
29	Selected Second-Order Hypsometric Curves	51
30	Third-Order Hypsometric Curves	51
31	Fourth-Order Hypsometric Curves	52

LIST OF PLATES

	following page
Plate 1 Cliff Stream Terrace	15
2 Headwater Drainage Areas	29
3 The Middle Reaches Of Alton Creek	39
4 Slope Break Between The Interfluve Surface And Valley Side Slope	50

CHAPTER I INTRODUCTION

I.1 Location Of The Study Area The location of the study area is shown in Figure 1. It comprises part of the terrace to the south-east of the Manawatu River just opposite Palmerston North City centre. Almost all the area of the two drainage basins studied is within the boundary of Palmerston North City which has been expanded since 1967 to include land on this side of the river. This suburb is generally known as Aokautere.

Both streams selected for study are secondary tributaries to the Manawatu River (Figure 2). They are here designated as Alton Creek, on the left, and Bolton Creek on the right, and the trunk stream they join before entering the Manawatu River is named Cliff Stream. The exact location of the study area can be found on NZMS 1 N149, the "Palmerston North" sheet, between grids E130 and E150, and N290 and N330. The township of Aokautere is about one mile northeast of the study area.

I.2 Aim The primary aim of the study was to investigate the characteristics of the fluvial landforms of these two basins which are believed to represent the overall characteristics of all drainage basins in the Aokautere area, and to seek explanation of the characteristics in terms of existing knowledge and ideas of

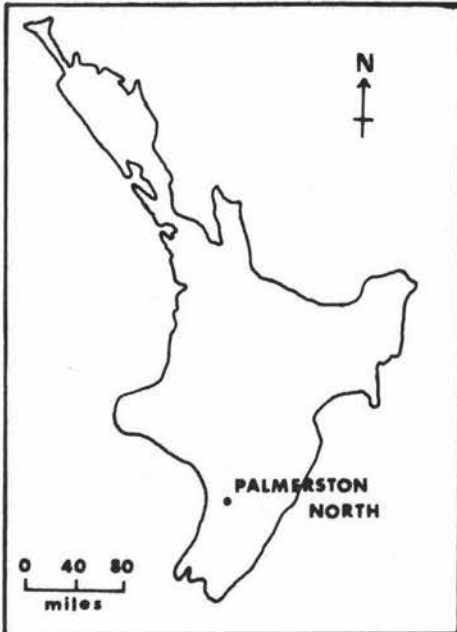


Fig. 1

Location Of The Study Area

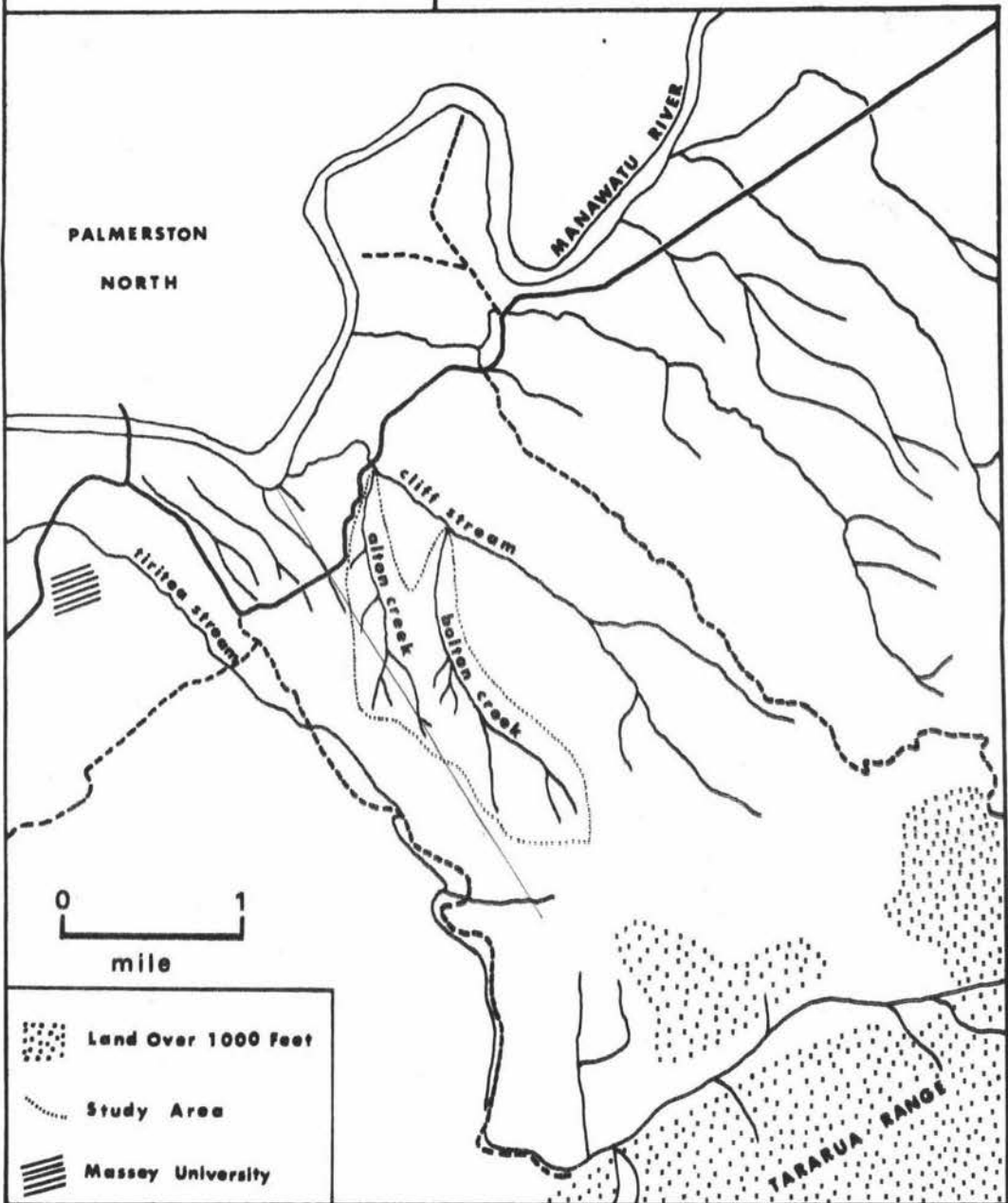


Fig. 2 Topographic Map Of Alton And Bolton Basins



the geomorphological history of the area.

The study was based upon several hypotheses. The first was that these drainage systems are generally in the state of disequilibrium but are evolving rapidly. The second was that the history of the formation of the present day relief in the Aokautere drainage basins is related to the denudation chronology of the main Manawatu River. The types of processes which developed the Aokautere basins may have been different from those operating in the Manawatu River, however, because the deposition of loess from the Manawatu River bed during periglacial climatic conditions might have interrupted the development of an already established drainage system on the original terrace surface. The third hypothesis was that within a single drainage basin are features of differing age, the age increasing with increasing order. The corollary is that morphometric properties tend to be similar among basins of same order.

I.3 Data A set of photogrammetric maps with scales of 1 inch to 2 chains and 1 inch to 6 chains with contours of five feet intervals was the primary source of quantitative landform data. Two missions of aerial photographs taken in 1950 and 1965 were also used. Geological information was derived from published and unpublished studies, and field work.

I.4 Techniques Most data were measured directly from maps and aerial photographs or derived

through applications of formulae. From the maps, linear values were measured with a chartometer or strings, and areal values by polar planimeter. Aerial photographs were studied stereoscopically by pocket and mirror-type stereoscopes.

Drainage basins were defined on the photogrammetric maps using the contours and aerial photographs. Streams were identified by contour indentation in the first instance, and then checked on the aerial photographs and in the field. Conversely, all streams identified in the field and on the photographs were located on the contour map. The method of ordering followed is as outlined by Strahler (1952:1120) in which all finger tip streams without tributaries are first order streams and every junction of two streams of the same order forms a segment of higher order.

I.5 Previous Research The most detailed and comprehensive studies on the geomorphology and geology of this area are those of Rich (1959) and Fair (1968). Rich studied the geological structure of the region, including faulting and stratigraphy. The formation on which the Aokautere streams are developed, called by him the Tiritea Formation, was described in detail. Fair gave a comprehensive account of the denudation chronology of the lower Manawatu River, especially the effects of the Pleistocene climatic fluctuations upon the formation of the Manawatu River terraces. She came to the conclusion that although the Manawatu Region is

tectonically unstable, the fluvial landforms of the Manawatu River valley have been mainly shaped by the effects of the past climatic fluctuations rather than by tectonic factors.

However, interest in the area goes back to 1910 when Adkin first described the "raised beach formation" of the Horowhenua plain. He considered the terrace bounding the Tararua foothills as a "raised beach formation" which was deposited under the Pleistocene sea. He distinguished the two significant layers of conglomerates as beach gravels deposited first when the sea was advancing and second when the sea was retreating.

Cotton (1918) named this same formation the Otaki Series. He postulated that the formation was old dune sand deposits whose material is similar to that of the present beach and the associated dunes. He described the gently undulating surface of the formation as a surface of erosion due to the effects of peneplanation.

In 1948, Oliver studied in detail the structure and history of the Otaki Series. Otaki Sandstones, as he named the formation, were identified as of marine origin, probably deposited under very shallow sea conditions. His study area came only to the southern bank of the Kahuterawa Stream. The equivalent formation to the north of the stream is Rich's Tiritea Formation.

Cowie (1961, 1964) studied the origin and distribution of the loess and Aokautere Ash in the Manawatu

region. He contended that the loess was deposited from the Manawatu river bed during the late Pleistocene. The Aokautere Ash was erupted during a late stage of the last glaciation, having been dated as 21,000 \pm 500 years B.P.

CHAPTER II CLIMATE AND GEOLOGY

II.I. CLIMATE The major climatic elements that affect runoff and erosion are temperature, rainfall, and wind. These three elements are here taken to describe the climate of the study area and they are summarised in Tables 1 to 6. The data are based upon records of the period from 1947 to 1966 for Palmerston North D.S.I.R. weather station which is located about two miles west of the study area. Its altitude of 110 feet above sea-level is approximately at the level of the basin mouth of the Alton and Bolton Creeks.

II.I.1 Temperature Table 1 shows a summary of records of mean temperature, mean daily temperature, and mean daily maximum and minimum temperatures, over the twenty year period. The temperature in general is mild, with an annual average temperature of 55.4°F , averaging just over 60°F in summer and not lower than 45°F in winter. The average range between warmest and coldest months is 18°F , which is only a little larger than the mean diurnal range. Mean daily maximum could reach 74°F in summer while a mean daily minimum of around 40°F during winter is common (Figure 3).

Temperature readings at four inches and three feet underground are shown in Table 2. These temperatures,

though warmer than that of the air in summer, and colder in winter, are of very small variation compared to the air temperature.

Table 3 shows the average number of days of ground frost. The occurrence of ground frost takes place mainly during winter months of June, July and August. But the number of occurrences on the whole is so few that its effect on the weathering of rocks is insignificant. Snow has never been recorded as having fallen in the area for the past twenty years.

II.I.2 Rainfall Rainfall of the area is moderate but reliable. Although there is no marked dry season, rainfall minima occur in March and September. Monthly maxima occur in early summer and early winter. Winter has a comparatively large amount of rain while summer has higher frequencies of maximum daily fall. However, over the twenty year period, not a single daily fall has ever exceeded three inches. Table 4 shows mean annual rainfall and number of rain days. Figure 4 shows the average monthly rainfall distributions.

II.I.3 Wind As compared to other places under the Middle New Zealand Zone climate⁽¹⁾, Palmerston North is relatively calm. Table 6 and Figure 5 show that the average percentage of calm days on the Beaufort Scale is 13.5 per cent a year. Besides, the winds are not strong. The average wind force ranges from 1.8 to 2.7 on the Beaufort Scale (Table 5).

Fig.3 Mean Temperatures

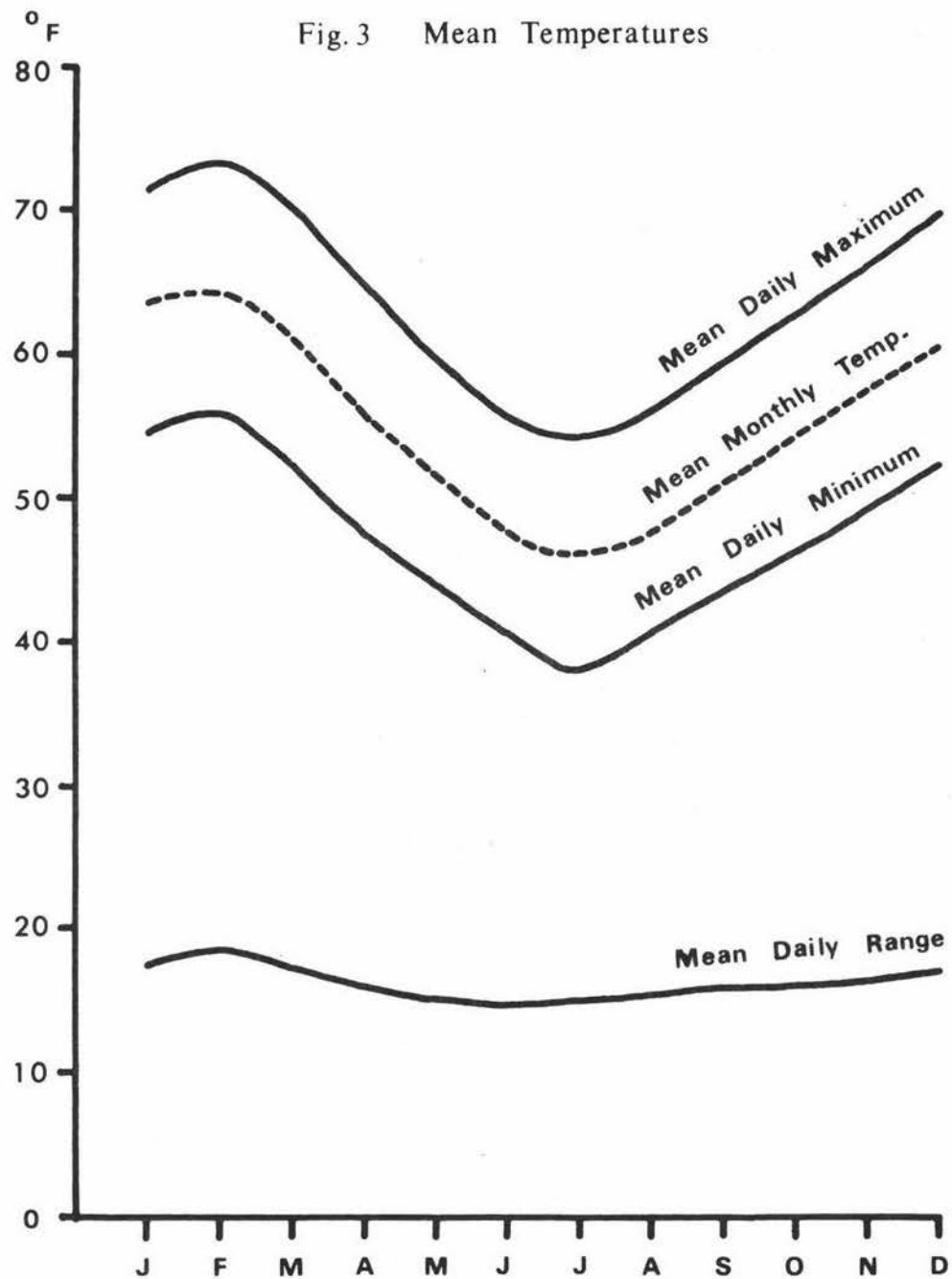


Fig.4 Monthly Rainfall

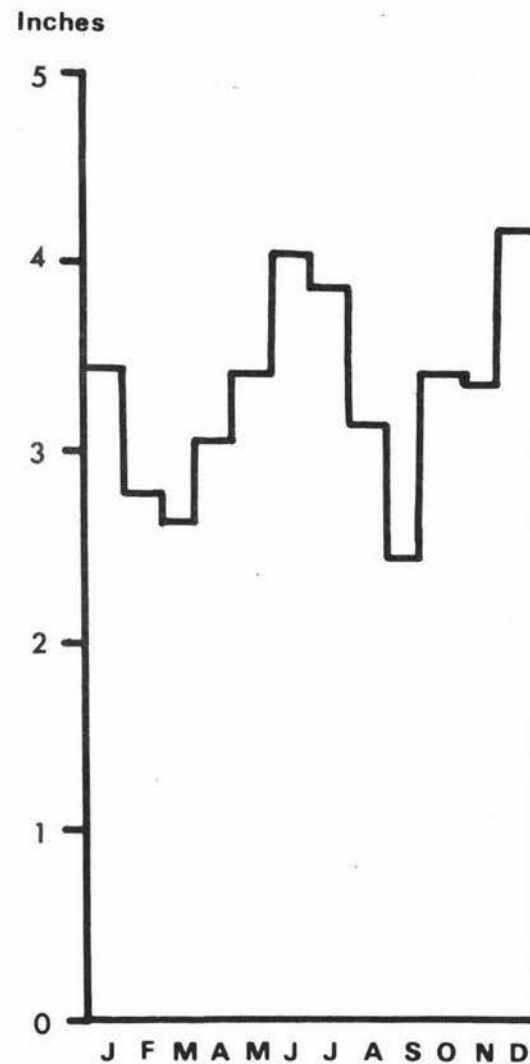


Fig.5 Mean Annual Percentage Frequency And Force Of Wind Directions

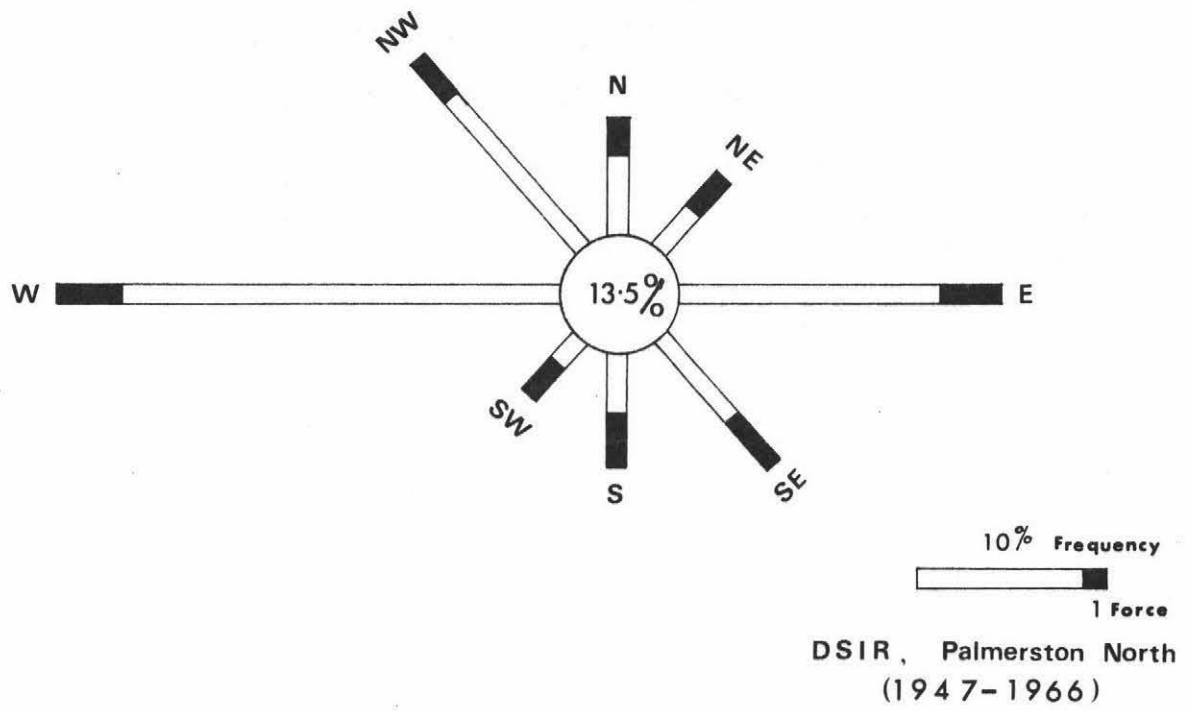


Table 1 Mean and Extreme Temperatures (°F)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Temp.	63.3	64.3	61.4	56.7	52.1	47.9	46.5	48.1	51.5	54.8	57.8	61.2	55.5
Mean Daily Max.	72.1	73.3	70.0	64.9	59.8	55.2	54.0	55.7	59.4	62.8	65.9	69.6	63.6
Mean Daily Min.	54.5	55.3	52.7	48.5	44.3	40.6	39.0	40.5	43.7	46.8	49.7	52.8	47.4
Mean Daily Range	17.5	17.9	17.3	16.3	15.4	14.6	15.0	15.2	15.6	16.0	16.2	16.8	16.2

D.S.I.R., Palmerston North (1947-1966)

Table 2 Earth Temperatures at Four Inches and Three Feet

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
At Four Inches	65.9	65.5	61.6	55.7	50.3	46.1	44.0	45.4	49.6	54.8	59.8	63.8	55.2
At Three Feet	66.0	67.1	65.6	61.7	57.1	52.8	49.8	49.8	52.1	55.6	59.7	63.4	58.4

Massey University, Palmerston North
(1947-1966)

Table 3 Number of Days of Ground Frost

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Days	0.1	0.4	0.8	3.0	6.5	10.7	13.6	11.0	5.9	2.6	0.8	0.1	52.8

Massey University - (1947-1960)
D.S.I.R., Palmerston North - (1961-1966)

Table 4 Rainfall in Inches

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall	3.44	2.78	2.63	3.05	3.41	4.03	3.86	3.15	2.41	3.41	3.38	4.17	39.72
No. of Raindays	11.5	9.5	12.0	13.5	15.0	17.0	17.0	15.5	13.5	15.5	15.0	14.0	169.0

D.S.I.R., Palmerston North (1947-1966)

Table 5 Wind Force

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Wind Force (Beaufort Scale)	2.5	2.3	2.2	1.9	1.8	1.8	1.8	2.0	2.4	2.7	2.8	2.7	2.2

D.S.I.R., Palmerston North (1947-1966)

Table 6 Wind Frequency and Force

	N	NE	E	SE	S	SW	W	NW	Calm
Wind Days	22	18	62	32	22	15	97	47	50
Ave. Force (Beaufort Scale)	1.9	2.1	3.0	3.2	2.7	2.2	3.2	2.7	

D.S.I.R., Palmerston North (1947-1966)

Gales are not common; over the twenty year period of observation, there were only 15 gales recorded.

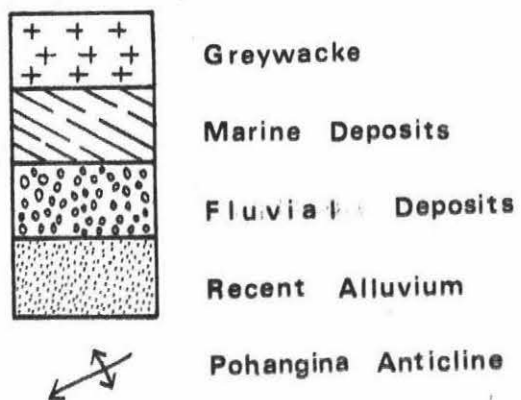
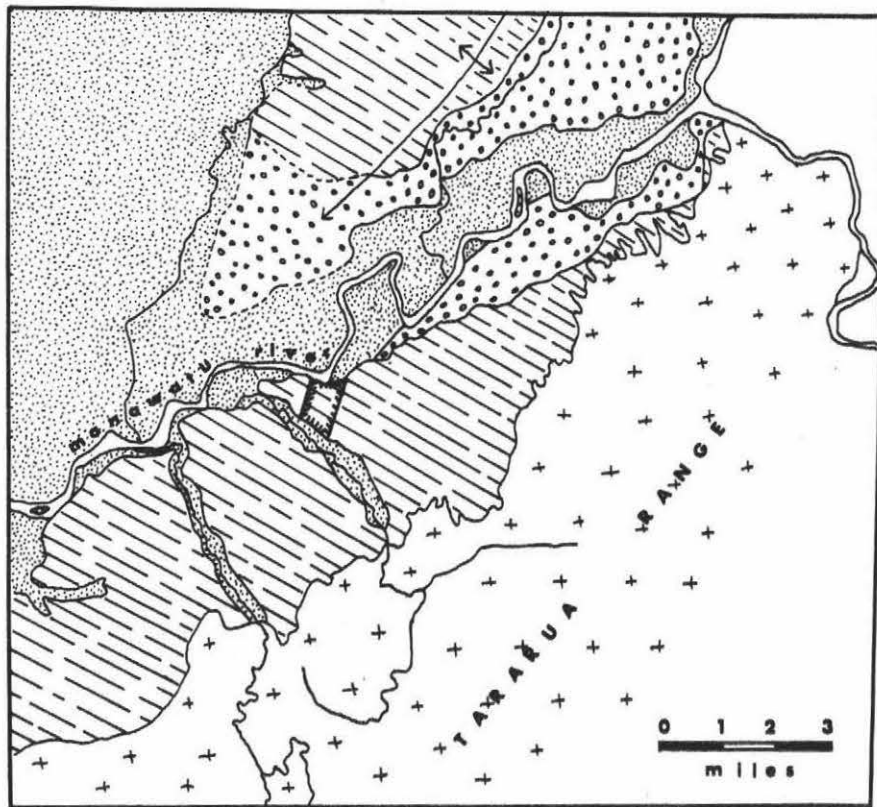
The dominant wind is from the west. The westerlies are most prevalent in the winter months and is in general stronger than other winds. Other prevailing winds are easterlies and north-westerlies.

II.II. GEOLOGY The terrace on which the Aokautere Streams are developed is known as the Tokomaru Terrace (Cowie, 1961:12), and its formation was described by Rich (1959:77) as the Tiritea Formation.

II.II.1 Stratigraphy It has been generally believed that the Tiritea Formation is an emerged marine terrace which was laid down during the Hawera Transgression and is a similar formation to the Otaki Sandstones south of Kahuterawa Stream (Oliver, 1948). The unit further north of Aokautere, the Tua Paka Formation, is also similar in many respects to the Tiritea Formation (Rich, 1959:77). In Figure 6 all the three units are collectively grouped under marine deposits, despite the age that decreases southwards.

The Tiritea Formation consists mainly of fine sandstones, siltstones, and conglomerates. At the river bluff near Anzac Park on the southeast bank of the Manawatu River where the marine terrace comes right to the edge of the river without being bounded by any river terraces, a very clear exposure of the succession

Fig.6 Palmerston North Area : Geology



of strata in the Tiritea Formation is observed. There are five major strata in the formation, which from below are silt, conglomerates (12 feet), fine sand (12 to 15 feet), conglomerates (15 to 20 feet), and sand-silt (75 feet)(Rich,1959:89-90). Overlying the surface of the marine deposited terrace are masses of airfall materials with thicknesses ranging from two to twenty feet. These airfall masses consist mainly of fine silt and some pumice ash. Cowie (1961:24,1964) identified the fine silt as loess and suggested that it had originated from the local aggradational river sediments of the late Pleistocene epoch. These fine particles were deflated by the then prevailing north-westerly winds and deposited to the southeastern regions of the river beds⁽²⁾. About half way through the thickness of the loess deposits is a band, two to five inches thick, of pumice ash called Aokautere Ash (Cowie,1961:21,1964a). The ash band is not observed in Alton and Bolton basins, either because it is heavily masked by the enclosing loess or because it has been eroded away.

The two strata of conglomerates separated by a layer of fine, loose sand are significant members of the Tiritea Formation. Both conglomerates are poorly consolidated with a sandy matrix and contain sub-angular to rounded greywacke pebbles averaging between one and two inches in their longest dimension. Lenses of very fine sands are found in both bands of

conglomerates but the upper stratum is relatively more sandy and less well sorted. A slight change of facies is observed in both strata between the bluff and several exposures towards the southeast. As far as the study area is concerned, the major strata observed on the bluff extend very continuously towards the southeast, that is, into the headwater areas of the Alton and Bolton Creeks. The general direction of flow of drainage systems on the terrace is from southeast to northwest, while Alton and Bolton Creeks flow almost at right angles to this direction.

II.II.2 Relief And Geomorphological History

The relief of the study area is dominated by the broad flat Tokomaru Terrace which forms the extension of the foothill region of the Tararua Range. The surface of the terrace is about 200 feet above the Manawatu River at the Anzac Park location and rises to about 500 feet where unconformities are found between the terrace formation and the greywacke of the Tararua Range. The actual Tararua foothill is overlain by the marine terrace thus resulting in an unusually broad and flat foothill extending for about three miles between the Manawatu River and Tararua Range. Alton and Bolton Creeks are developed on this terrace foothill. The entire drainage systems are within the terrace boundary with none of the tributaries being extended into the Tararua Range.

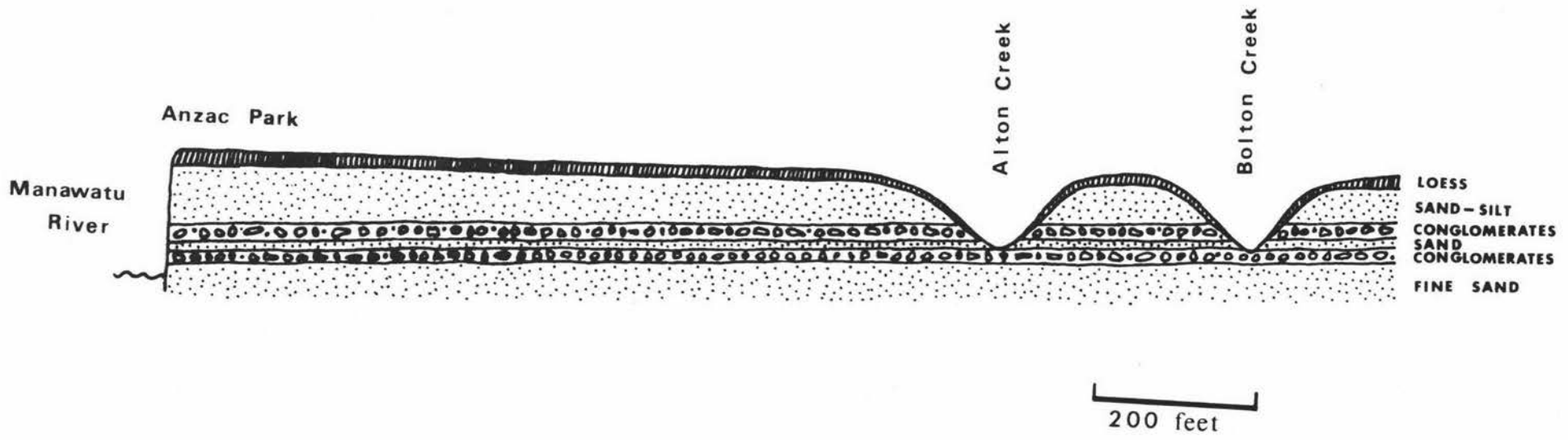
The retreat of the Hawera Sea and the emergence of the Tokomaru Terrace can be conveniently taken as the beginning of the geomorphological history of the area. Fair (1968:83) suggested 45,000 years B.P. as the date of the complete emergence of the Tokomaru Terrace. The emergence brought an end to the marine depositional process and at the same time the commencement of sub-aerial erosion on the surfaces of the marine terrace.

The interval between the exposure of the marine surfaces and the fall of the loess was about 8,000 years (Fair, 1968:83). Within this 8,000 year period, sub-aerial erosion could have been vigorous. At many localities in the area there is a gap in the stratigraphic sequence between the air fall materials and the underlying upper conglomerates. The absence of the uppermost sand-silt stratum of the Tiritea Formation in these localities suggests that this soft stratum was completely eroded away by processes of sub-aerial erosion within this 8,000 year interval. The Aokautere Streams were probably initiated as consequent streams flowing on slopes of initial surfaces when the marine terrace was first exposed. As the sand-silt stratum was soft and easily eroded, the drainage patterns could have been well established when the loess first began to fall. However, the upper conglomerates which underly the uppermost sand-silt stratum comprise a very much more resistant layer, which eventually might have slowed down the rate of erosion to a considerable extent.

The fall of the loess interrupted the development of the streams and it was in this period that the inception of the present day pinnate drainage pattern occurred.

Figure 7 illustrates the present northwest-southwest cross section of the Tokomaru Terrace. The diagram is bounded by the Manawatu River at the left where the marine terrace ends as a cliff at the bluff. To the right the profile runs across the middle reaches of Alton and Bolton Creeks. The strata of the Tiritea Formation are continuous near the river bluff, but become less continuous inland. Furthermore, in many localities the uppermost layer of sand and silt has been eroded away and its contact with the upper conglomerates has been replaced by airfall materials. Highest order segments of both Alton and Bolton Creeks have developed to the level of the lower conglomerates which offer rather strong resistance to downcutting. The lower conglomerates, as have been described, are less sandy and better sorted than their upper counterpart and so the resistance met at this layer naturally is greater than that encountered when the streams first reached the upper layer. However, most of the lower order streams in the catchments are still on the loess and sand-silt strata. At the mouth of both streams where they join the Cliff Stream, the stream levels have cut through the conglomerates and have reached the lowest stratum of the Tiritea Formation observed

Fig. 7 Northwest-Southeast Cross Section Of The Tiritea Formation



on the bluff, the stratum of silt and clay.

At the lower Cliff Stream valley a well-marked river terrace has been formed (Plate 1). The height of this terrace is ten to twenty feet higher than the Ashurst Terrace nearby in the Manawatu Valley. The Ashurst Terrace, according to Fair, was deposited in the Kumara-2 second interstadial period (1968:83). The evidence obtained in the Cliff Stream terrace, however, suggests that it is a degradational terrace cutting through the various strata of the Tiritea Formation (Figure 8). Though the height difference and nature of the formation distinguish them as different terraces, they are of very similar age. First, the absence of Aokautere Ash on both the Ashurst and Cliff Stream terraces suggests that they were formed only after the fall of the Aokautere Ash; second, the thickness of loess that covers both terraces is almost the same. Cliff Stream terrace has an average thickness of three feet while Ashurst Terrace two and a half feet. This difference in the nature of the formation of the terraces formed at almost the same time suggests the possibility that processes in the Manawatu River were different to those in its tributaries during the Pleistocene epoch. The small tributaries widened their valley floors by lateral corrasion while the trunk stream was transporting large quantities of debris.

Fig.8 Cross Profile Of The Cliff Stream Terraces

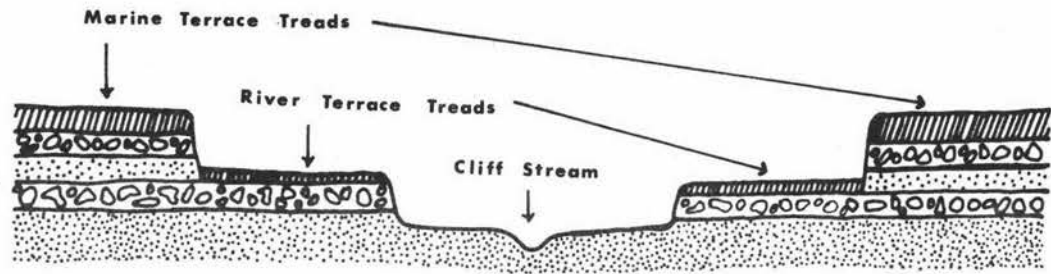




Plate 1 Cliff Stream Terrace. The tread is predominantly flat and is well marked at the edges. The marine terrace riser, masked with loess and fine-sand, is dominated by terracettes.

NOTES

- (1) Garnier (1958) classified climates of Taranaki, Manawatu, Wellington-Hutt, and Nelson areas under the Middle New Zealand zone type.
- (2) The deposition of loess could have begun as early as the Kumara-2 first advance in the Otiran Glaciation (Fair, 1968:83), and ended at least earlier than 3,000 years B.P. (Cowie, 1964 :392). The thickness of the deposits is greater near the river banks than those further inland.

CHAPTER III BASIN CHARACTERISTICS —
AREAL AND LINEAR

The recent recognition of geometrical relationships among various properties of drainage basins has led to the formulation of morphometric laws. The explanation of drainage basin characteristics by subsumption under laws has achieved the aims of classifying various types and forms of drainage basins and of describing drainage basin characteristics. This chapter and chapter IV analyse the morphometric properties of Alton and Bolton basins with the aim of assessing the degree of conformity of their compositions to the existing morphometric laws. The analysis explains the extent to which the components of the studied drainage basins conform to or depart from the characteristics predicted by the morphometric laws. Not all the aspects of the laws are conformed to; in many cases, additional explanation is needed.

Both the areas of Alton and Bolton drainage basins are small (Figure 2). Alton Creek drains an area of 8,752,362 square feet with a total channel length of 26,182 feet, and Bolton Creek has an area of 8,867,544 square feet and 29,668 feet of channel. Despite their small sizes, the streams are fourth order in rank, with drainage densities of 13.1 for Alton and 13.4 for Bolton. These densities are considered as moderate for basins in this type of climate under which drainage densities

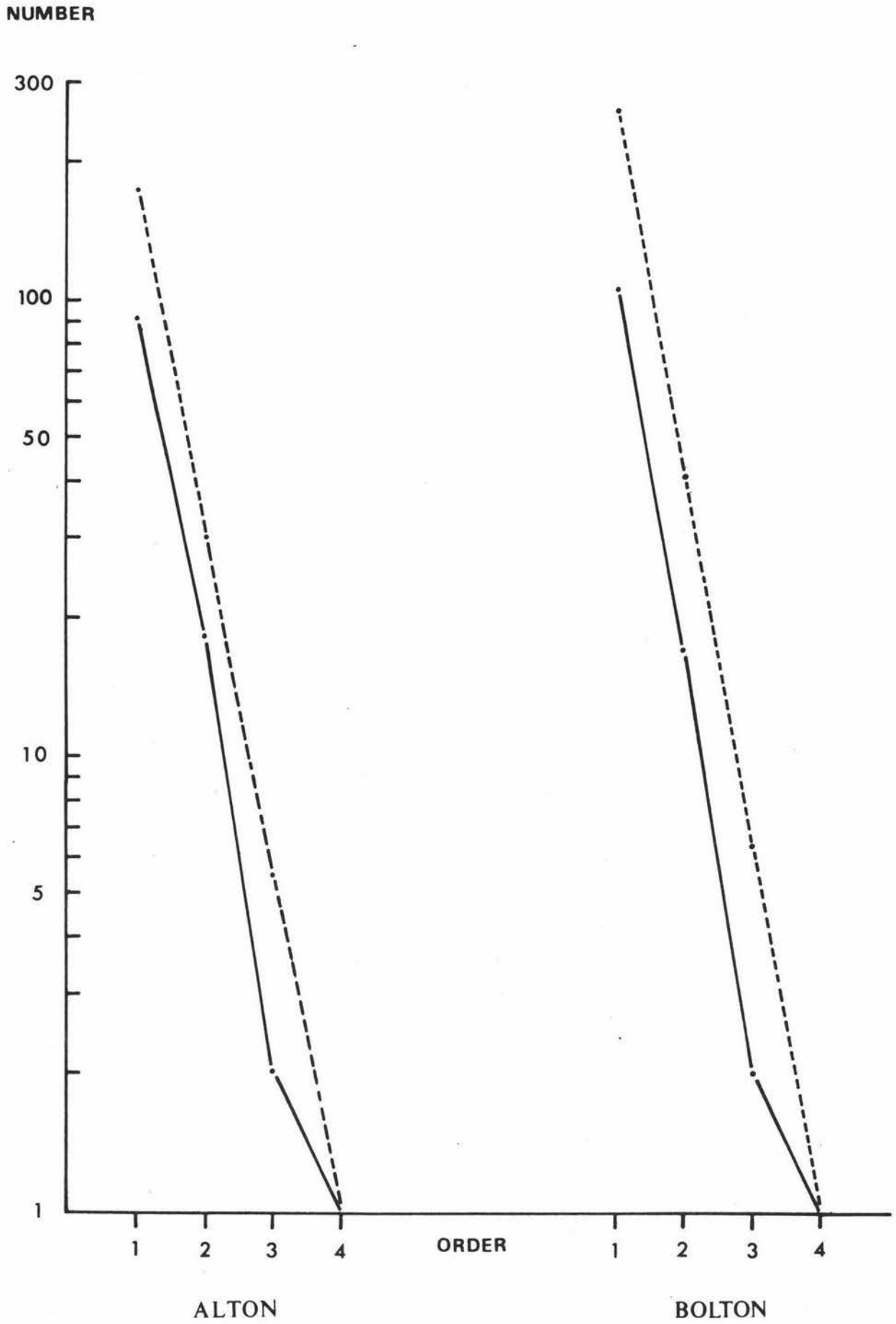
normally range between 5 and 20 (Schumm, 1956:602).

Both the Alton and Bolton Creeks are intermittent streams. For most of the year the channels are dry. Even channels of highest order dry up during the summer months leaving only small pools of water scattered along deeper sections of the lower reaches. In the winter months, the lower sections of the fourth order streams normally contain an average depth of water of between eight and ten inches and have an average channel width of two and half feet. The estimated discharge under such conditions is about 2.5 cusecs⁽¹⁾. The beds of these fourth order sections are floored by greywacke pebbles transported from the upper reaches of the streams or being scoured from the local channel banks; along the valleys, miniature floodplains are formed. Channels of first and second orders are mostly incipient valleys which contain water only immediately after intense rainfalls.

III.1 Stream Numbers Horton (1945:291) stated the Law of Stream Numbers⁽²⁾ as :

"The numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio." The relationship is expressed exponentially in Figure 9 for Alton and Bolton Creeks. Although the graphs of first to third orders are reasonably straight, especially that of the

Fig. 9 Relation Of Stream Order And Number



Bolton Creek, both graphs display slight concavities at the lowest ends. This indicates that the observed numbers of first, second and third order channels are proportional to each other but not to the highest or fourth order number.

Assuming that both creeks continue to develop so as to maintain their present weighted mean bifurcation ratio⁽³⁾, and also the fourth order status, the geometrical regressions of both creeks would appear as the dotted regressions in Figure 9. At this theoretical stage, regressions of both creeks would be straight.

A comparison of the observed regressions with the theoretical regressions indicates that the developments of the stream systems, although near parallel to the theoretical pattern of development, according to Horton's law of stream numbers, are still at some stage away from the described theoretical stage.

The distribution of stream numbers is connected with the pattern of the drainage system itself. The drainage pattern of the Alton and Bolton Creeks resembles the pinnate drainage pattern described by Parvis (1949), where the lower order channels join the main stream in a parallel manner. Von Bandat (1962) described such a pattern as dendritic-pectinate and associated it with loess formation. In Alton and Bolton basins, many of the **first and second order** streams join the trunk orders directly without passing through orders in between. This

has resulted in the high bifurcation ratio, especially that between second and third order streams, because a large proportion of second order channels join the fourth order segment without passing through the third order channels.

It could be suggested that the uppermost layer of loess and its underlying layer of siltstone and fine-sandstone strata of the Tiritea Formation have contributed to the formation of such a drainage pattern. Almost all the first and second order streams flow on these easily eroded strata and the development of channels is rapid. On the other hand, part of the third and fourth order segments of both creeks have developed into the lower strata of the Tiritea Formation which are more resistant than the two uppermost layers. The development of channels thus is more pronounced at the lower orders than at higher orders.

III.2 Stream Lengths The length component used in this study is the accumulated length⁽⁴⁾ rather than the segment length. This reduces the effect of the drainage pattern to a minimum.

The Law of the Stream Lengths⁽⁵⁾ was stated by Horton (1945:291) as : "The average lengths of streams of each of the different orders in a drainage basin tend closely to approximate a direct geometric series in which the first term is the average length of streams of the first order and the ratio is the stream length

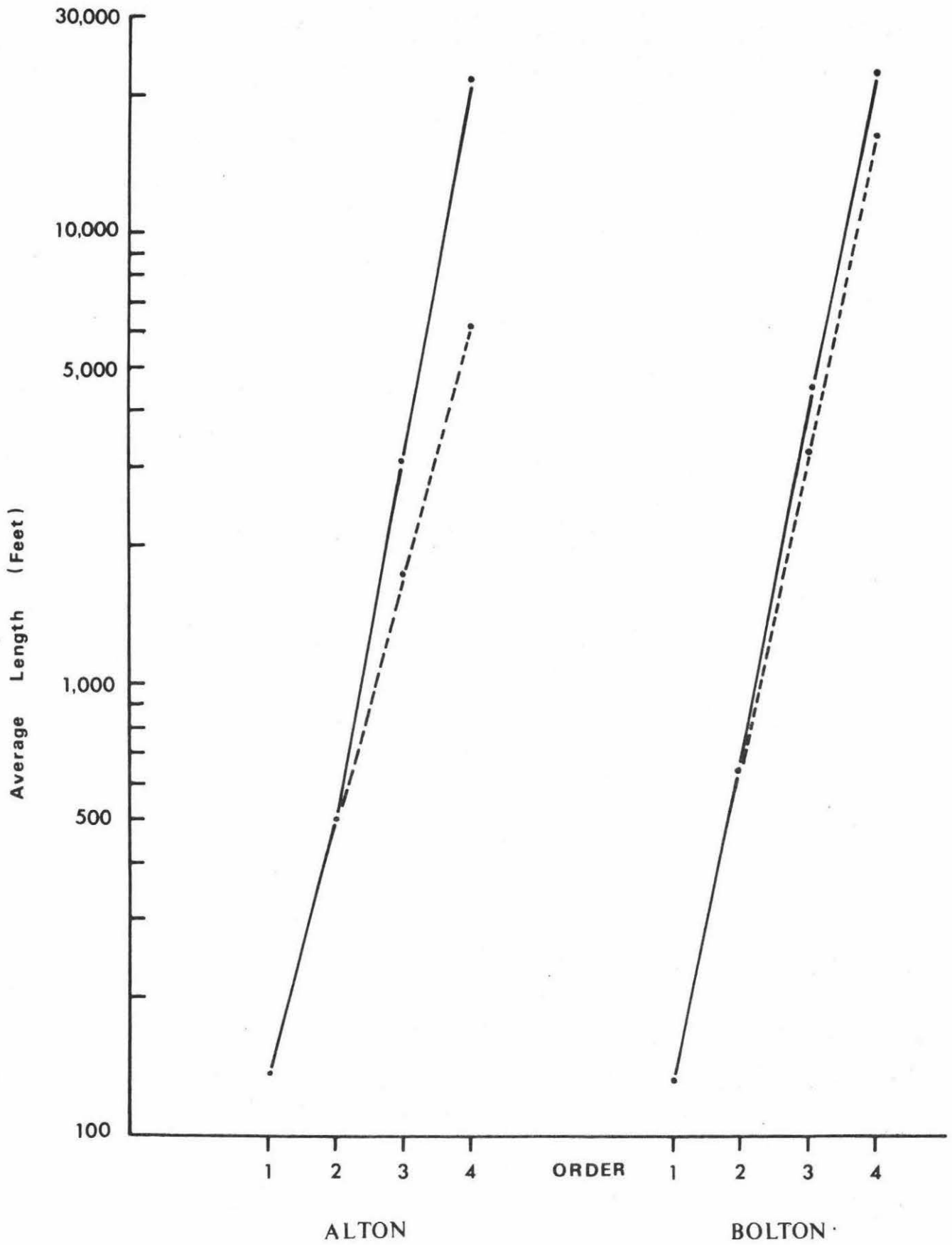
ratio". Figure 10 illustrates the exponential relationships between the average accumulated lengths and orders. The dotted regressions are the theoretical regressions of both creeks obtained according to the law.

The weighted mean stream length ratio of Alton Creek is 3.6 and that of Bolton Creek is 5.0. As stream length ratio is obtained by dividing stream length of the order by stream length of the next lower order, and as the basic stream lengths (first order stream lengths) are nearly the same for both creeks, it could be deduced that the ratio between higher and lower order stream lengths in Alton Creek is lower than that in the Bolton Creek. This has resulted in the considerably shorter lengths in the theoretical regression of the Alton Creek than that of the Bolton's.

A comparison between the observed and theoretical regressions shows that at the first and second order basins, the lengths of observed and theoretical stage are the same, but the difference increases with increasing order, especially for Alton Creek. This indicates a stage of inequilibrium relationships between the lengths of lower and higher orders, and is especially obvious in the Alton Creek.

III.3 Basin Areas Schumm (1956:606) proposed the Law of Basin Areas⁽⁶⁾ as : "The mean drainage basin areas of streams of each order tend to

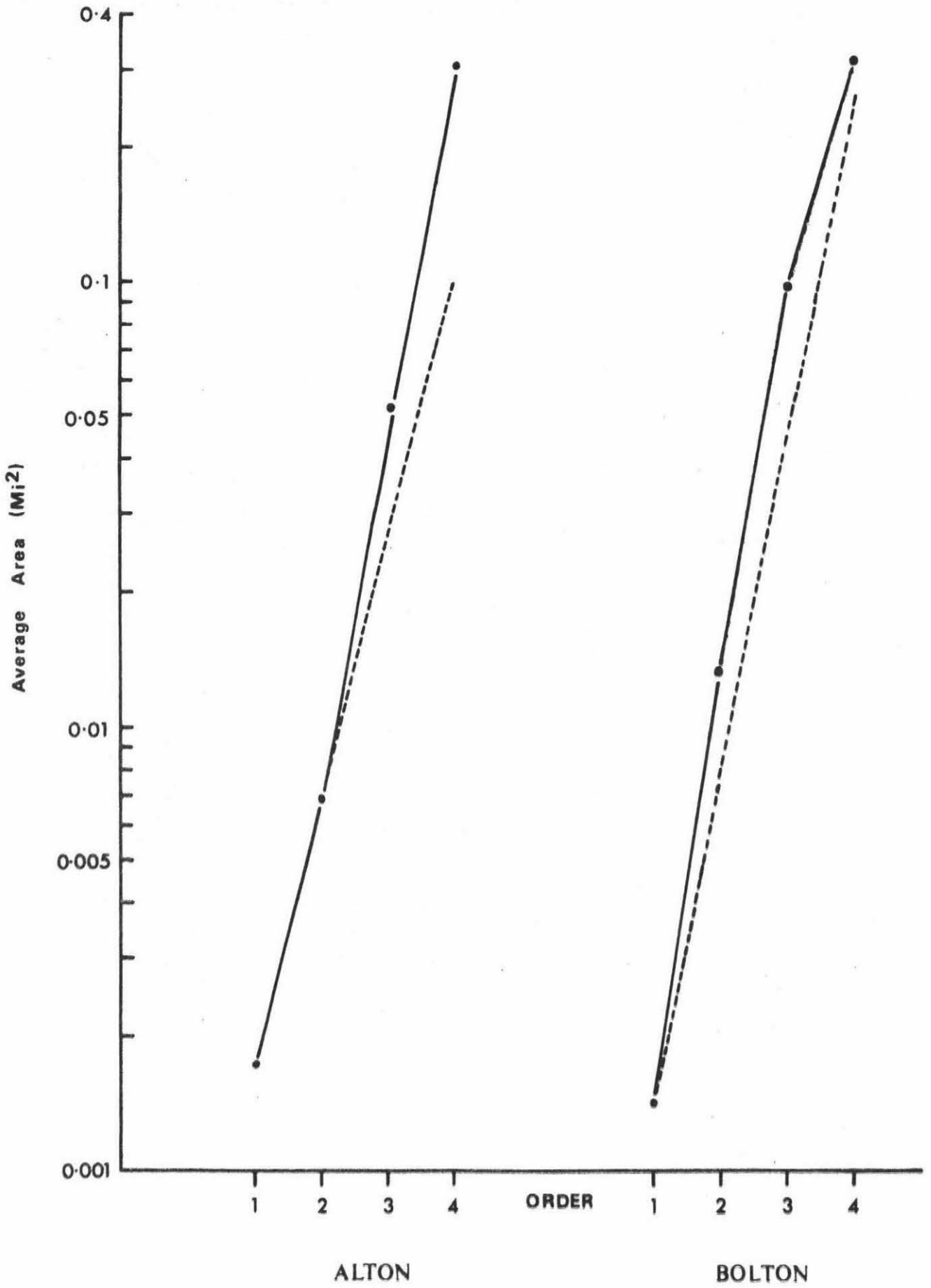
Fig.10 Relation Of Stream Order And Average Length



approximate closely a direct geometric series in which the first term is the mean area of the first order basins and the ratio is the basin area ratio". Figure 11 shows both observed and theoretical regressions for both creeks. These areal regressions show a similar regression pattern as that of the length regressions. The Alton Creek's graph resembles that of Figure 10 showing average lengths where the expected basin areas of the higher orders are considerably lower than those of the Bolton Creek. The observed and theoretical regressions of Bolton Creek are very close together except in second and third orders which is caused by the presence of two anomalous second order tributaries in the headwater area of Bolton Creek.

It can be concluded that the numbers, lengths and areas of Alton and Bolton Creeks do not conform exactly to the laws of morphometry. This indicates that the relationships between the variables and orders are still in an unbalanced stage where further development will be needed before the relationships in the systems reflect the stage of equilibrium as stated in the laws. Alton Creek shows a greater deviation in regression patterns of lengths and areas. The cause could be attributed to the loss of its headwater areas to the Tiritea Stream. It is believed that at a stage in the late Pleistocene epoch, the Tiritea Stream, which was then at a higher level than its present day level,

Fig.11 Relation Of Stream Order And Average Area



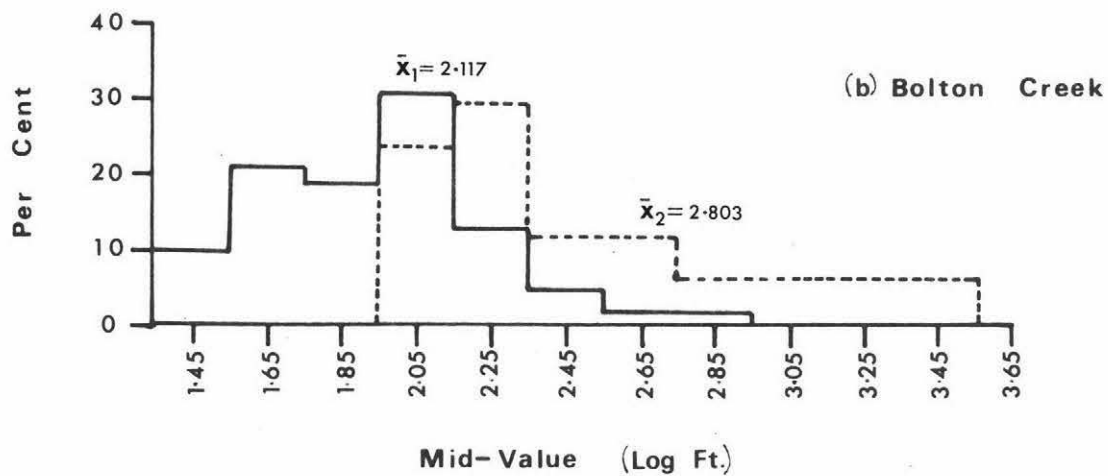
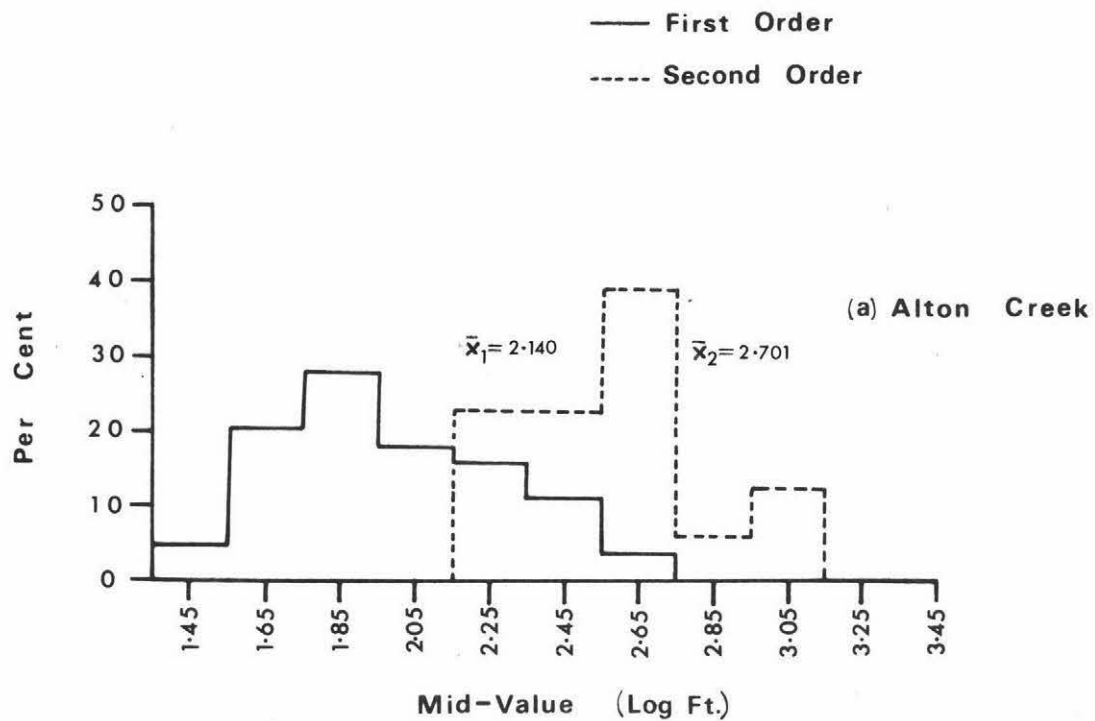
eroded part of the Tokomaru Terrace where Alton headwater areas used to be. The loss of length and area is difficult to replace or readjust. Therefore the adjustments of the relationships of length and area with order after the interruption have been slow. Stream numbers, on the other hand, can adjust to such an interruption more quickly than lengths and areas of the basins; and considering the length of time since the interruption occurred, the adjustments of the stream numbers in Alton Creek have been rapid.

III.4 Frequency Distributions Of Lengths And Areas

Because of the small number of streams in higher orders, only first and second order streams are taken for study; and for convenience of interpretation of summary statistical measures, the values of length (feet) and area (square feet) are transformed into log values and are shown diagrammatically in Figures 12 and 13.

Frequency distributions of lengths of both creeks are very similar (Figure 12). Both creeks show slight positive skewness with higher frequencies occurring at lower values. They have very similar means and modes at first order, but those of the second orders differ considerably. The Alton second order shows a sharp drop at the class centred on 2.85 immediately after the modal class, while the corresponding order of Bolton

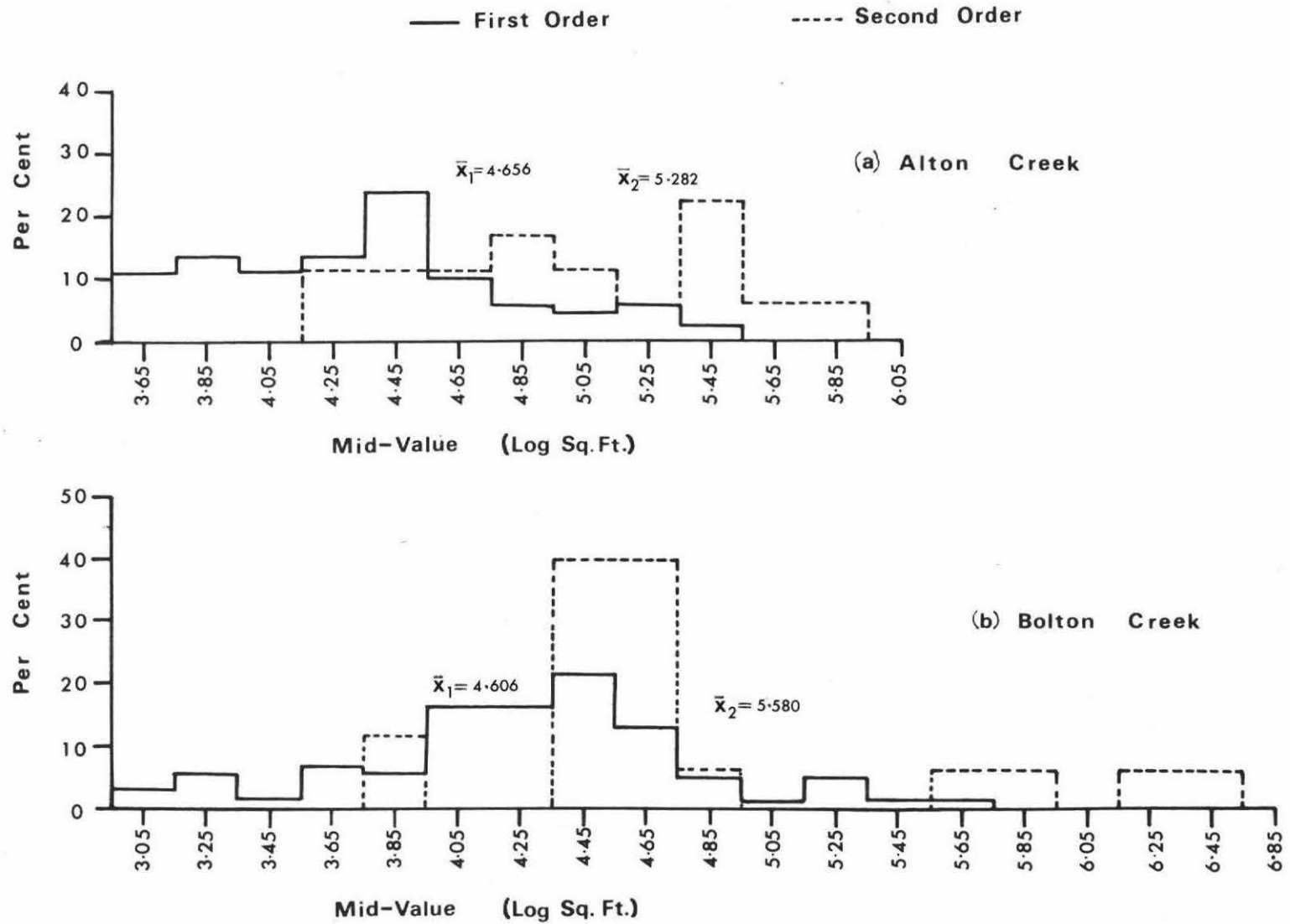
Fig.12 Histograms Showing Log Distribution Of Channel Lengths



Creek has its modal class centred on 2.25. Frequencies decrease slowly and extend into a higher range of values, producing a higher degree of skewness than for Alton Creek. Though their mean values are similar, Bolton has a wider range of values. However, the transition range between first and second orders of both creeks are similar. Alton ranges from 2.16 to 2.75 and Bolton ranges from 1.96 to 2.95. These broad transition zones suggest the lack of equilibrium in the systems of the basins as an equilibrium system normally has a sharper distinction between lengths of higher and lower orders.

Frequency distributions of areas vary remarkably between the two basins, although their mean values are nearly the same. Again, Bolton basin has a wider range than Alton basin; and its distributions are more dispersed (Figure 13). The first order of Alton Creek has a standard deviation of 0.462 and a coefficient of variation of 10.6 per cent, while the second order has values of 0.479 and 9.6 per cent respectively. Correspondingly, the Bolton first order has a standard deviation of 0.529 and a coefficient of variation of 12.5 per cent. As far as areas are concerned, their first order basins show similar distributions but the distributions of second order basins vary considerably. The transition between first and second orders in Alton Creek occurs continuously from 4.16 to 5.55, while that of the Bolton Creek occurs mainly from 3.76 to 5.75. Again, these wide transition zones indicate the lack

Fig.13 Histograms Showing Log Distribution Of Basin Areas



of equilibrium of the basin developments. Due to the wide range of transition zones between the two orders, it is difficult to draw a lower limit for the second order basin areas, or an upper limit for the first order areas. It could only be deduced that first order basins with areas larger than 112,200 square feet are likely to be developed into second order basins.

A few points about the frequency distributions of length and area of the two creeks can be observed. First, dispersions in Bolton Creek, both in length and area, are greater than for Alton Creek. This indicates that the lengths and areas of Bolton Creek are more varied than in Alton Creek. Second, the distributions are skewed, mainly positively, with Bolton's second order length distributions being most strongly skewed. Channel lengths are short and basin areas are small. Over 70 per cent of the first order channels of each basin are shorter than 180 feet, and about 30 per cent shorter than 80 feet. Second order channels have a wider range of lengths and the two creeks vary considerably. The minimum channel lengths of first order channels in both basins are between 40 and 50 feet, while the lower limits of second orders range between 100 and 150 feet. However, short second order channels are plentiful in both the creeks. The minimum first order basin area is 3,000 square feet; and over half of the number of first order basins of both creeks fall into the class of between 3,000 and 30,000 square feet. The transition

limits between the two orders, especially for area, are difficult to decide. The upper limit of the first order basin areas can be as high as 278,000 square feet, while some second order basins have areas as low as the lower limit of first order basin areas. These broad overlappings are identical in the distributions of length and area of both creeks; and these can be attributed to the lack of equilibrium in the systems of both creeks.

III.5 Relation Between Area And Length

As stream numbers, lengths and areas are all related to orders, they should therefore be related to each other.

Figures 14 to 17 show the regressions between areas and lengths within each order. Again, due to the small number of basins of higher orders, only first and second order basins were taken to investigate the degree of correlations between the two variables. The results reveal that high degree of correlations exists. The correlation coefficient of Alton's first order basins is 0.71 and second order basins 0.79; while in Bolton Creek, the first order coefficient is 0.85 and that of the second order is 0.75. All these relationships are positively correlated so that larger basins tend to have longer channels. The correlation coefficient marks an increasing degree of correlation from first to second order in Alton Creek, but decreasing in

Fig.14 Relation Of Channel Length To Basin Area
Alton First Order

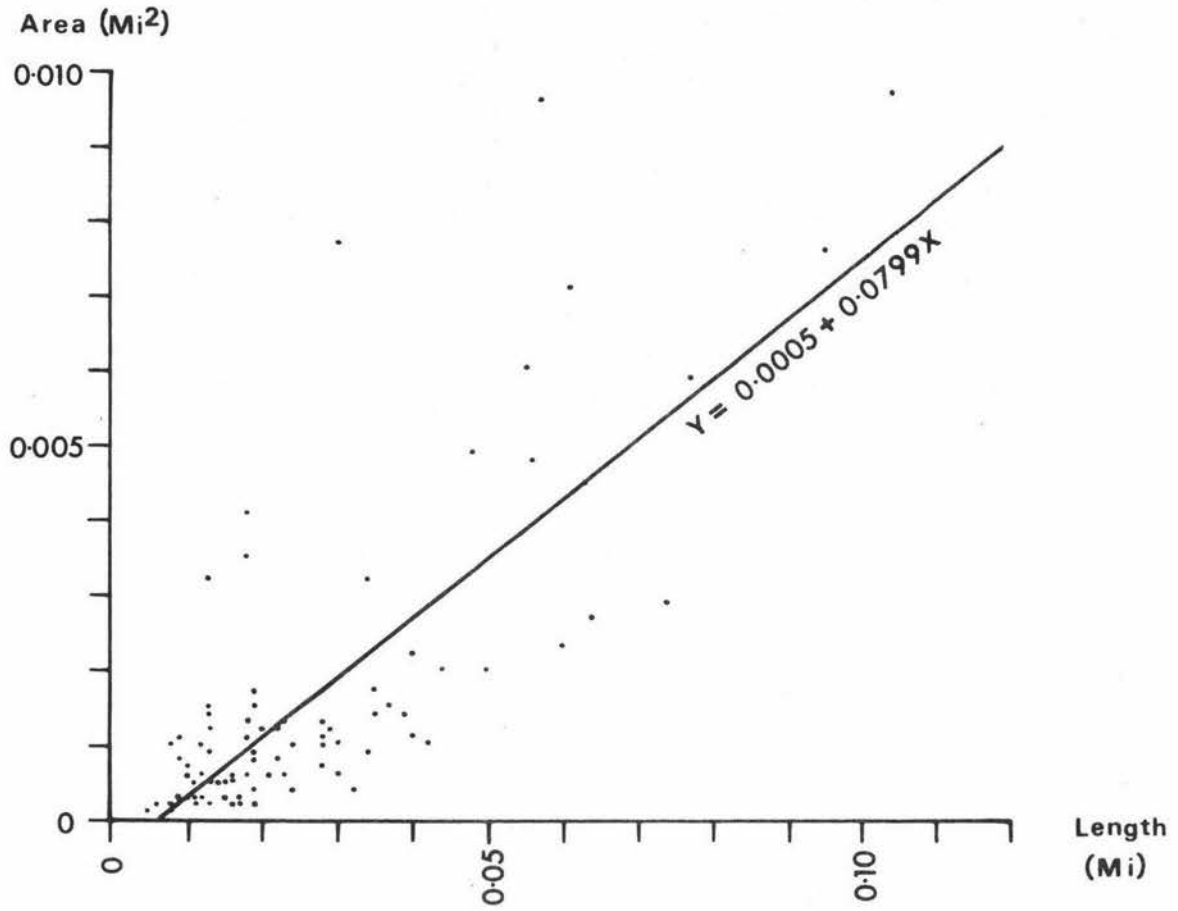


Fig-16 Relation Of Channel Length To Basin Area
Bolton First Order

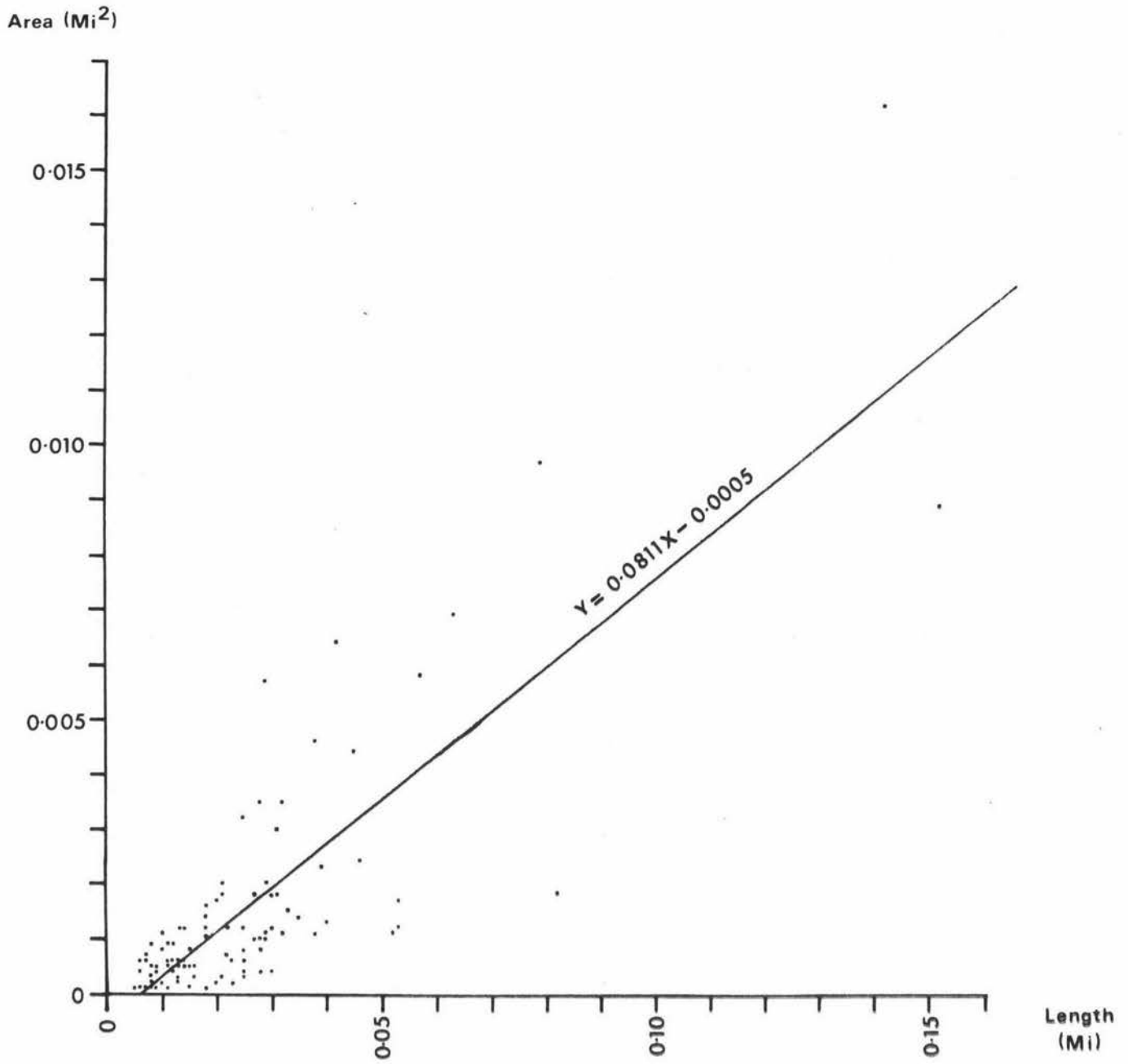


Fig.15 Relation Of Channel Length To Basin Area
Alton Second Order

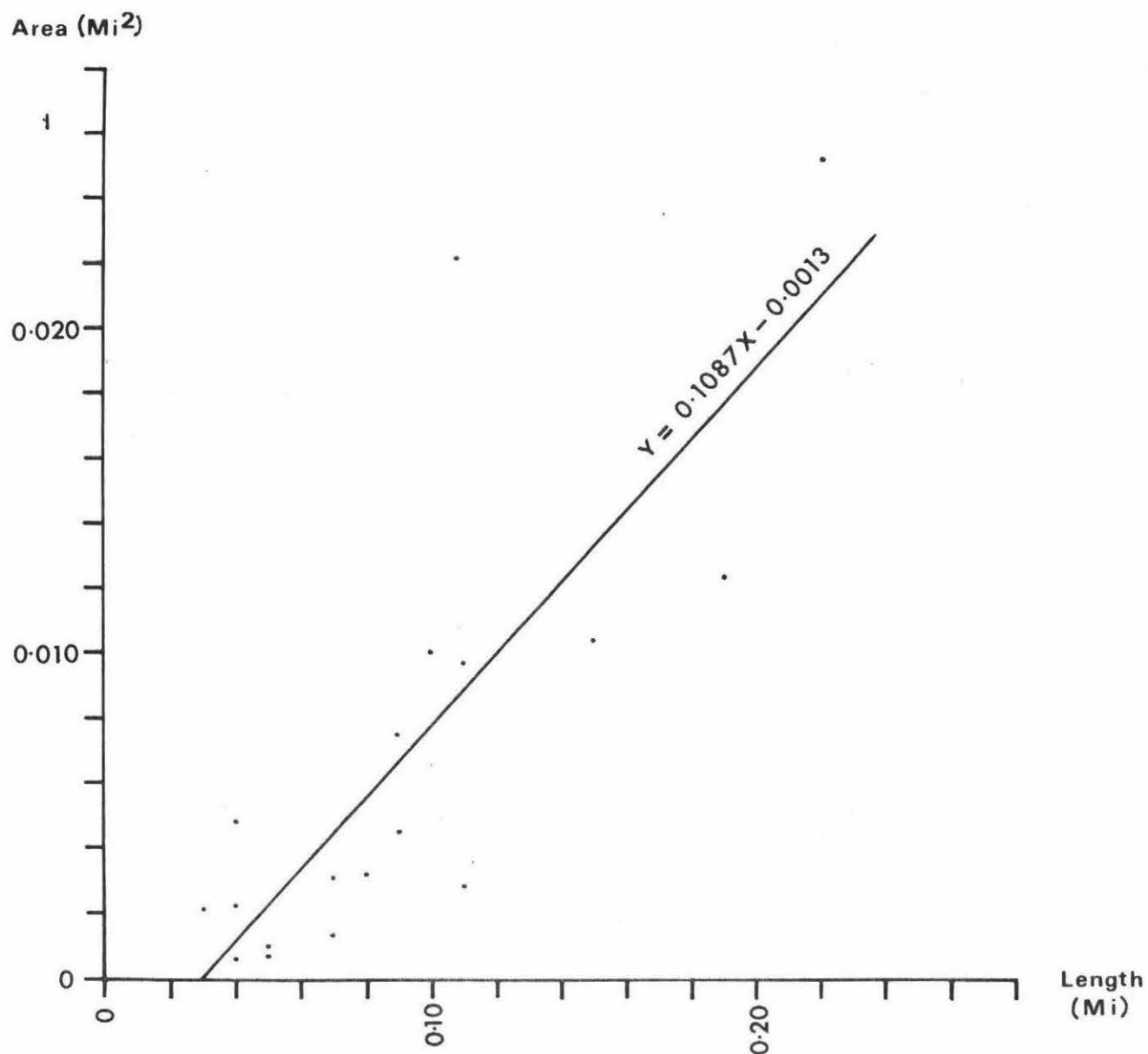
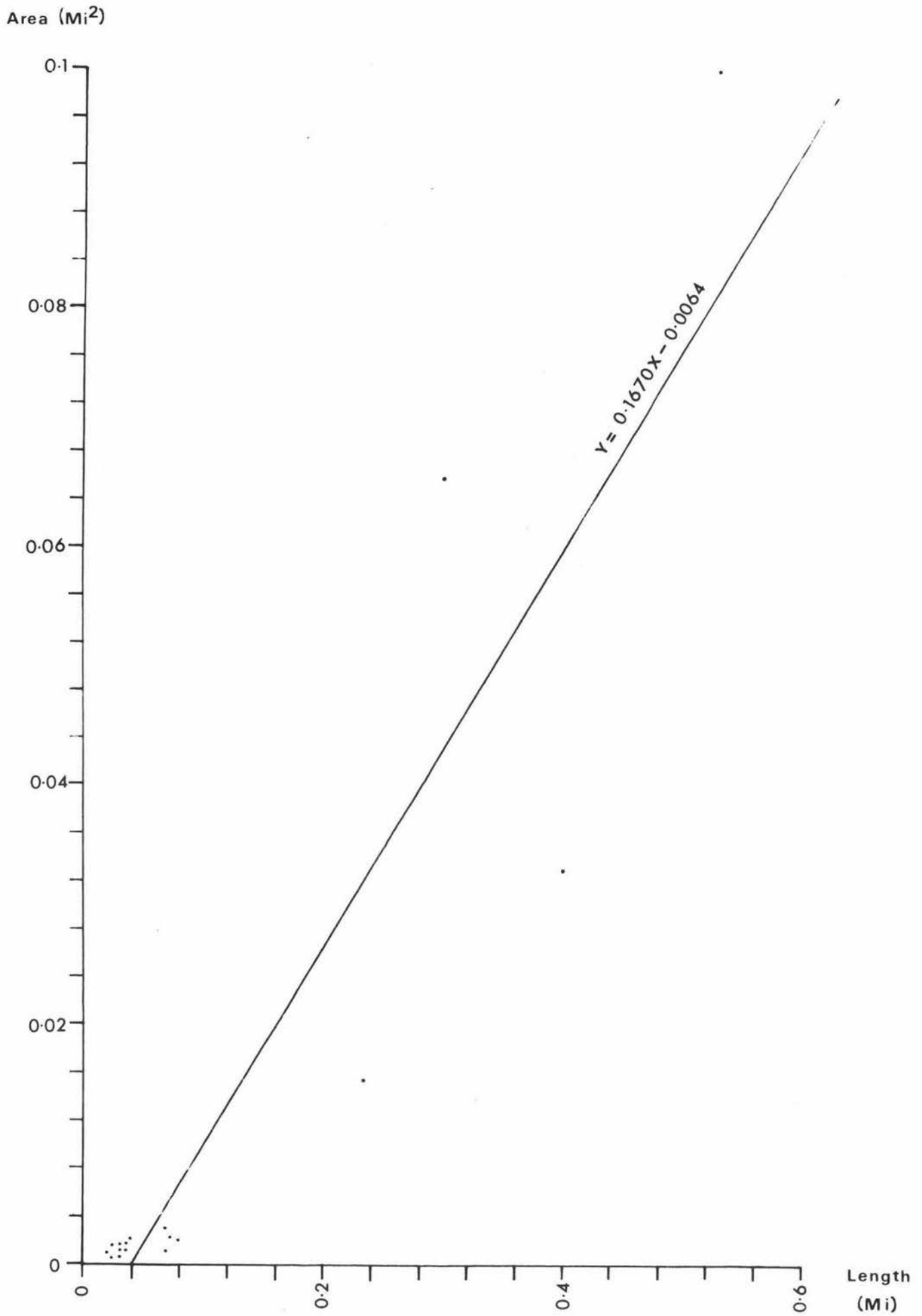


Fig.17 Relation Of Channel Length To Basin Area
Bolton Second Order



Bolton Creek. The regression equations show that all the expected values of basin areas of the first order basins of both creeks, and the second order of the Alton Creek, based upon unchanged channel length, are slightly higher than the observed basin areas. This indicates that a majority of these basins have a slightly long channel length for the basin area drained. However, there is also a considerable number of basins whose areas are exceedingly large for the existing channels.

III.6 Drainage Density And Constant Of Channel Maintenance

The relationship between channel length and basin area can also be expressed in terms of drainage density and constant of channel maintenance. Drainage density is a measure of the degree of dissection while the constant of channel maintenance measures the erodibility of the land surface. The former is expressed as miles per square mile and the later as square miles per mile.

It has been suggested that drainage density is independent of order and that the drainage density of the total basin tends to approximate the mean drainage density of first order basins (Morisawa, 1962:1035; Hack, 1957:66). However, this property does not appear to be present in either creek. First order basin densities are highest in the systems and drainage densities decrease towards higher orders until the total basin order (Table 7). The total basin density of

Table 7 Drainage Density
(Mi/Mi²)

ORDER	ALTON CREEK	BOLTON CREEK
First	15.3	17.8
Second	14.2	9.2
Third	11.2	8.6
Fourth	13.1	13.4

Alton Creek is closer to the first order density than that of the Bolton Creek. The relationship of drainage density and relief is discussed in Chapter IV.

The constant of channel maintenance expresses the basin area in square miles required to maintain a mile of channel and is the minimum area required for the development of a drainage channel (Schumm, 1956:607). It is the reciprocal value of drainage density so that the higher the drainage density, the lower the constant of channel maintenance.

Alton's first order average constant of channel maintenance is 0.065, but 50 per cent of the basins are between 0.011 and 0.039. Correspondingly, 45 per cent of Bolton's first order basins fall within this range. Of the second order basins, 39 per cent of Alton basins have a constant of channel maintenance between 0.011 and 0.029 and 41 per cent of Bolton's are within this range. For both the orders, the

Table 8 Constant Of Channel Maintenance
(Mi^2/Mi)

ORDER	ALTON CREEK	BOLTON CREEK
First	0.065	0.056
Second	0.070	0.108
Third	0.089	0.116
Fourth	0.076	0.074

highest frequencies occur in the class from 0.021 to 0.029. This indicates that a greater proportion of the basins have a constant of channel maintenance that is well below the average value obtained for each order. These basins are normally basins which are of smaller area or basins which are formed on valley side slopes of higher order channels at the lower reaches of the streams. The high average values (Table 8) are the result of the presence of basins of very poor drainage which are normally situated on the large interfluvial plateau at the headwater areas (Plate 2).

III.7 Basin Shapes The shape of basins is relatively more stable than other variables. Miller (1953, cited in Gray, 1961:1220) had suggested that the stability could be an expression of universal equilibrium basin form.

Two indices, the elongation ratio and roundness number, are used to investigate the shapes of the



Plate 2 Basins of very poor drainage are normally observed at headwater areas of both creeks. The channels of these basins are not well defined and valley side slopes merge gently with the terrace surface without obvious break of slope. The rushes in this particular basin also signify the lack of effective drainage.

Aokautere basins. The elongation ratio is derived by the method described by Schumm (1956:612) which can be stated as $R_e = \frac{D}{L_m}$, where R_e is the elongation ratio, D the diameter of a circle with area equal to the basin, and L_m is the maximum length of the drainage basin parallel to the principal drainage line.

The roundness number is the ratio between the area of the drainage basin and the area of circle whose diameter is the L_m used in the elongation ratio. It can be stated as $N_r = \frac{A}{A_m}$, where N_r is the roundness number, A the area of drainage basin, and A_m is the area of a circle whose diameter is the maximum length of the basin parallel to the principal drainage line.

Both indices describe the shapes of basins in terms of the closeness of the actual shape to a circle. The nearer the basin shape is to a circle, the greater the index becomes. The theoretical maximum value is unity. But in reality, no basin shape can achieve unity. While Schumm's elongation ratio is a ratio between the length of the idealised circle's diameter to the actual maximum length of the basin, the roundness number expresses the areal ratio between the idealised circle area drawn around the maximum length and the actual area of the basin.

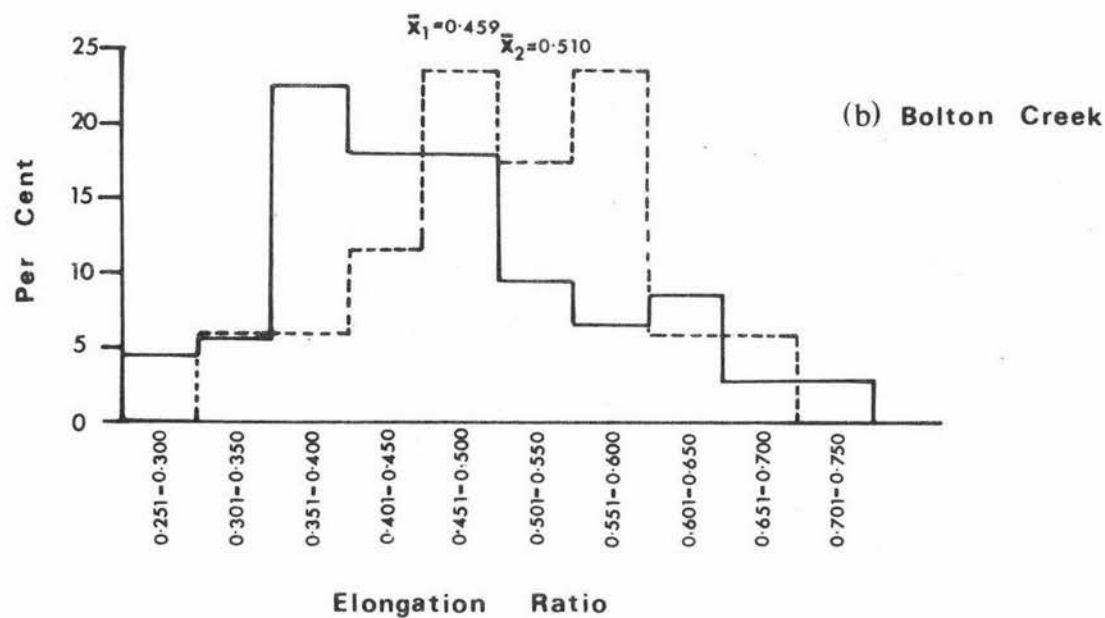
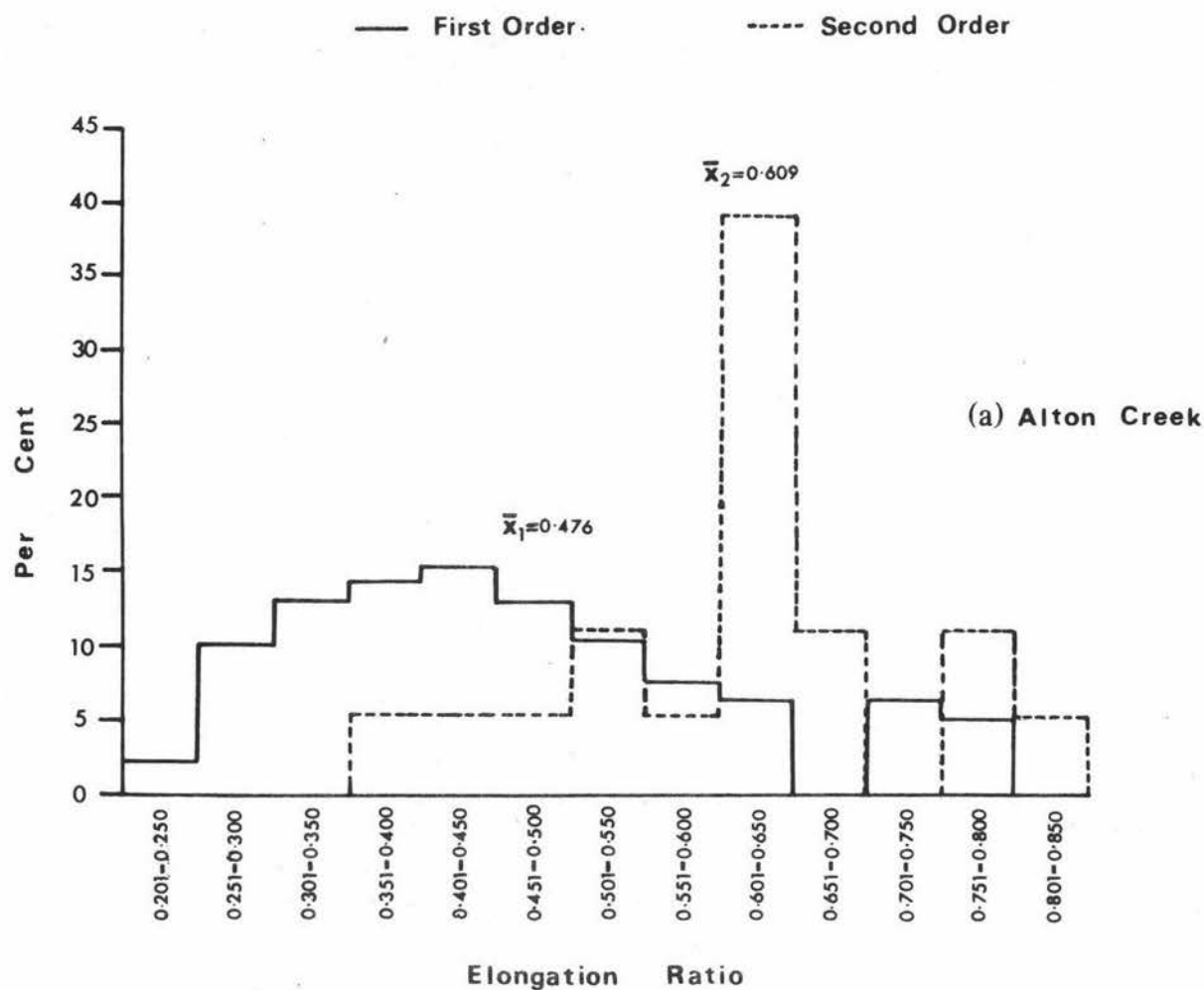
Because of the squares involved in the calculations, the roundness number generally has a lower value than the elongation ratio. The use of areal values in the roundness number brings out a greater range between basins and also results in greater departures from unity. Therefore although the roundness number provides impressive visual distinctions, the values it generates are too often over-emphasised. However, the roundness number is useful in describing basins with identical linear shapes but different areal irregularities.

Table 9 Elongation Ratio

ORDER	ALTON CREEK	BOLTON CREEK
First	0.476	0.459
Second	0.609	0.510
Third	0.651	0.449
Fourth	0.344	0.326

Table 9 shows the average elongation ratios of all orders of both creeks, and Figure 18 illustrates the frequency distributions of first and second order basin shapes of both creeks. There is an obvious increase of ratio from the first to second order basins, but in general, there is no definite association between the shape and order of basins. The average ratios, except the second and third order basins of Alton Creek, are relatively low⁽⁷⁾ illustrating the elongated shape

Fig.18 Frequency-Distribution Histograms Of Elongation Ratio



of the basins. The histograms show that the overlapping between first and second order ratios are great, covering almost the total range. This reflects the lack of distinction between shape and order association. The first order Alton basins are close to normal while those of the corresponding order of Bolton Creek are skewed slightly to the right. However, the similar pattern of distributions of the elongation ratio groups and average values show that the shape of the first order basins of both creeks are very similar. Those of the second order basins are not so similar. While Bolton's second order basin shape increases slightly from the first order shapes, Alton's second order ratio rises considerably, resulting in a high frequency in the 0.601 to 0.650 class while other low frequencies spread over a wide range.

III.8 Summary The relationships between stream number, length and area, although departing from the morphometric laws, show trends similar to those described in these laws. Given adequate time for development, the relationships should fit the criteria prescribed in the laws.

Frequency distributions of length and area show that there are large overlaps between first and second order basins reflecting the lack of length and area identifications in basins of these two orders.

The correlations between lengths and areas are positive but not very high. There are two extreme types of basin. Firstly there are basins with relatively long channels for the size of the basins and secondly there are basins of large areas with relatively short channels. This has resulted in the characteristics shown in the drainage density, constant of channel maintenance and the shapes of basins.

NOTES

- (1) The field measurements were obtained during June, October and November. Discharge was estimated by the equation $Q = AV$ (Morisawa, 1968:21), where Q is discharge in cubic feet per second, A is cross-sectional area of the channel, and V is mean velocity. Mean velocity was estimated by disposing matchsticks on stream water, and the time taken for the first matchstick to travel 10 feet downstream along the channel was recorded. Each process was repeated three times and the average speed obtained was the estimated stream velocity of the section.
- (2) The Law of Stream Numbers can be expressed as $N_x = R_{bw}^{(u-x)}$, in which N_x is the number of

stream of the order x , u is the trunk order, and R_{bw} is the weighted mean bifurcation ratio.

- (3) Weighted mean bifurcation ratio (R_{bw}) was obtained by Schumm's method (1956:603) where each rank of bifurcation ratio is multiplied by the total number of streams of the two orders involved, and the sum of these multiplications divided by the total number of streams involved in the multiplication.
- (4) Accumulated length was first suggested by Brascoe (1959) to substitute segment length. Under this definition, a second order length, for example, includes not only the second order segment, but also the lengths of all first order channels that have joined to form the second order basin.
- (5) The Law of Stream Lengths can be expressed as $\bar{L}_x = \bar{L}_1 R_{lw}^{(x-1)}$, in which \bar{L}_x is the average length of streams of order x , \bar{L}_1 is the average length of first order channel, and R_{lw} is the weighted mean stream length ratio. Stream length ratio (R_1) $= \frac{\bar{L}_x}{\bar{L}_x - 1}$; and method of deriving weighted mean stream length ratio is similar to that of obtaining weighted mean bifurcation ratio.
- (6) The Law of Basin Areas can be expressed as $\bar{A}_x = \bar{A}_1 R_{aw}^{(x-1)}$, in which \bar{A}_x is the average

area of basins of order x , \bar{A}_1 is the average area of first order basins, and R_{aw} is the weighted mean basin area ratio. Basin area ratio (R_a) = $\frac{\bar{A}_x}{\bar{A}_x - 1}$; and method of deriving weighted

mean basin area ratio is similar to that of obtaining weighted mean bifurcation ratio.

- (7) Comparisons of basin shapes of several areas were given in Schumm, S.A., 1956:612 where ratios of over 0.6 are common.

CHAPTER IV BASIN CHARACTERISTICS - RELIEF

IV.1 Drainage Basin Relief Cotton (1949:149) described the vital characteristics of mature relief as sharp and uneven crestlines formed by the intersection of steep valley side slopes. However, the stages of landform and channel evolution, though parallel, are never quite co-existent (Cotton, 1941:55). In his works of the late fifties and early sixties, Cotton (1958,1962,1963) used the term "feral relief" for the finely dissected landforms of New Zealand particularly common on the greywacke ranges of the North Island. Most of the works were on the origin of feral relief rather than on quantitative description. However, an estimate of drainage density was given as around 100 for the feral relief of Wellington Peninsular (Cotton, 1958:199).

Selby (1967) studied the relief of the greywacke ranges in the south Auckland area and compared its geometry with that of Dartmoor and Unaka drainage basins⁽¹⁾. He concluded that New Zealand has a finer texture and the morphometric properties do generally conform to the existing laws (1967:41). However, the maps which Selby's study was based on were one inch to one mile maps and his fourth order channels were obviously not the highest order in the system. Therefore the values he obtained

from his study area cannot be validly compared with those of the present study.

Not all parts of New Zealand are finely dissected. In the southwestern Manawatu area where geology is similar to the Aokautere area, Oliver (1948) found that river basins have broad and flat interfluves and box shaped river valley with steep valley side slopes. The streams are small and valleys are large in the lower courses while towards the headwater area valley side slopes are replaced by amphitheatre valley heads.

The relief of the Aokautere area is closer in similarity to the type described by Oliver than to the "feral relief" common in many parts of the country. There are two possible reasons for this. First, much of Cotton's "feral relief" with serrate characteristics **refers** to landforms in the stage of maturity or sub-maturity where dissection has taken place over a considerable period of time, while forms of the study area suggest a younger stage of development from those described by Cotton. Second, a great number of landforms studied by Cotton are found in the greywacke regions where geology is entirely different from the loess and marine sandstones of the Aokautere area. Therefore while the climatic regimes that affected the North Island as a whole may be similar, the lengths of time available for erosion and the materials on which the drainage systems are developed are very different for "feral relief" and Aokautere relief.

IV.2 Erosional Surfaces Most of the surfaces of the study area are under good pasture. Only a small percentage of the total area is under scrub and secondary trees, and bare ground is negligible. The surfaces can be generally considered as free from a dense cover of vegetation and are uniformly exposed. The top three to four inches of surface soil on the marine terrace comprises a black humus-enriched layer underlain by yellow brown subsoil derived from loess. Lower level surfaces have mixtures of loess and recent alluvium. Greywacke pebbles derived from the terrace conglomerates are commonly found on inclined surfaces and valley floors.

All surfaces of the study area are erosional surfaces, including the miniature flood plains developed in the highest order valleys. Field observations suggest that colluvium derived from valley side slopes, rather than stream alluvium, is dominant in the formation of the miniature floodplains. The colluvium transported onto the valley floors as a result of mass movement and slope failure is normally not entirely washed away unless there is a prolonged period of flood water. However, the colluvium is normally smoothed by flood water before the establishment of grass. Some debris has had grass developed on it before being smoothed by flood water and this has resulted in bumps which form irregular debris deposits along the valley floors.

The interfluvial hills of the area are broad and flat, resembling the original surfaces of the marine terrace. However, such features were described by Horton (1945:361) as "residual hills" because they are in fact remnants of original surfaces. The original surfaces have been removed through overland flow and surface wash.

Between the valley floors and the flat-topped interfluvial hills the valley side slopes are dominated by mass movement features, predominantly terracettes. Terracettes are most common in middle and lower reaches of the main valley (Plate 3), but are also found in large lower order valleys. Minor slumps are normally associated with the terracettes. In a few localities where slopes are steep, scree creep is present where conglomerates are exposed.

IV.3 Total Relief The net elevation between the lowest and highest points of a basin is an important factor in considering the erosional power within a basin. The greater the elevation range, the greater the potential energy, and the conversion to kinetic energy of streamflow results in the development of more complicated landforms⁽²⁾.

Table 10 shows the average total relief of all orders of Alton and Bolton Creeks. The variable is measured in feet and is rounded to the nearest half foot.



Plate 3 The middle reaches of Alton Creek. Mass movement features dominate the valley side slopes whose breaks with the flat topped interfluvial hills are obvious. In the background is the Tararua Range.

Table 10 Average Total Relief (Feet)

ORDER	ALTON CREEK	BOLTON CREEK
First	74.5	76.5
Second	95.0	110.5
Third	108.5	190.5
Fourth	274.0	316.0

The mean total relief of both creeks is very similar for first order basins, but it varies with increasing order. Alton Creek has a generally lower total relief than Bolton Creek, especially in the third and fourth order basins.

A log-linear relationship normally exists between average total relief and order. The derived morphometric law states that the average total relief of basins of each order forms a direct geometric series in which the first term is the average total relief of the first order basin and the ratio is the total relief ratio (Morisawa, 1962:1035). The relationship is plotted in Figure 19 and a regression line is eye-fitted to each group of data. A good fit is achieved in Bolton Creek while in Alton Creek residuals are larger. The slopes of the regression lines are approximately equal.

IV.4 Relief Ratio Schumm (1956:612) devised the relief ratio and defined it as the ratio between total relief and longest dimension of the

Total Relief (Feet)

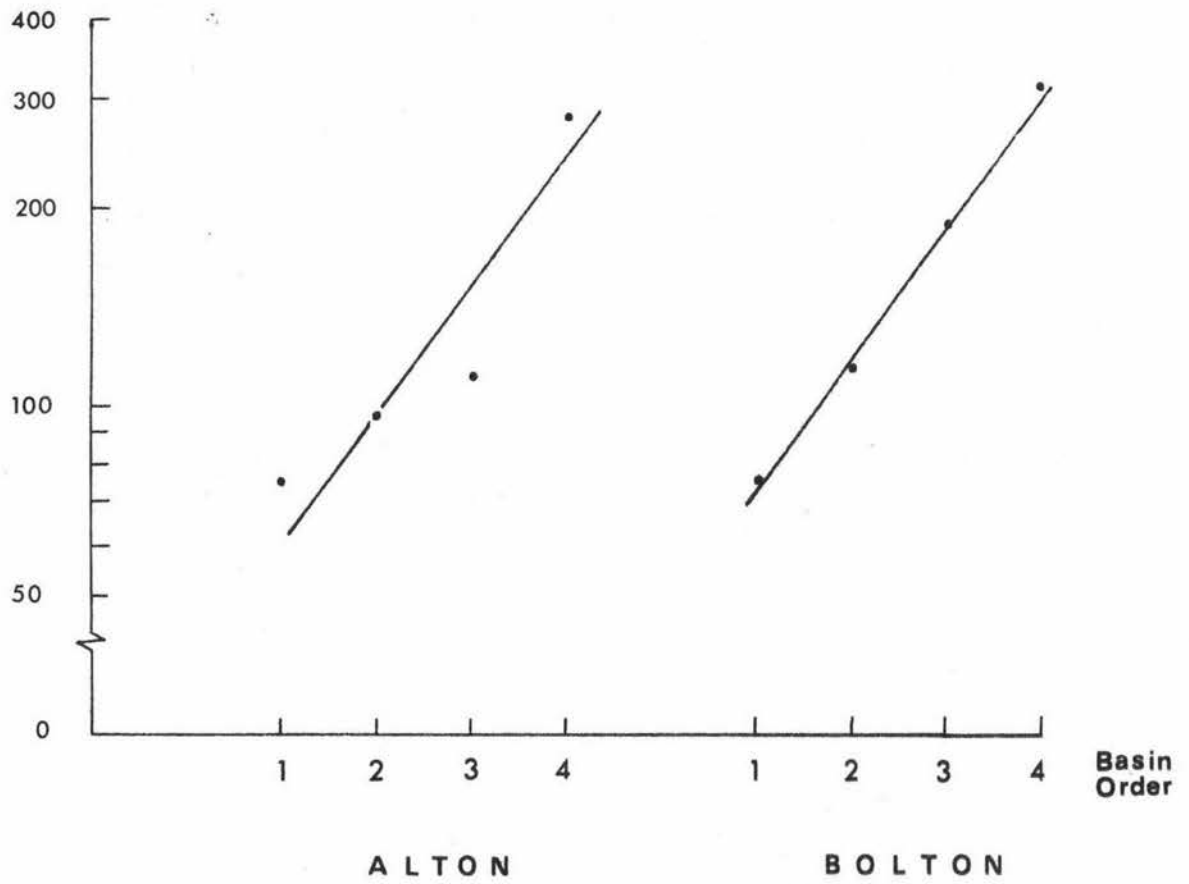


Fig.19 Relation Of Basin Order And Average Total Relief

drainage basin parallel to the principal drainage line. It is in fact the result of the combined expression of total relief and longest dimension of the drainage basin. Table 11 shows the average relief ratio of Alton and Bolton Creeks.

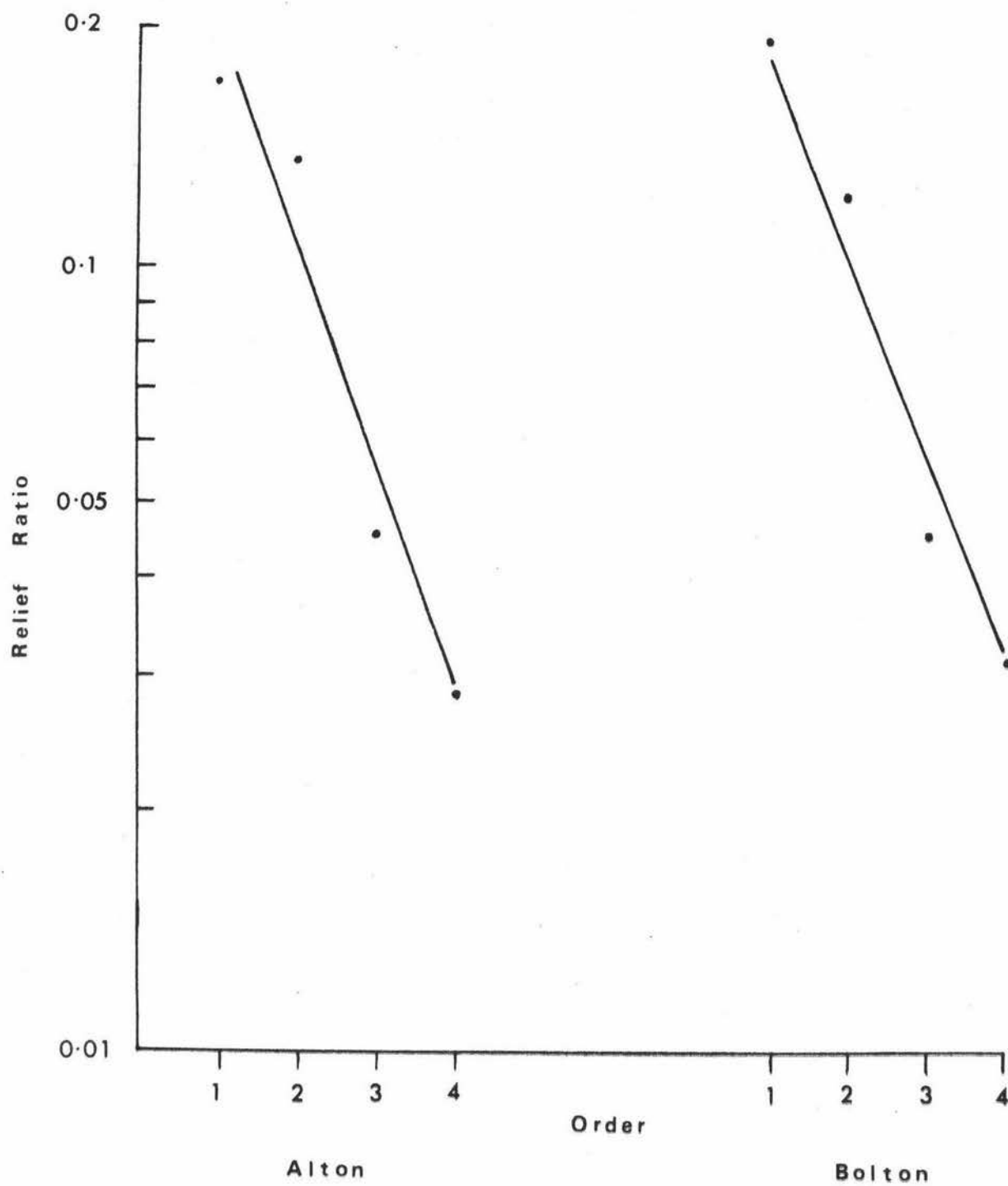
Table 11 Relief Ratio

ORDER	ALTON CREEK	BOLTON CREEK
First	0.198	0.229
Second	0.172	0.209
Third	0.054	0.045
Fourth	0.028	0.030

No valid law has yet been devised for the relief ratio; but the main function of the ratio is to enable comparison of the relief of basins regardless of differences in scale of topography. Figure 20 shows the exponential relationship between the relief ratio and order of the two creeks, with relief ratio on the log scale and order on the linear scale. The regression lines are eye-fitted and both creeks display considerable similarity in the relationships of relief ratio among the orders.

Despite the high residual values for the total relief regression for Alton Creek, the regression for the relief ratio has much smaller residuals and is very similar to that of Bolton Creek. As relief ratio is

Fig.20 Relation Of Basin Order And Relief Ratio



the combined expression of total relief and longest dimension of basins, it therefore suggests that the longest dimension of the basins has been adjusted to compensate for the abnormal total relief relations to present consequently a similar relief ratio regression pattern to that of the Bolton Creek.

The residuals in the average total relief of Alton Creek in Figure 19 can be explained by the incision of the Tiritea Stream discussed in the previous chapter. This incision has not only reduced the area and shortened the lengths of the tributaries at the headwater of Alton Creek, but has also eroded away a great part of the higher relief at the headwater areas of Alton Creek. Therefore the Alton drainage system has not only been reduced in terms of space and length, but also of height. From this investigation, it can be concluded that the interruption of area, length and height is more difficult to adjust. The internal variables, such as the long dimension which is very much the shape of the basins, could react more independently to adjust to the interruption.

IV.5 Relation Between Drainage Density And Relief Ratio

Within homogeneous areas of similar development, Schumm (1956:613) found that drainage density is a power function of the relief ratio, and, in mature basins, a definite positive correlation exists between

these two variables. A correlation and regression analysis is worked on the first and second order basins of Alton and Bolton creeks and it is concluded that this statement is applicable. Due to the few numbers of basins, third and fourth orders are not studied.

The power form relationships between drainage density and relief ratio of first and second order basins of both creeks are shown in Figures 21 to 24. The correlation coefficients obtained are high. The first order correlation coefficient of Alton Creek is 0.87 and that of Bolton Creek is 0.65. The Alton second order correlation coefficient is 0.90 and Bolton's is 0.93.

Tables 12 and 13 show the observed and expected values of drainage density and length of overland flow, and the observed values of relief ratio. The expected values are obtained from the regressions in Figures 21 to 24, holding the observed relief ratio constant. The results show that both drainage density and length of overland flow at present are very different from the expected values. The observed drainage densities are low for the observed relief ratio, while the length of overland flow should reduce to a shorter length. It is deduced that the development of the drainage basins in the near future would be not so much of the lowering of the local relief as the increase of drainage density and decrease of the length of overland flow. The relief

Fig.21 Relation Of Drainage Density To Relief Ratio
Alton Creek, First Order

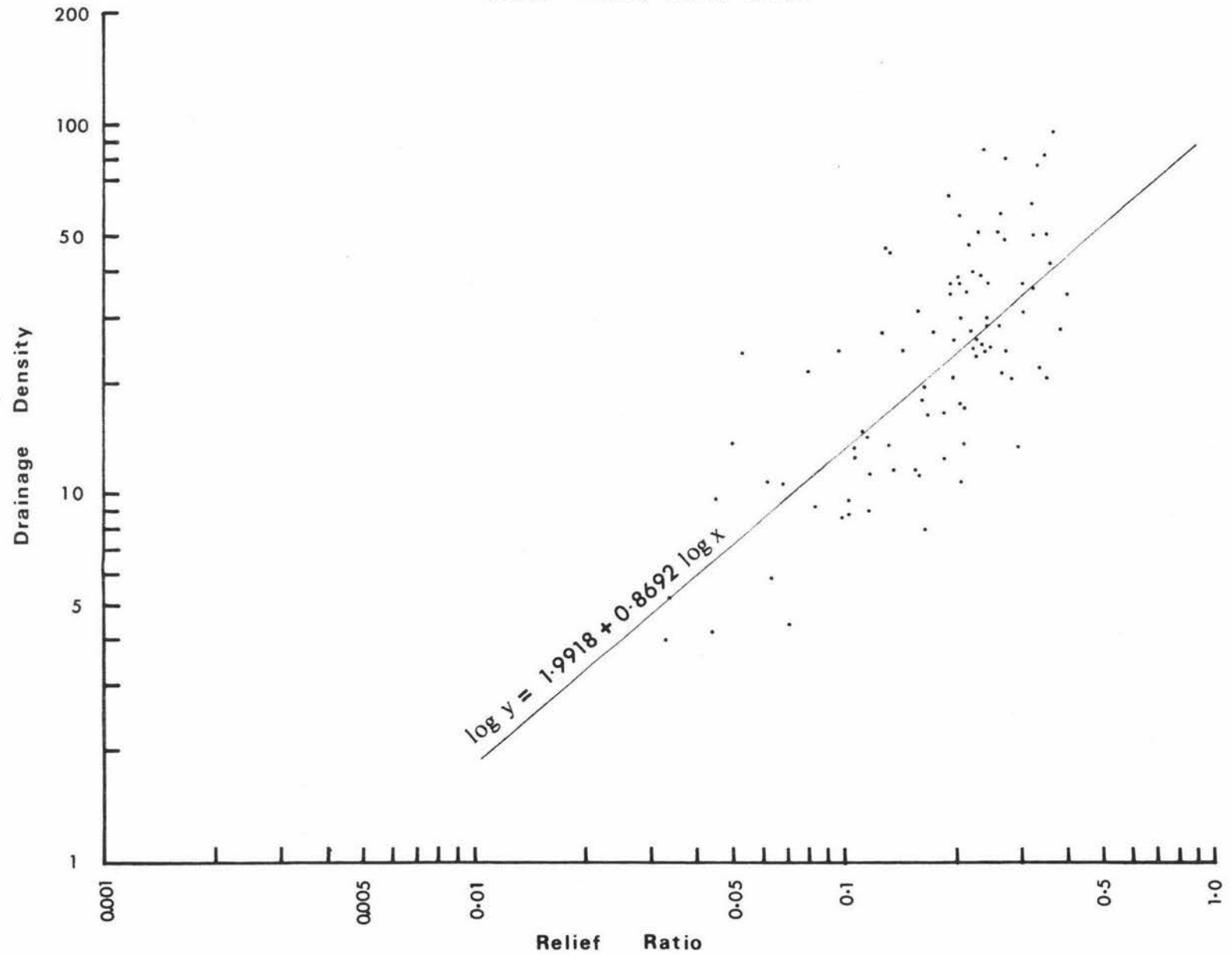


Fig.22 Relation Of Drainage Density To Relief Ratio
Alton Creek, Second Order

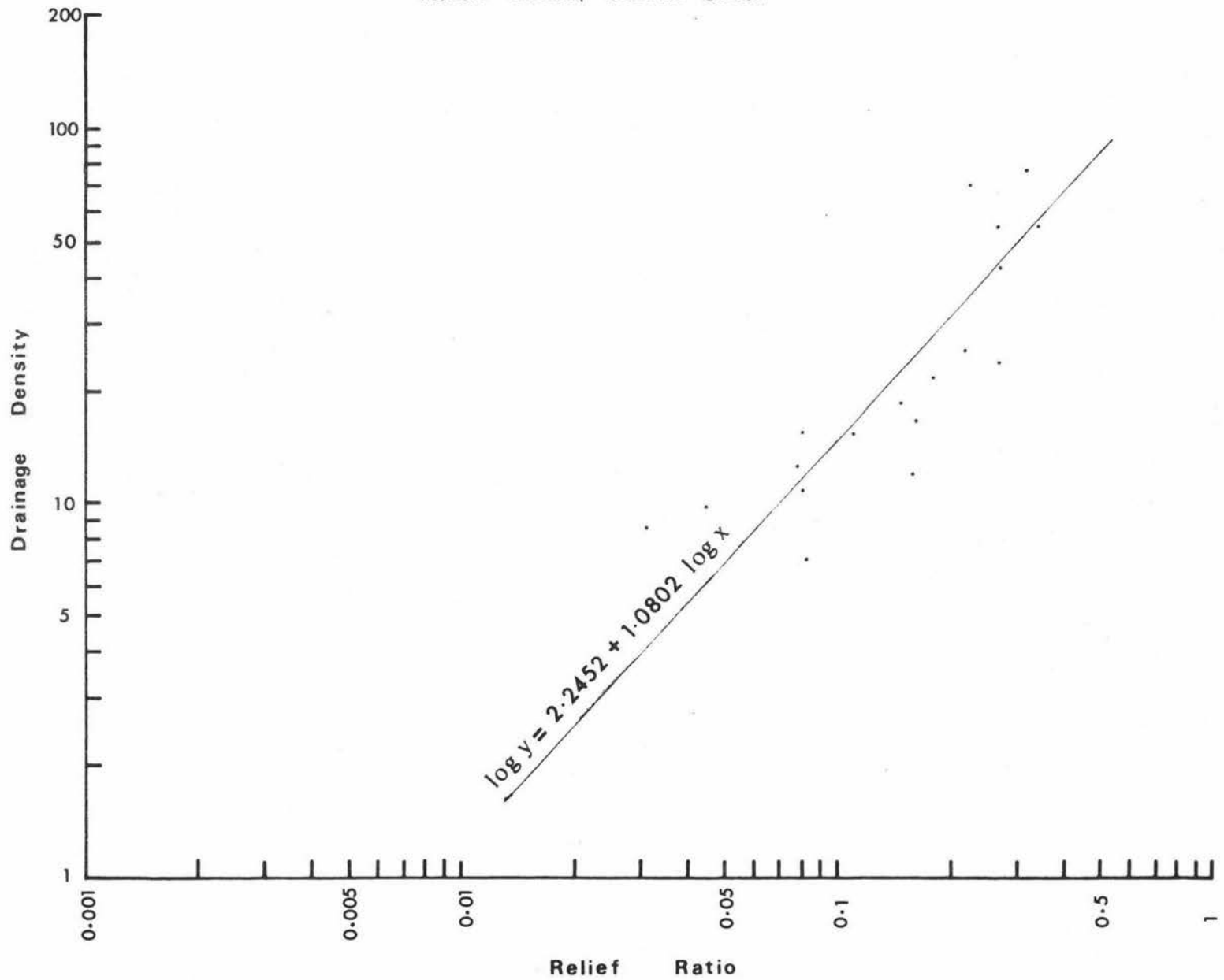


Fig.23 Relation Of Drainage Density To Relief Ratio
Bolton Creek, First Order

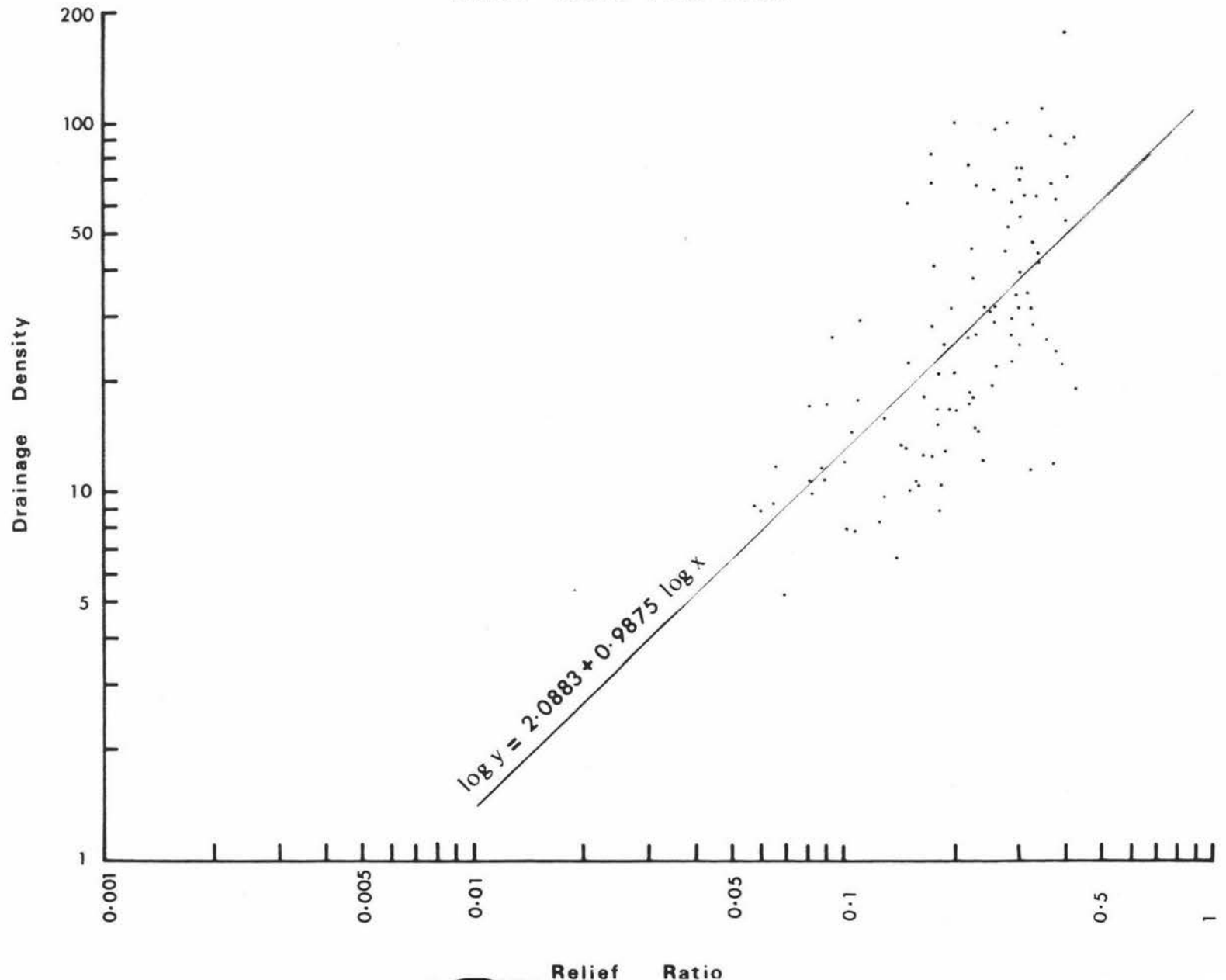


Fig.24 Relation Of Drainage Density To Relief Ratio
Bolton Creek, Second Order

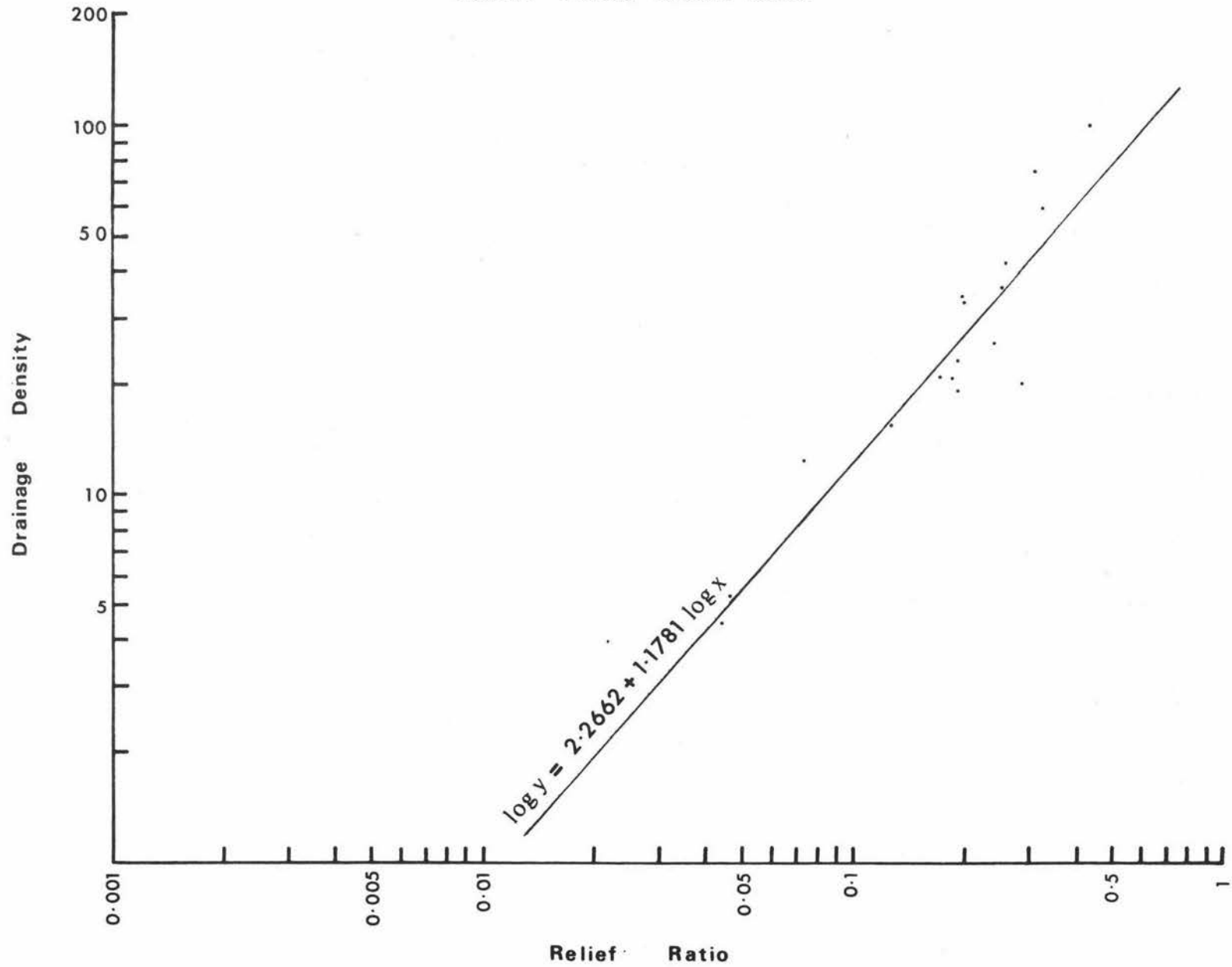


Table 12 Observed Average Values Of
Relief Ratio, Drainage Density
And Length Of Overland Flow

	Alton Creek		Bolton Creek	
	1st Order	2nd Order	1st Order	2nd Order
Relief Ratio	0.198	0.172	0.229	0.2
Drainage Density	15.3	14.2	12.5	9.2
Length of Over- land Flow (Mile)	0.033	0.035	0.040	0.05

Table 13 Expected Average Values Of Drainage
Density And Length Of Overland Flow
Derived From The Observed Relief Ratio

	Alton Creek		Bolton Creek	
	1st Order	2nd Order	1st Order	2nd Order
Drainage Density	23.5	26.3	28.6	29.1
Length of Over- land Flow (Mile)	0.021	0.019	0.017	0.0

ratio will remain unchanged until the drainage density has reached the expected values, which could be achieved through the development of higher bifurcations or increase of channels, reducing the length of overland flow and eliminating surface wash and inter-basin areas.

IV.6 Channel Gradient

Table 14 Average Channel Gradient *

ORDER	ALTON CREEK	BOLTON CREEK
First	17.0	18.5
Second	11.5	15.0
Third	2.5	2.0
Fourth	1.5	1.5

* To the nearest half degree

Morisawa (1962:1044) observed that the relationships between both relief ratio and stream gradient and order were not suitably expressed by Horton's Law of Stream Gradients⁽³⁾. However, she noted that stream gradient, like relief ratio, decreases consistently with increasing order. Study from the relief ratio and stream gradient of the first and second order basins of Alton and Bolton Creeks confirmed Morisawa's statement. Figure 25 shows the plot of average channel gradient against order on a linear-log scale which illustrates similar relationships as exist between the relief ratio and order in Figure 20.

Figures 26(a) and (b) show the frequency distribution histograms of the channel gradient of first and second order basins of both creeks. The first order basins of both creeks show slight left skewness with high frequencies occurring at higher gradients. The

Fig. 25 Relation Of Basin Order And Channel Gradient

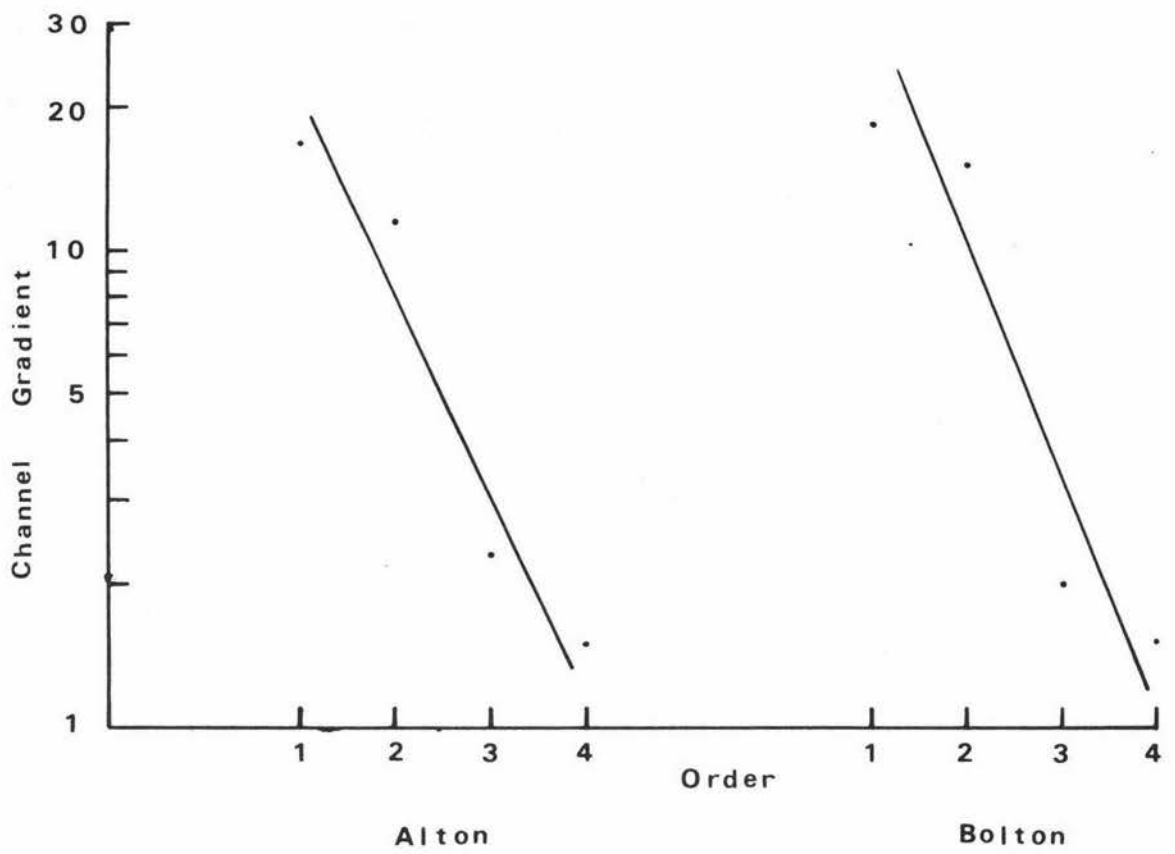
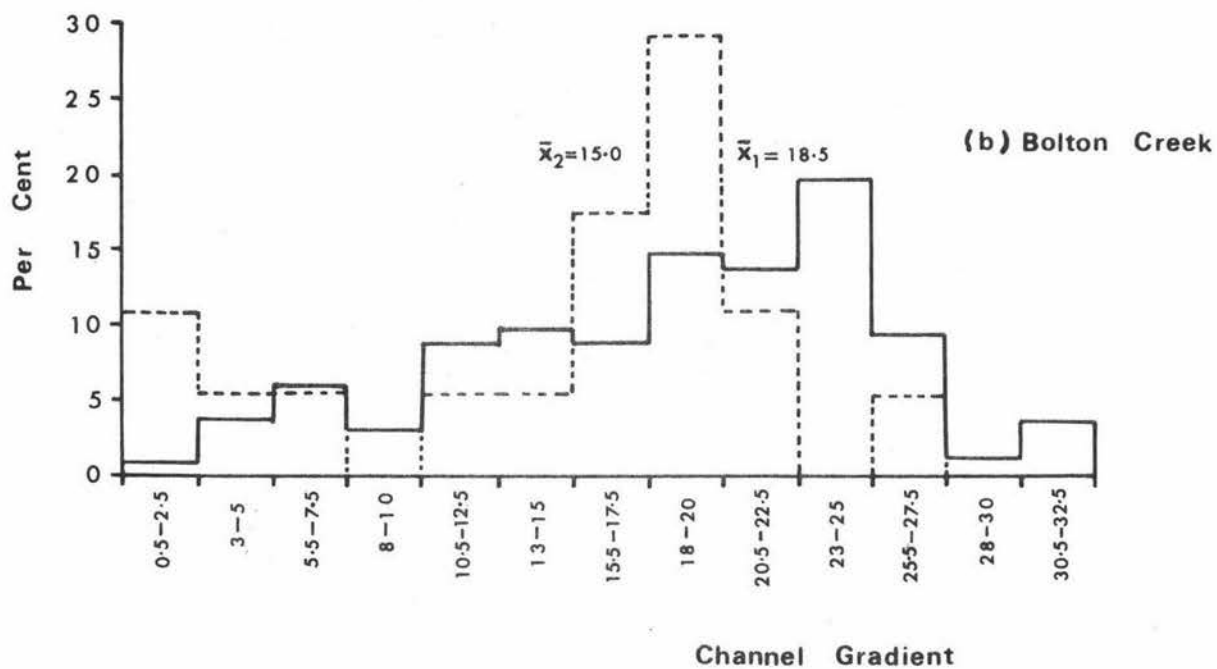
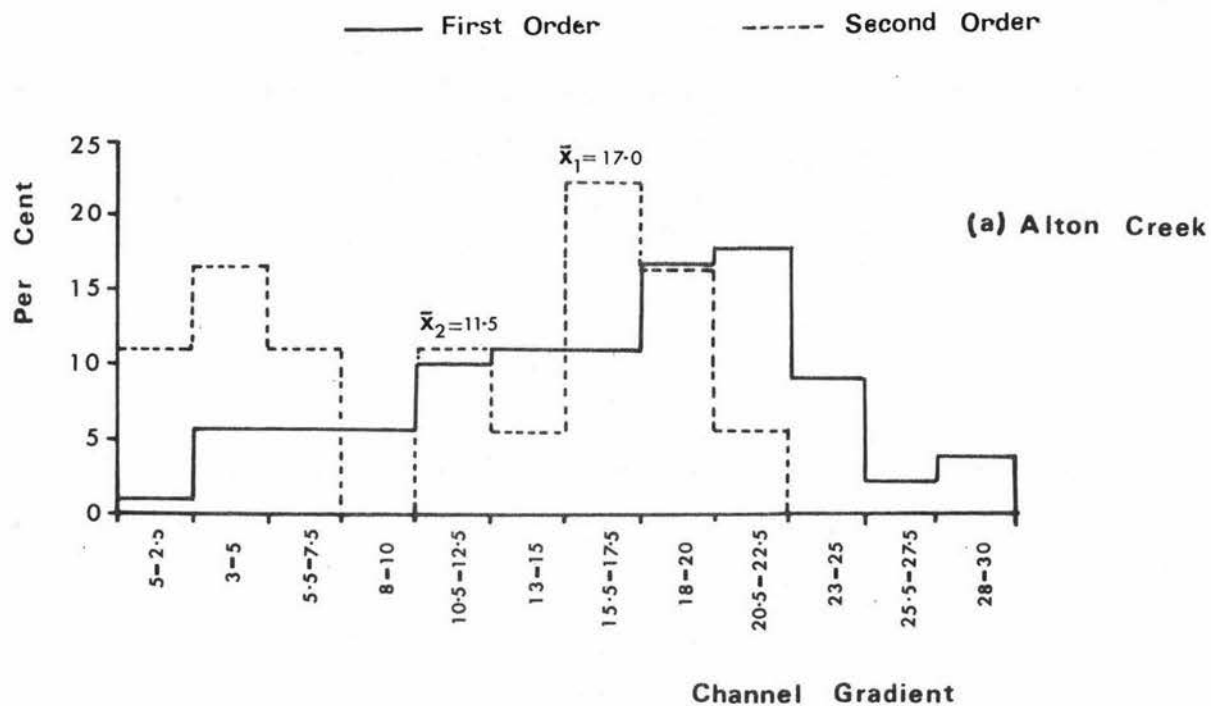


Fig. 26 Frequency Distribution Histograms Of Channel Gradient



second order basins show considerable increases of frequencies in lower gradients, but the modes are above the mean values. In the Alton second order distributions, the histogram shows a tendency towards the development of a bimodal distribution with a mode at the 15.5 to 17.5 class and the other developing at the 3 to 5 class. The large overlap between the first and second order distributions indicates that although the mean gradient show the difference between first and second order gradients, the overlapping is so broad that a marked distinction is difficult to distinguish.

Stream gradient of channels that were developed on the terrace surfaces is lower than those developed on valley side slopes of the main streams. Most of the first and second order channels of the Alton and Bolton Creeks are developed on the valley side slopes of the fourth order channels, resulting in the abrupt break of channel gradients from the average gradients of the third and fourth order channels. This reflects the effects of the ground slope on the first and second order channel gradients. The dissection of these lower order basins has yet to reach the characteristic gradient for the geology of the area.

IV.7 Maximum Slope Angle Strahler (1950:685) outlined the law of constancy of slopes which states that within an area of uniform lithology, soils, vegetation and climate, and stage of

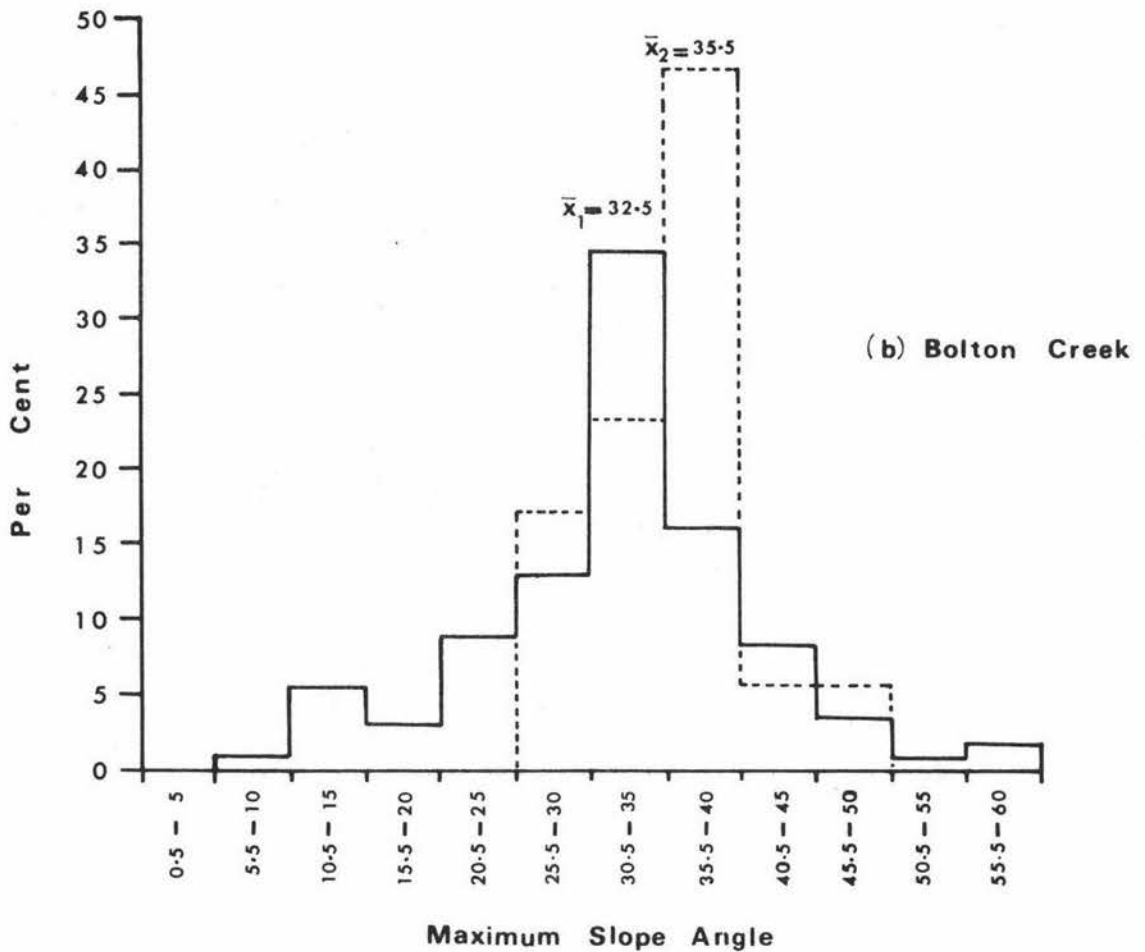
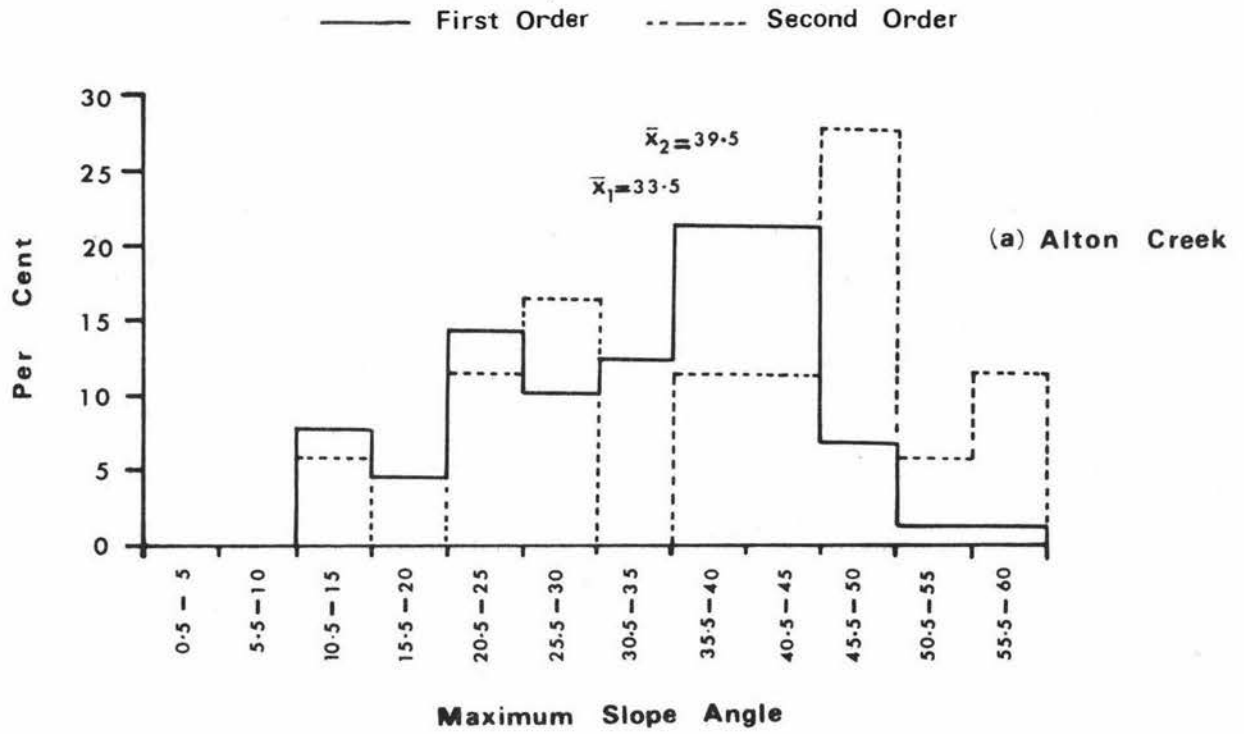
development, maximum slope angles tend to be normally distributed with low dispersion about a mean value determined by the combined factors of drainage density, relief and slope-profile curvature.

This law is tested on the frequency distributions of the first and second order basins of both creeks and the histograms are shown in Figures 27(a) and (b). The means and modes of both creeks are similar, but the standard deviations are considerably different between the two creeks. The degree of dispersion in both orders of Alton Creek are higher than the corresponding orders of Bolton Creek. Distributions in Bolton Creek, especially that of the second order basins, have very low dispersions approaching very closely to Strahler's descriptions.

From Strahler's point of view, and since both creeks are developed under similar physical conditions, this variation in the nature of frequency distributions suggests the difference in the stage of development between the two creeks.

IV.8 Hypsometric Integral Hypsometric analysis is the study of the distribution of ground surface area with respect to elevation (Strahler, 1952:1118). The hypsometric integral, which is equivalent to the ratio of area remaining to the total original area available for erosion, was obtained

Fig. 27 Frequency Distribution Histograms Of Maximum Slope Angle



by the method outlined by Strahler (1952:1120-1121).

Strahler (1952:1130-1131) envisaged that there are two major stages in landform development⁽⁴⁾. Basins with integrals higher than 60 per cent are considered to be in disequilibrium, while basins with integrals between 35 per cent and 60 per cent are in the equilibrium stage. Basins with integrals lower than 35 per cent are in the monadnock phase where total relief is abnormally large in comparison to the general relief features.

Table 15 Percentage Frequency Distributions of Hypsometric Integral Of First And Second Order Basins, Alton And Bolton Creeks

Basin	Order	Monadnock	Equilibrium		Disequilibrium		
		Phase	Stage		Stage		
		0.350 & Below	0.351- 0.500	0.501- 0.600	0.601- 0.700	0.701- 0.800	0.801 & Above
ALTON	First	Nil	2.2%	5.6%	31.1%	38.9%	22.2%
	Second	Nil	Nil	11.1%	16.7%	50.0%	22.2%
BOLTON	First	Nil	2.8%	18.9%	33.0%	35.8%	9.5%
	Second	Nil	6.0%	17.6%	17.6%	29.4%	29.4%

This concept of classification is applied to the analysis of the hypsometric integrals of the first and second orders of Alton and Bolton Creeks, and the percentage frequency distributions are shown in Table 15.

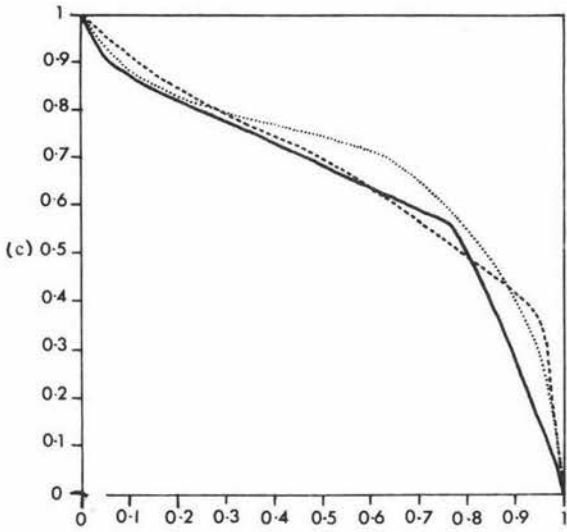
Table 16 Average Hypsometric Integrals

ORDER	ALTON CREEK	BOLTON CREEK
First	0.731	0.689
Second	0.739	0.701
Third	0.695	0.626
Fourth	0.649	0.612

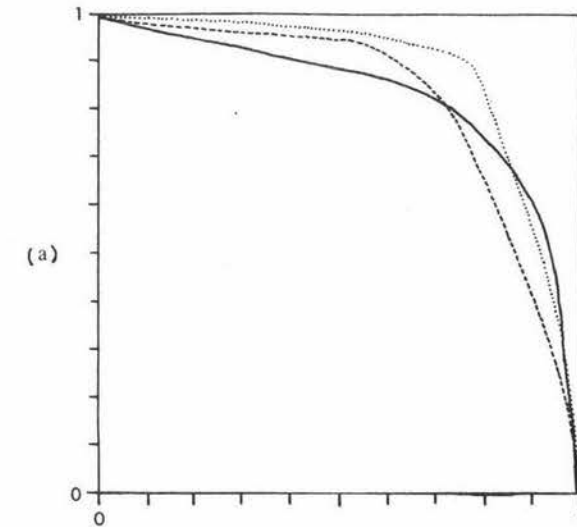
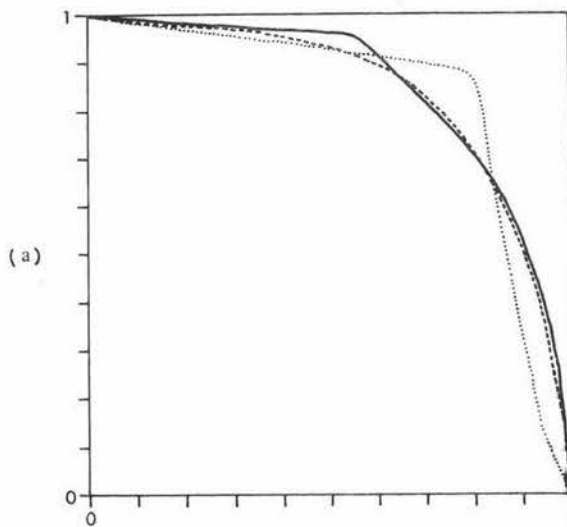
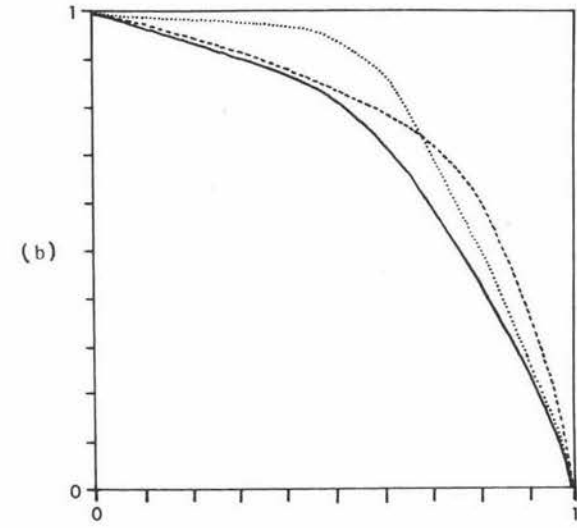
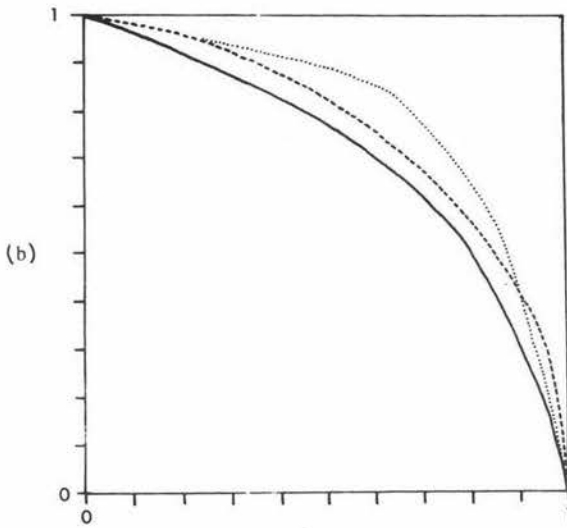
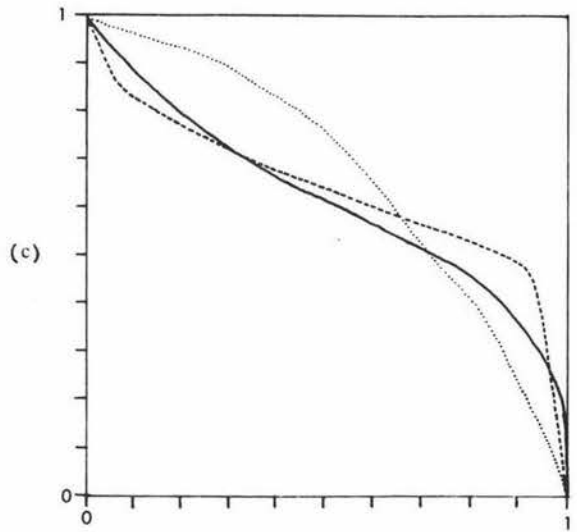
Of the first order basins, 92.2 per cent of those in Alton Creek and 78.3 per cent of Bolton Creek belong to the category of disequilibrium stage. Three sub-classifications of integrals in disequilibrium stage are found to be useful for the description of the study area. On the very top of the scale of disequilibrium is the above 80 per cent category where most of the surfaces in a basin are yet to be developed into valley side slopes. Figure 28(a) shows the common hypsometric curves under this category observed in the **first order** basins of both creeks. The curves indicate that only slight erosion has taken place while most of the land-mass still remains. The steep lower portion is normally caused by the decrease of area at the mouth of the basin and by the abrupt break where the lower order basin joins a channel of higher order, which in the study area could well be a third or fourth order stream. 22.2 per cent of Alton's first order basins belongs to this category while the proportion in Bolton Creek is con-

FIG 28 SELECTED FIRST-ORDER HYPSONOMETRIC CURVES

ALTON CREEK



BOLTON CREEK



siderably lower. This is not due to heavy dissection of Bolton's first order basins but because a great number of the basins are developed on valley side slopes of higher order channels; the general erosion as related to the relief has actually been the result of the larger higher order channels rather than of the first order basins.

Basins which had 20 to 30 per cent of mass removed are more stable than the previous category (Figure 28b). This category contains the highest frequencies of the first order basin distributions of both creeks. Although nearly 30 per cent of the total landmass has been removed, the hypsometric curves display obvious broad interfluvial areas with only minor relief features at the headwater areas. However, valley side slopes become prominent at this stage of development and the break between these valley side slopes and the flat interfluvial areas is normally marked by formations of mass movement features (Plate 4). First order basins of this category of integrals are mostly basins that were developed on the valley side slopes of higher order channels.

Of the first order basins, one-third of the total of each creek are at the lower interval of the disequilibrium stage where 30 to 40 per cent of the original landmass had been removed. The hypsometric curves show a distinctive relief where headwater areas had been **considerably eroded and the vertical rise at the lower**



Plate 4 Slope break between the interfluvial surface and valley side slope.

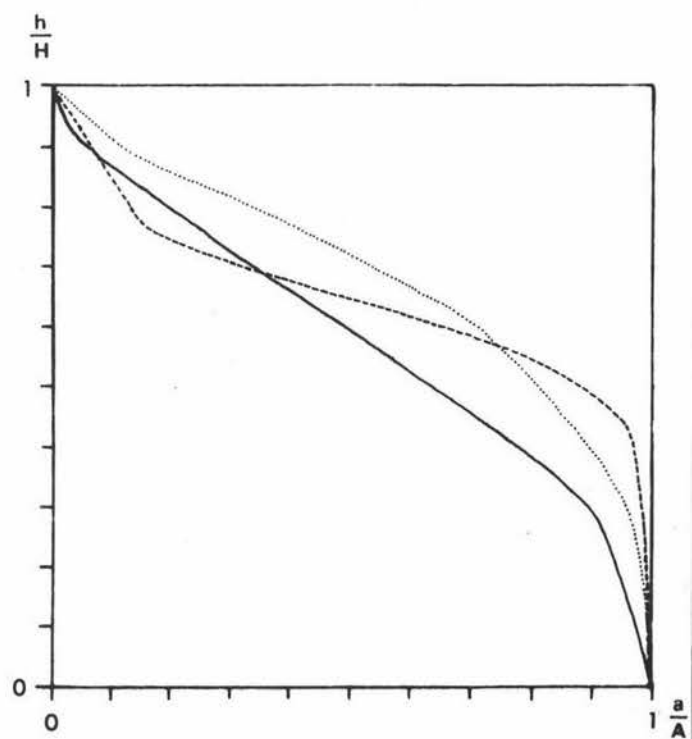
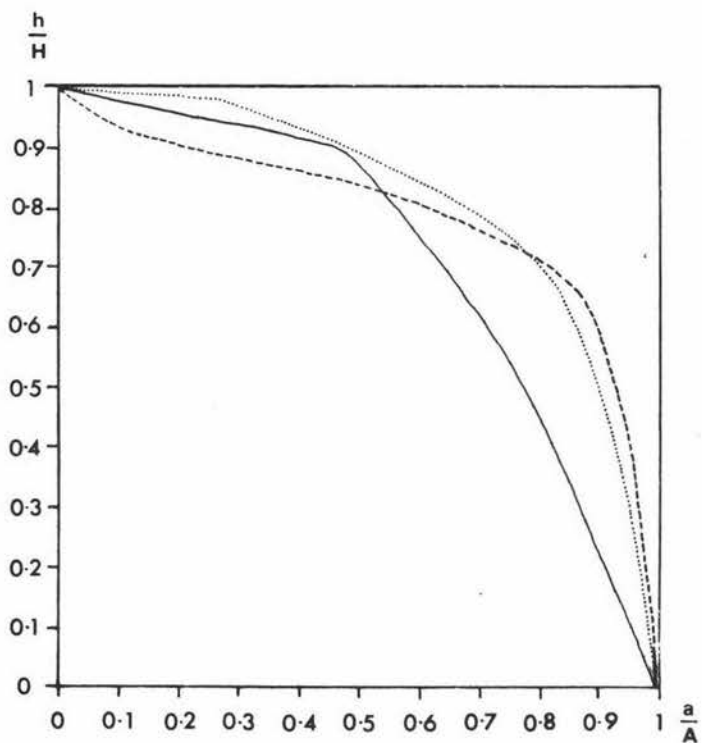
end reduced so that a near model S-shape is approached (Figure 28c). The landmass removed is normally balanced at the basin mouth.

Frequency distributions of second order integrals show a similar range to that of the first order integrals. In Alton Creek, there is a decrease of frequency in the 70.1 to 80 per cent group, but slight increases in the upper equilibrium and upper disequilibrium categories. Frequencies in Bolton's equilibrium stage do not vary much from the first order integrals but there is a slight decrease in lower disequilibrium compensated for by increases in upper disequilibrium. Figures 29(a) and (b) show selected hypsometric curves illustrating the common forms of curves observed in the second order basins of both creeks. The diagrams show that these second order basins also consist of relief which is not extensively dissected, where broad flat interfluves still occupy large proportions of the basins.

There are only two third order basins in each creek. Their hypsometric curves are shown in Figure 30. In contrast to the first and second order curves, the third order curves are appreciably different between Alton and Bolton Creeks. The Alton third order basins show a remarkable youthful stage of development as compared to the third order basins of Bolton Creek where a considerable amount of landmass had been eroded. The headwater areas of both the basins of Alton Creek are broad and

Fig.29 Selected Second-Order Hypsometric Curves

(a) ALTON CREEK



(b) BOLTON CREEK

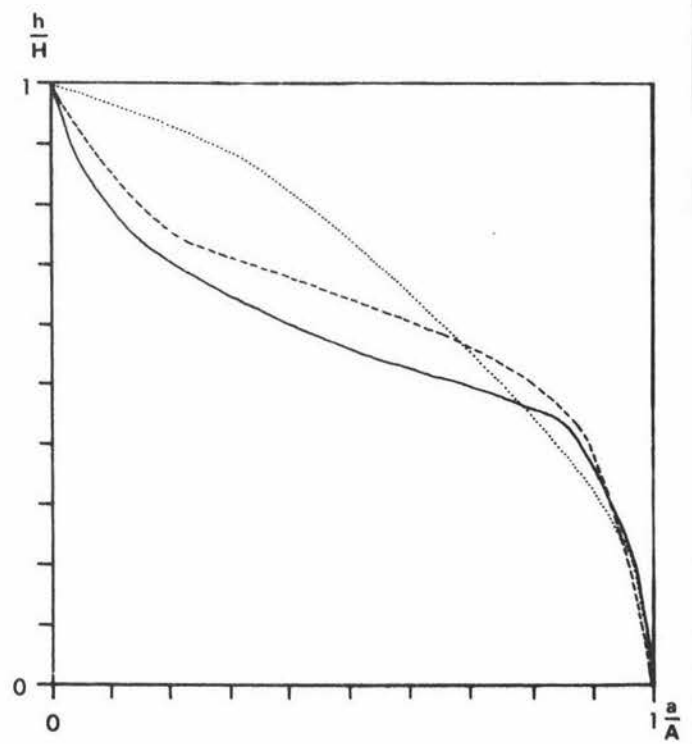
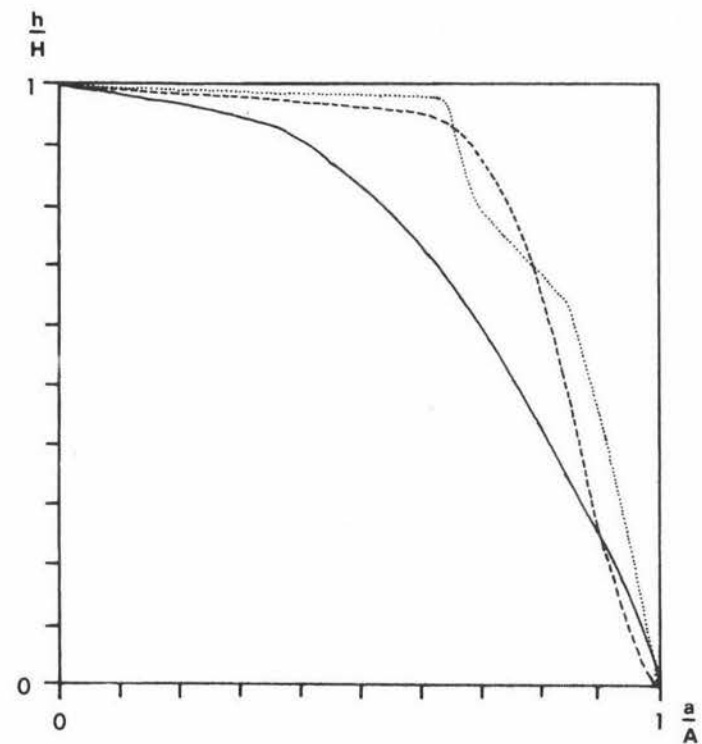
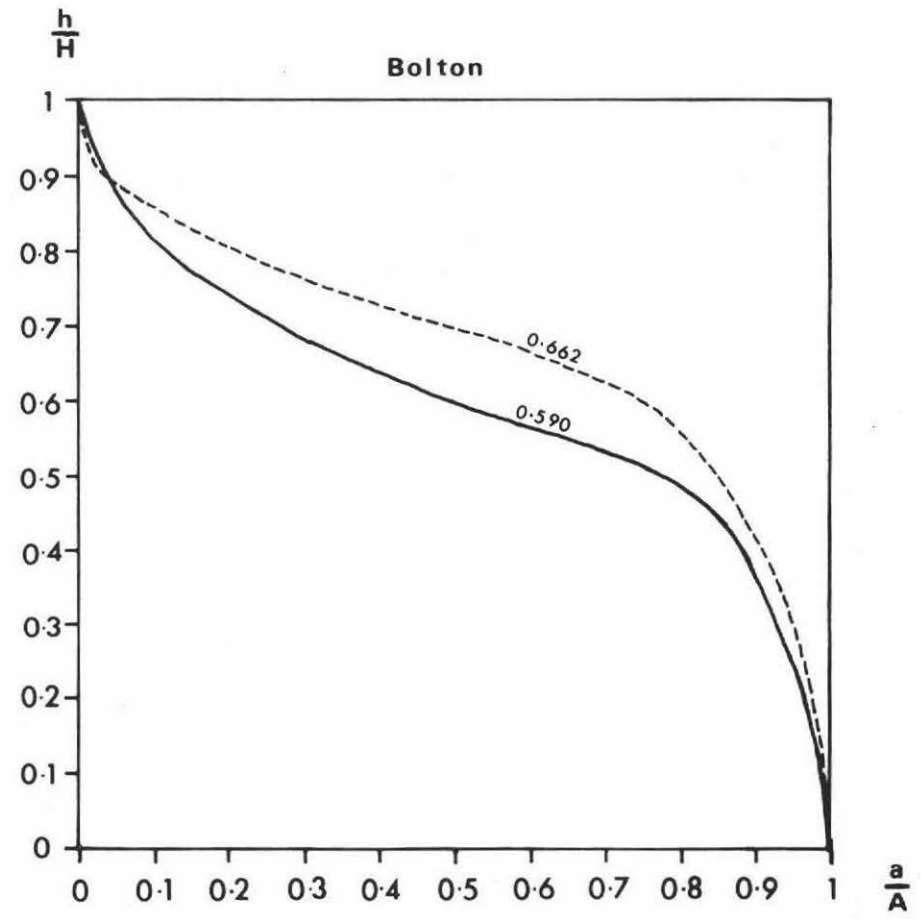
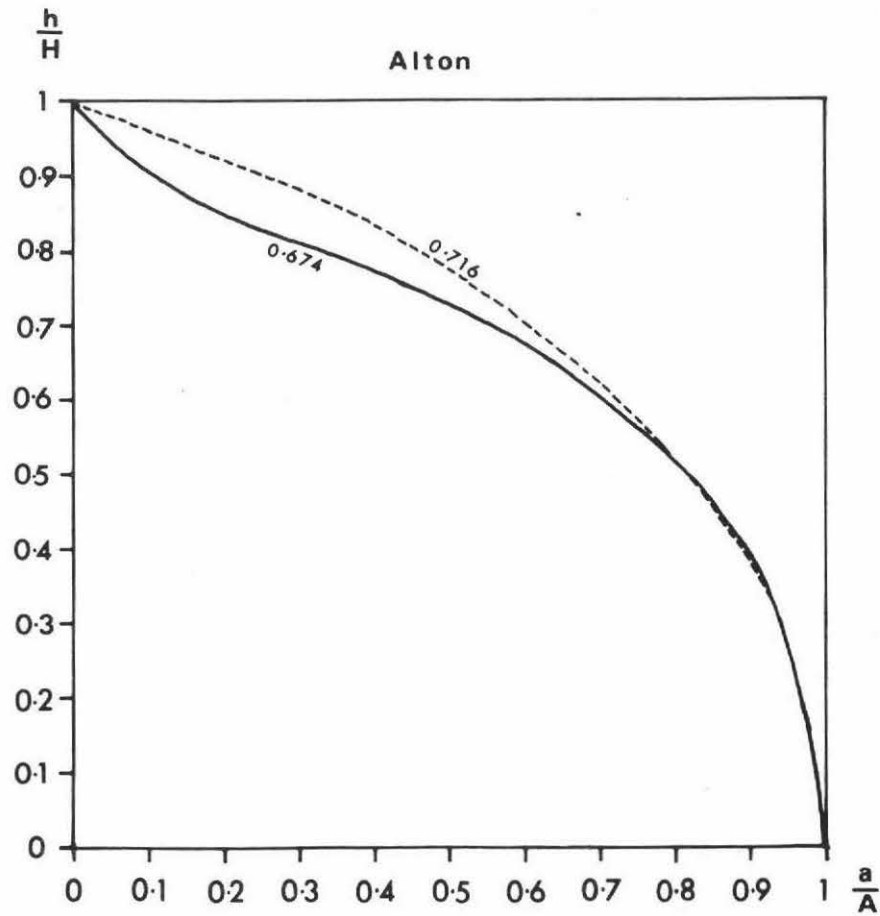


Fig. 30 Third-Order Hypsometric Curves



free of erosion. On the other hand, both basins of Bolton Creek show considerable erosion at the headwater areas and shorter vertical distances at the lower ends, giving a closer approximation to the S-shaped model curve.

The hypsometric integrals of the fourth or total order of both creeks are at the lower end of the interval of the stage of disequilibrium where more than one third of the original landmass had been removed by erosion. The curves are very close to the typical S-shape of the model hypsometric curve (Figure 31). Relief exists at the headwater areas of both creeks but in general the upper and middle reaches of the basins still consist of broad basin areas. The lower reaches near the mouths of basins consist of small areas where over 30 per cent of the altitudes enclose about 10 per cent of the total areas. Slight differences between the two basins at the middle and upper portions above the one third total altitude are observed, but below that altitude both basins display very similar features. No obvious geological effect is observed on the curves.

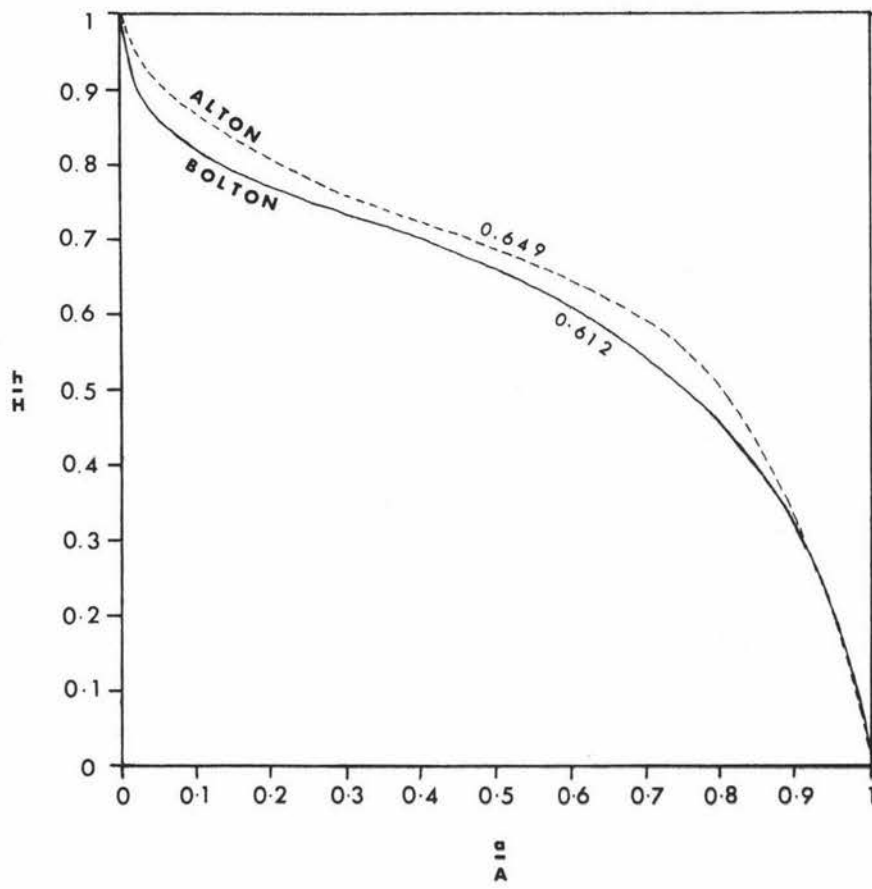
IV.9 Correlation Of Relief Variables

Strahler (1950:

1136) observed

that in mature basins, the hypsometric integral is normally negatively correlated with drainage density, total relief, stream gradient, and maximum slope. Based upon this postulate, an investigation was made into the relationships between hypsometric integral and the above mentioned four variables of the first and second order

Fig. 31 Fourth-Order Hypsometric Curves



basins of both creeks. The investigation, however, shows that in the first and second order basins of Alton and Bolton Creeks, these variables are in many cases only weakly correlated and more often than not, the correlation is positive. Table 17 shows the correlation coefficients between hypsometric integral and various variables of each order.

Table 17 Table Of Correlation Coefficients

Basin	Order	Max.Sl.	Ch.Sl.	T.Re.	Dd	
ALTON	First	0.18	0.20	0.03	-0.27	
	Second	0.39	0.44	0.41	0.03	Hyp.Int.
BOLTON	First	0.12	0.29	0.02	-0.24	
	Second	-0.10	0.58	-0.35	-0.20	

A negative correlation pattern exists in the second order basins of Bolton Creek except for channel slopes. This general increase of negative correlations from the first order basins to second order basins in Bolton Creek, suggests, in Strahler's terms, a higher degree of maturity in the second order basins. However, the degree of negative correlation is low and so they are still to reach full maturity. Basins of other orders do not display any obvious pattern of negative correlation between hypsometric and the rest of the variables. Among them, patterns of relationships between

Alton's and Bolton's first order basins are similar indicating that the relationships between hypsometric integral and the rest of the variables occur in the same manner in both first order basins. The complication of relationships increases with increasing orders.

The only variable that exists in a negative correlation with hypsometric integral throughout most of the first and second order basins is drainage density. It is inversely related to the hypsometric integral in three of the four groups of data, but is virtually unrelated to the hypsometric integral in Alton's second order basins.

The positive relations between hypsometric integral and channel slope is noteworthy, especially in the second order basins, indicating that channel slope not only does not increase when hypsometric integral becomes lower, as suggested by Strahler, but tends to decrease with decreasing integral.

The relation between total relief and hypsometric integral is low in the first order basins of both creeks. However, it becomes more prominent in second order basins where it is positive in Alton Creek and negative in Bolton Creek. A similar situation arises for the relationship between maximum slope angle and hypsometric integral. The positive correlation between these two variables in Alton's second order basins is considerably higher than in other cases.

It can be concluded that among the first order basins of the two creeks, the patterns of correlation between hypsometric integral and the rest of the variables are very much the same, and that the relationships vary among the second order basins. Bolton Creek resembles very closely Strahler's postulated condition while the Alton Creek presents a pattern of relationships remarkably at variance to his description.

It also suggests that while drainage density adjusts readily to changes in the hypsometric integral, channel gradient is the slowest among the four variables to reach a stable negative relationship. In this case study, where a large number of channels are developed on valley side slopes of higher order basins, Strahler's postulation of the negative trend of development might not occur at all.

IV.10 Summary Relief features of the study area are no where close to Cotton's description of "feral relief". The large flat interfluves and gentle slopes are in sharp contrast to the fine texture serrate landforms predominant in many parts of the North Island. The hypsometric integral, as an index measuring the amount of erosion that has taken place, indicates that a very high proportion of basins are in the stage where only a minor portion of the original landmass has been removed. However, the eroded portion increases with increasing order.

Relief ratio, which represents the general inclination of a basin, is relatively high for the drainage density and length of overland flow. Channel gradient and maximum slope angle further demonstrate this feature and emphasises the effect of an antecedent surface slope where the present drainage systems are established.

Total relief of third and fourth orders of Alton Creek show a marked set back by the stream capture of the Tiritea Stream. This, together with the phenomena discussed in the previous chapter, demonstrates that the loss of length, area, and height is difficult to re-adjust.

The abnormal relationships observed between hypsometric integral and total relief, drainage density, channel gradient and maximum slope angle reveal the unbalanced relationships among these variables.

NOTES

- (1) Chorley, R.J. and M.A. Morgan, 1962, Comparison of morphometric features, Unaka Mountains, Tennessee and North Carolina, and Dartmoor, England; Geol.Soc.Am.Bull., vol. 73(1): 17-34.
- (2) Leopold, L.B. and W.B. Langbein, 1962, The concept of entropy in landscape evolution; U.S.Geological Survey Professional Paper 500A, 20pp.

- (3) Law of Stream Gradients (Horton, 1945:195, cited in Morisawa, 1962:1034) : The mean channel gradients of each order form an inverse geometric series with order, where the first term is gradient of the first order segment and the slope of the curve is the slope ratio.
- (4) Strahler (1952:1130) : "From the standpoint of hypsometric analysis, the development of the drainage basin in a normal fluvial cycle seems to consist of two major stages only; (i) an inequilibrium stage of early development, in which slope transformations are taking place rapidly as the drainage system is expanded and ramified, (ii) an equilibrium stage in which a stable hypsometric curve is developed and maintained in a steady state as relief slowly diminishes. The monadnock phase with abnormally low hypsometric integral, when it does occur, can be regarded as transitory, because removal of the monadnock will result in restoration of the curve to the equilibrium form The hypsometric curve of the equilibrium stage is an expression of the attainment of a steady state in the processes of erosion and transportation within the fluvial system and its contributing slopes."

CHAPTER V CONCLUSIONS

This study, which has involved only two drainage basins, does not claim to have investigated aspects of all the drainage systems developed on the Tokomaru Terrace. However, it has provided some comprehensive insight into the forms and features of the Alton and Bolton basins, which could be regarded as a possible basis for future explanation of the characteristics of the Aokautere drainage systems.

The study of the linear, areal and relief characteristics of the Alton and Bolton Creeks has proven that most of the basins of all orders are in the state of disequilibrium. However, rapid changes are underway to achieve the state of equilibrium by adjustments of the internal variables. The major factor in causing this unbalanced state is the difference in length of time available for basin development. Basins of higher orders which have had more time available for development tend to have achieved characteristics closer to the equilibrium state. This has resulted in the existence of characteristic features of differing ages in a single drainage system and so the spatial features of differing ages in a single drainage system and the spatial features of different properties are in fact the sequence of facets of gradual growth of the systems.

The criteria of assessing the state of equilibrium in drainage basins were based upon work done overseas which obviously was on very different types and sizes of landforms. Even the scales of maps used have varied. This inevitably has resulted in differences of values of absolute properties of the systems involved. Therefore no absolute comparison of orders has been attempted between the present study area and results of other studies. All comparisons have been made on a relative basis.

The study has also revealed that detailed morphometric study on very large scale maps may possibly lead to different types of conclusions from those studies based on small scale maps of extensive areas. A **large** scale study like this has very high chances of discovering phenomena of minor importance, which may eventually lead to interpretations of different meanings in landform analysis.

Although the small size of the study area has precluded the study of large scale features of "historical inheritance", it has to some extent expressed the non-continuous nature of New Zealand landform history and its high tempo of temporal changes as discussed in Chapter II.

Developments toward equilibrium can also be disrupted by a neighbouring system. Alton Creek, which is

developed on the same geology and under the same climate as Bolton Creek, has remarkably different and more unstable morphometric characteristics due to the capture of parts of its catchment areas by the neighbouring Tiritea Stream.

REFERENCES

- Abrahams, A.D., 1968, Distinguishing between the concepts of steady state and dynamic equilibrium in geomorphology. Earth Sci. Jnl., vol. 2(2): 160-166.
- Adkin, G.L., 1910, The post-Tertiary geological history of the Ohau River and of the adjacent coastal plain, Horowhenua County, North Island. Trans. N.Z. Inst., vol. 43: 496-520.
- Birot, P., 1968, The cycle of erosion in different climates. Batsford, London.
- Broscoe, A.J., 1959, cited in Bowden and Wallis, 1964.
- Bowden, K.L. and J.R. Wallis, 1964, Effect of stream ordering technique on Horton's laws of drainage composition. Bull. Geol. Soc. Am., vol. 75: 767-774.
- Carter, C.S. and R.J. Chorley, 1961, Early slope development in an expanding stream system. Geol. Mag., vol. 98: 117-130.
- Chorley, R.J., 1957, Climate and morphometry. Jour. Geol. vol. 65: 628-635.
- 1957a, Illustrating the laws of morphometry. Geol. Mag., vol. 19: 140-150.
- 1958, Aspects of the morphometry of poly-cyclic drainage basins. Geog. Jour., vol. 66: 370-374.

- Chorley, R.J.** and M.A. Morgan, 1962, Comparison of morphometric features, Unaka Mountains, Tennessee and North Carolina, and Dartmoor, England. Bull. Geol. Soc. Am., vol. 73(1):17-34.
- Cole, J.P. and C.A.M. King, 1968, Quantitative Geography. John Willey & Sons, London, New York and Sydney.
- Conacher, A.J.**, 1967, A systems approach to the description and interpretation of the landsurface of the northern half of North Island, New Zealand. Earth Sci. Jnl., vol 1(2):118-123.
- Cotton, C.A.** 1918, The geomorphology of the coastal district of southwestern Wellington. Trans. R. Soc. N.Z., vol. 50:212-222.
- 1941, Landscape. University Press, Cambridge.
- 1942, Geomorphology. Whitcombe & Tombs, Christchurch and London.
- 1949, Landscape as developed by the processes of normal erosion.
- 1958, Fine-textured erosional relief in New Zealand. Zeit. für Geom., NF Band 2(3):187-210.
- 1962, The origin of New Zealand feral (fine-textured) relief. N.Z. Jour. Geol. Geophys., vol. 5(2):269-270.

- Cotton, C.A., 1963, Development of fine-textured landscape, relief in temperate pluvial climates. N.Z. Jour. Geol. & Geophys., vol. 6(4):528-533.
- Cowie, J.D., 1961, Aokautere Ash in the Manawatu District, N.Z., and its significance to soils and soil formation in the sand country of the Manawatu-Horowhenua District, N.Z. Unpublished Msc. Thesis, Victoria University of Wellington.
- 1964, Loess in the Manawatu District, N.Z. N.Z. Jour. Geol. & Geophys., vol. 7(2):389-396.
- 1964a, Aokautere Ash in the Manawatu District, N.Z. N.Z. Jour. Geol. & Geophys., vol. 7(1):67-77.
- Davis, W.M., 1899, The geographic cycle. Geog. Jour., vol. 14:481-504. Chapter 13 in Johnson, D.W., 1909 (ed) Geographical Essays, republished 1954, Dover Publications.
- Eyles, R.J., 1968, Stream net ratios in West Malaysia. Bull. Geol. Soc. Am., vol. 79:701-712.
- Fair, E.E., 1968, Structural, tectonic and climatic control of the fluvial geomorphology of the Manawatu River west of the Manawatu Gorge. Unpublished Msc. Thesis, Massey University.

- Garnier, B.J., 1958, The climate of New Zealand, A geographic survey. Arnold, London.
- Gray, D.M., 1961, Interrelationships of watershed characteristics. Jour. Geophys. Res., vol. 66: 1215-1223.
- Gregory, S., 1968, Statistical methods and the geographer. 2nd ed., Longmans, London.
- Hack, J.T., 1957, Studies of longitudinal stream profile in Virginia and Maryland. U.S. Geol. Surv. Prof. Paper 194B.
- _____ 1960, Interpretation of erosional topography in humid temperate regions. Am. J. Sci., vol. 258A: 80-97.
- Horton, R.E., 1945, Erosional development of stream and their drainage basins; hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Am., vol. 56: 275-370.
- King, C.A.M., 1966, Techniques in geomorphology. Arnold, London.
- Leopold, L.B. and W.B. Langbein, 1962, The concept of entropy in landscape evolution. U.S. Geol. Surv. Prof. Paper 282B.
- Leopold, L.B., M.G. Wolman and J.P. Miller, 1964, Fluvial processes in geomorphology. Freeman, San Francisco.

- Melton, M.A., 1958, Correlation structure of morphometric properties of drainage systems and their controlling agents. Jour. Geol., vol. 66: 442-460.
- 1960, Intravalley variation in slope angles related to microclimate and erosional environment. Bull. Geol. Soc. Am., vol. 71: 133-144.
- Morgan, R.P.C., 1971, A morphometric study of some valley systems on the English Chalklands. Trans. Inst. Brit. Geogr. vol. 54: 33-44.
- Morisawa, M.E., 1962, Quantitative geomorphology of some watersheds in the Appalachian Plateau. Bull. Geol. Soc. Am., vol. 1025-1046.
- Morisawa, M.E., 1968, Streams, their dynamics and morphology. McGraw-Hill, New York.
- Oliver, R.L., 1948, The Otaki Sandstone and its geological history. D.S.I.R. Memoir No. 7.
- Parvis, M., 1949, Drainage pattern significance in airphoto identification of soils and bedrocks. Photogramm. Engng. vol. 16: 387-408.
- Rich, C.C., 1959, Late Cenozoic history of the lower Manawatu valley. Unpublished Ph.D. thesis, Harvard University. Microfilm lodged in Massey University, Palmerston North.

- Saunders, B.G.R. and A.G. Anderson (ed), 1964, Introducing Manawatu. Massey University, Palmerston North.
- Schumm, S.A., 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, N.J. Bull. Geol. Soc. Am., vol. 67: 597-646.
- Schumm, S.A. and R.W. Lichty, 1965, Time, space and causality in geomorphology. Am. J. Sci., vol. 263: 110-119.
- Selby, M.J., 1967, Aspects of the geomorphology of the greywacke ranges bordering the lower and middle Waikato Basins. Earth Sci. Jnl., vol. 1(1): 37-58.
- Selby, M.J., 1970, Slopes and slope processes. New Zealand Geographical Society, Waikato branch.
- Strahler, A.N., 1950, Equilibrium theory of erosional slopes approached by frequency distribution analysis. Am. J. Sci.,
- 1952, Dynamic basis of geomorphology. Bull. Geol. Soc. Am., 63: 923-938.
- 1952a, Hypsometric (area-altitude) analysis of erosional topography. Bull. Geol. Soc. Am., 63: 1117-1142.
- 1954. Statistical analysis in geomorphic research. Jour. Geol., vol. 62: 1-25.

- Strahler, A.N., 1956, Quantitative slope analysis.
Bull. Geol. Soc. Am., vol. 67: 571-596.
- 1957, Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Un., vol. 38: 913-920.
- 1958, Dimensional analysis applied to fluvially eroded landforms.
Bull. Geol. Soc. Am., vol. 69: 279-300.
- 1964, Quantitative geomorphology of drainage basins and channel networks. In Chow, V.T., 1964 (ed) Handbook of applied hydrology, McGraw-Hill, New York.
- Von Bandat, H.F. 1962, Aerogeology. Gulf, Texas.